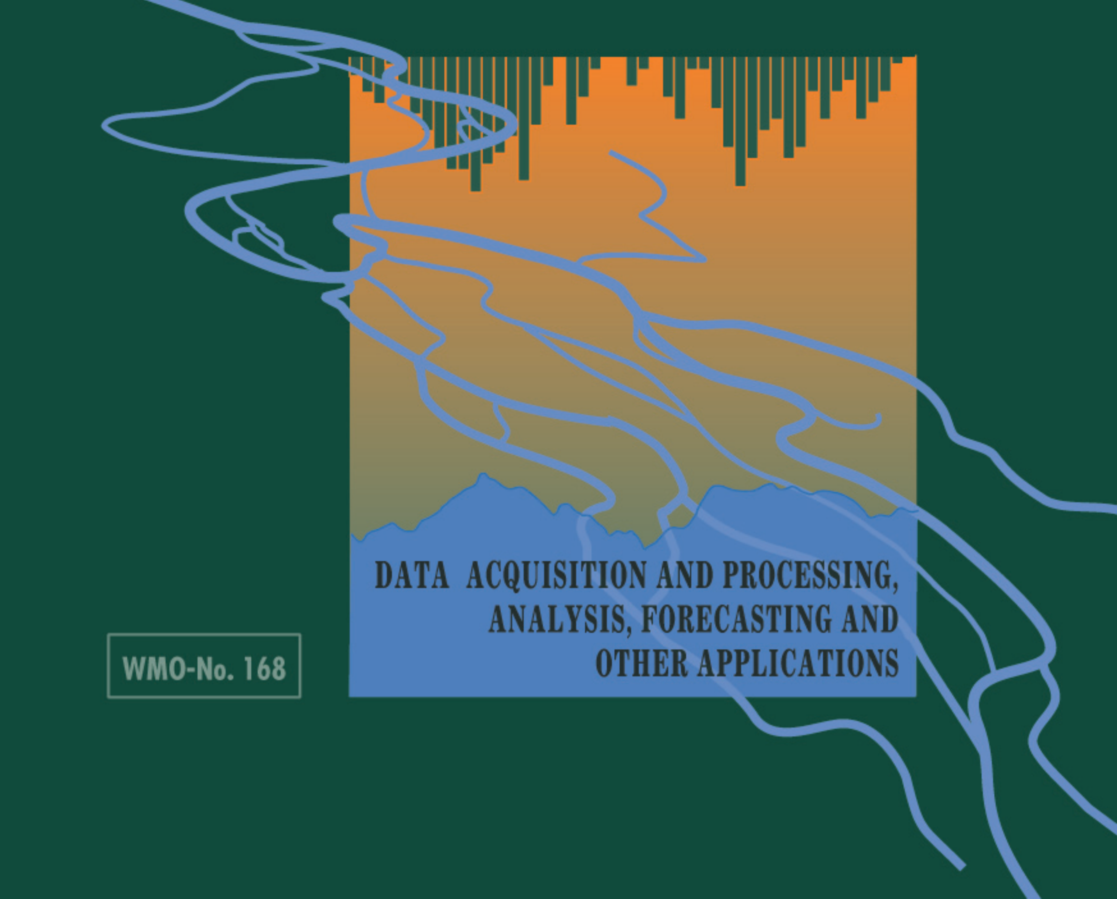
World Meteorological Organization

Welcome

GUIDE
TO HYDROLOGICAL PRACTICES



DATA ACQUISITION AND PROCESSING, ANALYSIS, FORECASTING AND OTHER APPLICATIONS

WMO-No. 168

World Meteorological Organization

GUIDE

TO HYDROLOGICAL PRACTICES

Fifth edition
1994

DATA ACQUISITION AND PROCESSING,
ANALYSIS, FORECASTING AND
OTHER APPLICATIONS

WMO-No. 168

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PREFACE

One of the purposes of the World Meteorological Organization is to promote standardization of meteorological and hydrological observations and to ensure uniform publication of observations and statistics. With this aim in view, the World Meteorological Congress has adopted *Technical Regulations* which lay down the meteorological and hydrological practices and procedures to be followed by Member countries of the Organization. These *Technical Regulations* are supplemented by a number of *Guides,* which describe in more detail the practices, procedures and specifications which Members are invited to follow or implement in establishing and conducting their arrangements for compliance with the *Technical Regulations* and in developing and operating Meteorological and Hydrological Services in their respective countries.

The present publication originated from the first session (Washington, 1961) of the WMO Commission for Hydrology, which recognized the urgent need for the preparation of a guide to hydrological practices. The first edition was published in 1965 as the *Guide to Hydrometeorological Practices.*

The second and third editions of the *Guide* were published in 1970 and 1974, respectively. The third edition was renamed *Guide to Hydrological Practices* in recognition of the broader scope of its contents. The revision and the substantial additions to the *Guide,* approved by the Commission at its fifth session (Ottawa, 1976), made it necessary to publish the fourth edition in two volumes. Volume I dealt with data acquisition and processing, and Volume II dealt with analysis, forecasting and other applications. Volumes I and II of the fourth edition were published in 1981 and 1983, respectively.

At its eighth session (Geneva, 1988) the Commission approved a new layout for the fifth edition of the *Guide,* whereby the chapters of the fourth edition would become parts which would be subdivided into chapters, each with its own list of references. It decided that each chapter would treat one hydrological variable or subject and expressed the view that such an arrangement would simplify consultation, future revisions and cross-referencing with the *HOMS Reference Manual.* This edition of the *Guide* consists of six parts containing 59 chapters and is published as a single volume. In addition to the present English version, the *Guide* is translated into the other three official languages of the Organization (French, Spanish and Russian). Also, as with previous versions, several Members of the Organization have announced their intention to translate this *Guide* into their national language.

The aim of the *Guide to Hydrological Practices* is to provide, to all those engaged in the field of hydrology, information on current practices, procedures and instrumentation, which would help them in successfully carrying out their work. Complete descriptions of the theoretical bases and the range of applications of hydrological methods and techniques are beyond the scope of this *Guide*. However, references to such documentation are provided wherever applicable.

It is hoped that this *Guide* will be of use, not only to Hydrological and Meteorological Services, but also to as many agencies as possible worldwide which are involved with water-resources monitoring and assessment. Users of the *Guide* are invited to continue sending to the Secretary-General their comments and suggestions for its further improvement.

It is with great pleasure that I express the gratitude of the World Meteorological Organization to the more than forty experts from around the world who have contributed to the preparation of this edition of the *Guide*. Special thanks are due to Messrs M. Roche (France) and A. R. Perks (Canada) for their efforts in compiling the initial draft and for the review of Part B; Messrs A. Hall and B. Stewart (Australia) for their review of Part C; Drs F. Bultot (Belgium), S. Zevin (USA) and V. R. Schneider (USA) for their review of Parts D, E and F, respectively. For new material which has been prepared, our deep appreciation goes to Mr M. Normand (France) for Chapter 15 (soil-moisture measurements); Dr P. Pilon (Canada) for Chapter 36 (flood-flow frequency); Dr G. Young and Mr A. Perks (Canada) for Chapter 48 (sustainable water development) and to Dr L. Goda (Hungary) for Chapter 57 (navigation and river training). Our particular gratitude goes to Dr M. Moss (USA) for his assistance in putting together the final draft and to Dr O. Starosolszky (Hungary) for his guidance throughout the preparation of this edition of the *Guide*.

G. O. P. Obasi
Secretary-General

PART A
GENERAL

CHAPTER 1
INTRODUCTION TO THE *GUIDE*

1.1 Scope of the *Guide*

Hydrology is the science that deals with the occurrence and distribution of the waters of Earth, including their chemical, biological and physical properties, and their interaction with the physical environment. As such, it is the basis for solving practical problems of floods and droughts, erosion and sediment transport, and water pollution. Indeed, increasing concerns for the pollution of surface waters and groundwaters, acid rain, drainage of wetlands and other types of land-use change, together with the threats to water resources posed by climate change and sea-level rise, have highlighted the central role of hydrology in many environmental initiatives.

This *Guide* addresses these and several other aspects of the hydrological cycle, especially its phases upon and under the surface of the land. Naturally, it is focused on those areas that fall within the scope of the hydrology and water-resources activities of the World Meteorological Organization to enhance the support to National Hydrological Services and services with a similar mission. Accordingly, the *Guide* treats the main variables of the hydrological cycle and their expression through the movement and storage of water:

(*a*) Precipitation;
(*b*) Snow cover (distribution, depth, density, water equivalent);
(*c*) Water level (rivers, lakes, reservoirs, wells and boreholes);
(*d*) Streamflow, sediment discharge, and surface-water quality;
(*e*) Evaporation and evapotranspiration;
(*f*) Soil moisture; and
(*g*) Groundwater, including water quality.

1.2 Plan and content of the *Guide*

Activities in hydrology at the national level have increased rapidly during the past decades. There are also numerous bilateral assistance programmes in this field, in addition to those of the United Nations and its specialized agencies, and it is not unusual for hydrological programmes to overlap in a particular country. All this has increased the need for international guidance material and standards, and it is hoped that this *Guide* will fulfil this need.

To meet all such requirements, continuing efforts are being made to expand and improve this *Guide*, this being now the fifth edition. The *Guide* is composed of six parts:

Part: A	General - Chapters 1 to 5
B	Hydrological Instruments and Methods of Observation and Estimation - Chapters 6 to 18
C	Collection, Processing, and Dissemination of Hydrological Data - Chapters 19 to 25
Part: D	Hydrological Analysis - Chapters 26 to 40
E	Hydrological Forecasting - Chapters 41 to 46
F	Applications for Water Management - Chapters 47 to 59

Chapters 1 to 5 (Part A) provide information of a general nature concerning the water-related activities of WMO and of other international organizations, as well as the WMO standards and regulations in hydrology and on the functions and responsibilities of national Hydrological Services.

Chapters 6 to 25 (Parts B and C) deal with instruments and methods of observation, the design of hydrological networks, and the collection, processing and publication of data. WMO Members are invited to follow and implement these various practices and specifications in developing and operating their national Hydrological Services. The adoption of the recommended practices would be of special benefit in countries where hydrological networks are being established, or are otherwise operated by a number of governmental and private agencies and institutions. These chapters overlap, to some extent, with material presented in other WMO guides, but emphasis is placed here on water-resources development and management. It is expected that this *Guide* will be used by agencies other than Hydrological Services, and it was therefore considered preferable that it be essentially complete, rather than rely on excessive reference to other WMO guides.

Chapters 26 to 59 (Parts D, E, and F) deal with methods of analysis, hydrological forecasting, and other applications to water-management projects and problems. While a measure of standardization has been achieved (and continued progress may be expected) with respect to instruments, methods of observation and publication practices, this is hardly the case with respect to hydrological analysis and applications. Therefore, alternative approaches to the solution of selected problems that have been demonstrated, through experience, to be both practical and satisfactory are described. The aim has been to draw attention to the existence of the several useful techniques and to present the principal features and advantages of each, rather than to recommend any one in preference to the others. The multitude of factors involved (hydrological and climatic regime, available information and data, purposes to be served, etc.) dictate that sound recommendations be made on a full understanding of individual situations. During the past few years, the increasing availability of microcomputers has permitted the introduction of more sophisticated analytical methods and techniques. Since some of these have now been adopted widely, they have been introduced into this *Guide*.

As previously mentioned, duplication exists, and some material would be equally appropriate in two or more chapters. For example, there is no clear distinction between processing and analysis of data. If monthly isohyetal maps are published, they may be considered to constitute processed precipitation data. Under other circumstances, the preparation of an isohyetal map is one step in the analysis of hydrological data to develop a rainfall-runoff relationship for forecast purposes. A similar difficulty arises in connection with other derived hydrological and climatological elements. An attempt has been made to minimize such difficulties through cross-references among chapters.

A full description of the theoretical base for the recommended practices, and detailed discussion of their methods of application are beyond the scope of this *Guide*. For such details, the reader is referred to appropriate WMO manuals and technical reports, as well as to other textbooks, handbooks, and agency manuals. References appear at the end of each chapter.

1.3 Cross-reference between the *Guide* and the *HOMS Reference Manual*

In order to provide an easy cross-reference to the *Hydrology Operational Multipurpose System (HOMS) Reference Manual (HRM)* (section 2.3), references (in square brackets) to relevant subsections of the *HRM* are included on the right margin of the headings of *Guide* sections, when appropriate.

CHAPTER 2

WATER-RELATED ACTIVITIES OF WMO

2.1 General overview

The World Meteorological Organization (WMO), of which some 172 States and Territories are Members, is a specialized agency of the United Nations. According to Article 2 of the Convention of WMO [1], the purposes of the Organization are:

(*a*) To facilitate worldwide cooperation in the establishment of networks of stations for the making of meteorological observations as well as hydrological and other geophysical observations related to meteorology, and to promote the establishment and maintenance of centres charged with the provision of meteorological and related services;
(*b*) To promote the establishment and maintenance of systems for the rapid exchange of meteorological and related information;
(*c*) To promote standardization of meteorological and related observations and to ensure the uniform publication of observations and statistics;
(*d*) To further the application of meteorology to aviation, shipping, water problems, agriculture and other human activities;
(*e*) To promote activities in operational hydrology and to further close cooperation between Meteorological and Hydrological Services; and
(*f*) To encourage research and training in meteorology and, as appropriate, in related fields and to assist in coordinating the international aspects of such research and training.

The Organization consists of the following:

(*a*) The World Meteorological Congress is the supreme body of the Organization. It brings together the delegates of all Members once every four years to determine general policies for the fulfilment of the purposes of the Organization;
(*b*) The Executive Council, composed of 36 directors of national Meteorological or Hydrometeorological Services, meets at least once a year to supervise the programmes approved by Congress;
(*c*) The six regional associations (Africa, Asia, South America, North and Central America, South-West Pacific, and Europe), composed of Member Governments, coordinate meteorological and related activities within their respective Regions;
(*d*) The eight technical commissions, composed of experts designated by Members, study matters within their specific areas of competence. (Technical commissions

have been established for basic systems, instruments and methods of observation, atmospheric sciences, aeronautical meteorology, agricultural meteorology, marine meteorology, hydrology, and climatology);

(*e*) The Secretariat serves as the administrative, documentation, and information centre of the Organization. It prepares, edits, produces, and distributes the publications of the Organization, carries out the duties specified in the Convention and other Basic Documents and provides secretariat support to the work of the constituent bodies of WMO described above.

Figure 2.1 shows the organizational structure of WMO and Figure 2.2 delineates the six regional associations of WMO.

2.1.1 *Purpose and scope of water-related activities*

The commitment in the field of operational hydrology, as set out in the above-mentioned Article 2(*e*) of the Convention, is exercised through the Hydrology and Water Resources Programme (HWRP). This programme assists the Hydrological Services of Members in matters of operational hydrology and in mitigating water-related hazards, such as floods and droughts. It also promotes cooperation between countries at regional and subregional levels, particularly where shared river basins are concerned, including education and training activities in hydrology.

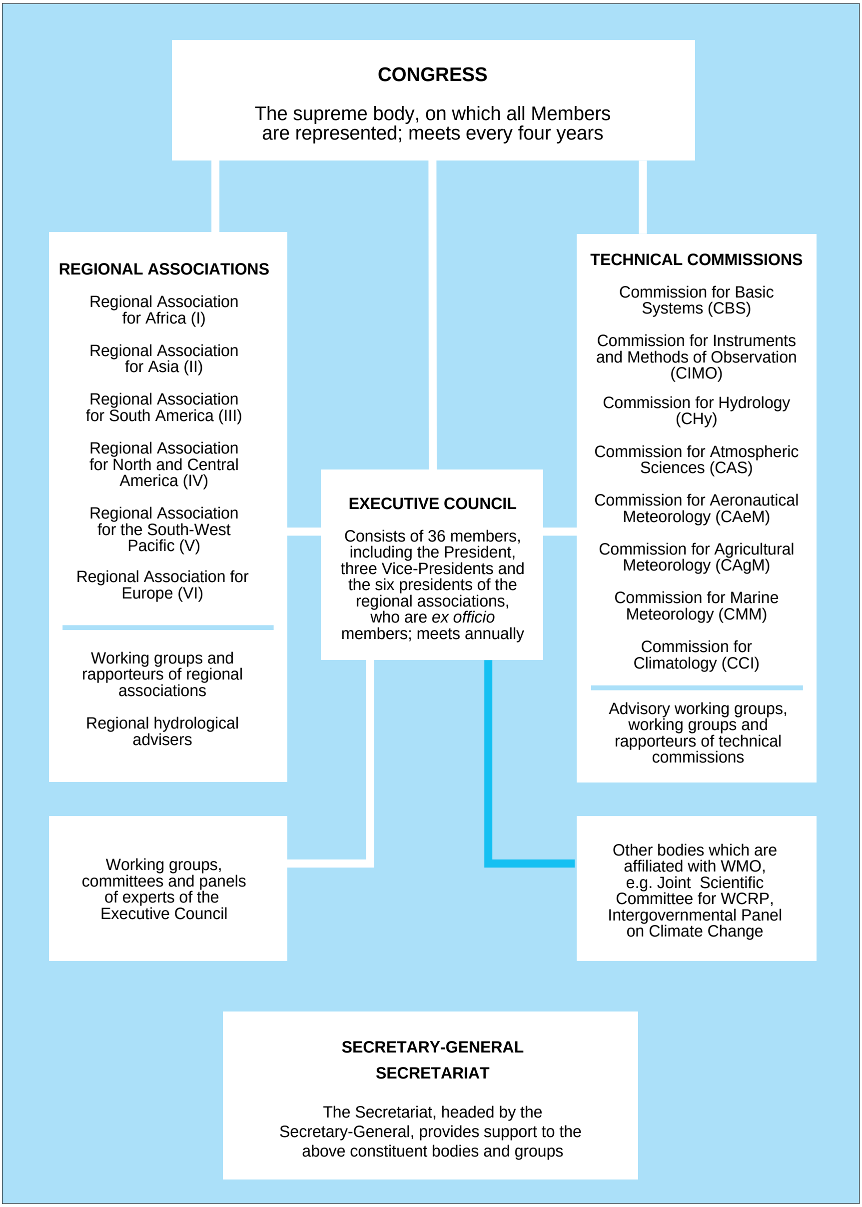
The scope of the HWRP is basically operational hydrology which, as defined in the WMO General Regulations [2], comprises:

(*a*) The measurement of basic hydrological elements from networks of meteorological and hydrological stations: collection, transmission, processing, storage, retrieval, and publication of basic hydrological data;
(*b*) Hydrological forecasting;
(*c*) The development and improvement of relevant methods, procedures, and techniques in:
  (i) Network design;
  (ii) Specification of instruments;
  (iii) Standardization of instruments and methods of observation;
  (iv) Data transmission and processing;
  (v) Supply of meteorological and hydrological data for design purposes;
  (vi) Hydrological forecasting.

It should be noted that hydrological data here are taken to include data on the quantity and quality of both surface water and groundwater. Operational hydrology is therefore strongly interrelated with water-resource assessment.

The current overall main objective of the HWRP, as given in the Third WMO Long-term Plan (1992-2001) [3], is:

> “To ensure the assessment and forecasting of the quantity and quality of water resources, in order to meet the needs of all sectors of society, to enable mitigation of water-related hazards, and to maintain or enhance the condition of the global environment.”



CONGRESS

The supreme body, on which all Members are represented; meets every four years

REGIONAL ASSOCIATIONS

Regional Association for Africa (I)

Regional Association for Asia (II)

Regional Association for South America (III)

Regional Association for North and Central America (IV)

Regional Association for the South-West Pacific (V)

Regional Association for Europe (VI)

Working groups and rapporteurs of regional associations

Regional hydrological advisers

EXECUTIVE COUNCIL

Consists of 36 members, including the President, three Vice-Presidents and the six presidents of the regional associations, who are *ex officio* members; meets annually

TECHNICAL COMMISSIONS

Commission for Basic Systems (CBS)

Commission for Instruments and Methods of Observation (CIMO)

Commission for Hydrology (CHy)

Commission for Atmospheric Sciences (CAS)

Commission for Aeronautical Meteorology (CAeM)

Commission for Agricultural Meteorology (CAgM)

Commission for Marine Meteorology (CMM)

Commission for Climatology (CCl)

Advisory working groups, working groups and rapporteurs of technical commissions

Working groups, committees and panels of experts of the Executive Council

Other bodies which are affiliated with WMO, e.g. Joint Scientific Committee for WCRP, Intergovernmental Panel on Climate Change

SECRETARY-GENERAL

SECRETARIAT

The Secretariat, headed by the Secretary-General, provides support to the above constituent bodies and groups

Figure 2.1 — Organizational structure of the World Meteorological Organization.

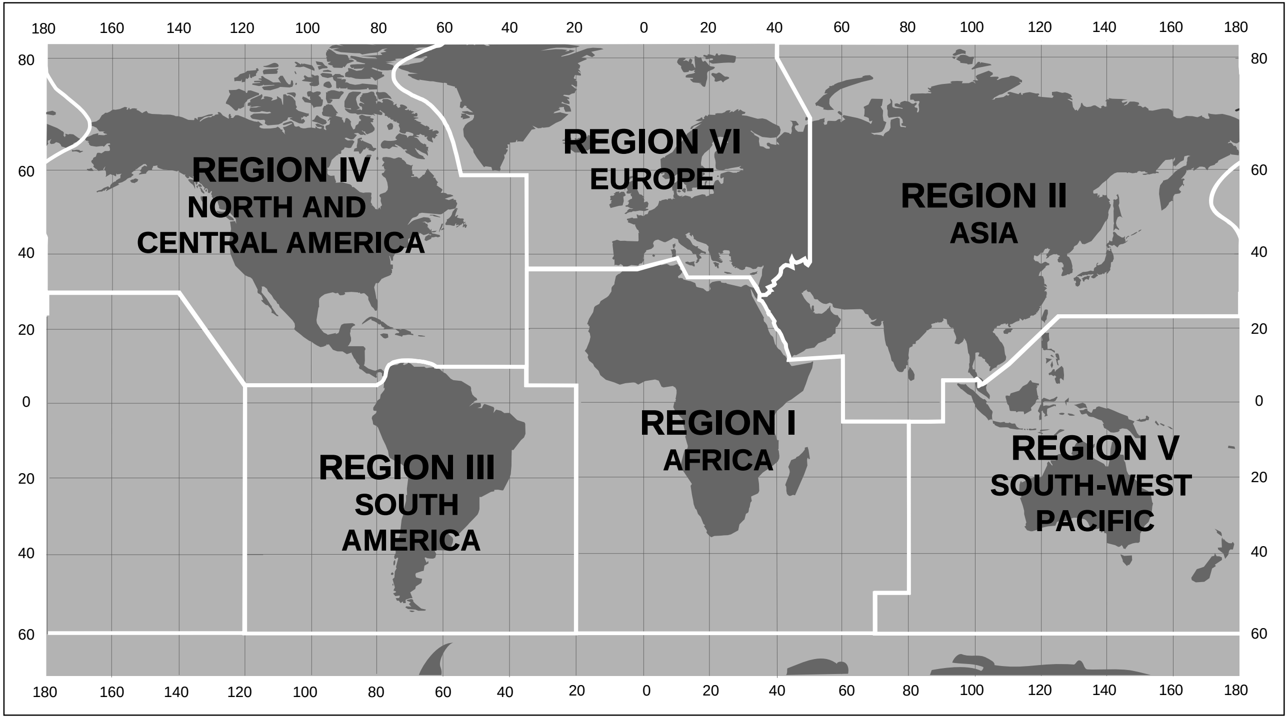


Figure 2.2 — Limits for WMO Regions.

This objective accords with the recommendations of the UN Water Conference (Mar del Plata, 1977) [4] and the International Conference on Water and the Environment (Dublin, January 1992) [5].

The HWRP is closely linked to other WMO Programmes having important hydrological components, such as the Tropical Cyclone Programme (TCP) and the World Climate Programme (WCP). In addition, a substantial proportion of WMO's technical cooperation is in the field of operational hydrology, funded largely through the UNDP. Regional aspects of projects covered by the HWRP are implemented principally by the six regional working groups on hydrology in WMO's six regional associations. The HWRP contributes to, or has links with, a large number of other international programmes, including those of UNESCO, UNEP, WHO, FAO, and the UN Regional Economic Commissions.

Because of the leading role the Organization plays regarding natural hazards, such as tropical cyclones, floods and droughts, the United Nations International Decade for Natural Disaster Reduction (IDNDR, 1990-1999) [6] has called for a significant response from WMO.

2.1.2 *Programme organization*

The HWRP, one of the major Programmes of WMO, has three mutually supporting components:

Operational Hydrology Programme (OHP) — Basic Systems

- This component concentrates on the basic organization, operation, and development of Hydrological Services. It includes the development, comparison, standardization, and improvement of hydrological instruments and methods for the collection and archiving of water-resources information (quantity and quality of both surface water and groundwater), and human-resource development. Specific support for the transfer of technology is provided through the Hydrological Operational Multipurpose System (HOMS) (section 2.3).

Operational Hydrology Programme — Applications and Environment

- This component brings together hydrological activities in support of water-resources development and management, including hydrological modelling and forecasting, and the provision of data for a range of projects, including those for environmental protection. It contributes to various meteorological and climatological programmes of WMO, such as the Tropical Cyclone Programme and the World Climate Programme.

Programme on Water-related Issues

- This component contributes to the international programmes of other bodies within the UN family (Chapter 5), and to those of intergovernmental organizations and non-governmental organizations through inter-agency coordination and collaboration in water-related activities, including regional projects associated with large international river basins.

The future development of the HWRP is set out in WMO's successive Long-Term Plans [3] as agreed by the Congress of WMO. The regular programme of WMO provides four-year budgets for implementation of activities under the HWRP.

2.1.3 *Programme implementation*

The OHP is planned and executed under the aegis of the WMO Commission for Hydrology (CHy). Implementation is principally through a system of working groups and individual rapporteurs, who address specific aspects of operational hydrology appropriate to their expertise, through the convening of technical meetings and symposia, and through organizing training courses.

Specific projects are designed to investigate and compare technology, such as instruments, forecasting models and network-design techniques. Project results are published, principally in the series of WMO Operational Hydrology Reports. The essence of these and other activities are summarized in this *Guide to Hydrological Practices,* which provides guidance to key subjects over a wide range of climate and terrain conditions. Agreed standard practices are published in Volume III (Hydrology) of the *WMO Technical Regulations* [2] (see also Chapter 4).

Working groups on hydrology are also established by the six regional associations of WMO to address some topics covered by the HWRP and others relevant to the hydrological problems of their respective Regions, including:

(*a*) Surveys of the adequacy of networks of hydrological stations, hydrological data-transmission and processing facilities, data banks, and hydrological forecasting;
(*b*) The application of WMO standards and recommended practices in hydrology;
(*c*) The development and promotion of the Hydrological Operational Multipurpose System (HOMS); and
(*d*) Contributions to projects under the World Climate Programme-Water.

The Hydrological Operational Multipurpose System (HOMS) is a technology-transfer system for operational hydrology, established in 1981, under the OHP. Its aim is to assist hydrologists, primarily in developing countries, by making available to them appropriate, modern technology to help solve their hydrological problems. A description of HOMS is provided in section 2.3.

Two computer databases have been established as part of the HWRP, namely:

(*a*) The Hydrological Information Referral Service (INFOHYDRO), which contains information on national and regional hydrological agencies, networks, and data banks of WMO Members;

(*b*) The Global Runoff Data Centre (GRDC) at the Federal Institute of Hydrology, Koblenz, Germany, which holds daily and monthly flow records of selected stations from over one hundred countries.

Both these databases are regularly updated, and the key information is published. Detailed information on these databases is provided in section 2.2.

2.1.4 *Human-resources development*

Training in hydrology consists of a number of different approaches, including in-service training, training in educational institutions, workshops, seminars, and short-term residency of experts. WMO grants fellowships for study in operational hydrology and organizes training courses. It also prepares and publishes related guidance and training material. Much of the Organization's support for training activities is undertaken in collaboration with UNESCO. Training in hydrology is described in section 2.4.

2.1.5 *Technical cooperation*

The objective of WMO's Technical Co-operation Programme is to assist Members in developing their capabilities and self-reliance to the point where efficient hydrological and meteorological services can contribute effectively to economic and social development. Presently, there are three major sources of support, while a much smaller amount is channelled through HOMS activities:

(*a*) The United Nations Development Programme (UNDP);
(*b*) WMO's Voluntary Co-operation Programme (VCP). Individual countries request assistance of various types and individual donors agree to support the requests that they are willing to fund (the VCP was recently expanded to hydrology and water resources); and
(*c*) Trust fund arrangements by means of which assistance is provided by donor countries to specific projects.

Other funding sources, such as the World Bank, the regional development banks and funds, or economic groupings like the Southern African Development Community (SADC), augment the assistance provided. Technical cooperation funds allocated under the regular budget of WMO are very limited, and are used almost exclusively for training and fellowships.

On average, 40 per cent of WMO's total technical assistance expenditure each year is in the field of hydrology and hydrometeorology. On request, sectoral advisory services in hydrology are offered to UNDP field offices and to WMO Members.

2.2 International databases

2.2.1 *Hydrological Information Referral Service* (*INFOHYDRO)*

The Hydrological Information Referral Service (INFOHYDRO) is a service for the dissemination of information on:

(*a*) National and international (governmental and non-governmental) organizations, institutions and agencies dealing with hydrology;
(*b*) Hydrological and related activities of the bodies mentioned in (*a*);
(*c*) Principal international river and lake basins of the world;
(*d*) Networks of hydrological observing stations of WMO Members — number of stations and duration of records;
(*e*) National hydrological data banks — status of collection, processing, and archiving of data; and
(*f*) International data banks related to hydrology and water resources.

INFOHYDRO as a metadatabase does not contain or handle actual hydrological data, nor does it duplicate national referral systems. It is designed to facilitate the prompt dissemination of updated hydrological information to Member countries, particularly for the benefit of their experts, agencies, and enterprises engaged in water-resources assessment, development, and management requiring support from national, regional, or international agencies dealing in operational hydrology. The information available in INFOHYDRO provides a good indication of water resources-assessment activities of Member countries.

The *INFOHYDRO Manual* [7] contains information concerning the entire database and its operation. It also contains all hydrological information available at present in INFOHYDRO. Thus, the *Manual* comprises, in a single volume, comprehensive information on the Hydrological Services of all countries and their data-collection activities.

INFOHYDRO is maintained as a computerized database, in which data can be supplied on diskettes. Information can be supplied for particular countries or WMO Regions and can consist of any of the items described under (*a*) to (*e*) above. Requests should be addressed to WMO.

2.2.2 *Global Runoff Data Centre (GRDC)*

On 1 May 1987, a permanent Global Runoff Data Centre (GRDC) was established at the Federal Institute of Hydrology in Koblenz, Germany under the auspices of WMO.

The GRDC operates for the benefit of WMO Members and the international scientific community. It provides a mechanism for the international exchange of data pertaining to river flows and surface-water runoff on a continuous long-term basis. The GRDC receives data from many sources, principally through WMO. All data archived at the GRDC are available to users.

As of November 1991, the GRDC data bank consisted of flows for 2 930 stations from 131 countries. Complete daily flows were available for 1 478 stations, and daily flows for only a part of the record were available for a future 186 data series. Monthly flows were available for 1 266 stations.

The core of the data bank is the daily flows for 1 237 stations from 75 countries that were collected initially by WMO under the WMO/ICSU Global Atmosphere Research

Programme (GARP) for use in validation of atmospheric general circulation models (GCMs), and later within the World Climate Programme (WCP). The first available year for this set of data was 1978, and there are data up to 1980 from nearly all of the stations. Data from 40 countries are also available up to 1982-1983 and from Australia up to 1984-1985. The database is being updated from time to time.

The stations have been selected according to the following criteria:

(*a*) Uniform national geographical distribution (consistent with network conditions), with higher densities in areas of rapid variation of flow;
(*b*) Coverage, to the greatest extent possible, of each type of homogeneous hydrological region of each country;
(*c*) Relatively small river basins (up to about 5 000 km^2, and in exceptional cases, up to 10 000 km^2);
(*d*) Flow data representing natural river flow, i.e., they should have been corrected for any significant diversions, abstractions, and redistributions by storage; and
(*e*) Good quality of records.

The GRDC has developed a set of programmes to provide users with a selection of retrieval options to make the data and information readily accessible. The following retrieval options are currently available: tables of daily or monthly mean flows; hydrographs of daily or monthly mean flows; flow-duration curves or tables; and station and catchment information.

Requests for data may be made in writing or by personal visit to the GRDC in Koblenz. Charges might be assessed to cover the costs of providing services to users (e.g., costs of tapes or diskettes, mailing and handling charges). The charges could be waived if the individual or institution were a contributor of data to GRDC.

2.2.3 *World Climate Data Information Referral Service (INFOCLIMA)*

The World Climate Data Information Referral Service (INFOCLIMA) is a service for the collection and dissemination of information on the existence and availability of climate data in the world. The information comprises, in particular:

(*a*) Descriptions of available data sets, held at data centres and/or published;
(*b*) Climatological and radiation-station networks of the world and their histories;
(*c*) National climatological data banks including status of collection, processing, and archiving of data.

The INFOCLIMA referral service is implemented by WMO under the World Climate Programme.

INFOCLIMA information is obtained from Member countries of WMO and, as regards data sets, also from contributions by individual data centres and international organizations. INFOCLIMA does not handle actual climate data but provides information on the existence and availability of climate data in the world. It is maintained as a computerized database.

The INFOCLIMA catalogue contains descriptions of data sets that originate from a particular data collection or data-processing programme. The information on data sets submitted by Members and international centres is edited and entered into the INFOCLIMA computerized database in a standardized format after verification has taken place with the centres involved. Tape or diskette copies of portions of the database will soon be available upon request.

For practical purposes, climate data have been divided into a number of categories, namely upper-air data; surface climatological data; radiation (surface) data; maritime and ocean data; cryosphere data; atmospheric composition data; hydrological data; and historical and proxy data.

One copy of the entire catalogue [8], or of the hydrological data extract can be provided free of charge upon request to WMO.

2.3 The Hydrological Operational Multi-purpose System (HOMS)

In recent decades, hydrological science and technology have made substantial progress, and significant contributions have been made in the development and management of water resources. The technology transfer system HOMS, developed by WMO and in operation since 1981, offers a simple but effective means of disseminating a wide range of proven techniques for the use of hydrologists.

2.3.1 *Structure of HOMS*

HOMS transfers hydrological technology in the form of separate components. These components can take many forms, such as sets of drawings for constructing (or instruction manuals for) hydrological equipment, reports describing a wide variety of hydrological procedures, and computer programs covering the processing, quality control and storage of hydrological data, as well as modelling and analysis of the processed data. About 400 components are available, which are operationally used by their originators, thus ensuring that each component is useful and that it actually works. To date, 35 countries have provided components to HOMS. Each component has a two page summary description, written in a standard format, giving information on the content and applicability of the component package, together with details of the originator and available support. These descriptions are held in the *HOMS Reference Manual (HRM)* [9], a copy of which is kept in each country participating in HOMS. The *Manual* is divided into sections and sub-sections on the basis of subject matter, as shown in Table 2.1, and the components are coded according to topic and complexity.

Cross-references to HOMS are given at the head of the sections of this *Guide.* The *HRM* contains a complete cross-reference to the *Guide.*

HOMS components can be grouped into sequences of compatible components that can be used to carry out larger tasks. The sequences also provide a means of accessing the component or components needed for some particular task.

2.3.2 *Organization and operation of HOMS*

HOMS is organized as a cooperative effort of WMO Members, with about 117 countries (February 1994) participating. Each participating country designates a HOMS National Reference Centre (HNRC), which is usually in some part of the national Hydrological Service. Regional focal points for specific areas have also been formed.

The functions of an HNRC include:

(*a*) Proposing suitable national components and sequences for use in HOMS;
(*b*) Processing requests from other HNRCs for nationally-supported components;
(*c*) Obtaining components from abroad for national users; and
(*d*) Bringing HOMS to the attention of potential users in the country, and assisting with the selection and use of appropriate components.

The international activities of HOMS are supervised and coordinated by a steering committee that works within the framework of the WMO Commission for Hydrology. The HOMS Office in the WMO Secretariat keeps the HNRCs up-to-date by the provision of supplements to the *Reference Manual* containing details of new components and by publishing a newsletter on HOMS activities.

Hydrologists, who wish to make use of HOMS components, should contact the HNRC of their country where they will be able to consult the *HOMS Reference Manual* [9]. The HNRC will also be able to advise on the choice of components. Once it is decided which components are needed, the HNRC will be able to forward the formal requests to the HNRCs concerned. The HOMS Office monitors requests and is able to help with administrative formalities when required.

TABLE 2.1
HOMS sections and sub-sections

Section A	Policy, planning, and organization
Section B	Network design
Section C	Instruments and equipment
C00	General
C05	Water quality, instruments monitoring several variables
C06	Water temperature
C09	Sediment load
C10	Suspended load
C12	Bed load
C14	Wash load
C16	Chemical quality
C21	Biological quality
C25	General meteorological data; climate and weather stations

Table 2.1 *(continued)*

C26	Precipitation, general
C27	Precipitation, manual and storage gauges
C30	Precipitation, recording and telemetering gauges
C33	Precipitation, measurement by radar
C35	Air temperature
C37	Soil temperature
C39	Humidity
C41	Sunshine hours
C43	Solar radiation
C45	Evaporation, general
C46	Evaporation, pans and tanks
C48	Evaporation, lysimeters
C52	Wind velocity and direction
C53	Snow, depth and water equivalent
C55	Soil moisture, general
C56	Soil moisture, soil samplers
C58	Soil moisture, nuclear methods
C60	Soil moisture, electrical methods
C62	Soil moisture, tensiometers
C65	Groundwater, level
C67	Groundwater, borehole loggers
C71	Water level or stage
C73	Stream discharge, flumes, weirs, ultrasonic, and electromagnetic methods
C79	Water velocity, current meters or floats
C85	River gauging, general
C86	River gauging, cableways
C88	River gauging, cranes, bridge frames, winches, and reels
C90	River gauging, equipment for use in boats
C92	Ice measurements
Section D	Remote sensing
Section E	Methods of observations
E00	General
E05	Water quality
E09	Sediment
E25	Meteorological observations for hydrology
E53	Snow and ice, glaciology
E55	Soil moisture
E65	Groundwater
E70	Surface water, level and flow

Table 2.1 *(continued)*

E71	Water level
E73	Discharge measurement, dilution gauging
E79	Velocity measurements, use of current meters
E85	Measurement of hydrological characteristics from maps
E88	Surveying
Section F	Data transmission
Section G	Data storage, retrieval and dissemination
G00	General
G05	Standards, manuals and recommendations
G06	Systems for storing general hydrological data
G08	Surface water or river data storage systems
G10	Groundwater data storage systems: levels, water chemistry, well yields and flows
G12	Meteorological data storage systems
G14	Water quality data storage systems
G20	General hydrological data tabulation programs
G25	Hydrological yearbooks
G30	Information or data dissemination systems
G40	Transfer of data between authorities, standards, recommendations, manuals and methods of coding
G42	Transfer of data between authorities, programs implementing the standards in G40
Section H	Primary data processing
H00	Systems processing several types of data
H05	General water quality data
H06	Water temperature data
H09	Sediment transport data
H16	Chemical quality data
H21	Biological quality data
H25	General meteorological data for use in hydrology
H26	Precipitation data, non-radar
H33	Radar precipitation data, including calibration by comparison with telemetering gauges
H35	Air temperature data
H39	Air humidity data
H41	Solar data, sunshine hours or radiation
H45	Evaporation data
H52	Wind data
H53	Snow and ice data, snow cover, depth, water equivalent
H55	Soil moisture data

Table 2.1 *(continued)*

H65	Groundwater data
H70	Surface water (level and flow), general
H71	Water level data, river stage, lake or reservoir levels
H73	Discharge data, all ranges
H76	Derivation of rating curves, converting stage to flow by means of rating curves
H79	Water velocity data, computing discharge from point velocity measurments
H83	Processing of historical flood information
Section I	Secondary data processing
I00	General
I05	General water quality data
I06	Water temperature data (includes ice phenomena in rivers)
I09	Sediment transport data
I25	General meteorological data for use in hydrology
I26	Precipitation data
I36	Airborne pollution
I41	Solar data, sunshine hours or radiation
I45	Evaporation, general
I50	Evaporation, computation from meteorological measurements
I53	Snow data
I55	Soil moisture data
I60	Water balance
I65	Groundwater levels
I71	Water level data
I73	Discharge data
I80	Low flows
I81	Floods and flood frequency analysis
Section J	Hydrological forecasting models
J04	Forecasting streamflow from hydrometeorological data
J10	Streamflow routing for forecasting
J15	Combined streamflow forecasting and routing models
J22	Seasonal flow forecasting
J28	Forecasting low flows
J32	Forecasting soil moisture
J45	Ice forecasts
J54	Forecasting surface water temperature
J55	Forecasting surface water quality
J65	Forecasting sediment yield
J80	Analysis of model performance

Table 2.1 *(continued)*

Section K	Hydrological analysis for the planning and design of engineering structures and water-resource systems
K10	Regional analysis
K15	Site-specific flood studies
K22	Rainfall-runoff simulation models
K35	Streamflow simulation and routing
K45	Routing through reservoirs and lakes
K54	Water temperature studies
K55	Water quality studies
K65	Sediment studies
K70	Economic evaluation of water-resource projects and flooding
K75	Designing and operating policies of reservoirs
Section L	Groundwater
L10	Analysis of data from wells and boreholes
L20	Aquifer simulation models
L22	Calibration and verification of groundwater models
L30	Groundwater forecasting
Section X	Mathematical and statistical computations
Section Y	Training aids in operational hydrology

The original aim of HOMS was for the free transfer of technology in all areas of hydrology. However, some software packages are of commercial origin and therefore need to be paid for. In the case of transfers to developing countries, the necessary funds sometimes can be found from international or bilateral aid agencies, and a number of donor HNRCs have arrangements with their countries' aid agencies for funding transfers.

2.4 **Training in hydrology**

Most Hydrological Services recognize three categories of personnel, namely professional hydrologists, hydrological technicians and hydrological observers. The WMO *Guidelines for the Education and Training of Personnel in Meterology and Operational Hydrology* [10] defines these categories as follows:

(*a*) Professional hydrologists — This is personnel with a university degree in civil engineering, agricultural engineering, mining, geology or geophysics or the equivalent, who have subsequently specialized in hydrology or other fields related to water sciences. Their tasks and activities can range from management of Hydrological Services to research and training and may include hydrological design of water-resources projects and analysis of hydrological data;

(*b*) Hydrological technicians — The personnel of this category can be divided into two groups:
  - (i) Those with 12-14 years of primary, secondary, and supplementary education, including specialization in one of the hydrological activities; and
  - (ii) Those with 10 years of primary and secondary education and technical hydrological training.

  The personnel of the first group are referred to as senior technicians and the second group as junior technicians. Their duties include assisting professional hydrologists and supervising the work of hydrological observers. More specifically, they deal with duties, such as special measurements, data collection and processing, installation of hydrological equipment, and training of hydrological observers.

(*c*) Hydrological observers — The basic education of this category is at least nine years of primary and secondary schooling, supplemented by technical training in one of the fields of hydrological activity. Their duties include taking observations, keeping records, and maintaining the less sophisticated instruments installed at their duty stations.

WMO and UNESCO have also recommended the number of staff required in each of the above categories related to the size of the observational network. Table 2.2, taken from the UNESCO/WMO *Water Resource Assessment Activities — Handbook for National Evaluation* [11], gives the numbers required in each category per 100 hydrometric and precipitation/evaporation stations. In using this table, it should be noted that most of the observers may be assumed to work part-time or to be volunteers, and thus do not form part of the full-time staff of the Hydrological Service. However, they will need training, and these numbers are included here to give an estimate of the volume of training to be provided.

Curricula for personnel in these categories are detailed in the WMO *Guidelines for the Education and Training of Personnel in Meteorology and Operational Hydrology* [10]. Hydrological observers are largely trained on the job, while technicians will have some formal post-school technical college training, as well as a large element of on-the-job training. Professional hydrologists, on the other hand, will be graduates of a university-level institution. First-degree courses rarely specialize in hydrology so the degree subject will be in civil engineering, environmental science, geography, science (particularly one of the geosciences), agriculture, or a similar subject. Many professional hydrologists also take a postgraduate diploma or master’s degree and, at this level, courses specializing in hydrology or water resources are widely available.

A number of international postgraduate courses in hydrology have been established at universities and similar institutions with the sponsorship of UNESCO. Details of these courses can be obtained from UNESCO.

WMO provides support to training, particularly of professional hydrologists. For the lower level staff, WMO support is usually in the form of training of trainers. Short courses

TABLE 2.2

Manpower requirements for the collection, processing, and analysis of surface-water data

Item	*Number of staff per 100 stations*			
	Professional	*Technicians*		*Observers*
		Senior	*Junior*	
I Hydrometric stations				
Field operations and maintenance	1	5	5	100
Data processing, analysis and interpretation	2	3	3	-
Supervision	0.5	-	-	-
Sub-total	3.5	8	8	100
II Rainfall and evaporation station				
Field operations and maintenance	0.5	2	2	100
Data processing, analysis and interpretation	1	2	2	-
Supervision	0.25	-	-	-
Sub-total	1.75	4	4	100

Source: World Meteorological Organization, 1984: Guidelines for Education and Training of Personnel in Meteorology and Operational Hydrology, WMO–No. 258, Geneva.

NOTES: 1. Many observers work part-time or on a voluntary basis.
2. The same field staff often performs the tasks included in items I and II.
3. Topographical and hydrographical characteristics and ease of access condition manpower needs in the field and maintenance operations. Therefore, the figures shown will have to be adjusted in each case.

for professional hydrologists on particular aspects of operational hydrology are organized from time to time, as funding permits. Often these courses are organized for a particular WMO region. Details of the courses planned are circulated to the Meteorological and Hydrological Services of WMO Members. Other short courses are organized by WMO

Members themselves, with invitations being sent to other Members. WMO technical cooperation projects all have a training element, and, in the case of regional projects, training can become a very large proportion of a project's activities.

WMO also provides a limited number of fellowships for training usually for a recognized international course such as those sponsored by UNESCO. Applications for these fellowships have to be made through the Permanent Representative of the applicant's country with WMO.

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CHAPTER 3

HYDROLOGICAL SERVICES

3.1 Functions of Hydrological Services

Accurate information on the condition and trend of a country's water resources — surface and sub-surface, quantity and quality — is required for economic and social development and for maintenance of environmental quality. Uses of water-resources information are many and varied. Almost every sector of a nation's economy uses water information for planning, development, or operational purposes. Water is of inestimable value to all countries, and as competition for water increases, water information grows in value. Because the cost of government programmes must be properly justified, it is becoming very important to demonstrate the benefits of hydrological information [1]. Ratios of benefit to cost of up to 40:1 have been cited (that is, the value of the information is forty times its cost of collection). Benefit-cost ratios in the range 5 to 10 seem to be generally plausible, with values of 9.3 and 6.4 being found in studies in Canada and Australia [2, 3]. Regardless of the actual numerical values, water managers in all countries subscribe to the view that water information is a cost-effective programme and is a prerequisite for wise water management.

3.1.1 *Uses of hydrological information*

The primary role of a Hydrological Service, or equivalent agency, is to provide information to decision makers on the status and trends of a country's water resources. Such information may be required for:

(*a*) Assessing a country's water resources (quantity, quality, distribution in time and space), the potential for water-related development, and the ability to supply actual or foreseeable demands;
(*b*) Planning, designing, and operating water projects;
(*c*) Assessing the environmental, economic, and social impacts of water resource management practices, existing and proposed, and adopting sound policies and strategies;
(*d*) Assessing the impacts on water resources of other non-water sector activities, such as urbanization or forest harvesting; or
(*e*) Providing security for people and property against water-related hazards, particularly floods and droughts.

In general, a Hydrological Service provides the necessary information for water-resources assessment, which is defined [4, 5] as:

> "The determination of the sources, extent, dependability, and quality of water resources, upon which is based an evaluation of the possibilities for their utilization and control."

With the growing recognition of such issues as global climatic change and the environmental impacts of urbanization, there is an increasing emphasis upon reliable water information as the foundation for sustainable development and management of water resources. This implies that future generations, as well as the present one, will continue to enjoy adequate and available water supplies to meet their social, environmental, and economic needs. A hydrometric programme designed purely for currently defined needs may be inadequate in the long term.

3.1.2 *Functions and responsibilities of a Hydrological Service*

Water-resources information may be required at a single, specific place, such as at a proposed dam site, or across an entire region, for example along a proposed highway route that crosses numerous watercourses. In the first case, information may be economically collected at the single site or in the catchment area upstream. Such information might be called use-specific. In the second case, it would be impracticable to collect information at every river crossing. General purpose data, representative of the whole region, must then be collected at a few locations, and a means must be provided of transferring the information to other sites for which no data are available. To achieve this capability, a basic network of observation stations will be required. The principal characteristic of the data obtained from such a network is that they may be used for a variety of unforeseen purposes. They are representative of the hydrology of the area, and they must be collected to standards that are able to meet the reasonable requirements of any likely user.

To meet these requirements, a Hydrological Service must:

(*a*) Establish the requirements of existing or possible future users of water-resources information;

(*b*) Define the standards (accuracy, precision, timeliness, accessibility, etc.) of the data that are implied by those requirements;

(*c*) Design and establish hydrometric networks to measure the various types of data required. Both use-specific and basic networks, that may be complementary or even overlapping, may be needed;

(*d*) Develop methods for transferring information from measurement sites to other locations in the region for which it is representative;

(*e*) Collect data and maintain quality control of the data-collection process by inspection of field installations and field practice;

(*f*) Process and archive data and maintain control of the quality and security of the archived data;

(*g*) Make the data accessible to users, when, where, and in the form they require, including:
  (i) Dissemination of hydrological forecasts and warnings;
  (ii) Publication of yearbooks of basic data in paper, microfiche, or computer compatible (CD-ROM, floppy disk, etc.) form;
  (iii) Preparation of reports on water resources in which data are comprehensively analysed. This may include media such as hydrological atlases or databases in geographical information systems; informative or educational material for use by the general public, the news media, and schools;
  (iv) Information for project design including the frequencies of streamflow extremes;

(*h*) Inform potential users of the information that is available and assist them to make the best use of it;

(*i*) Develop new technology and carry out research into hydrological and related processes to assist the user in interpreting and understanding the data;

(*j*) Develop staff (training) and other functions related to quality assurance, such as the preparation of instruction manuals and assessment or acceptance testing of new instrumentation;

(*k*) Ensure coordination with other agencies that acquire water-related or other relevant information, such as hydrogeological, water-use, topographic, land-use, or climatic information.

A simplified schematic flow chart is given in Figure 3.1.

The Hydrological Service may carry out these functions as a service to a particular client, such as a power company, perhaps on contract. On the other hand, it might provide an entirely public service, using funds provided from general taxation, because its products are of value to the public at large. Whichever is the case, considerable emphasis must be placed upon communicating with the users, both to determine their requirements and to ensure that the Hydrological Service's products are readily accessible and used to the greatest extent possible. Increasingly, natural resources are managed in an integrated fashion, which requires that a variety of different types of data be available — hydrological, geological, topographic, land use, socio-economic (e.g. water use), and so on. Rapidly evolving computer technology facilitates this, but often outstrips the ability of organizations to collaborate and exchange information.

3.1.3 ***Types of data required***

Many classifications have been proposed for the uses of hydrological information [6]. The areas of application identified by Hydrological Services in just three countries, Canada, Australia and the United States [2, 3, 7], indicate the diversity of uses for streamflow data alone, and of course other types of hydrological data have additional applications. In a rather novel approach to classification, the UNESCO/WMO *Water Resource Assessment Activities — Handbook for National Evaluation* [4] recognized a number of types of

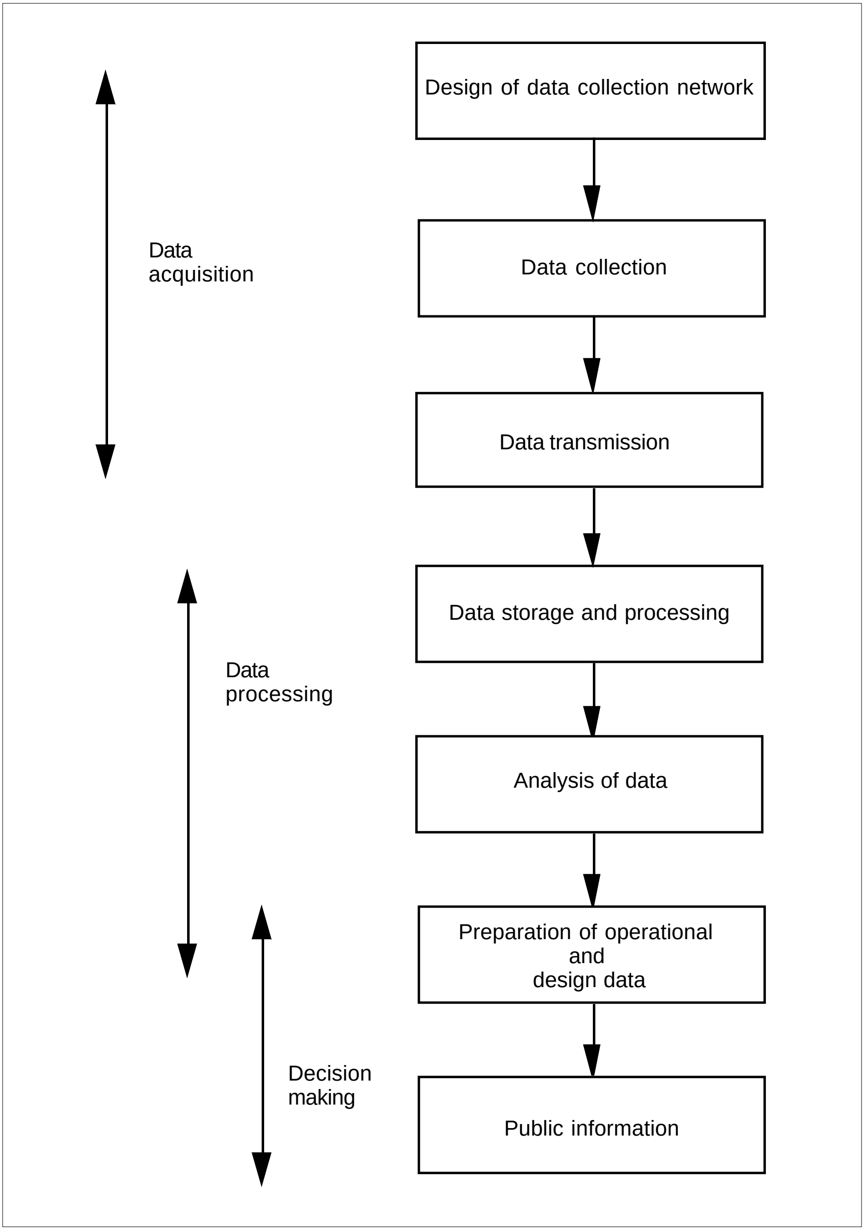

Figure 3.1 — Activities of a Hydrological Service.

water-resource projects that required hydrological information (section 50.4). A similar tabulation with a more conventional definition of water-information sectors is provided by the Australian Water Resources Council [3].

For basic water-resources assessment purposes, the major elements of the hydrological system that must be considered can be classified as inflows, storages, and outflows (Figure 3.2). In many cases, other types of data would be required, including data on groundwater levels and water quality, water use (consumption, irrigation return flows, nonconsumptive uses, such as the biological oxygen demand (BOD) of wastes disposed to a watercourse, etc.), and non-hydrological data, such as the intensity of use for recreation or bathing, the quantity of fish harvested from a watercourse, and so on.

Together these imply a vast range of water-related data and information that the Hydrological Service and other related agencies may need to supply. Different levels of economic and social development, the sensitivity of the natural environment to disturbance by human activity, and the nature of the physical environment itself (climate, topography, the abundance or otherwise of water, and so on), all determine the level of information required. One framework that has been proposed [4] is the transition from ecological orientation to construction orientation and finally to resource-management orientation. In each phase, different types of information are

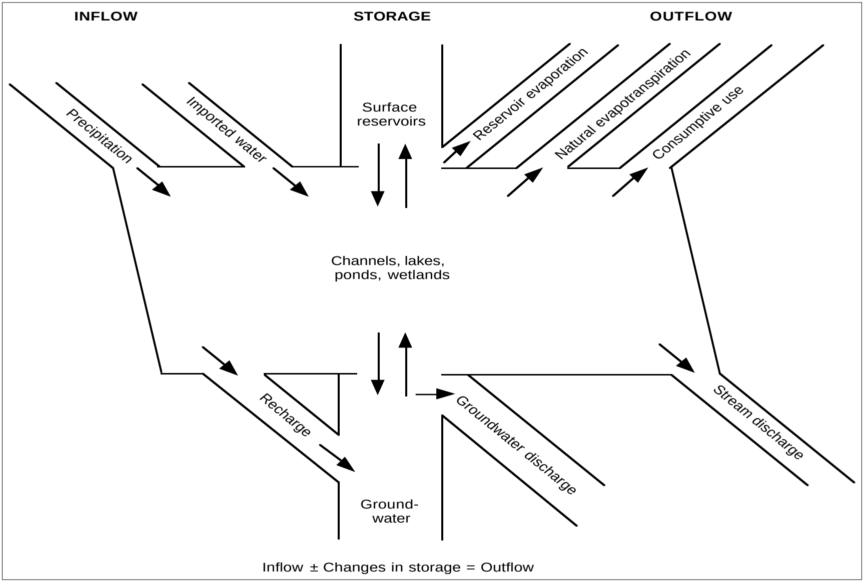

Figure 3.2 — Diagram showing major elements of a hydrological system need for a water budget of a typical river basin in a sub-humid region.

required, depending on the number and types of decision that are to be made. In the first phase, society essentially adapts to the environment including the natural hydrological regime. In the second, the water resource is increasingly exploited, but is still abundant relative to demand. Decision-making tends to focus on means of exploiting the resource by construction of dams, irrigation schemes, and so on. The main requirement for information relates to the statistics of spatial and temporal variability of the water resource. In the third phase, the resource is no longer relatively abundant. Human activity is itself markedly influencing (usually in a negative way) the size and quality of the resource. Decision-making is increasingly focused on regulating demand and supply to allocate efficiently a valuable resource amongst competing users. Hence, information is required not just on the status of the water resource, but also on usage and the impact of that usage.

The range of possible alternative decisions increases through the three phases. Hence, the need for more and different types of information increases. This implies a progressive evolution in the role of a Hydrological Service of a given country and also that Hydrological Services in different countries may have very different requirements placed upon them. Nevertheless, providing information on water quantity—total volumes, year to year variability, extreme values—is perhaps the basic activity for most Hydrological Services. Water quality is of rapidly growing importance in many countries because of its significance for consumptive uses (domestic water supply, industrial and agricultural purposes), in-stream uses (fish resources, aquaculture, recreational and bathing use) and because of environmental concerns (eutrophication of lakes, damage to natural freshwater and estuarine ecosystems).

3.1.4 *Real-time forecasting of extremes*

The preceding sections have emphasized the water-resources assessment role of Hydrological Services, which requires long, continuous records and an eye on future needs, as well as present day management. However, a major requirement in many countries is the provision of forecasts and warnings of extreme hydrological events, principally floods, droughts, storm surges, and avalanche hazards. Many of these events are both weather and water related, so that forecasts are commonly provided in cooperation with the national Meteorological Service. Because of the immediate social importance of such extreme events, close collaboration with agencies such as the Ministry of Civil Defense or the police force is also common. Such agencies have the infrastructures necessary to issue warnings, to evacuate people, or to provide relief and assistance for damage repairs.

Although the information needed to provide forecasts and warnings may ostensibly be similar to that required for water-resources assessment, (i.e. precipitation intensities, water levels, and so forth), in fact the specific requirements are very different. In forecasting, the greatest need is for information to be timely, easily understood, and reliable so that rapid decisions can be made with confidence. High precision, continuous data collection, or conformity to scientifically-based sampling designs may be less important. The disparity between data requirements for resource assessment and forecasting/warning may present significant practical difficulties to a Hydrological Service charged with both responsibilities and may require virtually separate instrumentation, data transmission systems, and data dissemination procedures.

3.2 Organization of Hydrological and Meteorological Services

The manner in which Hydrological Services are organized varies widely from country to country as a function of such factors as the governmental and political system, the size of the country, its stage of economic development, the physical environment, and the particular information needs of the country. As indicated in section 3.1.3, information needs evolve with time, which implies that the most appropriate form of organization for providing information may also change with time.

There are four main patterns of organization [6]:

(*a*) A combined Hydrological and Meteorological Service that is a distinct arm of a central Government;
(*b*) A separate Hydrological Service, most likely as part of a central government department that has the primary responsibility for water;
(*c*) No single Hydrological Service, and responsibility for acquiring water-resources information and for other aspects of operational hydrology is shared by several central government departments;
(*d*) Various aspects of operational hydrology are the responsibility of several or many specialized agencies that operate at the site, river basin, provincial or regional government level probably with the coordination by a central government body.

Combinations of these patterns may be found in some countries. Recently, there has been a trend towards commercialization of Hydrological Services and institutes, as Governments require them to become more market-driven. In the extreme case, this could result in establishing a Hydrological Service or institute as a private sector company from which the Government and other clients purchase the service that they require on contract.

It is a common practice for the national Meteorological Service to provide weather forecasts and a wide range of water-related meteorological and climatological data for operational hydrology. Often, however, data-collection networks operated by meteorological services focus on airports and urban areas because of the strong historical relationship between meteorology and aviation and the location of observers. Hence, Hydrological Services — whether at national, state, or local level — are likely to supplement data obtained from Meteorological Services with data that they themselves collect. Additional telemetered raingauges or river-monitoring stations are sited in unpopulated headwater areas to provide early flood warning or supplementary data-collection networks required for detailed water-resources assessment on a full catchment basis.

The history of water-resources development in many countries, in which the initial emphasis was on exploitation for hydroelectricity or irrigation or on flood control, has led to a situation where hydrology and water-resources assessment is the responsibility of government departments, such as the Ministry of Energy or the Ministry of Agriculture and Fisheries. Indeed, frequently, several such departments have developed their own programmes of water-resources assessment and management. Many countries, as a consequence, have several data collection networks and several hydrological archives. There are, in such circumstances, dangers of duplication of effort, inconsistent standards of data-collection, incompatible data processing and archiving, and a failure to make full use of all available information or outright competition for resources.

Almost all countries recognize the need for the coordination of agencies with water-related responsibilities, and many have established coordinating bodies at the central government level. There are excellent examples where such coordination has been successful, but coordination and collaboration require a considerable amount of communication and hard work to be wholly effective. So there are also many countries where arrangements have not been effective. Some of the most successful examples of coordination may be found in international river basins, where all countries have a common interest in standardizing their data-acquisition techniques, facilitating communication, and so on.

In principle, the most effective arrangement would be for all water-related activities to be located in a single agency. However, in practice, countries with fragmented hydrological services may assess and manage their water resources as effectively as others with a centralized service. While there seems to have been a recent trend for increased coordination or centralization of water-related functions, some countries have been moving in the opposite direction and relegating responsibilities as much as possible to the local level. The principal need is for an unhindered flow of information to be achieved from the data provider to the data user. Arrangements to achieve this — a ministry of water resources, an inter-agency coordinating committee or a water resources council with responsibility for national oversight or simple day-to-day contact — can be varied to suit the particular circumstances. Several publications [6, 8, 9] provide examples and guidance on arrangements for Hydrological Services.

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CHAPTER 4

HYDROLOGICAL STANDARDS AND REGULATIONS

4.1 Units and symbols

Standardization of units and symbols is desirable and can be achieved through the use of those recommended in Tables 4.1-4.3 [1, 2]. Commonly used units and conversion factors are also given. An attempt has been made to make all symbols and units in the *Guide* conform to those in the tables.

4.2 Recommended practices and procedures

Uniformity and standardization used where appropriate in hydrological practices and procedures will facilitate cooperation among Members. Recommended hydrological practices and procedures are described in subsequent chapters of the *Guide.* However, the reader should refer to Volume III of the *Technical Regulations* [3] for the text of the recommended practices and procedures for hydrology, as approved by WMO.

Standard and recommended meteorological practices and procedures are contained in Volume I of the *Technical Regulations* [4]. Detailed guidance about instruments and methods of observation is given in Part B of this *Guide*, as well as in other WMO guidance material such as in the *Guide to Meteorological Instruments and Methods of Observation* [5], and in the *Guide to Climatological Practices* [6]. Methods for the collection and storage of hydrological data described in Part C of this *Guide* should be applied whenever possible.

For convenience, the general recommended practices and procedures are summarized below. Members are invited to implement these recommended practices and procedures in developing their hydrological services and activities:

(*a*) The basic network of hydrometric stations should provide the essential data and information with which to conduct an overall assessment of national or regional water resources. The recommended minimum network densities are contained in Chapter 20 of this *Guide.* In view of the close relationship between meteorology and hydrology, good coordination between climatological and hydrometric networks is advantageous;

(*b*) Stations in the basic network should be operated for a relatively long period — i.e., at least 10 years — to obtain satisfactory information on mean values of the observed parameters and on their temporal variations;

TABLE 4.1

Recommended symbols, units and conversion factors

I	*II*	*III*	*IV*	*V*	*VI*	*VII*
Item	*Element*	*Symbol*	*Units*		*Conversion factor**	*Remarks*
			Recommended	*Also in use*		
1	Acceleration due to gravity	*g*	$m\ s^{-2}$	$ft\ s^{-2}$	0.305	ISO
2	Albedo	*r*	Expressed as a decimal			
3	Area (cross-sectional) (drainage basin)	*A*	m^2 km^2	ft^2 acre ha $mile^2$	0.0929 0.00405 0.01 2.59	ISO ISO
4	Chemical quality		$mg\ l^{-1}$	ppm	~ 1	(For dilute solutions)

NOTE: Where international symbols exist these have been used where appropriate and are indicated as ISO in the last column.

* Col. IV = Conversion factor (Col. VI) × Col. V.

Table 4.1 *(continued)*

I	*II*	*III*	*IV*	*V*	*VI*	*VII*
Item	*Element*	*Symbol*	*Units*		*Conversion factor**	*Remarks*
			Recommended	*Also in use*		
5	Chezy coefficient $[v\ (R_hS)^{-1/2}]$	C	$m^{1/2}\ s^{-1}$	$ft^{1/2}\ s^{-1}$	0.552	ISO
6	Conveyance	K	$m^3\ s^{-1}$	$ft^3\ s^{-1}$	0.0283	ISO
7	Degree day	D	Degree day	Degree day	Conversion formula: °C = 5/9 (°F-32)	Col. IV is based on °C scale and Col. V on °F scale
8	Density	p	$kg\ m^{-3}$	$lb\ ft^{-3}$	16.0185	ISO
9	Depth, diameter, thickness	d	m cm	ft in	0.305 2.54	ISO
10	Discharge (river flow) (wells)	 Q Q_{we}	 $m^3\ s^{-1}$ $1\ s^{-1}$	 $ft^3\ s^{-1}$ gal (U.S.) min^{-1}	 0.0283 0.063	 ISO

Table 4.1 *(continued)*

I	*II*	*III*	*IV*	*V*	*VI*	*VII*
Item	*Element*	*Symbol*	*Units*		*Conversion factor**	*Remarks*
			Recommended	*Also in use*		
	(unit area-Q A^{-1}, or partial)	q	m^3 s^{-1} km^2 1 s^{-1} km^{-2}	ft^3 s^{-1} $mile^{-2}$	0.0109 10.9	ISO
11	Drawdown	s	m cm	ft	0.305 30.5	
12	Dynamic viscosity (absolute)	η	N s m^{-2}			ISO Pa, s, kg m^{-1} s^{-1} also in use
13	Evaporation	E	mm	in	25.4	
14	Evapotranspiration	E_T	mm	in	25.4	
15	Froude number	Fr	Dimensionless number			ISO
16	Head, elevation	z	m	ft	0.305	ISO

Table 4.1 *(continued)*

I	*II*	*III*	*IV*	*V*	*VI*	*VII*
Item	*Element*	*Symbol*	*Units*		*Conversion factor**	*Remarks*
			Recommended	*Also in use*		
17	Head, pressure	h_p	m	kg (force) cm^{-2} lb (force) in^{-2}	10.00 0.705	
18	Head, static (water level) $= z + h_p$	h h	cm m	ft	30.05 0.305	ISO
19	Head, total $= z + h_p + h_v$	H	m	ft	0.305	ISO
20	Head, velocity $= v^2 (2g)^{-1}$	h_v	cm m	ft	30.5 0.305	
21	Hydraulic conductivity (permeability)	K	cm s^{-1}	m d^{-1} ft min^{-1}	0.00116 0.508	

Table 4.1 *(continued)*

I	*II*	*III*	*IV*	*V*	*VI*	*VII*
Item	*Element*	*Symbol*	*Units*		*Conversion factor**	*Remarks*
			Recommended	*Also in use*		
22	Hydraulic diffusity = $T C_s^{-1}$	D	cm^{2} s^{-1}			
23	Hydraulic radius = $A P_w^{-1}$	R_h	m	ft	0.305	ISO
24	Ice thickness	d_g	cm	in	2.54	
25	Infiltration	f	mm	in	25.4	
26	Infiltration rate	I_f	mm h^{-1}	in h^{-1}	25.4	
27	Intrinsic permeability	k	10^{-8} cm^{2}	Darcy	0.987	
28	Kinematic viscosity	v	m^{2} s^{-1}	ft^{2} s^{-1}	0.0929	ISO

Table 4.1 *(continued)*

I	*II*	*III*	*IV*	*V*	*VI*	*VII*
Item	*Element*	*Symbol*	*Units*		*Conversion factor**	*Remarks*
			Recommended	*Also in use*		
29	Length	*l*	cm m km	in ft mile	2.54 0.305 1.609	ISO
30	Manning’s coefficient = $R_h^{2/3} S^{1/2} v^{-1}$	*n*	s $m^{-1/3}$	s $ft^{-1/3}$	1.486	ISO l/n = k roughness coefficient can also be used.
31	Mass	*m*	kg g	lb oz	0.454 28.35	ISO
32	Porosity	*n*	%			α may also be used if needed
33	Precipitation	*P*	mm	in	25.4	

Table 4.1 *(continued)*

I	*II*	*III*	*IV*	*V*	*VI*	*VII*
Item	*Element*	*Symbol*	*Units*		*Conversion factor**	*Remarks*
			Recommended	*Also in use*		
34	Precipitation intensity	I_p	mm h^{-1}	in h^{-1}	25.4	
35	Pressure	p	Pa	hPa mm Hg in Hg	100.0 133.3 3386.0	see also: Head, pressure
36	Radiation** (quantity of radiant energy per unit area)	R	J m^{-2}	ly	4.187 x 10^4	
37	Radiation intensity** (flux per unit area)	I_R	J m^{-2} s^{-1}	ly min^{-1}	697.6	

** General terms. For detailed terminology and symbols see the WMO *Guide to Meteorological Instruments and Methods of Observation* (WMO–No. 8) [5].

Table 4.1 *(continued)*

I	*II*	*III*	*IV*	*V*	*VI*	*VII*
Item	*Element*	*Symbol*	*Units*		*Conversion factor**	*Remarks*
			Recommended	*Also in use*		
38	Radius of influence	r_2	m	ft	0.305	
39	Recession coefficient	C_r	Expressed as a decimal			
40	Relative humidity (moisture)	U	%			
41	Reynolds number	R_e	Dimensionless number			ISO
42	Runoff	R	mm	in	25.4	
43	Sediment concentration	c_s	kg m^{-3}	ppm	Depends on density	
44	Sediment discharge	Q_s	t d^{-1}	ton (U.S.) d^{-1}	0.907	

Table 4.1 *(continued)*

45 *I*	Shear stress *II*	τ *III*	Pa *IV*	*V*	*VI*	ISO *VII*
Item	*Element*	*Symbol*	*Units*		*Conversion factor**	*Remarks*
			Recommended	*Also in use*		
46	Slope (hydraulic, basin)	S	Dimensionless number			ISO
47	Snow cover	A_n	%			
48	Snow depth	d_n	cm	in	2.54	
49	Snow melt	M	mm	in	25.4	Normally expressed as daily
50	Soil moisture	U_s	% volume	% mass	Depends on density	
51	Soil moisture deficiency	U_s'	mm	in	25.4	

Table 4.1 *(continued)*

I	*II*	*III*	*IV*	*V*	*VI*	*VII*
Item	*Element*	*Symbol*	*Units*		*Conversion factor**	*Remarks*
			Recommended	*Also in use*		
52	Specific capacity $= Q_{we}\ s^{-1}$	C_s	$m^2\ s^{-1}$	$ft^2\ s^{-1}$	0.0929	
53	Specific conductance	K	$\mu S\ cm^{-1}$			at $\theta = 25°C$
54	Specific yield	Y_s	Expressed as a decimal			
55	Storage	S	m^3	ft^3	0.0283	
56	Storage coefficient (groundwater)	C_S	Expressed as a decimal			
57	Sunshine	n/N	Expressed as a decimal			Actual (n)/ possible (N) hours
58	Surface tension	σ	$N\ m^{-1}$			ISO

Table 4.1 *(continued)*

I	*II*	*III*	*IV*	*V*	*VI*	*VII*
Item	*Element*	*Symbol*	*Units*		*Conversion factor**	*Remarks*
			Recommended	*Also in use*		
59	Temperature	θ	°C	°F	Conversion formula °C = 5/9 (°F-32)	ISO t also in use
60	Total dissolved solids	m_d	mg l^{-1}	ppm	~ 1	(For dilute solutions)
61	Transmissivity	T	m^2 d^{-1}	ft^2 d^{-1}	0.0929	
62	Vapour pressure	e	Pa	hPa mm Hg	100.0 133.3 3386.0	
63	Velocity (water)	v	m s^{-1}	ft s^{-1}	0.305	ISO
64	Volume	V	m^3	ft^3 acre ft	0.0283 1230.0	ISO
65	Water equivalent of snow	w_n	mm	in	25.4	

Table 4.1 *(continued)*

I	*II*	*III*	*IV*	*V*	*VI*	*VII*
Item	*Element*	*Symbol*	*Units*		*Conversion factor**	*Remarks*
			Recommended	*Also in use*		
66	Weber number	W_e	Dimensionless number			
67	Wetted perimeter	P_w	m	ft	0.305	
68	Width (cross-section, basin)	b	m km	ft mile	0.305 1.609	ISO
69	Wind speed	u	m s^{-1}	km h^{-1} mile h^{-1} k$_n$ (or kt)	0.278 0.447 0.514	
70	Activity (amount of a radio activity)	A	Bq (Becquerel)	Ci (Curie)	3.7 x 10^{10}	IAEA
71	Radiation fluence (or energy fluence)	F	Jm^{-2}	erg cm^{-2}	10^{3}	IAEA
72	Radiation flux intensity (or energy flux intensity)	I	Jm^{-2} s^{-1}	erg cm^{-2} s^{-1}	10^{3}	IAEA

TABLE 4.2
Miscellaneous symbols

Item	*Element*	*Symbol*	*Remarks*
1	Concentration	c	ISO
2	Coefficient (in general)	C	ISO
3	Difference	Δ	ISO, values expressed in same units
4	Inflow	I	
5	Lag time	Δt	various units
6	Load	L	
7	Number of (or rank)	m	ISO
8	Outflow	O	
9	Recharge	f	(see Infiltration in Table 4.1)
10	Total number	N	

TABLE 4.3
Recommended units appearing in Table 4.1

Item	*Element*	*Symbol*	*Remarks*
1	Centimetre	*cm*	ISO
2	Day	*d*	ISO
3	Degree Celsius	*°C*	ISO
4	Gram	*g*	ISO
5	Hectare	*ha*	
6	Hectopascal	*hPa*	ISO
7	Hour	*h*	ISO
8	Joule	*J*	ISO
9	Kilogramme	*kg*	ISO
10	Kilometre	*km*	ISO
11	Knot	*kn, kt*	
12	Litre	*l*	ISO
13	Metre	*m*	ISO
14	Microsiemens	*µS*	
15	Milligram	*mg*	ISO
16	Millimetre	*mm*	ISO
17	Minute	*min*	ISO
18	Newton	*N*	ISO
19	Parts per million	*ppm*	
20	Pascal	*Pa*	ISO
21	Percentage	*%*	
22	Second	*s*	ISO
23	Tonne (metric ton)	*t*	ISO
24	Year	*a*	ISO
25	Bequerel	*Bq*	IAEA

(*c*) In addition to the basic network of stations, hydrological stations for special purposes may be established for special investigations during a limited period. The observation programme for such stations may contain many elements. To ensure continuous and reliable operation, regular and frequent inspection of all stations is a strong requirement;

(*d*) To avoid misunderstandings, stations should be identified by name and geographic coordinates, and, where applicable, by the name of the major river basin and the name of the river, lake, or reservoir on or in which the station is situated. An accurate and up-to-date directory of station characteristics and changes that occurred during the period of operation is indispensable;

(*e*) Uniformity in timing of the observations within a catchment area is desirable, but the intervals most appropriate for the elements being observed must be taken into account. Under exceptional conditions, e.g., floods, more frequent measurements of the appropriate elements should be made and should be promptly reported;

(*f*) For international exchanges, it is advisable to use the following time units: the Gregorian calendar year, the months derived from this year and the mean solar day from midnight to midnight, according to the zonal time. However, in some cases it may be preferable to use other periods more closely tied to the phases of the hydrological cycle;

(*g*) To make observed phenomena easier to interpret, it is desirable to give statistical presentations of the data, such as averages, maximum and minimum values, standard deviations, frequency distributions (tables or curves), etc. The frequencies derived from data collected over relatively short periods should be compared with long-period frequencies (30 years or more). In so doing, one can consider the character of an actual period against the background of the long-period average conditions. Some of the data will be published in hydrological yearbooks. For each station, such a statistical summary will clarify the significance of the data of the year concerned. A yearbook should contain complete information on all stations, including the name, coordinates, elevation, drainage area, observed phenomena, observation times, length of record, etc. Attention is drawn to the model tables in Chapter 25 of this *Guide;*

(*h*) For international use it is desirable to use the English, French, Russian or Spanish language and to employ only internationally recognized symbols, letters, abbreviations, and units;

(*i*) The observed and processed hydrological data will provide good insight into the hydrological conditions of the area concerned. They will be helpful in improving or in establishing a forecast programme for hydrological purposes, when such a programme is required. A programme of this kind should include forecasts of water stages, streamflow, ice conditions, floods, and storm surges.

4.3 Accuracy of hydrological measurements

4.3.1 *Basic principles*

Theoretically, the true values of hydrological elements cannot be determined by measurements because errors of measurement cannot be eliminated completely. The uncertainty in measurement has a probabilistic character that can be defined as the interval in which the true value is expected to lie with a certain probability or confidence level. The width of the confidence interval is also called error band.

If measurements are independent one from the other, the uncertainty in the results of measurements can be estimated by taking at least 20-25 observations and calculating the resulting standard deviation, and then determining the confidence level of the results. This procedure cannot usually be followed in hydrometric measurements, because of the change in the value to be measured during the measuring period. For instance, many consecutive measurements of discharge with current meters at constant stage is clearly impracticable in field conditions. Thus an estimate of the uncertainty has to be made by examining the various sources of errors in the measurement.

Another problem in applying statistics to hydrological data arises from the assumption that observations are independent random variables from a fixed statistical distribution. This condition is seldom met in hydrological measurements. River flow is, by nature, not purely random. It depends on previous values. It is generally accepted that some aspects of the departure of hydrological data from the theoretical concept of errors is not serious. However, it should be stressed that no statistical analysis can replace correct observations, in particular because spurious and systematic errors cannot be eliminated by such analysis. Only random errors can be characterized by statistical means.

This section contains definitions of basic terms related to the accuracy of hydrological measurements. Methods for estimating uncertainty are introduced and numerical values of accuracy, required for the most important hydrological parameters, are given. References to the existing recommendations contained in the WMO *Technical Regulations* [3] and other publications are also included.

4.3.2 *Definitions of terms related to accuracy*

The definitions of the terms related to accuracy given below take into account those given in the WMO *Technical Regulations,* Volume III — Hydrology [3], and in the WMO *Guide to Meteorological Instruments and Methods of Observation* [5]:

Accuracy: The extent to which a measurement agrees with the true value. This assumes that all known corrections have been applied.

Confidence interval: The interval which includes the true value with a prescribed probability and is estimated as a function of the statistics of the sample (Figures 4.1 and 4.2).

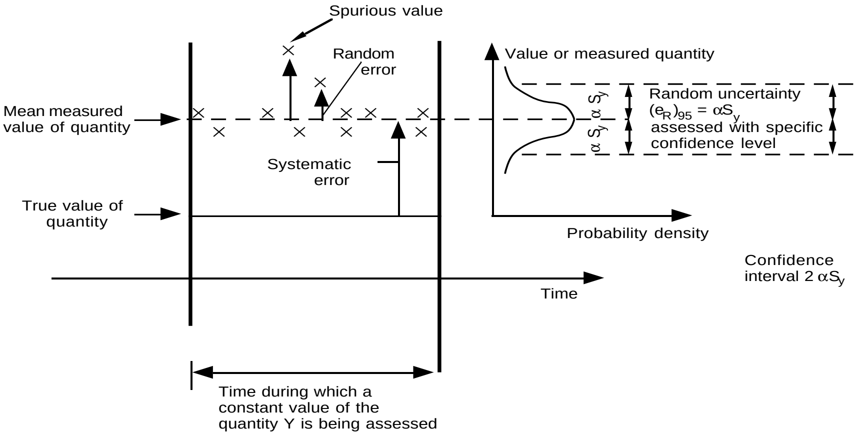

Figure 4.1 — Explanation of errors.

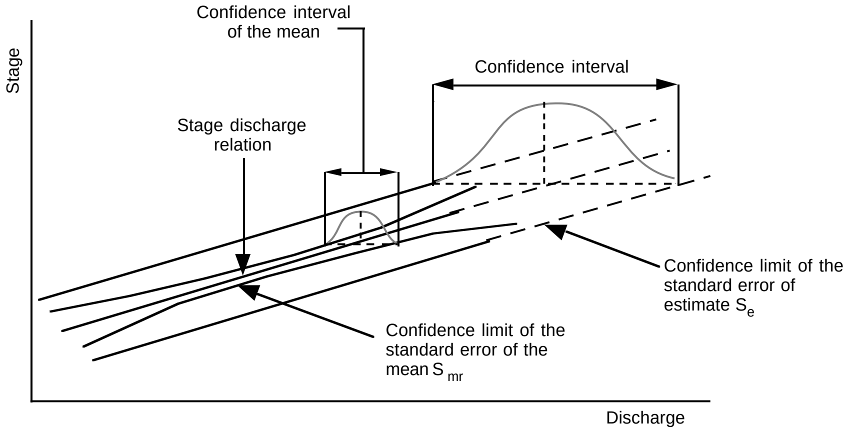

Figure 4.2 — Explanation of errors in a linear regression.

Confidence level: The probability that the confidence interval includes the true value (Figures 4.1 and 4.2).

Correction: The value to be added to the result of a measurement to allow for any known systematic error and thus to obtain a closer approximation to the true value.

Error: The difference between the result of a measurement and the true value of the quantity measured. (NOTE: This term is also used for the difference between the result of a measurement and the best approximation of the true value, rather than the true value itself). The best approximation may be a mean of several or of many measurements.

Expected value: The best approximation of the true value, which may be a mean of several or of many measurements.

Hysteresis (instrument): That property of an instrument whereby it gives different measures, for the same actual value, according to whether that value has been reached by a continuously increasing change or by a continuously decreasing change of the variable.

Measurement: An action intended to assign a number as the value of a physical quantity in stated units. (NOTE: The result of a measurement is complete if it includes an estimate (necessarily in statistical terms) of the probable magnitude of the uncertainty).

Normal distribution: A mathematically defined, symmetrical, bell-shaped, continuous distribution, traditionally assumed to represent random errors.

Precision: The closeness of agreement between independent measurements of a single quantity obtained by applying a stated measurement procedure several times under prescribed conditions. (NOTE: (*a*) Accuracy has to do with closeness to the truth, precision has to do only with closeness together; (*b*) Precision of observation or of reading is the smallest unit of division on a scale of measurement to which a reading is possible either directly or by estimation).

Random error: That part of the error that varies in an unpredictable manner, in magnitude and in sign, when measurements of the same variable are made under the same conditions (Figure 4.1).

Range: The interval between the minimum and maximum values of the quantity to be measured, for which the instrument has been constructed, adjusted, or set (NOTE: It can be expressed as a ratio of maximum and minimum measurable values).

Reference measurement: A measurement utilizing the most advanced state of science and the latest technologies. The result of the reference measurement is used to estimate a best approximation to the true value.

Repeatability: The closeness of agreement, when random errors are present, between measurements of the same value of a quantity obtained under the same conditions, i.e. the same observer, the same instrument, the same location, and after intervals of time short enough for real differences to be insignificant.

Reproducibility: The closeness of agreement between measurements of the same value of a quantity obtained under different conditions, e.g. different observers, instruments, locations, and after intervals of time long enough for erroneous differences to be insignificant.

Resolution: The smallest change in a physical variable that causes a variation in the response of a measuring system.

Sensitivity: The relationship of the change of the response to the corresponding change of the stimulus, or the value of the stimulus required to produce a response exceeding, by a specified amount, the response already present due to other causes.

Spurious value: Value known for certain to be in error, e.g. due to human mistakes or instrument malfunction (Figure 4.1).
Standard deviation (Sy): The positive square root of the sum of the squares of the deviations from the arithmetic mean, divided by *(n-1)*. It is given by:

$$S_y = \left[\frac{\sum_{1}^{n} (yi - \bar{y})^2}{n - 1} \right]^{1/2} \tag{4.1}$$

where $\bar{y}$ is the arithmetic mean of the sample of *n* independent measurements of the variable *y*, and *(n-1)* indicates the loss of one degree of freedom.
Standard error of estimate (S_e): A measure of the variation or scatter of the observations about a linear regression. It is numerically similar to the standard deviation except that the linear-regression relation replaces the arithmetic mean and *(n-1)* is replaced by (*n-m*):

$$S_e = \left[\frac{\sum (d)^2}{n - m} \right]^{1/2} \tag{4.2}$$

where *d* is the deviation of an observation from the computed regression value, *m* is the number of constants in the regression equation, and (*n-m*) represents the degrees of freedom in the equation derivation.
Systematic error: That part of the error that either:

(*a*) Remains constant in the course of a number of measurements of the same value of a given quantity; or
(*b*) Varies according to a definite law when the conditions change (Figure 4.1).

Tolerance: The permissible accuracy in the measurement of a specified variable.
Tolerance limit: The limiting lower or upper value specified for a quantitative characteristic.
True value: The value that characterizes a quantity in the conditions that exist at the moment when that quantity is observed. It is an ideal value that could be known only if all causes of error were eliminated.
Uncertainty: The interval about the measurement within which the true value of a quantity can be expected to lie with a stated probability (Figure 4.1). (NOTE: The numerical value of uncertainty is a product of the true standard deviation of the errors and a numerical parameter depending on the confidence level:

$$e = \pm\, \alpha\, \sigma_y \approx \pm \alpha s_y \tag{4.3}$$

The standard deviation, s_y, computed from *n* observations, approaches the true standard deviation, σ_y, as *n* approaches infinity. In the case of normal distribution of errors, numerical parameters are:

Confidence level	α
0.50	0.674
0.60	0.842
0.66	0.954
0.80	1.282
0.90	1.645
0.95	1.960
0.98	2.326
0.99	2.576
0.999	3.291

4.3.3 *Types of error*

Spurious errors should be eliminated by discarding the values of measurements concerned. These errors can be identified by a statistical-outlier test, such as the one described in ISO 5168 [7] that gives a rejection criterion.

Systematic error originates mainly from instrumentation and cannot be reduced by increasing the number of measurements, if the instruments and conditions remain unchanged. If the systematic error has a known value, this value should be added to or subtracted from the result of the measurement, and error due to this source should be considered zero. Systematic error should be eliminated by correcting, properly adjusting or changing the instrument, and/or by changing the flow conditions, e.g. the length of straight approach channel of a stream gauging section. These errors are often due to difficult measuring conditions, such as unsteady flow, meandering, and bad location of stations.

Random errors cannot be eliminated, but their effects can be reduced by repeated measurements of the element. The uncertainty of the arithmetic mean computed from n independent measurements is $\sqrt{n}$ times smaller than the uncertainty of a single measurement. The distribution of random errors can usually be assumed to be normal (Gaussian). For certain cases, normal distribution can or should be replaced by other statistical distributions.

4.3.4 *Sources of errors*

Each instrument and measuring method has its own sources of errors. Therefore, it would be difficult to list all possible sources of errors. The specific sources are usually mentioned in the descriptions of the design of the instruments and operating procedures, such as those in ISO Standards, and the WMO *Manual on Stream Gauging* [8]. Some typical sources of errors include:

(*a*) Datum or zero error originates from the incorrect determination of the reference point of an instrument, e.g. staff-gauge zero level, difference between the staff-gauge zero and the weir-crest levels;

(*b*) Reading error results from the incorrect reading of the indication by the measuring instrument, e.g. due to bad visibility, waves, or ice at the staff gauge;

(*c*) Interpolation error is due to inexact evaluation of the position of the index with reference to the two adjoining scale marks between which the index is located;

(*d*) Observation error is similar to the reading error and is attributed to the observer;

(*e*) Hysteresis (see foregoing definition);

(*f*) Non-linearity error is that part of error whereby a change of indication or response departs from proportionality to the corresponding change of the value of the measured quantity over a defined range;

(*g*) Insensitivity error arises when the instrument cannot sense the given change in the measured element;

(*h*) Drift error is due to the property of the instrument in which its measurement properties change with time under defined conditions of use, e.g. mechanical clockworks drift with time or temperature;

(*i*) Instability error results from the inability of an instrument to maintain certain specified metrological properties constant;

(*j*) Out-of-range error is due to the use of an instrument beyond its effective measuring range, lower than the minimum or higher than the maximum value of the quantity, for which the instrument has been constructed, adjusted, or set (e.g. unexpected high water level);

(*k*) Out-of-accuracy class error is due to the improper use of an instrument when the minimum error is more than the tolerance for the measurement.

4.3.5 *Secondary errors of measurement*

Hydrological observations are often computed from several measured components. For example, discharge at measuring structures is computed as a function of a discharge coefficient, characteristic dimensions, and head. For estimating the resultant uncertainty, the error transfer (propagation) theory of Gauss can be applied.

Resultant uncertainty is often referred to as overall uncertainty, which can be calculated from the uncertainties of the individual components if the errors of the individual components are assumed to be statistically independent.

If a quantity, Q, is a function of several measured quantities, x, y and z, the resultant uncertainty, e_Q, in Q due to uncertainties, e_x, e_y and e_z, in x, y and z, respectively, should be evaluated by the simplified equation of the transfer (propagation):

$$\left(e_Q\right)^2 = \left(\frac{\partial_Q}{\partial_x} e_x\right)^2 + \left(\frac{\partial_Q}{\partial_y} e_y\right)^2 + \left(\frac{\partial_Q}{\partial_z} e_z\right)^2 \tag{4.4}$$

where ∂_Q/∂_x, ∂_Q/∂_y and ∂_Q/∂_z are the partial differentials of the function expressing explicitly the relationship of the dependent variable with the independent variables.

In hydrological measurements, it is very rare that a measurement can be repeated under the same conditions in the field. The standard deviation should therefore be determined by using data of changing variables (as in the case of discharge-rating curve).

The standard error of estimate:

$$s_e = \left(\frac{\sum d^2}{n - 2} \right)^{1/2} \tag{4.5}$$

of the mean of observations is extremely important for characterizing the stage-discharge relationship, which needs special treatment because this relationship is not linear, but it is approximately logarithmic. It is an estimate of the accuracy of the computed mean relationship in a regression and, therefore, it is the range within which the true mean would be expected to lie (Figure 4.2).

$$s_{mr} = \frac{s_e}{\sqrt{n}} \tag{4.6}$$

For a two-variable relationship that is not linear, the relative standard deviation is more characteristic and can be computed as:

$$s_y\,\% = \left[\sum \left(\frac{\frac{y_m - y_c}{y_c}}{n - 1} \right)^2 \right]^{1/2} \tag{4.7}$$

where y_m is the measured value and y_c is the computed value from the regression equation (or read from a graph).

4.3.6 *Characterization of instruments and methods of observation*

Accuracy of a measuring instrument can be characterized by an uncertainty at a given value, corresponding to a maximum or minimum measurable value. The accuracy of an instrument without a reference value can be misunderstood or misinterpreted. The instrument accuracy is in many cases only one component of the overall accuracy of the measurement.

For characterization of uncertainty, the 95 per cent confidence level is commonly used. That is, in five per cent of the cases, the error could be outside the stated confidence interval. According to the WMO *Technical Regulations* [3], measurement uncertainties should be reported in one of the following forms:

(*a*) Uncertainties expressed in absolute terms:

Measured value of hydrological elements,
e.g. discharge
Q = ...

Random uncertainty
$(e_r)_{95}$ = ...

(*b*) Uncertainties expressed in percentage terms:
Measured value of the hydrological elements
Q = ...

Random percentage uncertainty
$(e_r)_{95\%}$ = ...%

In practice, uncertainties of measurements are given in a form where uncertainty is expressed as a ratio (or percentage) of Q_m, the measured value. For example in the case of $(e_r)_{95}$ = 10%, $Q_m \pm 0.10\ Q_m$ will contain the true value of $Q_{95\%}$ of the time. In this case, the uncertainty is formulated by assuming average measurement conditions.

4.3.7 ***Recommended accuracy of hydrological measurements***

The recommended accuracy depends mainly on the anticipated use of the measured data (the purpose of the measurement), on the potentially available instruments, and on the available financial resources. Therefore, it cannot be a constant value. Rather it should be a flexible range. The recommended accuracy levels are tabulated in Table 4.4 as a general guidance for instruments and methods of observation. In many countries, national standards regulate the required accuracies.

4.4 **Hydrological codes**

4.4.1 ***General***

All systems for the transmission of data make use of some form of coding methods, the purpose of which is to ensure that the information is transmitted quickly and reliably. In the case of fully automated systems, the information must be put into coded form before being processed. For these reasons, the codes are composed of standard forms that enable the information to be transmitted and given in a form compatible with processing. Such processing is usually preceded by quality control (section 22.1).

The structure of international codes is governed by convention, and codes are developed as a collective effort. For a long time, WMO has been developing codes to meet requirements for the exchange of meteorological data.

In operational hydrology, requirements for data are not on a worldwide scale, and yet there have been a multiplicity of codes introduced in this field. This led the WMO Commission for Hydrology to develop international hydrological codes. The

TABLE 4.4

Recommended accuracy (uncertainty levels) expressed at the 95 per cent confidence interval

Precipitation (amount and form)	3-7%
Rainfall intensity	1 mm/h
Snow depth (point)	1 cm below 20 cm or 10% above 20 cm
Water content of snow	2.5-10%
Evaporation (point)	2-5%, 0.5 mm
Wind speed	0.5 m/s
Water level	10-20 mm
Wave height	10%
Water depth	0.1 m, 2%
Width of water surface	0.5%
Velocity of flow	2-5%
Discharge	5%
Suspended sediment concentration	10%
Suspended sediment transport	10%
Bed-load transport	25%
Water temperature	0.1-0.5°C
Dissolved oxygen (water temperature is more than 10°C)	3%
Turbidity	5-10%
Colour	5%
pH	0.05-0.1 pH unit
Electrical conductivity	5%
Ice thickness	l-2 cm, 5%
Ice coverage	5% for ≥ 20 kg/m^3
Soil moisture	1 kg/m^3 ≥ 20 kg/m^3

NOTE: When a range of accuracy levels is recommended, the lower value is applicable to measurements under relatively good conditions and the higher value is applicable to measurements under difficult situation.

purpose of these codes is to cover general requirements so that, as far as possible, the procedures for coding and collecting hydrological data are standardized.

The WMO codes specifically relating to hydrology consist of the code forms HYDRA and HYFOR. The data transmitted in these standard forms are in accordance with WMO standards. Hence, these data can be routed over the World Weather Watch (WWW) telecommunication channels, if this is considered desirable.

These codes may be found to be particularly useful in the case of large national and international basins, in which a large number of stations are connected to a processing centre. The observations are coded, usually manually, by an observer, and then transmitted to a collecting centre for processing.

More recently the Binary Universal Form for the Representation of meteorological data (BUFR) code has been developed for the efficient computer exchange of meteorological data and the GRID code for grid- point data.

4.4.2 *Code forms*

The HYDRA and HYFOR codes are described in Volume I of the *Manual on Codes*, [9]. The reader may refer to this *Manual* to use the codes, which are described briefly below. The code form FM 67-VI HYDRA - Report of hydrological observation from a hydrological station, can be used to transmit:

(*a*) Hydrological data relating to stage;
(*b*) Hydrological data relating to discharge;
(*c*) Data relating to precipitation and snow cover;
(*d*) Data relating to air and water temperature;
(*e*) Data on the state of ice on the river, lake, or reservoir.

The code form FM 68-VI HYFOR - Hydrological forecast, can be used to transmit forecasts of stage, discharge, and ice phenomena.

4.4.3 *Hydrological observing station identification*

When transmitting data for a station, the station identifier is always given. As a basis for an international system of hydrological observing station identifier numbers, WMO has prepared lists of international indicators for basins in a given WMO Region, and the indicators of the countries for each basin in which the hydrological observing station is situated. These lists are given in Volume II of the *Manual on Codes* [9].

4.4.4 *BUFR and GRIB codes*

The FM 94-IX Ext. BUFR code was developed for archiving and exchanging meteorological data. It is designed for computer applications and is similar in concept to the data-compression techniques used in a number of hydrological data banks, as discussed in Chapter 24. An expansion of the BUFR code to include the exchange of hydrological data in this form through the WWW is currently being evaluated. When large volumes of data are involved, the BUFR code would have advantages over the HYDRA code.

The FM 47-IX Ext. GRID code is designed for the transmission of processed data in numerical grid-point form, e.g. the analyses and forecast fields of meteorological and other geophysical parameters. A shorter code, GRAF, is also available for the transfer of gridded data. The FM 92-IX Ext. GRIB code is another version of the GRID code that contains gridded data in binary form. All these codes are computer oriented but can be manually decoded. As remotely sensed and spatial or distributed data, including data from Geographical Information Systems are increasingly being used in operational hydrology, the wide use of these codes and their adoption to hydrological parameters is expected.

References

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8. World Meteorological Organization, 1980: *Manual on Stream Gauging.* Volumes I and II, Operational Hydrology Report No. 13, WMO–No. 519, Geneva.
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CHAPTER 5

INTERNATIONAL ORGANIZATIONS INVOLVED WITH HYDROLOGY AND WATER RESOURCES

5.1 General

This chapter provides an overview of the involvement of international organizations (governmental and non-governmental) in the field of water resources and of the various arrangements for system-wide and sectoral coordination and cooperation at the regional and global levels. It was prepared on the basis of information provided by the Secretariat of the Intersecretariat Group for Water Resources (ISGWR) of the UN Administrative Committee on Coordination (ACC) [1, 2] (see also section 5.4).

5.2 Intergovernmental organizations (IGOs)

These are organizations, established by agreements, to which two or more States are party. Such organizations may be global or regional. A number of these organizations are active in some form in the field of water resources. Table 5.1 lists those United Nations organizations and specialized agencies active on a global level, while Table 5.2 provides information about the regional organizations of the United Nations and of other regional organizations. Both tables include the official acronyms and the addresses of the organizations.

5.3 Nature and interrelationship of the activities of the UN organizations in water-resources development

The activities of the organizations of the United Nations system in the field of water resources are wide-ranging in scope and nature. Their involvement has grown during the past three decades, both in terms of the magnitude and complexity of the problems addressed. Table 5.3 presents a synoptic view of the involvement of the UN organizations with an indication of the main and applied areas of interest. The grouping has been done in accordance with the main areas of concern considered by the International Conference on Water and the Environment [3], namely:

(*a*) Water-resources assessment and impacts of climate change on water resources;
(*b*) Protection of water resources, water quality and aquatic ecosystems;
(*c*) Water and sustainable urban development and drinking water supply and sanitation in the urban context;

TABLE 5.1

Intergovernmental organizations dealing with hydrology and water resources — global *

Name	*Abbreviation*	*Address*
UNITED NATIONS		
Department of Economic and Social Development	DESD	United Nations Headquarters, New York, N.Y. 10017, USA
United Nations Children's Fund	UNICEF	Three United Nations Plaza, New York, NY l00l7, USA
United Nations Development Programme	UNDP	One United Nations Plaza, New York, NY l00l7, USA
United Nations Environment Programme	UNEP	P.O. Box 30552, Nairobi, Kenya
United Nations University	UNU	Toho Seimei Building, 15-1 Shibuya, 2-Chome, Shibuya-ku, Tokyo 150, Japan
World Food Programme	WFP	Via Cristoforo Colombo 426, 00145 Rome, Italy
United Nations Centre for Human Settlements	HABITAT	United Nations Office in Nairobi P.O. Box 30030, Nairobi, Kenya
Department of Humanitarian Affairs-Office of the United Nations Disaster Relief Co-ordinator	DHA-UNDRO	Palais des Nations, CH-l2ll Geneva l0, Switzerland
World Food Council	WFC	Via delle Terme di Caracalla, 00100 Rome, Italy

* Status in 1992.

Table 5.1 *(continued)*

International Research and Training Institute for the Advancement of Women	INSTRAW	P.O. Box 21747, Santo Domingo, Dominican Republic
SPECIALIZED AGENCIES AND OTHER ORGANIZATIONS		
International Labour Organisation	ILO	4, route des Morillons, CH-l2ll Geneva 22, Switzerland
Food and Agriculture Organization of the United Nations	FAO	Via delle Terme di Caracalla, 00100 Rome, Italy
United Nations Educational, Scientific and Cultural Organization	UNESCO	7, place de Fontenoy, 75700 Paris, France
World Health Organization	WHO	20, avenue Appia, CH-l2ll Geneva 27, Switzerland
World Bank	IBRD	l8l8 H Street, N.W., Washington, D.C. 20433, U.S.A.
World Meteorological Organization	WMO	P.O. Box 2300, CH-l2ll Geneva 2, Switzerland
International Fund for Agricultural Development	IFAD	Via del Serafico l07, 00l42 Rome, Italy
United Nations Industrial Development Organization	UNIDO	P.O. Box 300, Vienna International Centre, A-l400, Vienna, Austria
International Atomic Energy Agency	IAEA	P.O. Box l00, Vienna International Centre, A-l400 Vienna, Austria

TABLE 5.2
Intergovernmental organizations dealing with hydrology and water resources — regional *

Name	*Abbreviation*	*Address*
ORGANS OF THE UNITED NATIONS		
Economic Commission for Africa	ECA	P.O. Box 300l, Addis Ababa, Ethiopia
Economic Commission for Europe	ECE	Palais des Nations, CH-12ll Geneva l0, Switzerland
Economic Commission for Latin America and the Caribbean	ECLAC	Casilla l79-D, Santiago, Chile
Economic and Social Commission for Asia and the Pacific	ESCAP	The United Nations Building, Rajadamnern Ave., Bangkok 10200, Thailand
Economic and Social Commission for Western Asia	ESCWA	P.O. Box 927 115, Amman, Jordan
United Nations Sudano-Sahelian Office (UNDP)	UNSO	One United Nations Plaza, Room DC-1100, New York, NY l00l7, U.S.A.
Regional Commission on Land and Water Use in the Near east (FAO)	RNEA-LWU	Via delle Terme di Caracalla, 00100 Rome, Italy
OTHERS		
Arab Center for the Studies of Arid Zones and Drylands	ACSAD	P.O. Box 2440, Damascus, Syria
Caribbean Meteorological Organization	CMO	P.O. Box 46l, Port of Spain, Trinidad
Comité inter-etats de lutte contre la sécheresse dans le Sahel	CILSS	BP 7049, Ouagadougou, Burkina Faso

* Status in 1992.

Table 5.2 *(continued)*

Comité Regional para los Recursos Hídricos del Istmo Centroamericano	CRRH	c/o ICE, P.O. Box l0032, San José, Costa Rica**
Commission of the European Communities	CEC	200 rue de la Loi, Brussels l040, Belgium
Council of Europe	CE	Avenue de l'Europe, 67 Strasbourg, France
Council for Mutual Economic Assistance	CMEA	Prospekt Kalinina 56, Moscow G-205, Russian Federation
Energy Organization of the Great Lakes Countries	CEPGL	BP 58, Gisenyi, Rwanda
European Space Agency	ESA	8-l0 rue Mario Nikis, 75738 Paris, CEDEX l5, France
Comité interafricain d'études hydrauliques	CIEH	B.P. 369, Ouagadougou 01, Burkina Faso
Nordic Council	NC	Gamla Rigsdagshuset, Stockholm, Sweden
Organization of African Unity	OAU	P.O. Box 3243, Addis Ababa, Ethiopia
Organization of American States	OAS	Pan American Union Building, Washington, D.C. 20006, U.S.A.
Organization for Economic Co-operation and Development	OECD	Château de la Muette, 2 rue André Pascal, 75775 Paris, France

** Rotational Secretariat.

TABLE 5.3

Involvement of organizations of the United Nations system in water-resources development: indication of main and applied areas of interest *

Areas of concern	*Organizations with main concern in indicated areas*	*Organizations with interest in applied aspects of indicated areas*
1. Water-resources assessment and impacts of climate change on water resources	WMO, UNESCO, DESD, FAO, IBRD, IAEA	WHO, UNDP, ECA, ECE, ECLAC, ESCAP, ESCWA, UNDRO
2. Protection of water resources, water quality and aquatic ecosystems	WHO, WMO, UNEP, DESD, ECE	ALL OTHERS
3. Water and sustainable urban development and drinking water supply and sanitation in the urban context	IBRD, HABITAT, WHO, UNDP, UNICEF, INSTRAW	DESD, ECA, ECLAC, ESCAP, ESCWA, UNEP
4. Water for sustainable food production and rural development and drinking water supply and sanitation in the rural context	FAO, IBRD, UNDP, WFP, WHO, UNICEF, DESD, HABITAT, INSTRAW, ILO	ECA, ECLAC, ESCAP, ESCWA
5. Integrated water-resources management	DESD, ECA, ECE, ECLAC, ESCAP, INSTRAW, UNDP, IBRD	UNDRO, UNESCO, WMO, WHO, FAO

* Status in 1992.

(*d*) Water for sustainable food production and rural development and drinking water supply and sanitation in the rural context; and
(*e*) Integrated water resources and management.

These areas of concern also correspond to those of Chapter 18 of Agenda 21 of the United Nations Conference on Environment and Development (UNCED) [4]. A sixth area considered at the Conference, mechanisms for implementation and coordination at international, national and local levels, is relevant to the nature and scope of the activities of the organizations of the United Nations system, and to the means of coordination of these activities. Issues related to capacity building inevitably permeate all the areas depicted above.

Table 5.4 provides a more detailed view of the activities of the organizations. Each cell in the matrix shows which organizations are involved in development and management activities concerning specific water-resources sectors. The development and management functions have been classified as follows:

(*a*) Surface-water hydrology;
(*b*) Groundwater hydrology;
(*c*) Surface-water quality monitoring;
(*d*) Groundwater quality monitoring;
(*e*) Information on water use;
(*f*) Surface-water development;
(*g*) Groundwater development;
(*h*) Waste water re-use;
(*i*) Integrated water-resources management;
(*j*) Water use management;
(*k*) Waste water management;
(*l*) Strengthening of institutions;
(*m*) Legislation;
(*n*) Education and training;
(*o*) Human resources development.

The specific water-resources sectors are as follows:

(*a*) Agricultural water use;
(*b*) Drinking water supply;
(*c*) Industrial water use;
(*d*) Hydropower;
(*e*) Navigation;
(*f*) Flood control;
(*g*) Drought management;
(*h*) Multipurpose water use.

Additional information as to the nature of the involvement of each organization, as well as a description of the scope and nature of water-related activities of the

TABLE 5.4

Involvement of the organizations of the United Nations system in the field of water resources *

Development and management functions	*Specific sectors*							
	Agricultural water use	*Drinking water supply*	*Industrial water use*	*Hydropower*	*Navigation*	*Flood control*	*Drought management*	*Multi-purpose water use*
1 Surface water hydrology	DESD, ECA, FAO, IBRD	DESD, UNICEF, ECA, ESCAP, ESCWA, INSTRAW, IBRD, HABITAT	DESD, ECA, IBRD, HABITAT	DESD, ECA, INSTRAW, UNESCO, IBRD	DESD, ECA, ESCAP, IBRD	DESD, ECA, ESCAP, ESCWA, UNESCO, FAO, WMO, IBRD, HABITAT	DESD, ECA, ESCAP, ESCWA, UNESCO, FAO, WMO, IBRD	DESD, ECA, ESCAP, ESCWA, IBRD, UNESCO, WMO, HABITAT
2 Groundwater hydrology	DESD, ECA, FAO, IBRD	DESD, ECA, INSTRAW, IBRD, HABITAT	ECA, IBRD, HABITAT			ECA, HABITAT, UNESCO, WMO	DESD, ECA, ESCAP, UNESCO, FAO, WMO, IBRD	DESD, ECA, ESCAP, ESCWA, HABITAT, UNESCO, WMO, IBRD

* Status in 1992.

Table 5.4 *(continued)*

3	Surface water quality monitoring	DESD, ECA, FAO, WHO, IBRD	DESD, UNICEF, ECA, ESCAP, UNEP, WHO, IBRD, HABITAT	DESD, WHO, IBRD, HABITAT	ECA	ECA, ESCAP		DESD, ECA, UNESCO, FAO, WMO	DESD, ECA, ESCAP, UNEP, UNESCO, WHO, WMO, HABITAT
4	Groundwater quality monitoring	ECA, FAO, WHO, IBRD	UNICEF, ECA, ESCAP, UNEP, WHO, IBRD, HABITAT	WHO, IBRD, HABITAT				ECA, ESCAP, UNESCO, FAO, WMO	ECA, ESCAP, UNEP, UNESCO, WHO, WMO, HABITAT
5	Information on water use	ECA, ECE, ECLAC, ESCAP, INSTRAW, FAO, IBRD	UNICEF, ECA, ECE, ECLAC, ESCAP, INSTRAW, WHO, IBRD, HABITAT	ECA, ECE, ECLAC, ESCAP, IBRD, HABITAT	ECA, ECE, ECLAC, ESCAP, INSTRAW, IBRD	ECA, ECE, ECLAC, ESCAP,	ECA, ECE, ECLAC, ESCAP, UNESCO, WMO	ECA, ECLAC, ESCAP, UNESCO, WMO, FAO, IBRD	ECA, ECE, ECLAC, ESCAP, INSTRAW, HABITAT, UNESCO, WMO, IRBD

Table 5.4 *(continued)*

6	Surface water development	DESD, ECA, ESCAP, FAO, WFP, IBRD	DESD, UNICEF, ECA, ESCAP, WHO, WFP, IBRD, HABITAT	DESD, ECA, IBRD, HABITAT	DESD, ECA, ESCAP, IBRD	ECA, ESCAP, IBRD	DESD, ECA, ESCAP, ESCWA, FAO, WFP, IBRD, HABITAT, UNESCO, WMO	DESD, ECA, ESCAP, UNESCO, WMO, FAO, WFP, IBRD	DESD, ECA, ECLAC, ESCAP, ESCWA, WFP, UNESCO, WMO, IBRD, HABITAT
7	Groundwater development	DESD, ECA, ESCAP, FAO, WFP, IBRD	DESD, UNICEF, ECA, ESCAP, WHO, WFP, IBRD, HABITAT	ECA, IBRD, HABITAT				DESD, ECA, ESCAP, UNESCO, WMO, FAO, WFP, IBRD	DESD, ECA, ESCAP, ESCWA, WFP, IBRD, HABITAT, UNESCO, WMO
8	Waste water re-use	DESD, ECA, ECE, FAO, IBRD	DESD, WHO	ECA, ECE, WHO, IBRD, HABITAT				ESCAP	DESD, ECA, ECE, ECLAC, ESCAP, ESCWA, HABITAT, UNESCO, WMO

Table 5.4 *(continued)*

9	Integrated water-resources management	DESD, ECA, ECE, ESCAP, FAO, WHO, WFP, IBRD	DESD, ECA, ECE, ESCAP, WHO, WFP, IBRD, HABITAT	DESD, ECA, ECE, ESCAP, WHO, IBRD, HABITAT	DESD, ECA, ECE, IBRD	ECA, ECE, ESCAP, IBRD	DESD, ECA, ECE, ESCAP, ESCWA, WFP, IBRD, HABITAT, UNESCO, WMO	DESD, ECA, ECE, ESCAP, UNESCO, FAO, WMO, WFP, IBRD	DESD, ECA, ECE, ECLAC, ESCAP, ESCWA, WFP, IBRD, WMO, UNESCO, HABITAT
10	Water use management	DESD, FAO, ECA, ECLAC, ESCAP, IBRD	DESD, ECA, ECLAC, ESCAP, INSTRAW, WHO, IBRD, HABITAT	DESD, ECA, ECLAC, ESCAP, IBRD, HABITAT	ECA, ESCAP, ECLAC, INSTRAW, IBRD	ECA, ECLAC, IBRD	ECA, ECLAC, ESCAP, FAO, UNESCO, WMO, IBRD	ECA, ECLAC, ESCAP, FAO, IBRD, UNESCO, WMO	DESD, ECA, ECLAC, ESCAP, INSTRAW, UNESCO, WMO, IBRD, HABITAT

Table 5.4 *(continued)*

11	Waste water management	ECA, ECE, FAO, WHO, WFP	ECA, WHO, IBRD, HABITAT	ECA, ECE, WHO, IBRD, HABITAT					ECA, ECE, ECLAC, ESCAP, ESCWA, WMO, HABITAT, UNESCO
12	Strengthening of institutions	ECA, ECLAC, FAO, IBRD	UNICEF, ECA, ESCAP, ECLAC, WHO, IBRD, HABITAT	ECA, ECLAC, IBRD, HABITAT	ECA, ECLAC, IBRD	ECA, ESCAP	ECA, ECLAC, ESCAP, IBRD, HABITAT, UNESCO, WMO	ECA, ECLAC, UNESCO, FAO, WMO, IBRD	ECA, ECLAC, ESCAP, ESCWA, IBRD, HABITAT, UNESCO, UNESCO, WMO
13	Legislation	DESD, ECA, ECE, FAO	DESD, ECA, ECE, WHO, HABITAT	DESD, ECA, ECE	DESD, ECA, ECE	ECA, ECE, ESCAP	ECA, ESCAP, FAO, HABITAT	ECA, FAO	DESD, ECA, ECE, ECLAC, ESCAP, ESCWA, FAO, IBRD, HABITAT

Table 5.4 *(continued)*

14	Education and training	ECA, INSTRAW, FAO, WHO, WFP, IBRD	DESD, UNICEF, ECA, ESCAP, INSTRAW, WHO, IBRD, HABITAT	ECA, WHO, IBRD	ECA, INSTRAW, UNESCO, IBRD	DESD, ECA, ESCAP	ECA, ESCAP, WFP, UNESCO, WMO, IBRD, HABITAT	ECA, ESCAP, FAO, WFP, UNESCO, WMO, IBRD	ECA, ECLAC, ESCAP, INSTRAW, UNESCO, WMO, IBRD, HABITAT
15	Human resources development	ECA, INSTRAW, FAO, WHO, IBRD	DESD, UNICEF, ECA, ESCAP, INSTRAW, WHO, IBRD, HABITAT	ECA, IBRD, HABITAT	ECA, IBRD	ECA, ESCAP,	ECA, ESCAP, IBRD, HABITAT, UNESCO, WMO	DESD, ECA, ESCAP, UNESCO, FAO, WMO, IBRD	ECA, ESCAP, INSTRAW, IBRD, HABITAT, UNESCO, WMO

organizations of the United Nations system, with examples of typical projects executed by them, is provided in *The United Nations Organizations and Water* [1], and in *The United Nations Organizations and Water: Briefing Notes on the Scope and Nature of the Activities of the Organizations of the United Nations System* [2].

5.4 Arrangements for inter-organizational cooperation at the global, regional, and sectoral levels

To further their respective roles and to enhance the complementarity of their efforts to assist developing countries, the organizations of the United Nations system have formal arrangements for cooperation and collaboration in many programmes, including water. As can be seen from the summaries in Table 5.5, some of these arrangements are comprehensive in scope, spanning the entire field of water-resources development, and involving system-wide coordination at the global and regional levels. Others are of a sectoral nature and involve bilateral or multilateral collaboration within the framework of a particular aspect of water-resources development. Further details on these arrangements for inter-organizational cooperation are given in *The United Nations Organizations and Water* [1] and in *The United Nations Organizations and Water: Briefing Notes on the Scope and Nature of the Activities of the Organizations of the United Nations System* [2].

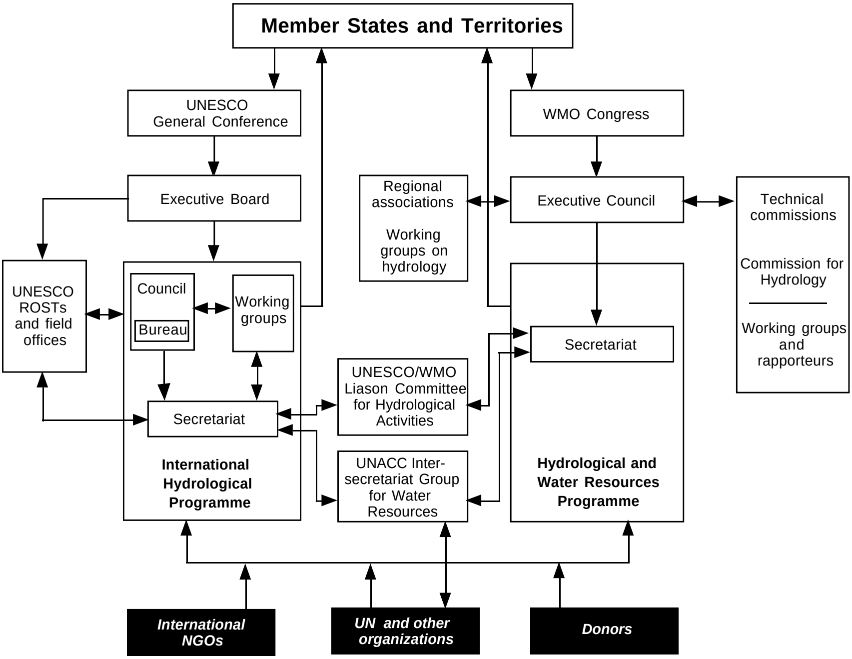
System-wide cooperation in the field of water is facilitated through the Intersecretariat Group for Water Resources of the UN Administrative Committee on Coordination, constituing an essential focus for collaboration in UN water-oriented activities. The IGO’s listed in Table 5.1 and the United Nations Regional Economic Commissions listed in Table 5.2 are members of this Intersecretariat Group.

As a particular example of inter-organizational cooperation, the joint WMO/UNESCO Liaison Committee for Hydrological Activities is instrumental in the coordination of relevant water-resource activities of both organizations.

The link between WMO and UNESCO and between their programmes in hydrology and water resources the Figure below is of special significance [5]. The emphasis given by UNESCO to research and education, with WMO concentrating on operational hydrology and services, provides an example of the amplification of efforts.

5.5 Non-governmental organizations (NGOs)

These are international organizations that are not established by intergovernmental agreement. They include organizations that accept members designated by government authorities, provided that such membership does not interfere with the free expression of the views of the organization. The NGOs involved with hydrology



Organizational linkages between WMO and UNESCO.

and water resources are listed alphabetically in Table 5.6. They may pertain to any of the following categories:

(*a*) Federations of international organizations;
(*b*) Universal membership organizations;
(*c*) Intercontinental membership organizations;
(*d*) Regional membership organizations;
(*e*) Semi-autonomous bodies; and
(*f*) Organizations of special form.

Table 5.6 is presented as follows:

(*a*) Column (1) Organization name: The name of the organization is normally given in English;
(*b*) Column (2) Acronym;
(*c*) Column (3) Organization address: The address given is that of the international secretariat or principal contact as of 1992. Some secretariats rotate or move to another address depending on the changes in the composition of the governing bodies.

TABLE 5.5
Arrangements for system-wide (global, regional) and sectoral (bilateral or multilateral) cooperation in water-resources development *

Name	*Scope*	*Organizations involved*
Administrative Committee on Coordination Sub Committee on Water Resources (ACC SCWR)	Overall coordination in the entire field of water.	All organizations active in the water field.
Terms of agreement:	1. Monitoring the Mar del Plata Action Plan. 2. Promotion of joint planning and review of water-related programmes. 3. Promotion of cooperation in the implementation of water-related activities at the country and regional levels.	
Steering Committee for Water Supply and Sanitation	Coordination of activities concerning water supply and sanitation.	UN, Regional Commissions, UNICEF, UNDP, UNEP, HABITAT, INSTRAW, FAO, UNESCO, WHO, IBRD, WMO, IRC.
Terms of agreement:	1. Promote water supply and sanitation at the global level, particularly within the programmes of the organizations of the United Nations system, and within the framework of water resources and environmental planning and management. 2. Monitor continuously and effectively needs and progress towards the achievement of national, regional and global objectives. 3. Ensure continuous and effective consultations among the organizations of the United Nations system through the exchange of information on policies, programmes, criteria and approaches, and the dissemination of information.	

* Status in 1992.

Table 5.5 *(continued)*

Inter-agency Task Force for Asia and the Pacific	Entire field of water.	ESCAP, UN/DESD, UNEP, UNICEF, UNIDO, UNDP, FAO, IBRD, ILO, UNESCO, WHO, WMO, IRC, IDB, MEKONG COMMITTEE.
Terms of agreement:	Promoting inter-organizational cooperation in the field of water resources at the regional level.	
Designated Officials for Environmental Matters (DOEM)	Coordination of system-wide activities in the field of environment, including those related to water-resources development.	All organizations concerned.
Terms of agreement:	Promotion of inter-organizational cooperation.	
FAO/World Food Programme	Supply food for projects promoting social and economic development, including irrigation.	FAO and UN World Food Programme.
Terms of agreement:	Mobilize and distribute supplies and food for: 1. Human-resources development in child feeding and school lunch programmes. 2. Infrastructure.	
World Bank/FAO cooperative programme	Project identification and preparation for investment in agriculture.	World Bank and FAO.
Terms of agreement:	Combining staff resources and experience in the identification and preparation of investment projects for World Bank financing; FAO’s contribution is made through its Investment Center.	

Table 5.5 *(continued)*

World Bank/UNESCO cooperative programme	Project identification for investment in the education sector.	World Bank and UNESCO.
Terms of agreement:	Joint undertaking of evaluation and project preparation in the field of education.	
World Bank/WHO Working Agreement in Water Supply and Sanitation	Pre-investment activities relative to water supply, waste disposal and storm drainage.	WHO and World Bank.
Terms of agreement:	Joint undertaking of pre-investment studies and missions to developing countries of common membership.	
World Bank/UNIDO	Project identification and preparation of labour intensive small-scale industries.	World Bank and UNIDO.
Terms of agreement:	Joint studies and missions to evaluate and prepare projects, with special emphasis on support of employment, intensive small-scale manufacturing and construction industries, including small-scale hydropower plants.	
World Bank/IFAD Working Agreement	Preparation and appraisal of agricultural and rural development projects.	World Bank and IFAD.
Terms of agreement:	Assistance by the World Bank in the preparation, appraisal, evaluation and supervision of projects for financing by IFAD or for co-financing by IFAD and the World Bank.	

Table 5.5 *(continued)*

Working Agreement in the Field of Hydrology and the Long-term cooperation between the Secretariats of UNESCO and WMO	Long-term cooperation in the field of hydrology.	UNESCO and WMO.
Terms of agreement:	1. Maintain and develop collaboration throughout the field of hydrology. 2. Establish close cooperation with their respective hydrology programmes (OHP of WMO and IHP of UNESCO).	
FAO/WMO Working Agreement in the Field of Hydrology and Water Resources	Hydrology and its application to agriculture.	FAO and WMO.
Terms of agreement:	General division of responsibilities between the two organizations for the collection and analysis of hydrological and meteorological data.	
WHO/FAO/UNEP Memorandum of understanding concerning water-borne diseases in Agricultural Water Development	Establish procedures for collaboration and joint action for the prevention and control of vector-borne diseases.	FAO, WHO, UNEP. It also provides for cooperation with other organizations.
Terms of agreement:	1. Hold meetings to examine programme activities and identify measures. 2. Exchange of information, project data, country briefs (profiles). 3. Prepare guidelines and training.	

Table 5.5 *(continued)*

FAO/WHO Memorandum of understanding concerning Rural Water Supply and Agricultural Development	Training of rural extension workers and integration of rural water supply and sanitation in rural development programmes.	FAO and WHO with provision for cooperation with other organizations.
Terms of agreement:	1. Joint planning and implementation of projects involving domestic water supply and irrigation in rural areas. 2. Undertake studies and training on the application of appropriate technology and benefits from rural water supply and sanitation.	
FAO/UNESCO Inter-secretariat arrangement in Hydrology and Water Resources	Programmes related to hydrology and water-resources development.	FAO, UNESCO.
Terms of agreement:	1. Regular consultations to harmonize planning of programmes of work in common areas. 2. Exchange of advice and information in hydrology and water resources.	
UNIDO/UNEP Joint Committee	Coordination of work relating to industrial use of water and environmental aspects of industrial development.	UNIDO, UNEP.
Terms of agreement:	The Committee meets annually to coordinate activities.	

TABLE 5.6

International non-governmental organizations (NGOs) dealing with hydrology and water resources *

Name	*Abbreviation*	*Address*
International Association of Hydrogeologists	IAH	National Rivers Authority, 550 Steetsbrook Road, Solihul, West Midlands, B91 1QT, U.K.
International Association of Sedimentologists	IAS	Université de Liège, Place du Vingt-Aout 7, B-4000 Liège, Belgium
International Association of Theoretical and Applied Limnology	SIL	Sil Secretariat/Central Office, Department of Biological Sciences, University of Alabama, Tuscaloosa, Alabama 35487-0344, U.S.A.
International Association for Water Law	IAWL	Via Montevideo 5, I-00198 Rome, Italy
International Association for Water Quality	IAWQ	Alliance House, 29-30 High Holborn, London WC1V 6BA, U.K.
International Council of Scientific Unions	ICSU	Bd. de Montmorency 51, F75016 Paris, France
- Committee on Space Research	COSPAR	see ICSU
- Committee on Science and Technology in Developing Countries	COSTED	see ICSU
- Committee on Data for Science and Technology	CODATA	see ICSU
- Committee on Water Research (ICSU-UITA)	COWAR	CHO-TNO, P.O. Box 6067, 2500 JA, Delft, The Netherlands
- Scientific Committee on Problems of the Environment	SCOPE	see ICSU

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* Status in 1992.

Table 5.6 *(continued)*

International Geographical Union (member of ICSU)	IGU	University of Alberta, Edmonton, Alberta, Canada T6G 2H4
International Institute for Applied Systems Analysis	IIASA	A-2361 Laxenburg, Austria
International Association on Water Pollution Research	IAWPRC	1 Queen Anne's Gate, London SW1H 9BT, U.K.
International Organization for Standardization	ISO	1, rue de Varembé, CH-1211 Geneva 20, Switzerland
International Society of Soil Science	ISSS	P.O. Box 353, 9 Duivendaal, 6700 AJ Wageningen, The Netherlands
International Training Centre for Water Resources Management	ITCWRM (CEFIGRE)	BP 13, Sophia Antipolis, F-06561 Valbonne CEDEX, France
International Union for Conservation of Nature and Natural Resources	IUCN	Avenue du Mont-Blanc, CH-1196 Gland, Switzerland
International Union of Geodesy and Geophysics (member of ICSU)	IUGG	Observatoire Royal, avenue Circulaire 3, B-1180 Brussels, Belgium
- International Association of Hydrological Sciences	IAHS	P.O. Box 6067, 2500 JA, Delft, The Netherlands
- International Association of Meteorology and Atmospheric Physics	IAMAP	National Centre for Atmospheric Research , P.O. Box 3000, Boulder, CO 80307 U.S.A.
International Union of Geological Sciences (member of ICSU)	IUGS	Maison de la Géologie, Rue Claude-Bernard 77, F-75005 Paris, France

Table 5.6 *(continued)*

International Water Resources Association	IWRA	University of Illinois, 205 North Mathews Avenue, Urbana, IL 61801 U.S.A.
International Water Supply Association	IWSA	1 Queen Anne's Gate, London SW1H 9BT, U.K.
Union of International Technical Associations	UITA	Unesco, 1 rue Miollis, F-75015 Paris, France
International Commission on Agricultural Engineering	CIGR	CHO-TNO, P.O. Box 6067, 2600 JA Delft, The Netherlands
International Union of Pure and Applied Chemistry	IUPAC	Bank Court Chambers, 2-3 Pound Way, Templars Square, Cowley, Oxford OX4 3YF, U.K.
- International Association for Hydraulic Research	IAHR	Rotterdamseweg 185, P.O. Box 177, 2600 MH Delft, The Netherlands
- International Commission on Large Dams	ICOLD	Bd. Haussmann 151, F-75008 Paris, France
- International Commission of Irrigation and Drainage	ICID	48 Nyaya Marg, Chanakyapuri, New Delhi 110021, India
- World Energy Conference	WBC	34 St. James Street, London SW1A 1HD, U.K.
Permanent International Association of Navigation Congresses	PIANC	WTC-Tour 3, 26e étage, Boulevard S. Bolivar 30, B-1210 Brussels, Belgium

Institutionalized cooperation in international river and lake basins

There are many international agreements and treaties that concern the joint use of international rivers and boundary waters, and many of these agreements and treaties have resulted in institutionalized cooperation among the countries concerned. The list of the main international institutions of this kind can be found by WMO Region in the *INFOHYDRO Manual* [6].

References

1. United Nations, 1982: *The United Nations Organizations and Water,* 83-00237, New York.

2. United Nations, 1992: *The United Nations Organizations and Water: Briefing Note on the Scope and Nature of the Activities of the Organizations of the United Nations System* (in preparation).

3. United Nations, 1992: *International Conference on Water and the Environment: Development Issues for the Twenty-first Century.* The Dublin Statement and Report of the Conference, 26-31 January 1992, Dublin, Ireland.

4. United Nations, 1992: *Conference on Environment and Development (UNCED) - Agenda 21,* Rio de Janeiro, Brazil.

5. World Meteorological Organization/United Nations Educational, Scientific and Cultural Organization, 1991: Progress in the implementation of the Mar del Plata Action Plan and a strategy for the 1990s. *Report on Water Resources Assessment.*

6. World Meteorological Organization, 1987: *Hydrological Information Referral Service — INFOHYDRO Manual.* Operational Hydrology Report No. 28, WMO–No. 683, Geneva.

PART B

HYDROLOGICAL INSTRUMENTS AND METHODS OF OBSERVATION AND ESTIMATION

CHAPTER 6

OVERVIEW OF HYDROLOGICAL INSTRUMENTS AND METHODS OF OBSERVATION

6.1 The hydrological cycle as the subject of observation

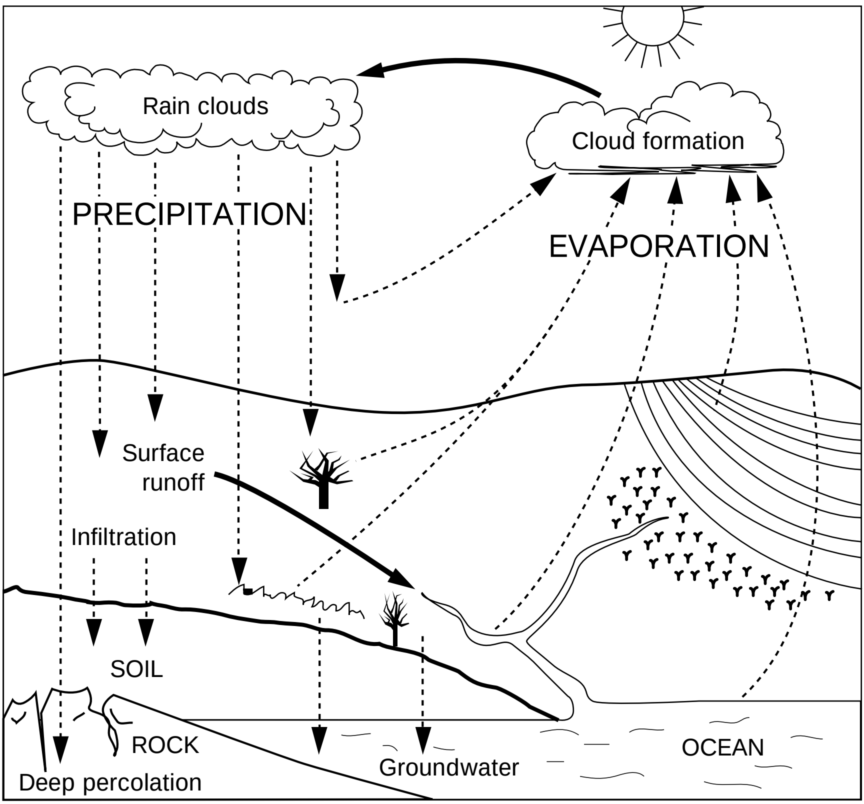
Water is found on Earth in significant amounts in all three of its physical phases: liquid, solid, and gaseous. It is also found in all three of Earth's major environments that are readily accessible to humans: the atmosphere, the seas and oceans, and the land masses. Because water can readily move from one environment to another and can change from one phase to another in response to its environment, it is a dynamic medium in both space and time. The Earth's system of repositories for storage of water and the multitude of paths among the many repositories has been conceptualized as a cycle, as shown in the Figure below. The science of hydrology has not traditionally encompassed the entire hydrological cycle, but has been limited to the land portion of the cycle and its interactions with the oceans and atmospheres.

Because mankind spends a predominant amount of his time in residence on the land surface and because water is both a necessity for life and a potential hazard to it, hydrological knowledge is valuable in providing for mankind's continuity and well being. One traditional means by which hydrological knowledge has been accumulated is through measurements of the storages and flows of water at distinct points in time and space. Such measurements, also known as data, are analysed and synthesized to generate hydrological knowledge or information. Part D of this *Guide* deals with hydrological analysis.

Two of the basic equations that describe the physics of the hydrological cycle are also pertinent in describing the systems that are used to make measurements of its transient properties: (1) the equation of continuity of mass; and (2) the equation of continuity of energy. For example, one form of the equation for continuity of mass:

$$Q = AV \tag{6.1}$$

often serves as the basis for the determination of the flow rate in a stream or canal. In this equation, Q is the instantaneous rate of flow through a cross-section of channel with area, A and average flow velocity, V. Traditionally, flow rate, also known as discharge, could not be measured directly for streams of even a modest size. On the other hand, cross-sectional area can be measured by sampling its spatial dimensions, and velocities can be sensed by the use of current meters. Thus, the use of this



The hydrological cycle is a closed system in that water circulation in the system always remains within the system. The whole cycle is driven by the excess of incoming solar radiation over outgoing radiation. The cycle consists of these subsystems: atmospheric, surface runoff, subsurface.

The general concept of the hydrological cycle.

equation, described in detail in Chapter 11, has permitted determinations of the rate of discharge of even the largest rivers of the world.

Another example of the role of the equation of continuity of mass can be found in the observation of evaporation of water from a lake surface. In this example, the equation takes the form:

$$P + I - O - E = \Delta S \qquad (6.2)$$

where P is the amount of precipitation that falls onto the surface of the lake during a period of observation, I is the inflow of surface water and groundwater during the period, O is the outflow of surface water and groundwater, E is the quantity of water evaporated from the surface of the lake during the period, and ΔS is the change in the volume of water in the lake during the period.

Precipitation can be measured according to the techniques described in Chapter 7; inflows and outflows can be measured using techniques described in Chapters 10, 11, 12, and 16; changes in the lake contents can be computed by relating the lake-surface elevations at the beginning and the end of the observation period to the respective contents at those times; and water level measurement is discussed in Chapter 10. By measuring or otherwise observing four of the five terms in equation 6.2, the fifth, evaporation can be computed algebraically.

The accuracy of the resulting estimate of evaporation, derived from the use of equation 6.2, is dependent upon the accuracies with which the other four terms are observed. Often the result is not satisfactory because of difficult conditions associated with one or more of the four terms. In such cases, it may be desirable to take advantage of the equation for the continuity of energy to estimate evaporation as a function of the energy required to convert the water from its liquid phase to vapour. Guidance for this approach is given in Chapter 9.

In addition to the topics mentioned above, this part of the *Guide* provides guidance on the estimation of snow cover and its properties (Chapter 8), on the measurement of sediment discharge (Chapter 13), the measurement of soil moisture (Chapter 15), and the sampling of many properties of the quality of water (Chapter 17).

The space limitations of this *Guide* restrict the amount of material that can be presented. For more detailed information on the subjects treated, the reader should consult these publications: for discharge measurement, the *Manual on Stream Gauging* [1] and on sampling, the *GEMS/Water Operational Guide* [2]. Although the existing international standards of ISO are not compulsory, the reader is also referred to their international standards dealing with methods for liquid flow measurements in open channels. ISO has developed more than 26 standards [3] for various types and methods of measurements. Valuable references can also be found in the proceedings of the international symposia, seminars, and workshops on hydrometry organized by IAHS, WMO and UNESCO.

This part of the *Guide* covers highly diversified instruments and methods of observation of hydrological variables. In practice, many classical methods of measurement described herein continue in use in spite of the advent of new technologies. Selection of new technologies must be made from a wide variety of available instruments and methods of observation that are continually expanding. There is a natural tendency for Hydrological Services to delay in the adoption of new technology because of the costs both of purchasing the equipment and of training its staff to use the new technology. Hydrological Services generally prefer to keep their instrumentation as homogeneous as feasible to minimize difficulties in training and in equipment maintenance.

6.2 Emerging technologies

The subsequent chapters of this part of the *Guide* deal with proven technologies that are commonly found in use in many parts of the world. However, as indicated above, there are new technologies evolving continuously. This section provides some insights into several of these so that Hydrological Services can be kept aware of their possibilities.

6.2.1 *Remote sensing*

In the field of hydrological measurements, two kinds of remote sensing techniques are commonly used: active (by emission of an artificial radiation beam toward the target, and analysis of the target response) or passive (by analysis of the natural radiation of an object).

In active methods, radiation may be high frequency electromagnetic (radar) or acoustic (ultrasonic devices). The apparatus may be installed on the ground (radar, ultrasonic), on airplanes, or on satellites (radar). Optical devices (laser) are not yet commonly used in hydrology. Active remote sensing is usually done on an areal basis, but may also be used for point-oriented measurements (ultrasonic).

In passive methods, the radiation is electromagnetic (from infrared to violet, and rarely ultraviolet). Most current applications are made by means of a multi-spectral scanner, which may be airborne, but is more frequently carried on a satellite. Passive sensing is always areal.

Radars are presently used for rainfall intensity measurements over a given area. Other uses of remote sensing in hydrology are still quite limited, but some use has been made in the measurement of water body areas and the extent of flood inundation. Furthermore, the use of hyperfrequencies (microwave) seems to offer some possibilities in the sensing of soil moisture.

6.2.2 *Micro-electronics*

An overview of the micro-electronic industry, its technical attributes, and the procurement and maintenance of micro-electronic technology helps to provide a better understanding of its application in hydrological instrumentation. It is not necessary for Hydrological Services to have expertise in the design and fabrication of micro-electronically based hydrological instrumentation.

The micro-electronics industry is very dynamic, with new electronic components and devices becoming available each year, and new companies being created to offer them. Each year new and more versatile commercial products are offered —

often at a lower price than the technology that it displaces. This occurs because of new manufacturing technology and design developments, and because of economies of scale, wherein the unit price of a component of a product, or the product itself, can be reduced if large quantities are manufactured. A low unit price is possible because the cost of design and set-up for manufacturing can be spread across many individual units.

It is equally important to be aware that the manufacture of many existing components and products is discontinued every year.

Unfortunately, the demand for hydrological instrumentation is usually very small in comparison to other commercial markets. Thus, the cost of such instrumentation does not benefit from the economies of scale to the degree that many other markets do.

Hydrological instrumentation is also required to operate unattended, on low electrical power and in an environment that may include wide ranges of temperature, moisture, dust and other environmental factors. This adds substantially to the unit costs. Other micro-electronic devices that have been designed for rugged environmental use, such as for the military, are often in a cost range beyond that of many Hydrological Services.

There is a substantial array of commercial hydrological instrumentation available. Much of this instrumentation is supplied by small- to medium-sized specialized companies. Each company publishes literature about the functional, interface, and environmental standards that the instrumentation will meet. It is the responsibility of the customer, when accepting the instrumentation, to verify that it does meet the published standards.

6.2.3 *Microprocessors*

Technically, microprocessors are computers. Their introduction into hydrological data collection took place in the mid-1970s with the manufacturing data-collection platforms (DCPs) for acquisition and transmission of hydroclimatic data.

Use of microprocessors permits an agency to :

(*a*) Correct, in real time, the signals given by the sensor;
(*b*) Compute, in the field, primary information from raw data (e.g. computation of mean, extraction of extreme);
(*c*) Convert a sensor signal into another parameter (e.g. a water level into a discharge by applying a rating-curve);
(*d*) Vary the measurement program (e.g. the frequency, according to the parameter value).

Microprocessors are also very useful in facilitating the application of other measurement methods (e.g. the moving boat method of discharge measurement) and in operations by performing, in real time, various data-computation procedures.

6.2.4 *Multi-parameter data loggers*

The functional characteristics of multi-parameter data loggers can be partitioned into measurement, storage and control, and for many loggers, the telemetry of hydrological data. These three functions are reflected in the architecture of data loggers. As the name implies, multi-parameter data loggers are designed to integrate data from two or more measurement subsystems with a storage-and-control subsystem. The data logger must interact with other outside influences, such as sources of electrical power, the hydrological environment itself, data displays, and operators who may be initializing or making routine contact with the subsystem.

The function of a hydrological-measurement subsystem is to sense a characteristic of water, and convert it to data form suitable to be displayed, recorded or processed. For example, mechanical water level measurements may be accomplished by use of a float to drive a pen on a recorder chart, or punch a paper tape, while micro-electronic systems generate an electrical signal. The mechanical water level device may also have a display that allows the current value of water level to be observed directly by a visiting observer. More recently developed subsystems utilize other measurement technologies.

Storage-and-control subsystems of multi-parameter data loggers accept signals from two or more measurement subsystems, and store these signals in a form for later retrieval, analysis, or telemetry. These signals may be relayed continuously or at fixed or irregular intervals of time. The command to transfer data may come from either side of the interfaces between subsystems. The communication of data across the interfaces must be clearly defined for each subsystem, and they must be compatible.

Many modern storage-and-control subsystems can perform complex analysis of data in real time and use such analyses to compute derived information, compact data, or institute some action. For example, some subsystems can collect data on a rapidly-changing condition, such as wind speed and direction (a highly variable set of parameters), and compute and store statistical data, rather than discrete data values.

The subsystem may take some automatic control action based on the value of the data received from the measurement technology. Modern subsystems are capable of initiating control signals to the measurement subsystem and causing additional data to be collected, or initiating control signals to the telemetry subsystem, resulting in the initiation of a warning or alert message to be transmitted.

Additionally, some multi-parameter data loggers that are equipped with telemetry can have their modes of operation remotely altered by interrogation through the telemetry subsystem.

Hydrological telemetry subsystems also consist of three elements, which are remote-site equipment, a communications medium — such as telephone lines or radio-communications links — and central receiving stations. The remote-site equipment is considered to be the multi-parameter data loggers defined earlier. The following discussion concentrates on the remote-site telemetry subsystem.

In some configurations, two-way communications between a remote hydrological station, and a central receiving station has been provided in the system design. In other cases, the system may be only designed for one-way communications from the remote site to the central receiving station. In the former case, the remote station is generally interrogated and commanded to transmit its data. In the latter case, the remote site initiates a transmission after a specified elapsed time or because hydrological data have exceeded some threshold condition. A transmission after an elapsed time may occur after a fixed- or random-time interval.

Current hydrological telemetry subsystems rely on microwave, radio, or telephone lines for communications. In microwave communication, the transmission is line of sight, while radio transmission may be line of sight or relayed via an intermediate medium. This medium may be a terrestrial relay link or earth-orbiting satellites.

In telemetry subsystems, there is a requirement for the remote-site system to meet the communications standards of the communications medium. For example, the characteristics of particular grades of telephone lines can only support certain speeds of data communications and the telemetry subsystem must conform to these speeds. Similarly, the use of a satellite relay for telemetry of data requires the remote-site system to broadcast data within precisely defined limits of emitted power, bit rate, and other communications standards. These of course are dictated by the operator of the satellite.

The key attributes of multi-parameter data loggers are their hardware, software, and physical attributes of size, weight, and electrical power.

The microprocessor, circuitry, and other physical components of multi-parameter data loggers are known as hardware. The key component of micro-electronic hardware is the microprocessor (section 6.2.3). The earliest microprocessors that were developed commercially were able to process four or eight bits of information simultaneously, and were known as 4-bit or 8-bit microprocessors, respectively. Subsequently, 16-bit and 32-bit microprocessors have been introduced.

Microprocessors in multi-parameter hydrological data loggers must be provided with a carefully defined sequence of instructions (software) to dictate the logger's operations. These instructions define many facets of the internal operation of the system, as well as how the microprocessor operates with other elements of hardware. Software determines how the microprocessor maintains track of time, how, and at what frequency it provides data to data-storage devices or to the telemetry subsystem, and a myriad of other tasks. Programming of the operation of the logger may be accomplished by means of a detachable device or by switches or a keyboard designed as integral parts of the storage-and-control subsystem.

Multi-parameter data loggers have become small and lightweight compared to the traditional hydrological data-collection instrumentation that they have replaced.

Because of their small size and low electrical power requirements, they are usually battery operated and can be packaged in small environmentally — protected cases. Many have displays, which permit a visiting technician or hydrologist to assess the status of the logger and review data that have been collected.

References

1. World Meteorological Organization, 1980: *Manual on Stream Gauging.* Volumes I and II, Operational Hydrology Report No. 13, WMO-No. 519, Geneva.
2. United Nations Environment Programme/World Health Organization/ United Nations Educational, Scientific and Cultural Organization/World Meteorological Organization, 1992: *Global Environment Monitoring System (GEMS)/Water Operational Guide.* Canada Centre for Inland Waters, Burlington, Ontario.
3. International Organization for Standardization, 1983: *Measurement of Liquid Flow in Open Channels.* ISO Standards Handbook 16, Geneva.

CHAPTER 7

PRECIPITATION MEASUREMENT

7.1 General requirements

The total amount of precipitation reaching the ground during a stated period is expressed as the depth to which it would cover a horizontal projection of the Earth's surface, if any part of the precipitation falling as snow or ice were melted. Snowfall is also measured by the depth of fresh snow covering an even horizontal surface. The primary aim of any method of precipitation measurement is to obtain representative samples of the fall over the area to which the measurement refers. There is a critical need in hydrology for accurate measurement of precipitation. Therefore, the choice of site, the form and exposure of the measuring gauge, the prevention of loss by evaporation, and the effects of wind and splashing are important considerations.

This chapter discusses the facets of precipitation measurement that are most relevant to hydrological practice. A more general discussion of the topic can be found in the *Guide to Meteorological Instruments and Methods of Observation* [1].

7.2 Gauge location

In a perfect exposure, the catch of the raingauge would represent the precipitation falling on the surrounding area. However, this is difficult to attain in practice because of the effect of the wind. Much care has to be taken in the choice of the site. Wind effects are of two types: the effects on the gauge itself, which generally reduces the amount of water collected, and the effects of the site on the wind trajectories, which are frequently more important and can give rise to either an excess or a deficiency in measured precipitation.

The disturbance created by an obstacle depends on the ratio of the obstacle's linear dimensions to the falling speed of precipitation. This effect is reduced, if not entirely overcome, by choosing the site so that the wind speed at the level of the gauge orifice is as small as possible, but so that there is not any actual blocking of precipitation by surrounding objects, and/or by modifying the surroundings of the gauge so that the airflow across the orifice is horizontal. All gauges in any area or country should have comparable exposures, and the same siting criteria should be applied to all.

The gauge should be exposed with its orifice being horizontal over ground level. Where possible, the gauge site should be protected from wind movement in all directions by objects (trees, shrubs, etc.) of as nearly uniform height as possible. The height of these objects above the orifice of the gauge should be at least half the distance from the gauge to the objects, but should not exceed the distance from the gauge to the objects (to avoid interception of precipitation that should reach the gauge). The ideal situation is to have the angle from the top of the gauge to the top of the encircling objects between 30° and 45° to the horizontal.

Objects such as wind-breaks, consisting of a single row of trees, should be avoided as protection for gauges, as they tend to increase turbulence at the gauge site. Isolated or uneven protection near the gauge should also be avoided because of variable and unpredictable effects on the gauge catch. When adequate protection from the wind is not possible, individual objects should not be closer to the gauge than a distance equal to four times their height. Subject to these limitations, a site that is sheltered from the full force of the wind should be chosen to avoid wind-caused measurement errors. Caution should always be exercised, so that the site chosen does not produce significant disturbances in the wind. Sites on a slope, or with the ground sloping sharply away in one direction — especially if this direction is the same as the prevailing wind — should be avoided.

The ground surrounding the gauge can be covered with short grass or be of gravel or shingle, but a hard flat surface, such as concrete, gives rise to excessive splashing. The height of the gauge orifice above the ground should be as low as possible because the wind velocity increases with height, but it should be high enough to prevent splash from the ground. A height of 30 centimetres is used in many countries, in those areas that have little snow and where the surroundings are such that there is no risk of the ground being covered by puddles, even in heavy rain. Where these conditions are not satisfied, a standard height of one metre is recommended.

In very exposed places, where natural shelter is not available, it has been found that better results can be obtained for liquid precipitation if the gauge is installed in a pit, so that the gauge rim is at ground level (Figure 7.1). A strong plastic or metal antisplash grid should span the pit with a central opening for the gauge funnel. The antisplash grid should be composed of thin slats about 12.5 centimetres deep, set vertically at about 12.5 centimetres spacing in a square symmetric pattern. The area surrounding the gauge should be level and without unusual obstructions for at least 100 metres in all directions.

An alternative installation, which is not quite so effective, is to install the gauge in the middle of a circular turf wall. The inner wall surface should be vertical with a radius of about 1.5 metres. The outer surface should slope at an angle of about 15° to the horizontal. The top of the wall should be level with the gauge orifice. Provision should be made for drainage. The pit gauge has been developed to measure liquid precipitation and should not be used for snowfall measurements.

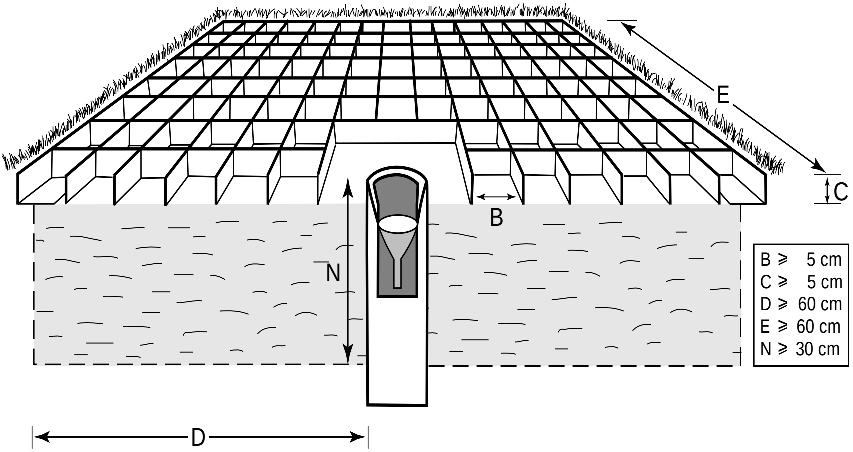


Figure 7.1 — Pit gauge for the measurement of liquid precipitation.

An alternative way of modifying the surrounding of the gauge is to fit suitably shaped windshields around the instrument. When properly designed, these enable much more representative results to be obtained than with unshielded gauges fully exposed to the wind. An ideal shield should:

(*a*) Ensure a parallel flow of air over the aperture of the gauge;
(*b*) Avoid any local acceleration of the wind above the aperture;
(*c*) Reduce to the degree possible the speed of the wind striking the sides of the receiver. The height of the gauge orifice above the ground is then much less important;
(*d*) Prevent splashing towards the aperture of the receiver. The height of the gauge orifice above the ground is then much less important;
(*e*) Not be subject to capping by snow.

Precipitation in the form of snow is much more subject to adverse wind effects than is rainfall. In exceptionally windy locations, the catch in a gauge, with or without a windshield, may be less than half the actual snowfall. Sites selected for measurement of snowfall and/or snow cover should, as far as possible, be in areas sheltered from the wind. Windshields attached to the gauges have been shown to be quite effective in reducing precipitation catch errors due to wind, especially for solid precipitation. No shield yet developed, however, will entirely eliminate wind-caused measurement errors.

7.3 Non-recording gauges [C27]

7.3.1 *General*

The non-recording gauges used by most Hydrological and Meteorological Services for official measurements generally consist of open receptacles with vertical sides, usually in the form of right cylinders. Various sizes of orifice and height are used in different countries and, therefore, measurements are not strictly comparable. The depth of precipitation caught in a gauge is measured by means of a graduated flask or dip-stick. In gauges having other than vertical sides, the measurement is made either by weighing or measuring the volume of the contents, or by measuring the depth with a specially graduated measuring stick or scale.

7.3.2 *Standard gauges*

The ordinary raingauge used for daily readings usually takes the form of a collector above a funnel leading into a receiver. The size of the opening of the collector is not important. A receiving area of 1 000 cm^2 is used in some countries, but an area of 200 to 500 cm^2 will probably be found most convenient. The area of the receiver may be made to equal 0.1 of the area of the collector. Whatever size is chosen, the graduation of the measuring apparatus must be consistent with it. The most important requirements of a gauge are as follows:

(*a*) The rim of the collector should have a sharp edge and should fall away vertically inside and be steeply bevelled outside. The design of gauges used for measuring snow should be such that errors due to constriction of the aperture, by accumulation of wet snow about the rim, are small;

(*b*) The area of the aperture should be known to the nearest 0.5 per cent and the construction should be such that this area remains constant;

(*c*) The collector should be designed to prevent rain from splashing in or out. This can be done by having the vertical wall sufficiently deep and the slope of the funnel sufficiently steep (at least 45°);

(*d*) The receiver should have a narrow neck and should be sufficiently protected from radiation to minimize loss of water by evaporation;

(*e*) When a part of precipitation comes in the form of snow, the collector should be deep enough to store the snowfall that can be expected during at least one day. This is also important to avoid the snow drifting out of the collector.

Raingauges for use at places where only weekly or monthly readings are taken should be similar in design to the type used for daily measurement, but with a receiver of larger capacity and stronger construction.

7.3.3 *Storage gauges*

Storage gauges are used to measure total seasonal precipitation in remote, sparsely inhabited areas. These gauges consist of a collector above a funnel, leading into a receiver large enough to store the seasonal catch. The criteria for exposure and shielding given in previous sections should also be considered in the installation of these gauges.

In areas where extremely heavy snowfall occurs, the collector must be placed above the maximum expected depth of snow cover. This may be accomplished by mounting the entire gauge on a tower or by mounting the collector on a 30 centimetres diameter steel pipe of sufficient length to place its catch ring above the maximum accumulated snow.

An antifreeze solution is placed in the receiver to convert the snow that falls into the gauge into a liquid state. A mixture of 37.5 per cent of commercial-grade calcium chloride (78 per cent purity) and 62.5 per cent water by weight makes a satisfactory antifreeze solution. Alternately, an ethylene glycol solution can be used. While more expensive, the ethylene glycol solution is less corrosive than calcium chloride and gives protection over a much wider range of dilution caused by ensuing precipitation. The volume of the solution placed in the receiver should not exceed one-third the total volume of the gauge.

An oil film should be used in the gauge to prevent loss of water by evaporation. An oil film about eight mm thick is sufficient. Low viscosity, non-detergent motor oils are recommended. Transformer and silicone oils have been found unsuitable.

The seasonal precipitation catch is determined by weighing or measuring the volume of the contents of the receiver. The amount of antifreeze solution placed in the receiver at the beginning of the season must be taken into account with either method.

7.3.4 *Methods of measurement*

Two methods are commonly used for measuring the precipitation caught in the gauge: a graduated measuring cylinder, and a graduated dip rod.

A measuring cylinder should be made of clear glass with a low coefficient of expansion and should be clearly marked with the size of gauge for which it is to be used. Its diameter should not be more than about one-third of that of the rim of the gauge.

The graduations should be finely engraved. In general, markings should be at 0.2 millimetre intervals with whole millimetre lines clearly indicated. It is also desirable that the line corresponding to 0.1 millimetre should be marked. Where it is not necessary to measure rainfall to this accuracy, every 0.2 up to 1.0 millimetre and every millimetre above that should be marked, with every 10 millimetre line clearly indicated. For accurate measurements, the maximum error of the graduations should not exceed ± 0.05 millimetre at or above the 2 millimetre graduation mark and ± 0.02 millimetre below this mark.

To achieve this accuracy with small amounts of rainfall, the inside of the measuring cylinder should be tapered at its base. In all measurements, the bottom of the water meniscus should be taken as the defining line. It is important to keep the measure vertical and to avoid parallax errors. It is helpful, in this respect, if the main graduation lines are repeated on the back of the measure.

Dip rods should be made of cedar or other suitable material that does not absorb water to any appreciable extent, and should have a capillarity effect that is small. Wooden dip rods are unsuitable if oil has been added to the collector, and rods of metal or other material from which oil can be readily cleaned must then be used. They should be provided with a brass foot to avoid wear and be graduated according to the relative areas of cross-section of the gauge orifice and the receiving can, making allowance for the displacement due to the rod itself. Marks at every 10 millimetre should be shown. The maximum error in the dip-rod graduation should not exceed ± 0.5 millimetre at any point. Although the measurement may be made with a dip rod, it should be checked by using a rain measure as well, whenever possible.

It is also possible to measure the catch by weighing. There are several advantages in this procedure. The total weight of the can and contents should be weighed, and the weight of the can should then be subtracted. There is no danger of spilling the contents, and none is left adhering to the can. However, the common methods are simpler and cheaper.

7.3.5 *Errors and accuracy of readings*

The errors involved in measuring the catch collected in a gauge are small compared with the uncertainty due to the effect of the exposure of the instrument if reasonable care is taken in the readings. Daily gauges should be read to the nearest 0.2 millimetre and preferably to the nearest 0.1 millimetre. Weekly or monthly gauges should be read to the nearest 1 millimetre. The main sources of error likely to arise are the use of inaccurate measures or dip rods, spilling of some water when transferring it to the measure, and the inability to transfer all the water from the receiver to the measure.

In addition to these errors, losses by evaporation can occur. These are likely to be serious only in hot dry climates, and with gauges visited only at infrequent intervals. Evaporation losses can be reduced by placing oil in the receiver or by designing the gauge so that only a small water surface is exposed, ventilation is poor, and the internal temperature of the gauge does not become excessive. Also, the receiving surface of the gauge must be smooth, so that the raindrops do not adhere to it. It should never be painted.

In winter where rains are often followed immediately by freezing weather, damage to the receiver, and consequent loss by leakage, can be prevented by the addition of an antifreeze solution. This again mainly applies to gauges visited infrequently. Allowance for the solution added must, of course, be made when measuring the gauge catch. All gauges should be tested regularly for possible leaks.

7.3.6 *Correction of systematic errors*

Because of the effects of wind, wetting, evaporation, blowing snow, and splashing, the amount of precipitation measured is usually lower (by three to 30 per cent or more) than that which actually fell. This systematic error may be corrected if the readings are to be used for hydrological calculations [2]. Before carrying out any corrections, the original measured data should be securely archived. Published data should be clearly labelled “measured” or “corrected”, as applicable.

The corrections for these effects are generally based on relationships between the components of the error and the meteorological factors. Thus, the loss from wind field deformation near the gauge rim is related to wind speed and precipitation structure. The latter can be characterized, depending on the time period used, by the proportion of rainfall at low intensity ($i_p \leq 0.03$ mm min^{-1}), by a logarithm of rainfall intensity, by air temperature and/or humidity, and the type of precipitation. Loss from wetting is related to the number of precipitation events and/or days, while loss from evaporation is a function of the saturation deficit and wind speed. Excess measured precipitation as a result of blowing or drifting snow is related to wind speed.

The above-mentioned meteorological factors may be derived from standard meteorological observations performed at the gauge site or in its vicinity, if daily corrections are to be applied. At sites without such meteorological observations, only estimates for time periods longer than one day, e.g. one month, should be used.

The value of the correction varies from 10 to 40 per cent for individual months, depending on the type of estimate of the meteorological factors employed.

The main components of the systematic error in precipitation measurement are given in Table 7.1.

The correction factor *k* for the effect of wind field deformation above the gauge orifice, estimated experimentally for various gauges, is given in Figure 7.2. It is a function of two variables, the wind speed during precipitation at the level of the gauge rim and the velocity of the falling precipitation particles. The latter depends on the structure of the precipitation.

The absolute value of wetting loss depends on the geometry and material of the gauge collector and container, on the number of measurements of precipitation, and on the amount, frequency, and form of precipitation. It is different for liquid, mixed and solid precipitation, and can be estimated by weighing or volumetric measurements in a laboratory. The wetting loss for solid precipitation is generally smaller than for liquid precipitation because the collector is usually wetted only once during snow melt.

The total monthly wetting loss, ΔP_1, can be estimated by using the equation:

$$\Delta P_1 = \overline{a}\, M \tag{7.1}$$

where ΔP_1 is the average wetting loss per day for a particular collector and M is the number of days with precipitation.

In cases where the amount of precipitation is measured more than once a day, the total monthly wetting loss is:

$$\Delta P_{1,2} = a^x\, Mp \tag{7.2}$$

TABLE 7.1

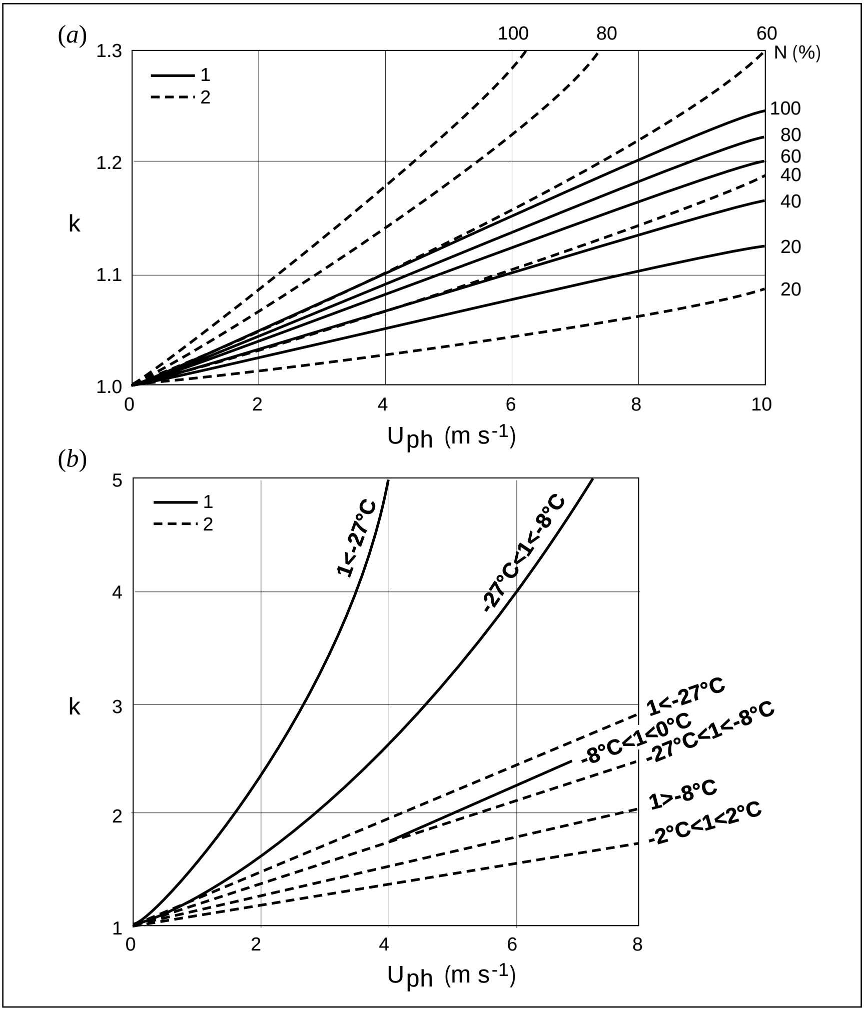
Main components of the systematic error in precipitation measurement and their meteorological and instrumental factors listed in order of general importance

$$P_k = kP_c = k\left(P_g + \Delta P_1 + \Delta P_2 + \Delta P_3 \pm \Delta P_4 - \Delta P_5\right)$$

where P_k is the adjusted precipitation amount, k is the correction factor, P_c is the precipitation caught by the gauge collector, P_g is the measured precipitation in the gauge, and P_1 — P_5 are corrections for components of systematic error as defined below:

Symbol	*Component of error*	*Magnitude*	*Meteorological factors*	*Instrumental factors*
k	Loss due to wind field deformation above the gauge orifice	2-10% 10-50% *	Wind speed at the gauge rim during precipitation and the structure of precipitation	The shape, orifice area and depth of both the gauge rim and collector
$\Delta P_1 + \Delta P_2$	Losses from wetting on internal walls of the collector and in the container when it is emptied	2-10%	Frequency, type and amount of precipitation, the drying time of the gauge and the frequency of emptying the container	The same as above and, in addition, the material, colour and age of both the gauge collector and container
ΔP_3	Loss due to evaporation from the container	0-4%	Type of precipitation, saturation deficit and wind speed at the level of the gauge rim during the interval between the end of precipitation and its measurement	The orifice area and the isolation of the container, the colour and, in some cases, the age of the collector, or the type of funnel (rigid or removable)
ΔP_4	Splash-out and splash-in	1-2%	Rainfall intensity and wind speed	The shape and depth of the gauge collector and the kind of gauge installation
ΔP_5	Blowing and drifting snow		Intensity and duration of snow storm, wind speed and the state of snow cover	The shape, orifice area and depth of both the gauge rim and the collector

* Snow.



Correction factor *k* as a function of the wind speed during precipitation at the level of the gauge rim (u_{ph}) and the parameter of the precipitation structure *N* and *t* for: (*a*) liquid precipitation; and (*b*) mixed and solid precipitation. 1 = Hellmann gauge without windshield; 2 = Tretyakov gauge with windshield; *t* = air temperature during snow storms; *N* = fraction in percentage of monthly totals of rain falling with an intensity smaller than 0.031 minimum [3].

Figure 7.2 — Correction factor *k* as a function of the wind speed.

where a^x is the average wetting loss per measurement of precipitation for a particular gauge and form of precipitation and Mp is the number of measurements of precipitation during the period concerned.

Evaporation loss can be estimated as follows:

$$\Delta P_3 = i_e \, \tau_e \tag{7.3}$$

The value of i_e depends on the construction, material, and colour of the gauge, on the form and amount of precipitation, on the saturation deficit of the air, and on wind speed at the level of the gauge rim during evaporation. It is difficult to estimate i_e theoretically because of the complex configuration of a precipitation gauge. However, i_e can be computed by using empirical equations or graphical functions as shown in Figure 7.3. The value of τ_e can be estimated by using precipitation-recording gauges, but it also depends on the number of precipitation observations per day. It is three to six hours for liquid precipitation if measured twice per day and six hours for snow because the evaporation takes place during the snowfall.

The error resulting from the blowing of snow into the gauge should be considered during snowstorms with wind speed larger than 5 m s^{-1}. The half day values can be estimated at the gauge sites with visual observations of the duration of blowing snow, and in those with known data for wind speed and number of days with both blowing and drifting snow. The long-term monthly averages can be estimated from the graph in Figure 7.4 if the duration of snowstorms and wind speed are known.

The net error due to splash-in and out of water can be either negative or positive, and therefore assumed as zero for most types of properly designed precipitation gauges (section 7.3.2).

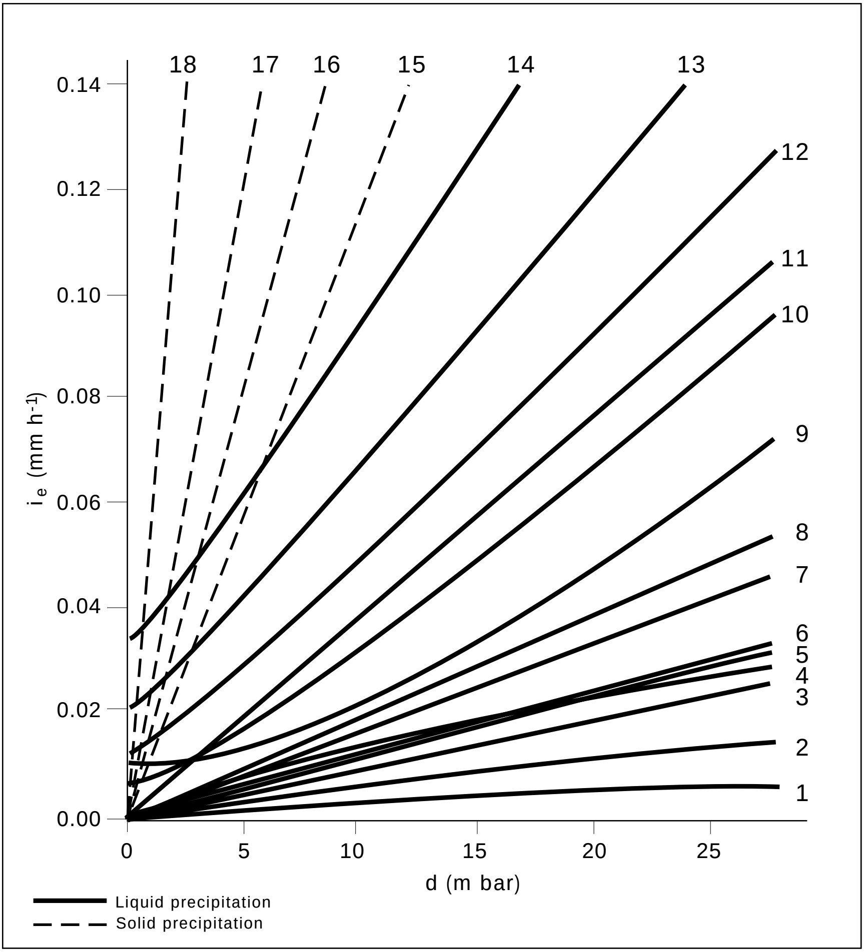
Besides these systematic errors there are random observational and instrumental errors. Their effect can often be neglected because of the high values of the systematic errors.

7.4 Recording gauges [C30]

Three types of precipitation recorders are in general use: the weighing type, the tipping-bucket type, and the float type. The only satisfactory instrument for measuring all kinds of precipitation utilizes the weight principle. The use of the other two types is primarily limited to the measurement of rainfall.

7.4.1 *Weighing type*

In these instruments, the weight of a receiving can plus the precipitation accumulating in it is recorded continuously, either by means of a spring mechanism or with a system of balance weights. Thus, all precipitation is recorded as it falls. This type of gauge normally has no provision for emptying itself, but by a system of levers, it is possible to make the pen traverse the chart any number of times. These gauges have to be



Intensity of evaporation (i_e) for various gauges: (*a*) Liquid precipitation: (i) Australian standard gauge 1, 2, 7, 11 for $P \leq 1$ mm; 1.1 to 20 mm; > 20 mm (all for wind speed, $u_e < 4$ m s^{-1}), and for $u_e \geq 4$ m s^{-1}, respectively; (ii) Snowdon gauge in a pit 3, 6, 8 for $P \leq 1$ mm, 1.1 to 10 mm and ≥ 10 mm, respectively; (iii) Hellmann gauge 4; (iv) Polish standard gauge 5; (v) Hungarian standard gauge 9; (vi) Tretyakov gauge 10, 12, 13, 14 for wind speeds at the level of the gauge rim of 0 to 2, 2 to 4, 4 to 6 and 6 to 8 m s^{-1}, respectively; (*b*) Solid precipitation: Tretyakov gauge 15, 16, 17, 18 for wind speeds 0 to 2, 2 to 4, 4 to 6 and 6 to 8 m s^{-1}, respectively, where i_e is the intensity of evaporation in mm h^{-1} and τ_e is the time elapsed between the end of the precipitation and the measurement of precipitation.

Figure 7.3 — Evaporation losses from precipitation gauges.

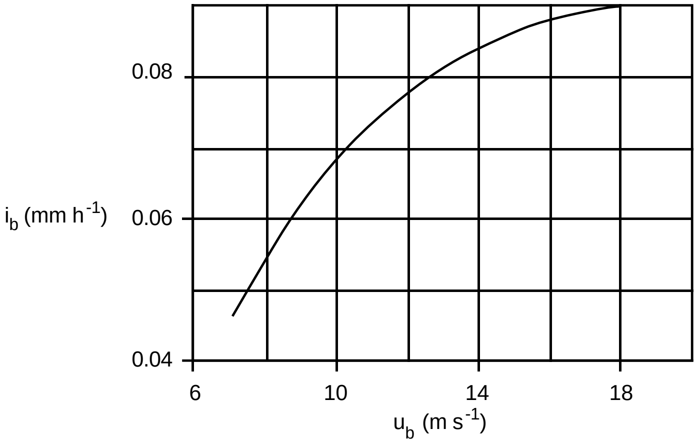


Figure 7.4 — Long-term seasonal intensity of blowing snow (i_b) as a function of long-term wind speed (u_b) at the level of the anemometer (10 to 20 m) during blowing snow.

designed to prevent excessive evaporation losses, which may be reduced further by the addition of sufficient oil or other evaporation suppressing material to form a film over the water surface. Difficulties caused by oscillation of the balance in strong winds can be reduced by fitting the instrument with an oil damping mechanism. The main utility of this type of instrument is in recording snow, hail, and mixtures of snow and rain. It does not require that the solid precipitation be melted before it can be recorded.

7.4.2 *Float type*

In this type of instrument, the rainfall is fed into a float chamber containing a light float. As the level of the water rises, the vertical movement of the float is transmitted, by a suitable mechanism, into the movement of the pen on the chart. By suitably adjusting the dimensions of the receiving funnel and the float chamber, any desired scale on the chart can be obtained.

To provide a record over a useful period (at least 24 hours is normally required) the float chamber has either to be very large (in which case a compressed scale on the chart is obtained), or some automatic means has to be provided for emptying the float chamber quickly whenever it becomes full. The pen then returns to the bottom of the chart. This is usually done with some sort of siphoning arrangement. The siphoning process should start fully at a definite time with no tendency for the water to dribble over, either at the beginning or at the end of the siphoning, which should not take longer than 15 seconds. In some instruments, the float chamber assembly is mounted on knife edges so that the full chamber overbalances. The surge of the water assists in the siphoning process, and when the chamber is empty, it returns to its original position. Other rainfall recorders have a forced siphon that operates in less than five seconds. One type has a small chamber separate from the main chamber which accommodates the rain that falls during siphoning. This chamber empties into the main one when siphoning ceases, thus ensuring a correct record of total rainfall.

A heating device should be installed inside the gauge if there is a possibility of freezing. This will prevent damage to the float and float chamber due to water freezing and will enable rain to be recorded during that period. A small heating element or electric lamp is suitable where a supply of electricity is available, but, if not, other sources of power have to be employed. One convenient method is to use a short length of heating strip wound around the collecting chamber and connected to a large capacity battery. The amount of heat supplied should be kept to the minimum necessary in order to prevent freezing, because the heat will affect the accuracy of the observations by stimulating vertical air movements above the gauge and by increasing evaporation losses.

7.4.3 *Tipping-bucket type*

The principle of this type of recording gauge is very simple. A light metal container is divided into two compartments and is balanced in unstable equilibrium about a horizontal axis. In its normal position the container rests against one of two stops, which prevents, it from tipping completely. The rain is led from a conventional collecting funnel into the uppermost compartment. After a predetermined amount of rain has fallen, the bucket becomes unstable in its present position and tips over to its other position of rest. The compartments of the container are so shaped that the water can now flow out of the lower one and leave it empty. Meanwhile, the rain falls into the newly positioned upper compartment. The movement of the bucket, as it tips over, is used to operate a relay contact and produce a record that consists of discontinuous steps. The distance between each step represents the time taken for a prespecified amount of rain to fall. This amount of rain should not be greater than 0.2 millimetre if detailed records are required. For many hydrological purposes, in particular for heavy rainfall areas and flood-warning systems, 0.5 to 1.0 millimetre buckets are satisfactory.

The main advantage of this type of instrument is that it has an electronic pulse output and can be recorded at a distance or for simultaneous recording of rainfall and river stage on a water stage recorder. Its disadvantages are:

(*a*) The bucket takes a small but finite time to tip, and during the first half of its motion, the rain is being fed into the compartment already containing the calculated amount of rainfall. This error is appreciable only in heavy rainfall [4];

(*b*) With the usual design of the bucket, the exposed water surface is relatively large. Thus, significant evaporation losses can occur in hot regions. This will be most appreciable in light rains; and (*c*) Because of the discontinuous nature of the record, the instrument is not satisfactory for use in light drizzle or very light rain. The time of beginning and ending of rainfall cannot be determined accurately.

7.4.4 *Rainfall-intensity recorder*

A number of rainfall-intensity recorders have been designed and have been used for special purposes. However, they are not recommended for general purposes because of their complexity. A satisfactory record of rainfall intensity can usually be determined from a float- or weighing-type recorder by providing the proper time-scale.

7.4.5 *Methods of recording*

Whether the rainfall recorder operates by the rise of a float, the tipping of a bucket, or some other method, these movements must be converted into a form that can be stored and analysed later. The simplest method of producing a record is to move a time chart by a spring or an electrically-driven clock, past a pen that moves as the float or weighing device moves. There are two main types of charts: the drum chart, which is secured around a drum that revolves once a day, once a week, or for such other period as desired, and the strip chart, which is driven on rollers past the pen arm. By altering the speed of the strip chart, the recorder can operate for periods from one week to a month or even longer. The time-scale on the strip chart can be large enough for intensity to be calculated with ease.

The value to be recorded may also be mechanically or electronically converted to digital form and recorded as a set of holes punched in paper tape at uniform time intervals for later automatic reading and processing. Magnetic media and solid state recorders are also used.

The movement of a float, bucket, or weighing mechanism can also be converted into an electric signal and transmitted by radio or wire to a distant receiver, where records may be collected from a number of recorders on data-logging equipment (section 6.2.4).

7.5 Snowfall

Snowfall is the amount of fresh snow deposited over a limited period. Measurements are made of depth and water equivalent.

7.5.1 *Depth of snowfall*

Direct measurements of fresh snow on open ground are made with a graduated ruler or scale. A mean of several vertical measurements should be made in places where there is considered to be an absence of drifting snow. Special precautions should be taken so as not to measure any old snow. This can be done by sweeping a suitable patch clear beforehand or covering the top of the snow surface with a piece of suitable material (such as wood, with a slightly rough surface, painted white) and measuring the depth down to this. On a sloping surface (to be avoided if possible) measurements should also be made with the measuring rod in a vertical position. If there is a layer of old snow it would be incorrect to calculate the depth of a snowfall from the difference between two consecutive measurements of the total depth of the fresh and old snow, because of the continuous settling of the old snow. Where strong winds have occurred, a large number of measurements should be made to obtain a representative depth.

The depth of snow may also be measured in a fixed container of uniform cross-section after the snow has been levelled without compressing. The container should be well above the average snow level, for example, at least 50 centimetres above the maximum observed level, and not exposed to drifting snow. The receiver should be at least 20 centimetres in diameter and should either be sufficiently deep to protect the catch from being blown out or else be fitted with a snow cross (i.e., two vertical partitions at right angles, subdividing it into quadrants).

Ordinary unshielded receivers are unreliable when the wind is strong because of the wind eddies around the mouth of the receiver. Their catch is usually much less than that of a shielded gauge. On the other hand, large errors may be caused, in spite of the use of a shield, by drifting snow being caught. Such errors can be reduced by mounting the gauges three to six metres above the surface.

7.5.2 *Water equivalent of snowfall*

The water equivalent of a snowfall is the amount of liquid precipitation contained in that snowfall. It should be determined by one of the methods given below. It is important to take several representative samples:

(*a*) Weighing or melting — Cylindrical samples of fresh snow are taken with a suitable snow sampler and either weighed or melted;

(*b*) Using raingauges — Snow collected in a non-recording raingauge should be melted immediately and measured by means of an ordinary measuring cylinder graduated for rainfall. The weighing-type recording gauge may also be used to determine the water content of snowfall. During snowfall periods, the funnels of the gauges should be removed so that any precipitation can fall directly into the receiver.

7.6 **Observation of rainfall by radar** **[C33]**

7.6.1 *Uses of radar in hydrology*

Radar permits the observation of the location and movement of areas of precipitation, and certain types of radar equipment can yield estimates of rainfall rates over areas within range of the radar [5]. For hydrological purposes the effective radar range [6] is usually 40-200 kilometres depending on the radar characteristics, such as antenna beam, power output, and receiver sensitivity. The hydrological range of the radar is defined as the maximum range over which the relationship between the radar echo intensity and rainfall intensity remains reasonably valid. The rate of rainfall in any area of precipitation within hydrological range can be determined provided the radar is equipped with a properly calibrated receiver gain control.

Precipitation attenuates the radar beam, and this effect is greatest for short wavelength radar. On the other hand, long wavelength radar does not detect light rain and snow as readily as shorter wavelength equipment. The selection of a suitable wavelength depends on climatic conditions and the purposes to be served. All three of the radar bands given in Table 7.2 are in use for observation of precipitation.

TABLE 7.2
Weather radar frequency bands

Band	*Frequency (MHz)*	*Wavelength (m)*
S	1 500 – 5 200	0.193 – 0.0577
C	3 900 – 6 200	0.0769 – 0.0484
X	5 200 – 10 900	0.0577 – 0.0275

7.6.2 *The radar-rainfall equation*

The radar equation is sometimes referred to as the free space maximum range equation (FSMR). This equation defines the maximum range that can be anticipated from a particular radar system. For precipitation targets, where rainfall is considered to have filled the radar beam, the equation has the form:

$$\bar{P}_r = \frac{P_t \pi^4 Arl[K]^2 Z}{8R^2 \lambda^4} \tag{7.4}$$

where $\bar{P}_r$ is the average power in watts received from a series of reflected pulses, P_t is the peak power transmitted in watts, A_r is the effective area of antenna in m^2, l is the pulse length in metres, R is the range in metres, λ is the wavelength in metres, $[K]^2$ is the refractive index term of rain (0.9313 for 10 centimetre radar equipment assuming a temperature of 10°C), Z is reflectivity and expressed as $\sum d^6$ per m^3, where d is the drop diameter in millimetres.

The rainfall rate in mm h^{-1} is related to the median drop diameter, as follows:

$$\sum d^6 = aP_i^b \tag{7.5}$$

where P_i is the rainfall intensity in mm h^{-1} and a and b are constants. Many determinations have been made of the drop size distribution measured at the ground and the conversion by means of the fall speeds of different sized drops to a particular rainfall rate. The most common equation in use is:

$$Z = 200P_i^{1.6} \tag{7.6}$$

7.6.3 ***Factors affecting measurements***

7.6.3.1 *Precipitation type*

Because the return signal is influenced by drop size and is proportional to the sixth power of the diameter of the hydrometer, it may be seen that a considerably stronger signal is received from the larger forms of precipitation. Hail, for instance, often gives an indication of intense precipitation, but snow yields relatively low reflectivity.

Another influence is the growth or dissipation of the drop after it has fallen out of the area encompassed by the beam and before it strikes the ground. Generally, the effect of evaporation on a drop as it falls to the ground is negligible in storms of high rainfall intensity. Growth of raindrops through accretion in lower cloud decks, however, may add appreciably to the size and number of drops below the radar beam. This is especially true of distances of over 130 kilometres from the radar site, where drops may fall through up to one thousand metres of stratiform clouds after leaving the radar beam and before striking the ground.

7.6.3.2 *Beam width*

At 160 kilometres, the radar beam may be several kilometres wide, depending on the beam width employed. Normally, there will be marked variations in the radar reflectivity within this large sampling volume. Thus, an average value over a large volume is obtained, rather than a point value. The radar equation is based on the beam being filled with meteorological targets. Therefore, one would not expect the values of rainfall rate obtained with a radar to be highly correlated with point raingauge measurements. However, the areal pattern displayed by radar should generally be much more representative of the true storm isohyetal configuration than that measured by most raingauge networks.

In showery conditions it has been found that the frequency of echoes recorded at 160 kilometres was only about four per cent of that of echoes recorded at 64 kilometres. Therefore, a shower which fills the beam at 64 kilometres would only fill about 1/8 of the beam at 160 kilometres. This result is due to a combination of beam width and beam elevation factors.

7.6.3.3 *Refraction of beam*

Radar waves are propagated through space with a refractive effect which gives the waves a curved path. The approximate mean radius is four-thirds the mean radius of the Earth. As a result of vertical moisture discontinuities, additional refractive bending of the radar beam can occur. This produces what is often called ducting or trapping of the radar beam and either causes the radar beam to recurve earthward or to be curved upward overshooting precipitation 80-120 kilometres away. The meteorological conditions favouring ducting (trapping) can be determined mathematically.

7.6.3.4 *Atmospheric attenuation*

Microwaves are attenuated by atmospheric gases, clouds, and precipitation. The attenuation experienced by radio waves is a result of two effects: absorption and scattering. In general, gases act only as absorbers, but cloud and raindrops both scatter and absorb. For radar sets operating at the longer wavelengths, attenuation is not a problem and can usually be neglected. The generally accepted form of expressing attenuation is in decibels.

The decibel (dB) is used as a measure of relative power and is expressed as:

$$dB = 10 \log_{10} \frac{P_t}{P_r} \tag{7.7}$$

where P_t and P_r would be the power transmitted and power received. Signal attenuation as related to rate of rainfall and wavelength is given in Table 7.3.

TABLE 7.3

Radar signal attenuation due to precipitation (dB km^{-1})

Rate of rainfall	*Wavelength (m)*			
(mm h^{-1})	*0.1*	*.057*	*.032*	*.009*
1.0	.0003	.002	.007	.22
5.0	.0015	.015	.061	1.1
10.0	.003	.033	.151	2.2
50.0	.015	.215	1.25	11.0
100.0	.030	.481	3.08	22.0

Distance (km) over which precipitation at a given rate of rainfall must extend to give an attenuation of 10 dB at various wavelengths

Rate of rainfall	*Wavelength (m)*			
(mm h^{-1})	*0.1*	*.057*	*.032*	*.009*
1.0	33 000	4 500	1 350	45
5.0	6 600	690	164	9.1
10.0	3 300	310	66	4.5
50.0	600	47	8	0.9
100.0	300	21	3.2	0.4

7.6.3.5 *Range attenuation*

The received signal power is inversely proportional to the square of the range to the target. Therefore it may be seen that this is another form of attenuation which occurs as the beam propagates into space with the signal being attenuated as the beam width increases with range. The radar pulse energy in the beam is dissipated much like the light waves in a flashlight beam. There is electrical compensation for range attenuation on the display scope in many modern radars.

7.6.4 ***Methods and procedures***

7.6.4.1 *Photographic methods*

For operational purposes, an automatic camera with rapid development facilities is used to photograph the repeater scope to provide multiple exposure transparency photographs. These multiple exposures taken every 10 minutes are used to detect areas of persistent and/or intense rainfall during the last hour or two. The brightest areas on the film represent either the most intense precipitation or that of greatest persistence, where the echo reinforces the brilliance with successive exposures. After rapid process development of the transparency, it is mounted in a slide holder and the echo images are projected onto a map where they can be outlined and compared with observed rainfall reports.

Ideally, echo areas sufficiently strong to saturate the same area during every exposure would produce a fully exposed area on the multiple exposure photograph. If a saturated area did not persist for the total number of exposures, the photograph would contain an echo area of something less than total exposure and would appear grey in the photograph.

If the radar is equipped with a stepped-gain receiver control (attenuators), an intensity parameter can be introduced into a multiple exposure photograph. This is accomplished by stepping the attenuators through selected decibel increments and taking a picture at each decibel level. This system further enhances the echoes on the transparency making recognition of the high-intensity rainfall areas easier. Periodic photos of the repeater scope are taken for analysis of storms in retrospect.

7.6.4.2 *Manual techniques*

(*a*) Contour tracing — The simplest analysis involves periodic tracing of echo positions on transparent acetate radarscope overlays, which have geographic boundaries outlined on them. Qualitative estimates can be made of the instantaneous storm intensity on the basis of echo appearance. Successive tracings of the scope display at 15 millimetre intervals can be superimposed to determine the areas affected, the direction of storm motion, echo persistence, and the area-intensity relationship;

(*b*) Stepped-gain contour tracing — If the radar is equipped with a stepped-gain receiver control (attenuators), an intensity parameter can be introduced onto the radarscope overlay. After every 15 minutes, the echoes at each of the selected decibel attenuator levels are contoured. The use of different colours will readily show the most intense cores of rainfall as well as the areal extent of the storm. Each decibel level, at a specific range, has a corresponding rate of rainfall. It is possible, using the attenuators, to determine the radar depicted rainfall rate for any precipitation echo within range. Determinations beyond 180 kilometres are of limited value because of poor correlation with observed rainfall on the ground;

(*c*) Grid overlay method — Other procedures can be used to evaluate rainfall from the radar echoes. The first provides information on whether precipitation is occurring and some indication of duration. In this method, a grid overlay is placed at time intervals on the radarscope, and a mark is placed in each grid where a precipitation echo is observed. At the end of a selected time interval, the grid with the most marks shows the area where precipitation has been occurring the longest.

The second method utilizes the attenuator controls on the radar. At frequent intervals, the attenuators should be stepped through selected decibel intervals. At each decibel level and corresponding range, the instantaneous rate of rainfall can be estimated and entered in the appropriate grid. These values can later be processed to furnish a total rainfall value.

7.6.4.3 *Automatic techniques*

An automatic electronic radar digitizer, capable of sampling radar echoes at the rate of 80 range-increments for each 2° of azimuth, has been developed. Its data are recorded on magnetic tape for immediate on-site computer analysis, transmission via data link to a remote computer, or for retention and later analysis. The results of this type of sampling are similar to those for manual methods, except that the number of discrete samples is larger by at least one order of magnitude than the finest grid overlay. The time required to sample and record the entire radar sweep is about four minutes.

7.6.5 ***Doppler radar***

The radars discussed so far in this chapter have been non-coherent. This means that, pulse-to-pulse, the transmitter frequency is not totally stable, though stable enough to be recognized by the radar receiver that examines the pulse amplitude on return rather than its frequency. Such radars are able to detect changes in the intensity of precipitation echoes and their relativity in size and location. It is possible to estimate their relative motion and, from that, the speed of movement of a target.

To measure the absolute speed of movement (or velocity) of a raindrop and its direction of movement instantaneously, it is necessary to use a radar with a very precise transmitter frequency and a receiver system sensitive to the changes of frequency induced by a moving target, even though in the case of meteorological targets these changes may be small. This type of radar is sometimes referred to as a coherent radar but more frequently as a Doppler radar because it uses the well-known Doppler effect. A more detailed discussion of this topic along with added references is found in the WMO *Use of Radar in Meteorology* [7].

Doppler radars have been used for research purposes for many years, both singly and, more recently, in multiple networks consisting usually of two or three radars. They have played a considerable part in the investigation of the atmosphere and are considered by some radar meteorologists to be indispensable in the study of the dynamics of air masses, particularly of convective clouds. However, problems of interpretation of data still exist, and it is only in very recent years that serious consideration has been given to their use in operational systems. In certain parts of the world, particularly those subject to violent weather, they are now operational systems and are now regarded as a highly desirable form of radar. They are inherently more complex and more expensive than conventional radars, and they require greater processing power and more maintenance effort. Despite this, radars with Doppler capability will form a large national network in the United States.

Doppler radars can be used for general forecasting purposes to provide data that may reveal signatures useful for the advanced warning of such phenomena as tornadoes and severe storms. Moreover, it can provide more information on their intensity and structure than any other practical means.

The most useful system is one which, in addition, can measure precipitation intensities in a conventional way as well as providing Doppler data. One important advantage of such a dual system is that it is possible to determine with some degree of accuracy the position and extent of permanent echoes — which are, by definition, stationary — from the Doppler channel. This information can then be used in an attempt to ensure that only precipitation data are measured by the non-Doppler channel. As with any other system of clutter removal, the method is unlikely to be totally successful since, under some transmission and weather conditions, permanent echoes can appear to move and, conversely, precipitation is sometimes effectively stationary.

To obtain echoes from refractive inhomogeneities and for the purpose of measuring precipitation intensity to the greatest possible ranges (compared to conventional non-Doppler radar) or for studying the structure of severe storms, longer wavelengths are necessary, preferably 10 centimetres.

7.7 **Observations by satellite**

Precipitation can be estimated by using images registered by scanners or by imaging microwave radiometers. Scanners are widely used in operational weather satellites. The amount of data from imaging microwave radiometers is very limited and cannot be used operationally at present.

Techniques have been developed for using images of geostationary or polar-orbiting satellites for estimating hourly, daily, and monthly precipitation. Images are taken in the visible and/or infrared parts of the electromagnetic spectrum and the estimation is based on the albedo and/or the temperature of the cloud tops as well as, on the shape, texture, and life history of the clouds. Satellite images can be used for estimating precipitation over areas ranging from the global to the very local scale in real or near-real time. This complements the conventional precipitation measurements in areas of sparse raingauge networks and can improve the accuracy of estimating precipitation for short time periods (several hours). Satellite-image based methods must be carefully adapted to the weather systems, terrain and meteorological conditions of the area. This can be done through extensive validation.

Hybrid methods, combining satellite images with radar or synoptic precipitation data, may be used to obtain the best possible result. Visual interpretation, together with some image processing, or automatic interpretation of satellite images are all used. The accuracy of the precipitation estimates or rainfall estimates varies, in general, between 10 and 50 per cent depending on the area studied and on the method used.

7.8 Dew

Although the deposition of dew, essentially a nocturnal phenomenon, is not spectacular as a source of moisture, being relatively small in amount and varying locally, it could be of significant interest in arid zones, where it could even be of the same order of magnitude as rainfall.

Since the process by which moisture is deposited on objects largely depends on the source of moisture, it is necessary to distinguish between dew formed as a result of downfall transport of atmospheric moisture condensed on cooled surfaces, known as dewfall, and that formed by water vapour evaporated from the soil and plants and condensed on cooled surfaces, known as distillation dew. Both sources generally contribute simultaneously to observed dew, although at times they operate separately. A further source of moisture results from fog or cloud droplets collected by leaves and twigs and reaching the ground by dripping or stem flow.

There has been a great tendency to overestimate the average dew over an area, and this is due primarily to overlooking the physical limits on possible quantities of dew. Examination of the energy-budget equation reveals that the latent heat of dewfall and/or distillation dew is unlikely to exceed net radiation and should be less if sensible and soil-heat transfers are taken into consideration. Under favourable conditions there is a definite limit, at the rate of about 1.1 mm h^{-1} for the average rate of dew over an area. However, dew may be substantially increased in local areas where mean temperatures are not horizontally homogeneous and there is small-scale advection from relatively warmer and moisture areas to cooler areas. Moreover, the one-dimensional form of energy-flux computations should be modified when applied to isolated plants because the pattern of radiation and moisture flux is quite different from that of a homogeneous source. This does not mean that the average deposit over a large horizontal area is affected but only that some parts gain at the expense of others. Actual deposition rates will generally fall well below the upper limit.

Much effort has been devoted, but without much success, to devising a means of measuring leaf wetness from artificial surfaces in the hope of yielding results comparable to those for natural conditions. A review of the instrumentation designed for measuring duration of leaf wetness and an assessment of the extent to which various instruments give readings representative of plant surface wetness is given in the appendix to the WMO *The Influence of Weather Conditions on the Occurrence of Apple Scab* [8]. Any of these devices can only be used as a qualitative guide in any particular situation, or as a crude means of regional comparison. Careful interpretation is required in either role. Unless the collecting surface of these gauges is more or less flush with the surface and of very similar properties, it will not correctly indicate the amount of dew that the natural surface receives.

Theoretically, the flux technique should give reasonable average values over an area, but lack of knowledge of transfer coefficients under very stable conditions makes it extremely difficult to implement. The only certain method of measuring net dewfall by itself is by a sensitive lysimeter. However, this method does not record distillation dew, since no change in weight accompanies distillation dew. The only generally accepted means of measuring total amount of dew is by the blotting technique, that is, by weighing a number of filter papers both before and after being thoroughly pressed against leaves.

A brief outline of dew measurement methods is given in the WMO *Guide to Meteorological Instruments and Methods of Observation* [1].

7.9 Sampling for precipitation quality

In recent years it has become increasingly apparent that deposition of atmospheric pollutants is of major ecological significance. Most notable have been the effects resulting from acidic precipitation in Scandinavia, eastern Canada and the north-eastern United States. For a complete picture of the atmospheric transport of toxic substances, both the wet and dry precipitation must be sampled and analysed as well as the air itself.

This section discusses the criteria necessary for the collection of liquid and frozen precipitation samples and of surface deposition. For the analysis of atmospheric deposition over periods of tens to hundreds of years, several other substrates have been found useful in providing a record. These include naturally-growing mosses, which quantitatively retain some metals, ice cores from glaciers, and bottom sediments.

7.9.1 ***Sample collectors***

7.9.1.1 *Rain collectors*

Many types of collectors have been used to sample precipitation, from a plastic, stainless steel, or glass container placed on location at the beginning of a precipitation event, to a sophisticated sequential sampler designed to collect precipitation samples automatically at selected intervals during an event.

A common device for the collection of both wet and dry deposition separately is the double bucket collector. One bucket is used to collect precipitation while the other bucket collects the dry deposition. The collector is equipped with an automatic sensing system that detects precipitation, liquid or frozen. At the onset of a precipitation event, a cover is moved from the wet bucket to the dry bucket. On cessation of the event, the cover automatically returns over the wet bucket.

The sample container normally used is a black polyethylene vessel. It consists of two parts. The top part is a removable rim that has been specially fabricated to ensure a sharply defined uniform area of collection. The second part is the bucket itself. Both the rim and the bucket must be rinsed with distilled, deionized water each time a sample is removed. When sampling precipitation for organic contaminants, a stainless steel or glass bucket must be used.

When directional information is desired, associated meteorological instruments can be utilized. Equipment has been designed in which precipitation is directed to one of a number of bottles depending on the direction of the wind by means of a wind vane.

7.9.1.2 *Snow collectors*

Modern snow collectors are similar to rain collectors, except that they are heated to thaw and store the entrapped snow as liquid in a compartment beneath the sampler.

7.9.1.3 *Dry deposition collection*

Many of the problems in snow collection also apply to the collection of dry deposition. The double bucket collector provides a measure of the amount, but considerable controversy exists about the relevance of such measurements. The air turbulence around such device is not the same as at the surface of a lake, for example, which leads to differences both in absolute collection efficiency and relative efficiency between different particle sizes. Other methods have been suggested, such as glass plates coated with sticky materials and shallow pans with liquids, aqueous ethylene glycol or mineral oil.

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CHAPTER 8

SNOW COVER

8.1 General

The snow that accumulates in a drainage basin is a natural storage reservoir from which a major part of some basin's water supply is derived. Water supply forecasts are of interest to farmers, ranchers, shippers, bankers, and agencies concerned with power production, water supplies, and flood control. Reliable forecasts of the seasonal snow-melt runoff can usually be made after several years of observation. Such forecasts are based on correlations between the weighted water equivalents of the snow cover at snow courses and the runoff measured at a gauging station.

This chapter describes procedures for collecting measurements of snow cover, snow depth, and water equivalent of snow. Guidance for the location of gauges that are to be used to measure snow depth and water equivalent of snow is provided in section 7.5 and discussion of the design of snow cover networks is given in section 20.2.1.2. Additional discussion of snow cover measurement is given in the WMO *Snow Cover Measurements and Areal Assessment of Precipitation and Soil Moisture* [1].

8.2 Snow courses

A snow course is defined as a permanently marked line, where snow surveys are taken each year. Snow courses must be carefully selected so that measurements of water equivalents will provide a reliable index of the water in snow storage over the entire basin.

In mountainous areas, the selection of appropriate locations for snow courses may be a challenging exercise because of the difficult terrain and serious wind effects. Criteria for an ideal location for a snow course in mountainous areas are:

(*a*) At elevations and exposures where there is little or no melting prior to the peak accumulation if the total seasonal accumulation is to be measured;
(*b*) At sites sufficiently accessible to ensure continuity of surveys;
(*c*) In forested areas where the sites can be located in open spaces sufficiently large so that snow can fall to the ground without being intercepted by the trees; and
(*d*) At a site having protection from strong wind movement.

Criteria for suitable snow course locations are the same as those for siting precipitation gauges for measurement of snowfall.

In plain areas, the snow course locations should be selected so that their average water equivalents will represent, as nearly as possible, the actual average water equivalent of the area. Thus, it is desirable to have snow courses in typical landscapes, such as in open fields and forests, with different snow accumulation conditions.

If the snow cover in an area under consideration is homogeneous and isotopic and if there exists a spatial correlation function for the depth or water equivalent of the snow, the length of the snow course or the number of measuring points along it needed to determine a mean value to a given accuracy can be determined [2].

8.2.1 *Points of measurement*

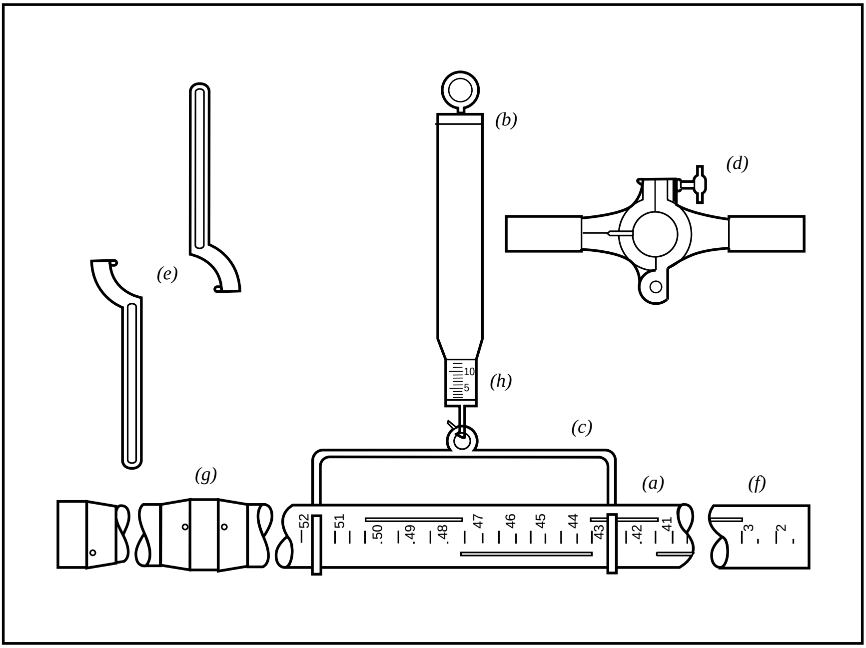
Measurements at a snow course in a mountainous terrain usually consist of samples taken at points spaced 20 to 40 metres apart. More samples will be required in large open areas where snow will tend to drift because of wind action. Because sufficient knowledge of the tendency of the snow to drift may be initially lacking, it may be necessary to provide for an extensive survey having long traverses and a large number of measurements. Once the prevailing length and direction of the snowdrifts have been ascertained, it should be possible to reduce the number of measurement points.

In plain regions, the distance between points of snow density sampling should be 100 to 500 metres. Depth of snow along the snow course should also be measured at about five equally spaced points between the density samples.

Each sampling point should be located by measuring its distance from a reference point marked on a map of the snow course. Stakes should be set high enough to extend above the deepest snow and offset from the course far enough not to affect the snow cover. They may be placed as markers opposite each point where snow samples are to be taken or, at as many points as necessary, to minimize possible error in locating the sampling point. The ground surface should be cleared of rocks, stumps, and brush for two metres in all directions from each sampling point. Watercourses and irregular ground surfaces should also be avoided by at least two metres. If a course meanders through timber and if small openings are used as places of sampling, each point should be located with respect to two or three marked trees.

8.2.2 *Snow-sampling equipment* **[C53]**

Snow-sampling equipment commonly consists of a metal or plastic tube (sometimes in sections for portability) with a snow cutter fixed at its lower end and with a length scale stamped on its exterior surface throughout its length, a spring or level balance for determining the weight of the snow cores, a wire cradle for supporting the tube while it is being weighed, and tools for operating the snow sampler. A typical set of equipment for deep snow, shown in the Figure below, is described in the following way:



Snow-sampling equipment (*a*) snow-sampling tube; (*b*) tubular spring balance; (*c*) cradle; (*d*) driving wrench; (*e*) spanner wrenches; (*f*) cutter; (*g*) screw couplings; (*h*) scale.

(*a*) Cutter — The cutter must be designed to penetrate various types of snow, through crusted and icy layers, and in, some cases, through solid ice layers of appreciable thickness that may form near the surface. The cutter must not compact the snow so that an excessive amount of snow is accepted by the interior of the cutter. The cutter must seize the core base with sufficient adhesion to prevent the core from falling out when the sampler is withdrawn from the snow. Small diameter cutters retain the sample much better than large cutters, but larger samples increase the accuracy in weighing.

The shape of the cutter teeth should be designed to allow sufficient backfeed on the cutter to remove the ice chips. The cutter should be as thin as practical but somewhat larger than the outside diameter of the driving tube. This construction allows the chips to find a dumping area when carried backward by the feed on the cutter. The horizontal cutting surface on the cutter blade should be sloped slightly backward to carry the chips away from the interior of the cutter and should be kept sharp so that there is a definite separation of the snow at the inner wall. A large number of teeth provide a smooth cut and keep the cutter free of large chunks of ice;

(*b*) Sampler tube — In most cases, the inside diameter of the driving tube is larger than the inside diameter of the cutter. The core, therefore, is able to proceed up the tube with a minimum of interference from friction on the wall. However, in normal snow, the core will tend to move over and rub on the walls of the driving tube. Therefore, the walls should be as smooth as possible so that the core may proceed upward without undue friction. In most cases, samplers are constructed of anodized aluminum alloy. While the surface may appear smooth, it cannot be assumed that this will assure nonadhesion of the snow, especially when sampling is made of wet spring snow with a coarse-grained structure. The application of wax may minimize sticking.

Some samplers are provided with slots so that the core length may be determined. In general, especially with wet snow, the core length inside may be considerably different from the true depth of the snow measured on the outer markings on the sampler. The slots also provide an entrance for a cleaning tool. The advantage of the slotting arrangement is that errors due to plugging may be immediately detected and erroneous samples may, obviously, be discarded at once. However, the slots may allow extra snow to enter the sampler and increase the measured water equivalent;

(*c*) Weighing apparatus — The standard way to measure the water equivalent of snow samples is to weigh the snow core collected in the sampler. The core is retained in the sampler, and the sampler and core are weighed. The weight of the sampler is known.

Generally, weighing is accomplished by means of a spring scale or by a special balance. The spring scale is the most practical approach as it may be easily set up and read even under windy conditions. However, the spring scale is accurate only to about 10 grams, and the error in weighing by this method may be appreciable for small diameter samplers and shallow depths of snow.

Scale balances, potentially more accurate, are very difficult to use in wind. It is doubtful if the intrinsically greater accuracy of this system can be realized except in calm conditions.

Another approach is to store the samples in plastic containers or bags and return them to a base station where they may be accurately weighed or melted and measured with a graduated cylinder. In practice, this procedure is difficult to carry out as the samples must be bagged without loss, carefully labelled, and carried back to the base. The advantage of measurement in the field is that any gross errors due to plugging the sampler, or losses due to part of the sample falling out, may be readily recognized, and repeat readings can be taken at once. The results may be recorded on site with other pertinent observations, and, if a good notebook is used, there can be little chance of confusion as to the location or the sampling conditions.

In all measurements of this type, the extremely difficult physical conditions under which observations must frequently be made should always be kept in mind, and practical consideration should prevail in sampler designs.

8.2.3 *Snow-sampling procedures*

Sampling points should be located by measuring from a reference mark, as indicated on the map of the snow course. Missing a point by more than a few metres may result in a significant error.

In order to cut the core, the sampler is forced vertically downward through the snow cover until it reaches the ground. If snow conditions permit, a steady downward thrust, causing an uninterrupted flow of the core into the tube, is best. A minimum amount of turning in a right-hand direction is possible without interrupting the downward thrust. This brings the cutter into play, which is desirable for quick penetration of thin ice layers.

With the cutter at or slightly below ground level and the sampler standing vertically, the reading on the scale that corresponds to the top of the snow is observed. When the depth that the sampler has penetrated beyond the bottom of the snow cover is ascertained and deducted from this reading, the result is recorded. This is an important reading because it is used in computing the snow density.

In order to prevent loss of core through the cutter while the sampler is withdrawn from the snow, sufficient soil is gathered in the cutter to serve as a plug. The extent to which this will have to be done depends on the condition of the snow. About 25 millimetres of solid soil may be required to hold slush. A trace of ground litter on the lower end of the sampler indicates that no loss has occurred.

The length of snow core obtained is observed through the tube slots and read on the scale on the outside of the sampler. After this reading is corrected for any foreign matter picked up in the cutter, it is recorded. The purpose of this reading is to provide a means for judging quickly if a complete sample of the snow cover has been obtained.

The measurement is completed by carefully weighing the snow core in the tube. The weight of the snow core in equivalent centimetres of water can be read directly on the scale of the balance. The density of the snow is computed by dividing the water equivalent of the snow by the depth of the snow. The density should be reasonably constant over the entire course. A large deviation from the average usually indicates an error in measurement at an individual point.

8.2.4 *Accuracy of measurements*

The accuracy of measurements of snow depth, d_n, or the water content, w_n, of snow cover at individual points of the snow course depends on the graduations of the scale being used and on instrumental and subjective errors.

A decrease in the errors in d_n or w_n can be achieved by taking the mean of several measurements at each separate point. If the errors in the individual measurements are independent, the necessary number of measurements to ensure that the desired relative accuracy of the mean values will be attained is determined from the theory of errors, as follows:

$$N = V_x / V_e \qquad (8.1)$$

where N is the number of measurements needed to attain the prespecified accuracy, V_x is the variance of the errors in the measurements, and V_e is the square of the acceptable standard error of estimate of the mean.

8.3 Depth and extent of snow cover

Measurements of snow cover over extended areas together with an established local correlation with density make it possible to approximate the water content of the snow pack.

8.3.1 *Measurement with graduated snow stakes*

The most common method for determining the depth of snow cover, primarily in regions of deep snow, is by means of calibrated stakes fixed at representative sites that can be inspected easily from a distance. This procedure may be acceptable if the representativeness of the site is proven and if the immediate surroundings of the site (about 10 metres in radius) are protected against trespassing. The readings are taken by sighting over the undisturbed snow surface.

The stakes should be painted white to minimize undue melting of snow immediately surrounding them. The entire length of the stake should be graduated in metres and centimetres.

In inaccessible areas, stakes are provided with crossbars so that they can be read from a distance with the aid of field glasses, telescopes, or from aircraft.

In the case of measurements of snow depth from aircraft, visual readings of snow stakes may be supplemented by large-scale photographs of the snow stakes, which make the readings less subjective.

8.3.2 *Measurement with snow tubes*

The vertical depth of snow cover is also measured by direct observation with a graduated snow tube, usually during the course of obtaining the water equivalent, as described in section 8.2.3.

8.3.3 *Measurement by photogrammetric methods*

Aerial photography can be used to provide data on the maximum depth of snow cover in barren and sparsely wooded mountainous basins, as well as the extent of the cover. For these purposes, aerial photographs of the basin should be obtained before the snow season and at about the time of maximum snow accumulation. Horizontal and vertical control stations for the photography are identified with tall poles so that the same points can be easily relocated on photographs after the snow cover. Snow depth is determined by subtracting photogrammetrically determined ground-surface elevations from similarly determined snow-surface elevations at sample points. Thus, an average depth of snow cover on the basin can be estimated. The accuracy of the determination of the depth of the snow cover by this method depends on the scale of the photographs and the accuracy of the horizontal and vertical control for the photography. A useful scale for aerial photography for this purpose is 1:6 000. For a deep snow cover and favourable photographic conditions, the accuracy may be within ±10 per cent of the depth of snow cover. Aerial photogrammetry is fairly costly, but its principal value is in providing information about the quantity and distribution of snow cover that cannot readily be obtained in any other way.

The elevation of the snow line on mountain slopes may also be determined by means of phototheodolite photography (terrestrial photogrammetry). The theodolite is positioned periodically at predetermined photo stations to photograph the snow line. Terrestrial photogrammetry can be used to advantage in small isolated areas where data are required periodically during the winter and spring seasons. The accuracy is comparable to aerial photogrammetry.

Satellite imagery can also be used to give a general determination of the extent of snow cover, both in mountainous and plain regions. The methods of processing and utilizing such information are dealt with in detail in Chapter 45.

8.4 **Radioisotope snow gauges**

Radioactive gamma sources are used in various ways to measure water equivalent of snow. Attenuation of gamma radiation may be used to estimate the water equivalent of a snow cover between a source and a detector. One type of installation (vertical) is used to measure total water equivalent above or below a point source. A second installation (horizontal) measures water equivalent between two vertical tubes at selected distances above the ground.

8.4.1 ***Vertical radioisotope snow gauges***

Measurement of snow density with the use of radioactive isotopes depends on attenuation of gamma rays traversing a medium. This attenuation is a function of the initial energy of the rays and the density and thickness of the substance traversed. A high energy source of gamma radiation is required, and cobalt-60 is frequently used for this purpose because of its high gamma energy and long half-life (5.25 years).

The source, contained in a lead shield, is placed so that the upper surface of the shield is on the same level as the ground surface, and the beams of gamma rays are directed on the radiation detector above the snow. The detector is a Geiger-Müller or scintillation counter. The impulses from the counter are transmitted to a scalar or, in the case of continuous recording, to an integrator and recorder.

The source of radiation may also be placed in the soil at a certain depth (50-60 centimetres) so that the gamma rays pass not only through the snow cover but also through a layer of soil. By this means, it is possible to obtain data during the melting of snow pertaining to the quantity of water permeating into the soil or flowing off the surface.

There is also a third way of placing the system in the field. The radiation detector-counter is placed under the ground surface and the source with shielding is placed above the expected maximum snow layer. This arrangement reduces temperature variations of the detector and provides a constant background count.

Installation of isotope snow gauges requires relatively expensive and complex instrumentation. In addition, adequate safety measures should be part of any installation, especially where a comparatively high energy source is required. In all cases, consultation with the appropriate licensing or controlling agencies during the development stage is essential and will eliminate many difficulties later on. Although these constraints may limit the use of these gauges, they are a valuable tool and provide the possibility of continuous recording that is particularly useful in inaccessible regions.

8.4.2 *Horizontal radioisotope snow gauges*

In France and in the United States, various modifications of telemetering radioisotope snow gauges have been developed, giving a horizontal and vertical profile of the layer of snow and transmitting the results of measurements to base stations via land, radio or satellite. In both types, the measuring element consists of two vertical tubes of the same length, at a distance of 0.5 to 0.7 metre from each other. One tube contains a source of gamma-radiation (137 C with a half-life of 34 years and activity of 10 or 30 millicuries), while the other contains a detector (Geiger-Müller counter or scintillation crystal with photo-multiplier). In the process of obtaining a profile, a special motor, synchronous with the detector, moves the radioactive source upwards and downwards in the tube.

By recording the intensity of the horizontal flux of gamma pulses outside and at various levels inside the layer of snow and by suitably processing the data at a base station, it is possible to determine the depth of snow cover and the density and water content of the snow at a given depth. Furthermore, freshly fallen snow, liquid precipitation, and the rate of melting of the snow can be determined.

One of these sets of equipment (United States) gives a profile at 1.25 centimetre intervals in the vertical (five different levels can be selected). The exposure for each interval is five to 12 seconds. A complete cycle of measurements of the layers of a snow cover, four metres in depth, takes about 30 minutes. The snow telemetering unit can be under the control of a base station, or it may operate independently, using its own power supply, or may be connected to the mains.

In the other set of snow measuring equipment (France), gamma pulses are summed, and a radio signal is sent at the end of the time required for the isotope detector system to move through 10 centimetres vertically. The speed of movement of the system in the tube is automatically regulated, such that 3 840 pulses correspond to a vertical movement of 10 centimetres. The final data on the density and water content of layers of snow are obtained by means of a calibration or analytical relationship between the number of pulses or the time to move through 10 centimetres, and the density of the snow.

8.5 Snow pillows

Snow pillows of various dimensions and materials are used to measure the weight of snow that accumulates. The most common pillows are flat circular containers (diameter 3.7 metres) of rubberized material filled with a non-freezing liquid. The pillow is installed on the surface of the ground, flush with the ground, or buried under a thin layer of soil or sand. In order to prevent damage to the equipment and to preserve the snow cover in its natural condition, it is recommended that the site be fenced. Under normal conditions, snow pillows can be used for 10 years or more.

Hydrostatic pressure inside the pillow is a measure of the weight of the snow on the pillow. Measurement of the hydrostatic pressure is by means of a float-operated water-level recorder or a pressure transducer.

Snow pillow measurements differ from those made with standard snow tubes, especially during the snow melt period. They are most reliable when the snow cover does not contain ice layers, which can cause bridging above the pillows. A comparison of the water equivalent of snow, determined by snow pillow, with measurements by the standard method of weighing, showed differences of five to 10 per cent.

8.6 Natural gamma radiation surveys

The method of gamma radiation snow surveying is based on attenuation by snow of gamma radiation emanating from natural radioactive elements in the ground. The greater the water equivalent of the snow, the more the radiation is attenuated. Measurement of gamma radiation can be made by terrestrial or aerial survey. The ratio of gamma radiation intensity measured above the snow cover to that measured over the same course before snow accumulation provides an estimate of the water equivalent.

8.6.1 *Aerial gamma surveys of snow cover*

While the snow course is a series of point measurements, the aerial survey is an integrated areal estimate of snow cover equivalent. The method is intended for mapping the water equivalent of snow in flat country or in hilly country with a range in elevation up to 400 metres. In regions with more than 10 per cent of their areas in marshland, the measurements of water equivalent of snow cover are made only for those areas without marshes, and the integrated characteristics are applied to the area of the entire basin. The usual flying height for an aerial gamma survey is 25-100 metres above the land surface.

Measurements consist of the total count for a large energy range and spectral counts for specific energy levels. The spectral information permits correction for spurious radiation induced by cosmic rays and radioactivity of the atmosphere.

The accuracy of an aerial gamma survey of snow cover depends primarily on the limitations of the radiation measuring equipment (e.g., the uniformity of operation of the measuring instruments), fluctuations in the intensity of cosmic radiation and radioactivity in the layer of the atmosphere near the ground, soil moisture variations in the top 15 centimetres, uniformity of snow distribution, absence of extensive thawing, etc. (e.g., steady flying conditions, errors in setting course for successive flights). The expected error ranges between ±10 per cent, with a lower limit of approximately 10 millimetres water equivalent.

Detailed experiments have shown that the standard deviation of measurements of the water equivalent of snow made from an aircraft over a course of 10-20 kilometres is about 8 millimetres and is of a random nature.

To obtain the water equivalent of snow over an area up to 3 000 km^2, with an error not exceeding 10 per cent, recommended lengths of course and distances between courses are given in the Table below.

Recommended lengths of flight courses (*L*) and distance between courses (*S*)

Natural regions	*S km*	*L km*
Forest-steppe	40–50	25–30
Steppe	40–50	15–20
Forest	60–80	30–35
Tundra	80–100	35–40

A great advantage of the gamma survey method is that it yields an aerial estimate of water equivalent over a path along the line of flight. The effective width of the path is approximately two to three times the altitude. A second advantage is that the attenuation rate of the gamma rays in snow is determined solely by the water mass independent of its state.

8.6.2 *Ground surveys*

A hand-carried detector provides a means for measurement of the averaged water equivalent for a band width of approximately eight metres for the length of the course. Water equivalents from 10 to 300 millimetres may be measured. The accuracy of the measurement ranges from ±2 millimetres to ±6 millimetres depending on changes in soil moisture, distribution of the snow, as well as the stability of the instrument system.

A stationary ground-based detector (such as a Geiger-Müller counter or scintillation crystal with photo-multiplier) may also be installed over a snow course area and be used to monitor the water equivalent of an area. However, the occurrence of precipitation carries considerable gamma radiating material to the snow cover, and measurements during and following precipitation are affected by this additional radiation. Decay of the radiating material permits accurate readings of the water equivalent, approximately four hours after precipitation ceases. Comparison of readings before and after the occurrence of precipitation will provide information on the change in the water equivalent of the snow cover.

8.7 Measurement of water equivalent by cosmic radiation

Like the gamma survey, this method is based on determining the ratio of the intensities of natural cosmic radiation, before and after snow cover. The water equivalent of snow is measured remotely at a number of representative points in the area, the radiation detector being situated at the level of the Earth’s surface.

Tests carried out with an instrument developed in the Soviet Union [3] have shown that, for the range 10-1 000 millimetres of water equivalent of snow, the standard deviation of measurements is 34 millimetres.

References

1. World Meteorological Organization, 1992: *Snow Cover Measurements and Areal Assessment of Precipitation and Soil Moisture* (B. Sevruk). Operational Hydrology Report No. 35, WMO–No. 749, Geneva.

2. Kazakevich, D. I., 1971: *Osnovy teorii slutchaynikh funktjij i ee primenenije v gidrometeorologii* (Foundation and application of the theory of random functions to hydrometeorology). Gidrometeoizdat, Leningrad.

3. Avdyushin, S. I., Barabanschikov, Yu. F., Kogan, R. M., Kulagin, Yu. M., Nazarov, I. M., Fridman, Sh. D. and Yudkevich, I. S., 1973: Opyt opredeleniya zapasov vlagi v snezhnom pokrove v gorakh po pogloshcheniyu galakticheskogo kosmicheskogo izlucheniya (Attempt at determination of water content of snow cover in mountain areas from absorption of galactic cosmic radiation). *Meteorologiya i Gidrologiya*, No. 12, December, pp. 98-102.

CHAPTER 9

EVAPORATION AND EVAPOTRANSPIRATION

9.1 General

Estimates of evaporation from water surfaces and the soil, and transpiration from vegetation are of great importance in hydrological studies. For example, estimates of evaporation may be critical in determining the feasibility of a proposed reservoir site and are useful in determining current operating procedures for a reservoir system. Evaporation and evapotranspiration are also important elements of any water-budget study. Estimates of average evapotranspiration from basins are required for conceptual hydrological modelling.

Direct measurement of evaporation or evapotranspiration from large water or land surfaces is not possible at present. However, several indirect methods have been developed that give acceptable results. Evaporation pans and lysimeters are used in networks, and these are discussed in this chapter. For existing reservoirs and for plots or small catchments, estimates can be made by water-budget, energy-budget, and aerodynamic approaches. These latter techniques are discussed in this chapter only from the point of view of instruments and observational requirements. Computation of evaporation and evapotranspiration from water and land surfaces by the various indirect methods is discussed in Chapters 37 and 38, respectively.

9.2 Pan evaporation [C46]

Evaporation records for pans are frequently used to estimate evaporation from lakes and reservoirs. Many different types of evaporation pans are in use. Some have square sections, while others are circular. Some are mounted entirely above the ground, while others are sunk in the ground so that the level of the water is approximately that of the ground. Evaporation pans are sometimes mounted on anchored floating platforms on lakes or other water bodies.

Among the various types of pans in use, there are three that deserve special mention. These are the US Class A pan and the GGI-3000 pan and the 20-M^2 tank of the former USSR. The former was recommended by WMO and IAHS as a reference instrument. Its performance has been studied under a range of climatic conditions within wide limits of latitude and elevation. The GGI-3000 pan and 20-M^2 tank are used in Russia and some other countries with different climatic conditions.

They possess reliable operational qualities and an extremely stable relationship with the meteorological elements that influence evaporation.

The WMO sponsored comparative observations [1] of the Class A pan, the GGI-3000 pan, and the 20-M^2 tank in several countries. This eventually led to some operational recommendations on the suitability of these pans in diverse climatic and physiographic conditions.

In addition to the pan, the following instruments are often used at pan evaporation stations:

(*a*) An integrating anemograph or anemometer at a height of one to two metres above the pan for determining wind movement over the pan;
(*b*) A non-recording precipitation gauge;
(*c*) Thermometers or thermographs to provide maximum, minimum, and current temperatures of the water in the pan;
(*d*) Maximum and minimum thermometers or thermographs for air temperatures or a hygrothermograph or psychrometer if data on the temperature and humidity of the air are desired.

The site of the pan should be reasonably level and free from obstructions. At sites where normal climate and soil do not permit the maintenance of a soil cover, the ground cover should be maintained as near as possible to the natural cover common in the area. Obstructions such as trees, buildings, shrubs, or instrument shelters should not be closer than four times the height of the object above the pan. Under no circumstance should the pan or instrument shelter be placed on a concrete slab or pedestal or over asphalt or crushed rock.

The instruments should be located on the evaporation station plot so as to prevent their casting shadows over the pan. The minimum size of the plot should be 15 by 20 metres. The plot should be fenced to protect the instruments and to prevent animals from drinking the water. The fence should be so constructed that it does not affect the wind structure over the pan.

At unoccupied sites, particularly in arid and tropical regions, it is often necessary to protect the pans from birds and small animals. This may be achieved by the use of:

(*a*) Chemical repellants. In all cases where such protection is used, care must be taken not to pollute the water in the pan; or
(*b*) A wire-mesh screen of standard design supported above the pan.

To estimate the error introduced by the wire-mesh screen on the wind field and thermal characteristics of the pan, readings from the protected pan should be compared with those of a standard pan at the nearest comparable occupied site.

The water level in the pan must be measured accurately before and after water is added. This may be done in two ways:

(*a*) The water level may be determined by means of a hook gauge consisting of a movable scale and vernier fitted with a hook enclosed in a still-water chamber in the pan. An alternative arrangement is to use a float. A calibrated container is used to add or remove water at each observation returning the water level to a prespecified point;

(*b*) The water level may be determined by the following procedure:
  (i) A vessel of small diameter fitted with a valve is placed on top of a benchmark below the water surface in the pan;
  (ii) The valve is opened and the water level in the vessel is allowed to equalize with the water level in the pan;
  (iii) The valve is closed and the volume of water in the vessel is determined accurately in a measuring tube;
  (iv) The height of the water level above the benchmark is determined from the volume of water in the vessel and the dimensions of the vessel.

Daily evaporation is computed as the difference in water level in the pan on successive days, corrected for any precipitation during the period. The amount of evaporation that has occurred between two observations of water level in the pan is determined by:

$$E = P \pm \Delta d \tag{9.1}$$

where P is the depth of precipitation during the period between the two measurements, and Δ is the depth of water added (+) to or removed (-) from the pan.

Several types of automatic evaporation pans are in use. The water level in the pan is kept automatically constant by releasing water into the pan from a storage tank or by removing water from the pan in the case of precipitation. The amount of water added to or removed from the pan is recorded.

9.3 Soil evaporimeters and lysimeters

Evapotranspiration can be estimated by the use of soil evaporimeters and lysimeters, by the water- or heat-budget methods, by the turbulent-diffusion method, or by various empirical formulae based on meteorological data. Use of soil evaporimeters and lysimeters allow direct measurement of evapotranspiration from different land surfaces and evaporation from the soil between cultivated plants. These instruments are simple and accurate if all requirements concerning their installation and observational techniques are fulfilled. Transpiration of vegetation is estimated as the difference between measured evapotranspiration and contemporaneously measured evaporation from the soil.

Soil evaporimeters and lysimeters are categorized according to their method of operation:

(*a*) Weight based, which use mechanical scales to account for changes in water content;
(*b*) Hydraulic based, which use the hydrostatic principle of weighing; and
(*c*) Volumetric based, in which water content is kept constant and evapotranspiration is measured by the amount of water added or removed.

There is no single standard instrument for measuring evapotranspiration.

General requirements for the location of evaporation plots are as follows:

(*a*) The site selected for the plot should be typical of the surrounding area with respect to irrigation, soil characteristics (texture, layering, genetical type), slope, and vegetative cover;

(*b*) The evaporation plot should be located beyond the zone of influence of individual buildings and trees. It should be situated at a distance not less than 100 to 150 metres from the boundaries of the field and not more than three to four kilometres from the meteorological station. Soil monoliths for inclusion in evaporimeters and lysimeters should be taken from within a radius of 50 metres of the plot, and the soil and vegetative cover of the monolith should correspond to those of the plot.

9.4 Snow evaporation

Evaporimeters made of polyethylene or colourless plastic are used in many countries for measuring evaporation from, or condensation on, snow cover. Snow evaporimeters should have an area of at least 200 cm^2 and a depth of 10 centimetres.

A sample of snow is cut to fill the evaporimeter, the total weight is measured, and the evaporimeter is set flush with the snow surface. Care should be taken that surface characteristics of the sample in the evaporimeter are similar to those of the snow cover in which it is placed. At the end of the measurement period, the evaporimeter is removed from the snow cover, the outside is wiped dry, and a second measurement of weight is made. The difference between initial and final weights is converted to evaporation or condensation in centimetres. Measurements during periods of snowfall or blowing snow are not valid. During melt, the evaporimeters should be weighed and new samples should be cut at more frequent intervals as the snow cover will be settling, exposing the edge of the evaporimeter and altering air flow over the sample.

9.5 Indirect methods

9.5.1 *General*

Owing to the difficulties involved in making direct observations of evaporation from lakes and reservoirs, indirect methods, such as the water budget, the energy budget, or the aerodynamic approach, are frequently used. The meteorological elements incorporated into these methods are solar and long-wave radiation, air and water-surface temperatures, atmospheric humidity or vapour pressure, and wind. Instruments and observational procedures for measuring these elements are described in the following subsections. The manner in which observations of the above elements are used in various indirect methods for estimating evaporation is described in Chapter 37.

9.5.2 *Solar radiation*

Incident total solar (short wave) radiation should be measured at a site near the reservoir with a pyranometer, and the output should be recorded continuously. Incoming short-wave radiation on a horizontal surface is measured with a pyranometer. Most modern types of pyranometers are based on multi-junction thermopiles and are covered by single or double glass domes which allow only radiation in the 0.3-3 µm to reach the sensitive pyranometer surface. Some types of pyranometer have the entire surface blackened with half the thermo-junctions attached to it, with the other junctions located so that they sense the slowly varying reference temperature of a shielded large brass block. Other types have a sensitive surface that consists of white and black-painted surfaces, with thermo-junctions attached to both.

9.5.3 *Long-wave radiation*

Long-wave radiation is measured indirectly with flat-plate radiometers. These instruments are not selective in response to different wavelengths and thus measure all wavelengths. The long-wave radiation is computed as the difference between the total radiation received from sun and sky, as observed with a radiometer, and the solar radiation measured with a pyranometer at the same site.

One type of long-wave radiometer consists of a flat five cm^2 plate mounted horizontally in the exhaust of a small blower. The plate is a sandwich with a blackened aluminium upper surface and a polished aluminium lower surface. A thermopile measures the vertical temperature gradient across an insulating sheet that forms the centre layer of the sandwich. The thermopile voltage is proportional to the heat flow down through the plate, which in turn is proportional to the energy received at the blackened surface after deduction of the black-body radiation. To correct for the black-body radiation, a separate thermocouple measures the black-surface temperature. The function of the blower exhaust is to minimize the effects of wind on the calibration coefficient of the device.

Another type of instrument, a net pyrradiometer, measures the difference between total (short-wave and long-wave) incoming (downward) and outgoing (upward) radiation. The instrument consists of a horizontally mounted plate with two blackened surfaces. Half the junctions of a thermophile are attached to the upper surface, and the others are attached to the lower surface, so that the thermopile output is proportional to net radiation in the 0.3-100 µm band. These instruments are divided into two types: those that are ventillated and those that are shielded to reduce convective heat transfer from the sensing element. Instruments should be mounted at least one metre above representative vegetation cover.

9.5.4 *Air temperature*

Air temperature should be measured two metres above the water surface near the centre of the reservoir. For small reservoirs, the air temperature may not be greatly modified in its passage across the water surface, in which case satisfactory measurements can be made at an upwind shore site.

Although observations of air temperature at intervals of one, four or six hours may be satisfactory, continuous records are desirable, especially in connection with humidity measurements. Electrical thermographs, utilizing thermocouple thermometers, are suitable for recording on the multi-channel recording potentiometers used for the radiation measurements.

In measuring air temperature, thermometers must be shaded from the sun without restricting natural ventilation. Special radiation shields have been designed for thermocouple thermometers.

Measurements of air temperature should be accurate to within ± 0.3°C.

9.5.5 *Water-surface temperature*

Several types of thermometers are used for the measurement of water temperature:

(*a*) Mercury-in-glass or mercury-in-steel (including maximum and minimum and reversing thermometer);
(*b*) Platinum-resistance or thermistor elements with electronic circuit and meter or recorder; and
(*c*) Thermocouple thermometers, with voltmeter, with or without recorder.

Particular applications will determine which thermometer is most suitable. For example, direct observations are best carried out with a mercury-in-glass thermometer, whereas continuous records may be obtained with resistance or thermocouple elements.

Thermographs, which produce a continuous record of temperature, usually comprise a mercury-in-steel sensing element immersed in the water, which is connected to a circular or cylindrical chart recorder with a Bourdon-tube transducer. Care should be taken in the installation of thermographs to ensure that measurements taken are representative of the water temperature [2].

In the case of automatic stations where the measurement, which will usually include other variables, is recorded on a magnetic tape or transmitted over direct wire or radio-telemetry systems, the platinum-resistance or thermistor thermometers are used most frequently. As these have no moving parts, they are more reliable and offer greater accuracy and sensitivity of measurement. The sensing element is usually connected to a Wheatstone-bridge circuit and an electronic amplifier to produce an output signal that is suitable for recording or transmission.

In general, the precision required for the measurement of water temperature is ± 0.1°C, except for special purposes where a greater accuracy may be required. However, in many circumstances precision of observation of ± 0.5°C is adequate and there are many instances where statistical temperature data are quoted to the nearest 1°C. Thus, it is important to specify the operational requirement so that the most suitable thermometer is selected.

9.5.6 *Humidity or vapour pressure of the air*

Humidity measurements are made at the same location as air temperature. Psychrometers utilizing thermocouple thermometers are best suited for recording purposes. The thermocouple thermometers described in section 9.5.4, with an additional thermocouple thermometer to record wet-bulb temperatures, will give adequate results. Wet-bulb thermocouples require a wick and a reservoir that should be so arranged that the water will arrive at the wet-bulb temperature. Wet-bulb thermometers must be shielded from radiation and must, at the same time, maintain adequate ventilation to obtain a true wet-bulb temperature. A shield similar to the one used for air temperatures will provide adequate ventilation if wind speeds are greater than 0.5 m s^{-1}. In practice, the shield for the wet-bulb thermometer is placed just below the air temperature shield.

If measurements of dry- and wet-bulb temperatures are made to within ± 0.3°C, the relative humidity should be within ± 7 per cent for moderate temperatures. This is adequate for determining vapour pressure.

9.5.7 *Wind*

Wind speed should be measured near the centre of the lake or reservoir at a height of two metres above the water surface. In practice, an anchored raft is used to support the instrumentation.

Any type of standard anemometer suitable for remote indication or recording should be adequate to determine the average daily wind speed. The three-cup rotor or fan anemometers are most suited for remote recording. Accuracy of wind measurements by the three-cup or fan anemometers is usually within ± 0.5 m s^{-1}, which is considered acceptable for evaporation measurements.

If a totalizing anemometer is used, provision must be made to read the counter at fixed intervals (preferably daily). If an electrical-contact anemometer is used, a recorder must be provided. This can be done by an electrical event marker on the margin of the temperature chart.

9.5.8 *Integrating devices*

Measurements of radiation and air temperature are usually made at the same locations, either at the centre of the lake or reservoir or at an upwind shore station. This permits recording several items in sequence on a single multi-channel recorder. Integrating devices are sometimes used with strip-chart recorders. These devices present a visual read-out of the average value of each item for the time period for which evaporation is to be computed (usually 10 days or two weeks).

References

1. World Meteorological Organization, 1976: *The CIMO International Evaporimeter Comparisons*. WMO-No. 449, Geneva.
2. Herschy, R. W., 1971: *River Water Temperature*. Water Resources Board, TN5.

CHAPTER 10

WATER LEVELS OF RIVERS, LAKES, AND RESERVOIRS

10.1 **General**

Water levels of rivers, lakes, or reservoirs may be used directly in forecasting flows, to delineate flood hazard areas and to design structures in or near water bodies. When correlated with stream discharge or with the storage volumes of reservoirs and lakes, water levels become the basis for computation of discharge or storage records. An expanded discussion of this topic is given in the WMO *Manual on Stream Gauging* [1].

Water level, or stage, is the elevation of the water surface of a stream, lake, or other water body relative to a datum [2]. It should be observed with a precision of one centimetre in general and to three millimetres at continuous-record gauging stations.

The site selected for observation of stage should be governed by the purpose for which the records are collected and by the accessibility of the site. Hydraulic conditions are an important factor in site selection on streams, particularly where water levels are used to compute discharge records. Gauges on lakes and reservoirs are normally located near their outlets, but sufficiently upstream to avoid the influence of drawdown.

10.2 **Gauges for measurement of stage** **[C71]**

10.2.1 ***Non-recording gauges***

Several types of non-recording gauges for measuring stage are used in hydrometric practice. The common gauges are of the following types:

(*a*) Graduated vertical staff gauge;
(*b*) Ramp or inclined gauge;
(*c*) Wire-weight gauge installed on a structure above the stream; and
(*d*) Graduated rod, tape, wire or point gauge for measuring the distance to the water surface.

10.2.2 ***Recording gauges***

Many different types of continuously recording stage gauges are in use. They may be classified according to both mode of actuation and mode of recording.

A commonly used installation consists of a stilling well connected to the stream by pipes and a float in the stilling well connected to a wheel on a recorder by a beaded wire or perforated tape. In high velocity streams, it may be necessary to install static tubes on the end of the intake pipes to avoid drawdown of the water level in the well.

Various pressure-actuated recording gauges in common use operate on the principle that pressure at a fixed point in the stream bed is directly proportional to the head of liquid above the point. Many gauges use a gas-purge system to transmit the pressure to the gauge. A small quantity of air or inert gas (e.g., nitrogen) is allowed to bleed through a pipe or tubing to an orifice in the stream. The pressure of the air or gas that displaces the liquid in the pipe is then measured and converted to a shaft rotation usually by a servomanometer, servo-beam-balance system, or pressure transducer. The main advantage of pressure-actuated recorders is that they do not require a stilling well, and they are not sensitive to sediment if its concentration is in the range normally encountered in a natural setting.

River stage may be recorded on graphical (analogue) recorders. The time and stage scales chosen for a particular station will depend on the range in stage, sensitivity of the stage-discharge relation, and runoff characteristics of the basin. The stage may be converted from analogue to digital form by means of electronic devices, some of which are operated manually to produce x and y coordinates of the stage record on paper tapes or magnetic tape.

Digital tape-punching recorders may be used instead of graphical recorders, and data can then be processed automatically. One digital recorder is a battery-operated, slow-speed paper-tape punch which records a four-digit number that represents the stage at preselected time intervals. The interval for a particular station is selected on the basis of the rapidity with which the stage can change and its significance to change in discharge. Flashy streams require shorter time intervals, and large streams allow longer time intervals.

Output from pressure transducers, shaft encoders, or other devices that provide voltage outputs representing the stage can also be recorded on electronic data loggers (section 6.2.4), or with appropriate interfaces, can be telemetered via radio or satellite systems to remote locations.

10.3 Procedures for measurement of stage

10.3.1 *Establishment of gauge datum*

To avoid negative readings, the gauge should be set so that a reading of zero is below the lowest anticipated stage. The gauge datum should be checked annually by levels from local benchmarks. It is important to maintain the same gauge datum throughout the period of record. If feasible, the local gauge datum should be tied to a national or regional datum.

10.3.2 *Recording gauges*

The graphical (analogue), digital, electronic, or telemetering device recorder is set by reference to an auxiliary tape-float gauge or to a staff gauge located inside the stilling well. In addition, a staff, ramp or wire-weight gauge set to the same datum, is necessary to compare the water surface elevation in the stilling well with that of the river. For gauges with gas-purge systems and no stilling well, the staff, ramp, or wire weight gauge in the river should serve as the reference gauge. Small differences usually will occur because of velocity past the ends of the intake pipes. Large differences indicate that the intake pipes may be obstructed.

10.3.3 *Winter operation of recording gauges*

(*a*) Float-actuated — This type of installation requires a stilling well that must be kept ice-free in winter. This can be done by heating the well with an electric heating lamp or a gas heater. Other devices to prevent freezing within a stilling well are: a temporary floor within the well at an elevation just below the frost line, and a vertical, open-ended tube, large enough in diameter to receive the float, and containing a layer of fuel oil on the water surface;

(*b*) Pressure-actuated servomanometer and servo-beam-balance — Although these gauges, which use a gas purge system, do not require a stilling well, they do use batteries and, in some cases, mercury in their operation. Under severe weather conditions, batteries will weaken and mercury will freeze at -39°C. Also, gear trains on some models tend to bind during cold weather because of differential contraction. However, proper safeguards, such as heating the instrument shelter, permits satisfactory operation throughout the winter;

(*c*) Pressure-actuated air bellows and transducers — These types of installations require neither a stilling well nor an operating medium subject to freezing. However, the accuracy of such instruments tends to be less than the others described in this section, particularly for large ranges in stage.

10.4 Frequency of stage measurement

The frequency of recording of water level is determined by the hydrological regime of the water body and by the purposes for collecting the data. Where a nearly continuous record is needed, systematic recordings, twice a day, supplemented by more closely-spaced readings during floods, are sufficient for many streams. Installation of water level recorders are essential for streams where the level is subject to abrupt fluctuations. The non-recording gauge is frequently used as a part of flood-forecasting systems, where a local observer is available to report on river stage. For purposes such as flood forecasting or flood management, telemetering systems may be employed to transmit data whenever the stage changes by a predetermined amount.

For some purposes, the recording of only the maximum stages during floods is sufficient and maximum-stage gauges are used.

A daily measurement of stage is usually sufficient in lakes and reservoirs for the purpose of computing changes in storage [3].

References

1. World Meteorological Organization, 1980: *Manual on Stream Gauging.* Volumes I and II, Operational Hydrology Report No. 13. WMO-No. 519, Geneva.

2. International Organization for Standardization, 1988: *Liquid Flow Measurement in Open Channels: Vocabulary and Symbols.* Third edition, ISO 772, Geneva.

3. International Organization for Standardization, 1981: *Liquid Flow Measurement in Open Channels.* Part 1: Establishment and operation of a gauging station and Part 2: Determination of stage-discharge relation. ISO 1100, Geneva.

CHAPTER 11

DISCHARGE MEASUREMENTS

11.1 General [E70]

River discharge, which is expressed as volume per unit time, is the rate at which water flows through a cross-section. Discharge at a given time can be measured by several different methods, and the choice of methods depends on the conditions encountered at a particular site.

11.2 Measurement of discharge by current meters [C79, C85, C86, C88, E79]

Measurement of discharge by the velocity-area method is explained by reference to Figure 11.1 The depth of flow in the cross-section is measured at verticals with a rod or sounding line. As the depth is measured, observations of velocity are obtained with a current meter at one or more points in the vertical. The measured widths, depths, and velocities permit computation of discharge for each segment of the cross-section. The summation of these segment discharges is the total discharge [1].

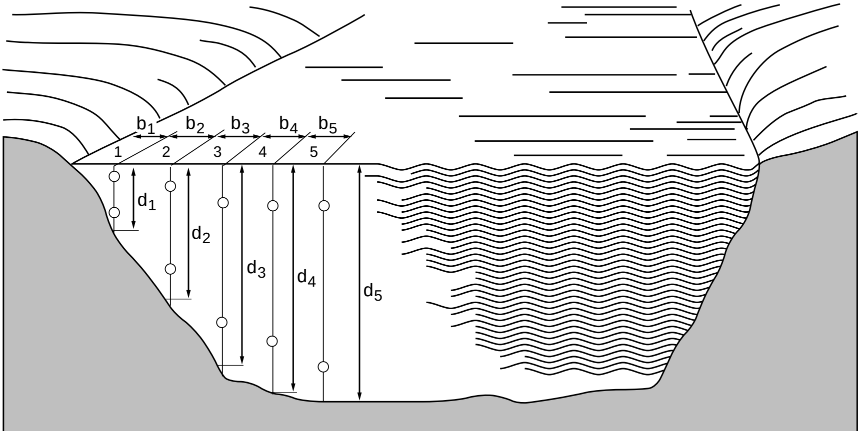


Figure 11.1 —View of a stream cross-section showing the location of points of observation.

11.2.1 *Selection of sites*

Discharge measurements need not be made at the exact location of the stage gauge because the discharge is normally the same throughout a reach of channel in the general vicinity of the gauge. Sites selected for measurements should ideally have the following characteristics [1]:

(*a*) The velocities at all points are parallel to one another and at right angles to the cross-section of the stream;
(*b*) The curves of distribution of velocity in the section are regular in the vertical and horizontal planes;
(*c*) The velocities are greater than 0.150 m s^{-1};
(*d*) The bed of the channel is regular and stable;
(*e*) The depth of flow is greater than 0.300 metre;
(*f*) There is no aquatic growth; and
(*g*) There is minimal formation of slush or frazil ice (see section 11.2.5.1).

11.2.2 *Measurement of cross-sections*

The accuracy of a discharge measurement depends on the number of verticals at which observations of depth and velocity are obtained. Observation verticals should be located to best define the variation in elevation of the stream bed and the horizontal variation in velocity. In general, the interval between any two verticals should not be greater than 1/20 of the total width and the discharge between any two verticals should not be more than 10 per cent of the total discharge.

Channel width and the distance between verticals should be obtained by measuring from a fixed reference point (usually an initial point on the bank), which should be in the same plane as the cross-section. Normally, the distance between verticals is determined from a graduated tape or beaded wire temporarily stretched across the stream or from semi-permanent marks painted on a bridge handrail or a suspension cable [1]. For large rivers, telemetry systems or triangulation practices can be used for measuring widths.

Depth may be read directly on a graduated rod set on the stream bed if measurement is by wading. If the drum-wire-weight system is used for measurement, the current meter and weight are lowered until the bottom of the weight just touches the water surface, and the depth dial reading is set at zero. The weight is then lowered until it rests on the stream bed, and the depth is read on the dial.

If the weight on the sounding line is not sufficient to keep the line perpendicular to the water surface, the angle between the line and the vertical should be measured to the nearest degree with a protractor. The relationship between the correct depth, d, and the observed depth, d_{ob}, based on the observed angle, φ, and the distance from the water surface to the point of suspension of the sounding line, x, is shown in Figure 11.2 and is given below:

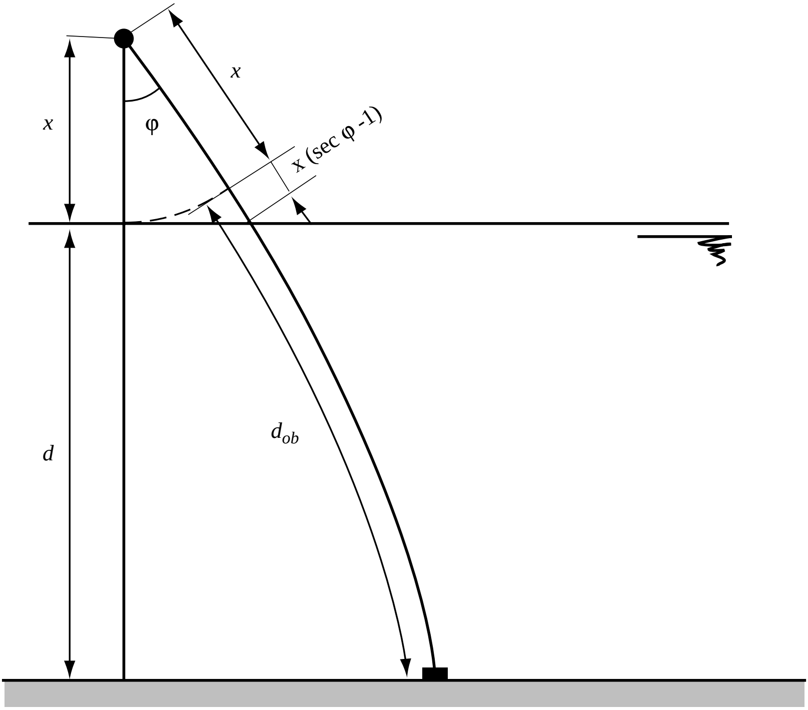


Figure 11.2 — Relationship between correct depth, *d* and observed depth, d_{ob}.

$$d = [d_{ob} - x\,(\sec \varphi - 1)][1 - k] \tag{11.1}$$

Values of *k* as given in Table 11.1 are based on the assumptions that the drag pressure on the weight in the comparatively still water near the bottom can be neglected and that the sounding wire and weight are designed to offer little resistance to the water current. The uncertainties in this estimation are such that significant errors may be introduced if the vertical angle is more than 30°.

TABLE 11.1

Correction factor *k* for given values of *φ*

φ	*k*	*φ*	*k*	*φ*	*k*
4°	0.0006	14°	0.0098	24°	0.0296
6	0.0016	16	0.0128	26	0.0350
8	0.0032	18	0.0164	28	0.0408
10	0.0050	20	0.0204	30	0.0472
12	0.0072	22	0.0248		

11.2.3 ***Measurement of velocity*** **[C79, E79]**

11.2.3.1 *Meters for measurement of velocity*

Velocity of flow at a point is usually measured by counting revolutions of a current-meter rotor during a short-time period measured with a stop-watch [1]. Two types of current-meter rotors are in general use: the cup type with a vertical shaft, and the propeller type with a horizontal shaft. Both types use a make-and-break contact to generate an electric pulse for indicating the revolutions of the rotor [2]. Optical, non-contact type counters are also in use with cup type meters.

Current meters are calibrated to cover the range in velocity of flow to be measured. Detailed calibration procedures are described in ISO 3455 [3]. Current meters may be calibrated individually or a group rating may be used. Individually calibrated meters should be recalibrated after three years or 300 hours of use or if their performance is suspect (*Technical Regulations,* Volume III, Annex 1).

11.2.3.2 *Measurement of velocity using the current meter*

Velocity is observed at one or more points in each vertical by counting revolutions of the rotor during a period of not less than 60 seconds and as long as three minutes if velocities are pulsating [1].

For shallow channels, the current meter should be held in the desired position by means of a wading rod. For channels too deep or swift to wade, it should be positioned by suspending it from a wire or rod from a bridge, cableway, or boat. When a boat is used, the meter should be held so that it is not affected by disturbances of flow caused by the boat. After the meter has been placed at the selected point in the vertical, it should be allowed to become aligned with the direction of flow before readings are started. If oblique flow is unavoidable, the angle of the direction of the flow normal to the cross-section must be measured and the measured velocity must be corrected. If the measured angle to the normal is γ, then:

$$V_{normal} = V_{measured} \cos \gamma \tag{11.2}$$

The current meter should be removed from the water at intervals for examination. For measuring very low velocities, special current meters may be used if they have been tested in this range of velocities for repeatability and accuracy.

The horizontal axis of the current meter should not be situated at a distance less than one and one-half times the rotor height from the water surface, nor should it be at a distance less than three times the rotor height from the bottom of the channel.

11.2.3.3 *Determination of mean velocity in a vertical*

The mean velocity of the water in each vertical can be determined by one of the following methods:

(*a*) Velocity distribution method;
(*b*) Reduced point methods; and
(*c*) Integration method.

Selection of the appropriate method depends on the time available, the width and depth of the water, the bed conditions, the rate of change of stage, the existence of ice cover, and the required accuracy.

Velocity distribution method

The measurement of the mean velocity by this method is obtained from velocity observations made at a number of points along each vertical between the surface of the water and the bed of the channel. The velocity observations at each position should be plotted in graphical form and the mean velocity should be determined by dividing the area of this plot by the depth. In developing the graph it may be necessary to estimate the velocities near the stream bed by assuming that the velocity for some distance up from the bed of the channel is proportional to the logarithm of the distance x from that boundary. If the observed velocity at points approaching the bed are plotted against log x, then the best-fitting straight line through these points can be extended to the bed and the velocities close to the bed read from this graph.

The velocity distribution method may not be suitable for discharge measurements made during significant variations of stage because the apparent gain in precision may be more than offset by errors resulting from the longer period required to make the measurement.

Reduced point methods

(*a*) One-point method — Velocity observations should be made at each vertical by placing the current meter at 0.6 of the depth below the surface. The value observed should be taken as the mean velocity in the vertical. Where measurements are made under ice cover, this method is applicable with a correction factor of 0.92 for depths shallower than one metre. Under ice conditions, the current meter may be placed at 0.5 of the depth. A correction factor of 0.88 is then applied to this result;
(*b*) Two-point method — Velocity observations should be made at each vertical by placing the current meter at 0.2 and 0.8 of the depth below the surface. The average of the two values should be taken as the mean velocity in the vertical;
(*c*) Three-point method — Velocity observations are made by placing the current meter at each vertical at 0.2, 0.6 and 0.8 of the depth below the surface. The average of the three values may be taken as the mean velocity in the vertical. Alternatively, the 0.6 measurement may be weighted and the mean velocity may be obtained from the equation:

$$\overline{v} = 0.25\ (v_{0.2} + 2v_{0.6} + v_{0.8}) \qquad (11.3)$$

(*d*) Five-point method — When the channel is free from ice and aquatic growth, the five-point method may be used. It consists of velocity measurements on each vertical at 0.2, 0.6 and 0.8 of the depth below the surface and as near as possible to the surface and the bottom. The mean velocity may be determined from a graphical plot of the velocity profile as with the velocity distribution method or from the equation:

$$\overline{v} = 0.1\ (v_{surface} + 3v_{0.2} + 3v_{0.6} + 2v_{0.8} + v_{bed}) \qquad (11.4)$$

(*e*) Six-point method — This method may be used in difficult conditions where, for instance, there is aquatic growth, or where there is a covering of ice. Velocity observations are made by placing the current meter at 0.2, 0.4, 0.6 and 0.8 of the depth below the surface and as near as possible to the surface and the bottom. The velocity observations are plotted in graphical form and the mean velocity is determined as with the velocity distribution method or from the equation:

$$\overline{v} = 0.1\ (v_{surface} + 2v_{0.2} + 2v_{0.4} + 2v_{0.6} + 2v_{0.8} + v_{bed}) \qquad (11.5)$$

The two-point method is used where the velocity distribution is normal and depth is greater than about 60 centimetres. The one-point method is used for shallower depths. The three-point method should be used for measurements under ice or in stream channels overgrown by aquatic vegetation. The five-point method is used where the vertical distribution of velocity is very irregular.

The accuracy of a particular method should be determined, if possible, by observing the velocity at six to 10 points in each vertical for the first few discharge measurements made at a new site.

Integration method

In this method, the current meter is lowered and raised through the entire depth at each vertical at a uniform rate. The speed at which the meter is lowered or raised should not be more than five per cent of the mean velocity of flow in the cross-section, and it should be between 0.04 and 0.10 m s^{-1}. The average number of revolutions per second is determined. Two complete cycles are made in each vertical and, if the results differ by more than 10 per cent, the measurement is repeated. This method is seldom used in water having a depth of less than three metres and velocities of less than 1 m s^{-1}.

11.2.4 ***Computations of discharge***

Arithmetical methods

(*a*) Mean-section method — The cross section is regarded as being made up of a number of segments bounded by two adjacent verticals. If $\overline{v}_1$ is the mean velocity at the one vertical and $\bar{v}_2$ the mean velocity at the adjacent vertical, and if d_1 and d_2 are the total depths measured at verticals 1 and 2, and b is the horizontal distance between verticals, then the discharge q of the segment is:

$$q = \left(\frac{\bar{v}_1 + \bar{v}_2}{2}\right)\left(\frac{d_1 + d_2}{2}\right)^{b} \tag{11.6}$$

The total discharge is obtained by adding the discharge from each segment;

(*b*) Mid-section method — The discharge in each segment is computed by multiplying *vd* in each vertical by a width, which is the sum of half the distances to adjacent verticals. The value of *d* in the two half widths next to the banks can be estimated. Referring to Figure 11.1, the total discharge *Q* is computed as:

$$Q = \bar{v}_1 d_1 \left(\frac{b_2 - b_1}{2}\right) + \bar{v}_2 d_2 \left(\frac{b_3 - b_1}{2}\right) + \ldots + \bar{v}_n d_n \left(\frac{b_n - b_{(n-1)}}{2}\right) \tag{11.7}$$

Graphical methods

(*a*) Depth-velocity integration method — The first step consists in drawing, for each vertical, the depth velocity curve, the area of which represents the product of the mean velocity and the total depth. The value of this product at each vertical is then plotted versus lateral distance and a curve is drawn through the points. The area defined by this curve is the discharge in the cross-section;

(*b*) Velocity-contour method — Based on the velocity-distribution curves of the verticals, a velocity distribution diagram for the cross-section is prepared showing curves of equal velocity. Starting with the maximum, areas enclosed by the equal velocity curves and the water surface should be measured and should be plotted in another diagram, with the ordinate indicating the velocity and the abscissa indicating the area. The area enclosed by the velocity area curve represents the discharge of the cross-section [1].

11.2.5 ***Measurement of discharge under ice cover***

Measurement of discharge under ice cover requires general knowledge of instruments and procedures described in sections 11.2.1 to 11.2.4. These sections deal only with equipment and procedures peculiar to the measurement of discharge under ice cover.

11.2.5.1 *Selection of site*

It is advisable to select alternate cross-sections during the open water season when channel conditions can be evaluated. At some stations, the same measuring section may be used during winter and summer, but it is more important that winter measurements be made under suitable conditions than it is to use the same measuring section. After initial selection, exploratory holes may be cut at quarter points along the section to detect the presence of slush ice or poor distribution of flow. Frazil ice should be avoided whenever possible because ice particles impede the operation of the meter and because of difficulty in determining ice thickness. Also, a small flow may occur through the frazil ice which cannot be measured by usual methods.

Winter freshets often lead to water breaking through the ice and forming two independent currents, one above and the other below the ice. Such locations should be avoided.

11.2.5.2 *Equipment*

(*a*) Cutting holes — When ice is thick, a mechanical ice auger, drill, or a chain saw is desirable for cutting holes. For thin ice, an ice chisel may be used;

(*b*) Determination of effective depth — Effective depth of water below ice cover is the total depth of water minus the distance from the water surface to the underside of the ice. The distance between the water surface in the ice hole and the underside of the ice may be measured using an ice-measuring stick or "ice-stick", which is an L-shaped graduated bar of appropriate length. The short projection of the L-shaped stick is held against the underside of the ice, and the depth to that point is read at the ice surface on the graduated portion of the stick. If there is slush under solid ice at a hole, the depth at which it ends, may be determined by suspending the current meter below the slush ice with the meter rotor turning freely and then raising it slowly until the rotor stops. This point is assumed to be the interface between water and slush;

(*c*) Current meter and weight assembly — If an ice auger or drill is used to cut holes through ice, a special current meter and sounding weight assembly is passed through the ice hole, which is generally about 150 millimetres in diameter. The assembly may consist of two teardrop-shaped lead weights, one above and one below the meter, or one teardrop-shaped weight below the meter. When the hole can be made large enough, the standard current meter and weight assembly can be used as described in section 11.2.3.1;

(*d*) Meter suspension — The meter suspension may be by a rod, handline, or a sounding reel. If the total depth of water under ice cover is greater than three or four metres, a reel or handline is usually used. The reel is mounted on a collapsible support set on runners. In extremely cold weather, the support may be equipped with a heated water tank or hot air chamber to keep the meter from freezing while moving the equipment from one position to the next. For shallower depths, where a meter without tail vanes is suspended by a rod through a drilled hole, the direction of current must be determined so that the meter can be properly aligned.

11.2.5.3 *Discharge measurement*

(*a*) Spacing of verticals — The information in section 11.2.2 is also applicable to the spacing of verticals under ice. However, in addition to the variation in elevation of the stream bed, variation in ice cover and slush ice thickness must also be taken into account in selecting the number and location of verticals. If the current is divided into different channels by slush ice, not less than three verticals should be used in each channel;

(*b*) Measurement of velocity — Ideally, velocity curves should be determined from velocity observations at every tenth of the effective depth in at least two verticals to determine what coefficients, if any, are necessary to convert the average velocity obtained by any standard open-water method of observation to an average velocity in a vertical under the ice cover. In shallow water, velocity may be observed at one point at either 0.5 or 0.6 of the effective depth, but a coefficient is normally required to convert the observed velocity to mean velocity. In deeper water (one metre more), velocity observations could include two observations at 0.2 and 0.8 of the effective depth, three observations at 0.15, 0.5 and 0.85 of the effective depth, six observations at 0.2, 0.4, 0.6 and 0.8 of the effective depth, and at points close to the top and bottom. The average velocity observed in the two- and three-point methods may be used as the mean in the vertical. For the six-point method, see section 11.2.3.3;

(*c*) General notes — When measuring discharge from an ice cover, appropriate safety precautions should be observed. For example, the safety of ice should always be tested by probing ahead with an ice chisel while moving across the ice. If the velocity measured under ice conditions is less than the accepted lower limit of the current meter, the cross-section should be moved to another reach of the river where the velocity is higher. Care must be taken to ensure that the meter is rotating freely and is not impeded by ice that accumulates on the meter and freezes while moving from one vertical to another. At the time the measurements are made, a complete description should be recorded of weather and ice conditions on the river, particularly at the control sections. This will aid in the later computation of discharge between measurements.

11.2.5.4 *Computation of discharge*

The computation of discharge under ice cover is the same as for open-water conditions described in section 11.2.4 except that effective depth is used instead of total depth of water.

11.2.6 ***Accuracy***

Accuracy of discharge measurements depends on the reliability of the meter rating, on the conditions of flow, and on the number of observations of depth and velocity obtained [4, 5]. Measurements are normally made by observing the depth and the velocity at two points, in 20 to 25 verticals in the cross-section. For this type of measurement under the flow conditions usually encountered, the standard error at the 95 per cent confidence level is about five per cent [1].

11.3 Measurement of discharge by the float method [C86]

This method should be used when either it is impossible to use a current meter because of unsuitable velocities or depths, or the presence of material in suspension, or when a discharge measurement must be made in a very short time.

11.3.1 *Selection of sections*

Three cross-sections should be selected along a reach of straight channel. The cross-sections should be spaced far enough apart for the time that the float takes to pass from one cross-section to the next to be measured accurately. A travel time of 20 seconds is recommended, but a shorter time may have to be used on small rivers with high velocities where it is often impossible to select an adequate length of straight channel.

11.3.2 *Floats*

Surface floats or rod floats may be used. A surface float has a depth of immersion less than one-quarter the depth of the water. Surface floats should not be used when they are likely to be affected by wind. A rod float has a depth of immersion exceeding one-quarter the depth of the water. Rod floats must not touch the channel bed. Floating trees or ice cakes may serve as natural floats during periods when it is unsafe to be on the river.

11.3.3 *Measuring procedure*

Float observations must be uniformly distributed over the width of the stream. Normally 15 to 35 float observations should be made. Where natural floats are used, at least 20 should be observed at various positions across the river.

The float should be released far enough above the upper cross-section to attain a constant velocity before reaching the first cross-section. The time at which the float crosses each of the three cross-sections should be noted with a stop-watch. This procedure should be repeated with the floats at several locations across the stream. Distances of the float from the bank as it passes each cross-section may be determined by suitable optical means, for example, a theodolite.

The depth of flow at points in the cross-section may be determined by surveying methods.

11.3.4 *Computation of velocity*

The velocity of the float is equal to the distance between cross-sections divided by the time of travel. The corrected velocity of flow in each section equals the float velocity multiplied by a coefficient that is based on the shape of the vertical velocity profile and the relative depth of immersion of the float. The coefficient to be applied to the measured velocity should be determined, if possible, for each site by an analysis of discharge measurements that have been made by current-meter. When such measurements are not available, an adjustment factor, *F*, from Table 11.2 may be used for rough estimation.

TABLE 11.2

Float velocity adjustment factor *F* as on function of *R*, the ratio of the immersed depth of float to depth of water

R	*F*
0.10 or less	0.86
0.25	0.88
0.50	0.90
0.75	0.94
0.95	0.98

When using natural floats, their velocity should be plotted as a function of the corresponding distance from the bank, and the mean surface velocity across the river should be determined from this plot. The mean velocity of flow in the cross-section is equal to the mean surface velocity multiplied by a coefficient, *K*, the value of which is deduced, if possible, from preceding measurements made with a current meter for smaller discharges.

11.3.5 *Computation of discharge*

Discharge in each stream-tube, or section, is computed by multiplying the average area of the cross-section of the stream tube by the mean velocity of flow in the stream-tube. The total discharge is the sum of these discharges [1].

11.4 Measurement of discharge by dilution methods [E73]

Measurement of discharge by this method depends on determining of the degree of dilution by the flowing water of an added tracer solution. The method is recommended only for those sites where conventional methods cannot be employed because of shallow depths, extremely high velocities, or excessive turbulence and debris. The two principal tracer methods used for discharge measurements are the constant-rate-injection method and the sudden-injection method. The general requirements (section 11.4.1) for both methods are the same [6, 7].

11.4.1 *General requirements*

A solution of a stable tracer is injected into the stream at either a constant rate or all at once. Computation of the stream discharge requires knowledge of the following factors:

(*a*) The rate of injection for the constant-rate-injection method or the total amount injected for the sudden-injection method;

(*b*) The concentration of the tracer in the injected solution; and

(*c*) The concentration of the tracer in the stream after it has been well mixed laterally.

The accuracy of these methods critically depends upon:

(*a*) Adequate mixing of the injected solution throughout the stream cross-section at the sampling section. If the tracer solution is continuously injected, the concentration of the tracer should be essentially constant throughout the sampled section. If the tracer is injected all at once, $\int_o^T cdt$ should be essentially the same at all points in the section, where c is the concentration and T is the time for all of the tracer to pass a particular point in the section. As a general guide only, the required length l between the injection and sampling section will be,

$$l = 0.13C\frac{(0.7C+6)}{g}\frac{b^2}{\bar{d}}\ (metric\ units) \tag{11.8}$$

where b is the average width of the wetted cross-section, $\bar{d}$ is the average depth of flow, C is the Chezy coefficient for the reach, and g is the acceleration of gravity;

(*b*) No absorption or adsorption of the added tracer by stream bottom materials, sediments, plants, or organisms, and no decomposition of the added tracer in the stream water. The concentration should be determined at the sampling section and at least one other cross-section downstream to verify that there is not a systematic difference in the mean concentration from one sampling section to another.

11.4.2 *Selection of site*

The primary criterion for the selection of sites for measurement of discharge by dilution is adequate mixing of the injected solution with the stream water in a short length of channel. Mixing is enhanced by high boundary roughness and features that cause the channel flow to be highly turbulent, such as at waterfalls, bends, or abrupt constrictions. Larger depth-to-width ratios result in shorter distances for the required mixing.

11.4.3 *Tracers and detection equipment*

Any substance may be used as a tracer if it:

(*a*) Dissolves readily in the stream's water at ordinary temperatures;

(*b*) Is absent in the water of the stream or is present only in negligible quantities;

(*c*) Is not decomposed in the stream's water and is not retained or absorbed by sediment, plants, or organisms;

(*d*) Its concentration can be measured accurately by simple methods;

(*e*) Is harmless to man, animals, and vegetation in the concentration it assumes in the stream.

The cheapest tracer is common salt. Where the tracer is instantaneously injected into the stream, the required quantity is not particularly large, and detection by conductivity methods is relatively simple.

Sodium dichromate is used extensively in the dilution method. Its solubility in water is relatively high (600 kg per m^3), and the salt satisfies most requirements of section 11.4.1. Colorimetric analysis [7] permits the measurement of very low concentrations of sodium dichromate.

Lithium chloride has a solubility in water of 600 kg per m^3. Flame photometric analysis can detect concentrations of lithium down to 10^{-4} kg per m^3.

Other chemicals used for dilution gauging are sodium iodide, sodium nitrite, and manganese sulphate.

Rhodamine WT dye is widely used in the United States in the dilution method. Its absorptive characteristics are much better than those of other rhodamine dyes. The concentration of the dye can be measured using commercially available fluorometers that can measure concentrations of 5 to 10 parts per billion (5 to 10 in 10^9).

Radioactive elements such as bromine 82, gold 198, iodine 131 and sodium 24 have been used as tracers. Concentrations of these elements as low as 10^{-9} may be determined accurately with a counter or count rate meter with the sensing probe suspended in the stream or in a standard counting tank. Although radioactive elements are ideal tracers for the dilution method, the health hazards may limit their use in measurement of stream discharge in some localities.

11.4.4 *Computation of discharge*

Equations used to compute the stream discharge, Q, are based on the principle of continuity of the tracer:

$$Q = \frac{Q_{tr}\, c_i}{c_s} \qquad \text{(continuous injection)} \qquad (11.9)$$

and

$$Q = \frac{c_i\, V}{\int_o^{\infty} c_s\, dt} \qquad \text{(sudden injection)} \qquad (11.10)$$

where Q_{tr} is the rate of injection, c_i is the concentration of injection solution, c_s is the concentration in the stream at the sampling section, V is the volume of injected solution, and t is time.

11.5 Measurement of corresponding stage [E71]

Stage and corresponding time should be noted at intervals to identify segments of total discharge with time and stage. Usually the stage at the mid-time of the measurement can be used as the stage corresponding to the measured discharge. If the stage does not change linearly with time the following weighting procedure should be used, where $\bar{h}$ is the weighted stage and $Q_1, Q_2, \ldots Q_N$ are segments of discharge corresponding to stages $h_1, h_2, \ldots h_N$

$$\bar{h} = \frac{Q_1 h_1 + Q_2 h_2 + \ldots + Q_N h_N}{Q_1 + Q_2 + \ldots Q_N} \tag{11.11}$$

11.6 Computations of discharge by indirect methods [E70]

11.6.1 *General*

During flood periods, it may be impossible to measure discharge directly because of the excessive rate of change of discharge, excessive velocities, debris, depths, or widths or because flooded conditions make roads impassable or measuring structures inaccessible. When such conditions occur, the peak discharge may be determined after the flood has subsided by computations that combine well established hydraulic principles with field observations of channel conditions and flood profiles. All the methods involve the simultaneous solution of continuity of mass and energy equations.

Such computations may be made for reaches of river channel, through roadway culverts and bridge openings, and over dams and highway embankments. Although the hydraulic formulae differ for each type of waterway, all the methods involve the following factors:

(*a*) Geometry and physical characteristics of the channel and boundary conditions of the reach used;
(*b*) Water-surface elevations at time of peak stage to define the cross-sectional areas and the head difference between two significant points; and
(*c*) Hydraulic factors, such as roughness coefficients based on physical characteristics.

11.6.2 *Field survey*

A reconnaissance study, from maps, by air, or by travel in the region, is made to select the most favourable site for determining discharge by one of the indirect methods. The site should be as close as possible to the desired measuring point, and large intervening tributaries or diversions should be avoided. The site must contain good high-water marks defining the water-surface profile during the peak.

A detailed survey is made to define channel geometry adjacent to and within the selected reach, the channel cross-sections, the dimensions and details of culverts, bridges, dams, roadways, or other artificial structures, and the positions and locations of high-water marks left by the flood. All factors that affect channel roughness are noted, and roughness coefficients are selected. Photographs should be taken of the cross-sections and reach to facilitate office evaluations of site conditions.

From the field survey notes, drawings are made showing the plan, the profiles of the channel bottom and high-water surface on both banks, the cross-sectional areas, and details of any artificial structures. Computations are made of hydraulic factors, and the discharge is computed.

11.6.3 *Slope-area measurements*

Slope-area measurements require a reach of river channel that is selected for uniformity or uniform variation in hydraulic properties [8]. Discharge is computed on the basis of a uniform flow equation, such as the Manning equation, involving channel characteristics, water-surface profiles, and roughness coefficients.

11.6.4 *Measurement of flow through culverts*

Peak discharge through culverts can be determined from high-water marks that define the headwater and tailwater elevations, from culvert geometry and slopes, and from cross-sections that define approach conditions. The head-discharge relationships of culverts have been defined by laboratory investigations and field verification. Peak discharge is determined by the application of continuity and energy equations between the approach section and a section within the culvert barrel. For convenience in computation, culvert flow has been classified into six types on the basis of the location of the control section and the relative heights of the headwater and tailwater elevations.

11.6.5 *Measurement of flow through width contractions*

The contraction of a stream channel by a roadway crossing creates an abrupt drop in water surface elevation between an approach section and the contracted section under the bridge. The contracted section formed by bridge abutments and the channel bed may be used as a discharge control to compute flood flows. The head on the contracted section is defined by high-water marks (upstream and downstream), and the geometry of the channel and bridge is defined by field surveys. The discharge equation results from a combination of the energy and continuity equations for the reach between these two sections.

11.6.6 *Measurement of flow over dams and highway embankments*

A weir, dam, or embankment generally forms a control section at which the discharge may be related to the upstream water-surface elevation. The peak discharge at the control section can be determined on the basis of a field survey of high-water marks and the geometry of the structure. The methods are derived from laboratory and field studies of the discharge characteristics of weirs, dams, and embankments.

The field work consists of a survey of headwater and tailwater elevations from high-water marks, an approach cross-section to define velocity of approach, and an exact determination of the profile of the control structure to assign the proper discharge coefficient. Coefficients are available for:

(*a*) Thin-plated weirs, either discharging freely or submerged;
(*b*) Broad-crested weirs, not submerged;
(*c*) Ogee or design-head dams, submerged or not submerged; and
(*d*) Many irregular shapes.

11.7 **Measurement of discharge under difficult conditions**

General discussion on the measurement of discharge under difficult conditions is provided in the WMO *Level and Discharge Measurements under Difficult Conditions* [9].

11.7.1 ***Unstable channels***

Channel instability is characterized by systematic shifts of the bed, by high silt content, and by the presence of various kinds of debris in the flow. Channel instability is a hindrance to the operation of a permanent gauging structure and/or measurement section. This problem can be minimized by selecting a site midway along a uniform and straight section of the river remote from various obstructions (bridges, etc.). The greatest stability in the banks is usually found at places where the channel narrows. On small rivers, the site should be convenient for the construction of a permanent measurement section.

On small streams, where there is no transport of large stones and debris, portable or permanently installed flumes may be used to measure flow. On small rivers, it is desirable, in some cases, to have an artificial section for measurements to improve the stage-discharge relationship. Improvements may take the form of a low weir or flume depending on the specific conditions at the site. The structure should be high enough to remove variable backwater from downstream but not so high as to cause excessive disturbances downstream. At low water, the structure should provide a sensitive relationship between discharges and water levels. To clean the crests of large structures and to provide a means for making current-meter measurements, a footbridge may be provided. Because of the large silt content of unstable channels, it is desirable to use current meters with a sealed contact chamber. Sounding rods should be provided with a foot to prevent them from sinking into the silt.

When measuring discharge by the velocity-area method, the depth is usually determined before and after measurement of the velocity. When the velocity is high, the presence of various kinds of debris in the stream may lead to external damage to the current meter. In such cases, it is advisable to compare the current-meter readings, before and after measuring the discharge, with the readings from a separate current meter not used in the measurement.

In rivers with intensive channel shifts, the distribution of velocity in a cross-section varies periodically. The choice of velocity verticals must be made by taking into account the velocity distribution at the time of measurement. The use of permanent verticals may lead to systematic errors. If there is intensive shifting of the channel, it is also desirable to use a reduced point method of velocity measurement and a reduced number of verticals [1].

If soundings have been made twice (before and after velocity measurements), the area of water cross-section is computed on the basis of the mean depths from the two soundings. On wide rivers, where the location of sounding verticals is determined by marks on the shore, the verticals obtained on the two runs may not coincide. In this case, an average cross-section profile of the measurement site is used to select depth values for the discharge computation.

11.7.2 ***Mountain streams***

Mountain streams are characterized by high flow velocities, shallow and uneven beds blocked by boulders and debris, transverse and uneven water-surface slopes, and transport of large but varying quantities of stones and pebbles. Measurement or gauging locations with these characteristics should be avoided if possible.

Due to very turbulent flows, it is desirable to use one of the dilution methods of flow measurement on small mountain streams (section 11.4). Improvements in the channel to make better measurements may be advisable. It may also be desirable to equip the site with a gauging bridge (section 11.2).

Current-meter measurements should be comprised of at least 20 verticals. Measurement of depth by wading rod in mountain streams does not lead to systematic errors. However, the use of a sounding weight with tailfin may lead to underestimates of the depth if the depth is small. For depths of about one metre, these differences from measurements made by wading rod may amount to about 2.5 to three per cent, while for depths of 0.4 to 0.8 metre, the difference may be as much at 10 to 15 per cent.

It is best to use the two-point method to measure velocities by current meter. The discharge is calculated as explained in section 11.2.4.

11.7.3 ***Measurement of unsteady flow***

11.7.3.1 *Measurement of discharge during floods*

Flood measurements on large rivers are best made from bridges, cableways, or boats. Portable electromechanical winches are available, which can be set up on special trucks, motorcars, and tractors. On large rivers, where there are no bridges or cableways, large vessels or ferries are used. Telemetric equipment may be set up on board the vessel and on the bank to determine the position in the channel. Ferries using a cable for the crossing are equipped with electric or mechanical engines for traction by the cable and for lifting and lowering the equipment. Generally, sounding weights of up to 200 kilograms are necessary because maximum velocities on large rivers may be as great as 6 to 8 m s^{-1}. Soundings of depth also may be made by echo sounder.

For flood measurements on small rivers, remote control or bank-operated traversing systems are particularly suitable. These systems may be portable and can be used at several sites, which need merely to be equipped with a main carrying cable across the river. If such systems are not available, easily transportable duraluminium boats or inflatable rubber rafts with outboard motors and equipment platforms can be used. Locations that are difficult to access may have to be reached by helicopter.

For very high velocities, surface floats or stroboscopic instruments for measuring velocities may be used. The stroboscope has a telescope that is directed towards the surface of the water and a number of rotating mirrors. The speed of rotation of the mirrors is chosen so that a stationary image of the surface of the water is obtained. The velocity of the flow is determined from the speed of rotation of the mirrors. The maximum speed measurable by this method is 15 m s^{-1}, but this maximum is dependent on the height of the observation point above the water surface. Measurements by stroboscope can be made in very turbid flow with floating ice and other solid matter preventing the use of a current meter. The coefficient for converting the surface velocity to the mean velocity at a vertical, determined by similar measurements under less difficult conditions, is usually equal to 0.85-0.90. Measurement of depth is commonly made by echo sounder or a standard cross-section is used.

For wide rivers, the moving boat method (section 11.8.2) may be used. This is a particularly convenient method if there are short breaks in the ice run or if there is debris. If there is ice or debris in some particular part of the flow, measurements may be made by the float method and by current meter during breaks in occurrence of such debris.

When there is a wide flood channel (three to 20 kilometres) with several sub-channels, measurements by current meter become extremely difficult. In this case, it may be possible to employ aerial photography using floats.

11.7.3.2 *Measurement of discharge in tidal reaches*

Where a measurement section is affected by ocean tides, the following effects must be taken into account:

(*a*) Continuous change of water level, with and without change of direction of the current;
(*b*) Continuous change of velocity with time, even at a single point in a vertical with considerable velocity gradients;
(*c*) Change in the time-distribution of velocity;
(*d*) Change of direction of the current for the tidal cycle with zero velocity;

(*e*) Presence of stratified flow with varying density and direction of flows;
(*f*) Considerable change in the width and cross-section of the flow; and
(*g*) Presence of large-scale turbulence (e.g., fluctuations with a period of more than 30 seconds and the amplitude of velocity variations up to 50 per cent) and of seiches.

The discharge of tidal river is generally determined by one of the following methods [10]: velocity-area method, volumetric method, or by solving the equation for unsteady flow. Where discharges are measured in tidal conditions, the moving boat method (section 11.8.2) may also be used, particularly at times when the distribution curve of velocities is close to its usual shape. Other methods, such as the ultrasonic method (section 11.8.3), may also be suitable.

In the method of computation of discharge by the velocity-area method, the velocity is measured during the entire flood-ebb cycle. Measurements are usually made at several points to be able to account for the different directions of flow. At the same time, the water level and the depths at verticals are measured continuously. Then, all measurements are reduced to a single time for which the discharge is calculated.

The accuracy of the velocity-area method is greater if:

(*a*) The tidal cycle during which the measurement is made is periodic or nearly periodic;
(*b*) Currents, particularly during the period of maximum flow, are parallel to each other and at right angles to the gauging site at all points;
(*c*) Curves of horizontal and vertical velocity distributions are of the regular shape encountered at the gauging site; and
(*d*) The transverse profile of the gauging site is uniform and lacks shallow areas.

The site selected should meet as closely as possible the following requirements:

(*a*) The river bed section should be straight and of regular shape;
(*b*) The depth of the water at the site should be such that current meters can be used effectively;
(*c*) The channel section should be stable during the tidal cycle;
(*d*) The discharge should be concentrated within channels whose cross-sections can be determined with a fair degree of accuracy;
(*e*) The site should not be near artificial or natural obstacles causing nonparallel flows;
(*f*) The gauging site should be clear of vegetation; and
(*g*) Oblique flow, backflow, and dead zones should be avoided.

The site should be conspicuously marked on both banks.

To determine discharge during the rise and recession of floods, measurements are made at each vertical during the entire tidal cycle. To determine accurately the moment of zero velocity, measurements begin and end half an hour before and after the tidal cycle. Depending on the equipment available and on the physical characteristics of the selected site, different procedures can be adopted for velocity measurements:

(*a*) If a sufficient number of boats are available, measurements are made simultaneously at all verticals during the entire tidal cycle;

(*b*) If only a limited number of boats are available, the chosen verticals are marked by anchored buoys. One or two boats are necessary to carry out the measurements, proceeding successively from one vertical to the next, at intervals of not more than one hour between each vertical. At least one additional boat remains permanently at one reference vertical, carrying out measurements continuously during the entire tidal cycle. In this case, the curves of velocity changes occurring over time at each vertical are plotted by using the concurrent velocities at the reference vertical as a basis of comparison;

(*c*) If the shape of the tidal curve does not change considerably from day to day and if at least two boats are available, then one of the boats is stationed at the reference vertical to carry out measurements during the whole tidal cycle for each day. The other boat carries out measurements during the whole cycle at each vertical, moving to a new vertical each day. In this case, the number of days required for the whole cycle of observations is equal to the number of velocity verticals;

(*d*) If there are different tidal amplitudes and if it is not possible to make measurements in many verticals, measurements are carried out at each vertical for the entire cycle at different tidal amplitudes during a lunar month and at spring and neap tides;

(*e*) If there is considerable pulsation, measurements should be carried out at each vertical with the aid of several current meters set at different heights for periods of ten to fifteen minutes. The mean velocity is determined for the mean period of time; and

(*f*) In the case of oblique currents, use must be made of direct reading current meters or of instruments capable of measuring the angle of deviation.

Where rapid velocity changes occur, the velocity values at the various points in the vertical must be adjusted to a specific time. For this purpose, velocity measurements are either repeated at all points in the vertical by moving from the bottom to the surface, or are measured only at one point at the surface.

For the computation of the discharge at each vertical, a curve of velocity changes with time is plotted, from which the value for a specified time is taken.

For the computation of discharge by the volumetric method, synchronous measurements of the water level are made at the boundaries of the measuring section or sections after their geometrical characteristics (cross-sections, lengths, and flooded areas) are determined. An additional gauging station is located on the river above the area of tidal effects so that the discharge attributable to the river can be determined. Where there are transverse slopes in wide estuaries, levels are measured at both banks. The difference in volumes of the tidal prisms during the accounting interval is computed from the change in mean depths and areas of water surface between the boundaries. To determine the mean discharge, the difference in the volume of the total prism is divided by the accounting period minus the inflow into the river.

In the method of computation of discharge from equations of unsteady motion, the solution of the equations of unsteady motion for the section under consideration is simplified by certain assumptions — such as parallel flow, uniform density — and that the channel is prismatic. Measurements are usually made for two typical (high and low) tidal cycles. The measurements are used to calibrate the parameters of the equations.

11.7.4 *Weed growth in stream channels*

Weed growth in rivers can cause relatively large errors. For small rivers, it is advisable, if possible, to construct artificial controls. If this is not possible, discharges should be measured by the velocity area method. For this purpose, a reach of the river six to 10 metres long should be kept clear of weed growth during the entire season. In addition, the banks should be kept cleared of shrubs and high grass over a somewhat larger reach.

The use of toxic substances to impede the growth of vegetation is effective for a short time only. Frequent clearing of the bed may be the most practical method. The weeds growing in the bed may be cut by a special machine attached to a mechanized chain saw or by the aid of an ordinary scythe.

Flow velocity in each vertical should be measured at three points (at depths of 0.15, 0.5 and 0.85). Where the depth of the vertical is less than 0.40 metre, velocity is measured by the single-point method.

In the discharge measurement notes, a short description of the actual state of weed growth could be given.

Because algae and weeds may wind around the propeller of the current meter, the instrument must be inspected and cleaned frequently during the measurement. Where measurements are made at one point only, the regularity with which signals are received must be carefully checked. Recently, experience has been acquired with the use of the electromagnetic method for gauging under such conditions (see section 11.8.4).

11.8 Non-traditional methods of stream gauging

11.8.1 *General*

Determination of discharge by the velocity-area method (Chapters 11 and 12), the dilution method (section 11.4), and by means of a hydraulic structure (Chapter 12) have certain limitations and are not applicable in some instances. Three relatively new methods of flow measurement in open channels are the moving boat method, the ultrasonic method, and the electromagnetic method.

11.8.2 *Moving boat method* **[E79]**

In this method, a boat is fitted with a specially designed component current-meter assembly that indicates an instantaneous value of velocity. A measurement is made by traversing the stream along a preselected path that is normal to the flow. During the traverse, which is made without stopping, an echo sounder records the geometry of the cross-section, and the continuously operating current meter measures the combined stream and boat velocities. These data, collected at some 30 to 40 observation points (verticals) across the path, are converted to discharge. The velocity recorded at each of the observation points in the cross-section is a vector quantity that represents the relative velocity of flow past the meter assembly. This assembly consists of a vane attached to a stainless steel shaft, which, at its upper end, incorporates a dial and pointer for reading the angle between the direction of the vane and the true course of the boat. This is performed by sighting on carefully located markers on the banks. About six traverses, in alternate directions, are usually taken and the measurements are averaged to give the discharge [11, 12].

The discharge is calculated in a similar manner to the conventional velocity-area method by summing the products of the segment areas and average velocities. Because the current meter is located about one metre below the surface, a coefficient is required to adjust the measured velocity. In large rivers, the coefficient is usually uniform across the section. Investigations on several rivers have shown that the coefficient generally lies between 0.90 and 0.92.

The moving boat method provides a single measurement of discharge, and an accuracy of ± 5 per cent is claimed at the 95 per cent confidence level.

11.8.3 *Ultrasonic (acoustic) method* **[C73]**

The principle of the ultrasonic method is to measure the velocity of flow at a certain depth by simultaneously transmitting sound pulses through the water from transducers located on either side of the river. The transducers, which are designed both to transmit and receive sound pulses, are located on opposite banks, so that the angle between the pulse path and the direction of flow is between 30° and 60°. The difference between the time of travel of the pulses crossing the river in an upstream direction and those travelling downstream is directly related to the average velocity of the water at the depth of the transducers. This velocity can be related to the average velocity of flow of the whole cross-section. The incorporation of an area computation into the electronic processor allows the system to output discharge.

Ideally, the transducers are set at a depth such that they measure the average velocity of flow. In practice, they are ultimately fixed in position so that for any change in stage, they probably will not be at the point of average velocity, and a coefficient is necessary to adjust the measured velocity.

There are two types of ultrasonic systems commonly in operation, the first where the transducers are fixed in position and the station is calibrated by current meter, and the second where the transducers are designed to slide on either a vertical or inclined assembly. In the latter method, the system is self-calibrating and no current-meter measurements are therefore necessary. By moving the transducers through a number of paths in the vertical (generally 7 to 10), velocity readings are obtained along these paths. From each set of the readings, vertical velocity curves are established over as large a range in stage as possible. It is then possible first, to estimate a suitable position for the fixing of the transducers in the vertical and, second, to establish a curve of stage against the coefficient of discharge as in the first method.

In rivers with small range in stage, a single path transducer system may be acceptable. For rivers with large variations in stage, a multipath system with several pairs of transducers may be necessary.

The accuracy of the ultrasonic method depends on the precision with which the travel times can be measured. The several techniques available at the present time are capable of measuring time to very high accuracy [13-21].

11.8.4 *Electromagnetic method*

The motion of water flowing in a river cuts the vertical component of the Earth's magnetic field, and an electromotive force (emf) is induced in the water that can be measured by two electrodes. This emf, which is directly proportional to the average velocity in the river, is induced along each traverse filament of water as the water cuts the line of the Earth's vertical magnetic field.

Figure 11.3 shows diagrammatically an electromagnetic gauging station where the coil is placed in the bed and the magnetic field is in the x direction, the emf is in the y direction, and the streamflow is in the z direction. Faraday's law of electromagnetic induction relates the length of a conductor moving in a magnetic field to the emf generated by the equation [22].

In practice, most river beds have significant electrical conductivity that will allow electric currents to flow in the bed. From practical considerations, the induced field will be spatially limited and electric currents flowing in the area outside the field will have the effect of reducing the output potential. Both of the above factors have the effect of reducing the signal and hence the voltage recorded. At an electromagnetic gauging station, it is necessary to measure both the bed and water conductivity.

The most suitable current for the coil is a direct current, the direction of which is reversed a few times a second and an alternating square wave with a frequency of about one hertz should be used. A typical installation may have a coil of 12 turns, each of 16 mm^2 double PVC insulated cable, and supplied with 25 ampere with a voltage across the coil of about 20 volts [22].

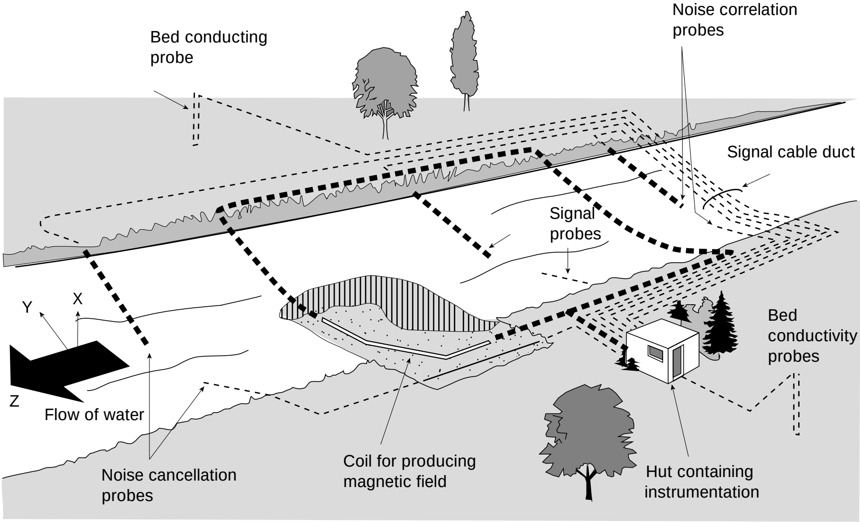


Figure 11.3 — Basic system of the electromagnetic method.

The electromagnetic method will be suitable for use in rivers with weed growth, high sediment concentration, or unstable bed conditions and gives a continuous record of the average velocity in the cross-section that can be combined with stage to give an on-site output of discharge.

The accuracy depends on the signal processing equipment detecting and measuring small potentials sensed at the voltage probes. It is possible to detect a signal of 100 nano volts (10^{-9} volts), which represents a velocity of approximately 1 mm s^{-1}. The electromagnetic gauging station requires on-site calibration by current meter or other means and a relation established between discharge and output.

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CHAPTER 12

STREAM GAUGING STATIONS

12.1 Purpose of stream gauging stations

The purpose of stream gauging stations is to provide systematic records of stage and discharge. Continuous streamflow records are necessary in the design of water supply and waste systems, in designing hydraulic structures, in the operations of water management systems, and in estimating the sediment or chemical loads of streams, including pollutants.

Since continuous measurement of discharge is not usually feasible, unless one of the methods in sections 11.8.3 and 11.8.4 is used, records of discharge are computed from the relationship between stage and discharge, as defined by periodic discharge measurements (Chapter 11) and a systematic record of stage (Chapter 10), or from a measuring structure that has been calibrated in either a laboratory or the field.

12.2 Selection of sites

The selection of streams to be gauged should be governed by the principles of network design (Chapter 20) and the proposed use of the data. The selection of a particular site for the gauging station on a given stream should be guided by the following criteria for an ideal gauge site:

(*a*) The general course of the stream is straight for about 100 metres upstream and downstream from the gauge site;
(*b*) The total flow is confined to one channel at all stages and no flow bypasses the site as sub-surface flow;
(*c*) The stream bed is not subject to scour and fill and is free of aquatic growth;
(*d*) Banks are permanent, high enough to contain floods, and are free of brush;
(*e*) Unchanging natural controls are present in the form of a bedrock outcrop or other stable riffle during low flow, and a channel constriction for high flow, or a fall or cascade that is unsubmerged at all stages to provide a stable relationship between stage and discharge. If no satisfactory natural low-water control exists, then installation of an artificial control should be considered;
(*f*) A site is available, just upstream from the control, for housing the stage recorder where the potential for damage by water-borne debris is minimal during flood stages. The elevation of the stage recorder itself should be above any flood likely to occur during the life of the station;

(*g*) The gauge site is far enough upstream from the confluence with another stream or from tidal effect to avoid any variable influences which the other stream or the tide may have on the stage at the gauge site;

(*h*) A satisfactory reach for measuring discharge at all stages is available within reasonable proximity of the gauge site. It is not necessary that low and high flows be measured at the same stream cross-section;

(*i*) The site is readily accessible for ease in the installation and operation of the gauging station;

(*j*) Facilities for telemetry or satellite relay can be made available, if required; and

(*k*) If ice conditions might occur, it will still be possible to record stage and measure discharge.

In many instances, it may be impossible to meet all of these criteria. Judgement is then required to select the most suitable site for the gauge.

12.3 **Stage-discharge controls**

The physical element or combination of elements that control the stage-discharge relationship is known as a control. The major classification of controls differentiates between section control and channel control. Another classification differentiates between natural and artificial controls.

Section control exists when the geometry of a single cross-section is such as to constrict the channel, or when a major downward break in bed slope occurs at a cross-section. The constriction may result from a local rise in the stream bed, as at a natural riffle or rock ledge outcrop or at a constructed weir or dam. It may also result from a local constriction in width, which may occur naturally or may be caused by some man-made channel encroachment, like a bridge with a waterway opening that is considerably narrower than the width of the natural channel.

Channel control exists when the geometry and roughness of a long reach of channel downstream from the gauging station are the elements that control the relationship between stage and discharge. The length of channel that is effective as a control increases with discharge. Generally, flatter stream gradients will result in longer reaches of channel control.

A low dam, weir, or flume is often built in the channel to provide an artificial control. Such controls are usually submerged by high discharges, but they provide a stable stage-discharge relationship in the low to medium flow range.

The two attributes of a good control are resistance to change — ensuring stability of the stage-discharge relationship — and sensitivity, whereby a small change in discharge produces a significant change in stage.

12.4 Measuring structures

At some gauging sites it is feasible to utilize an artificial control of such shape that head-discharge relationships can be determined without calibration, i.e., by the application of a discharge formula. There exists a set of weirs and flumes that have well-established relationships between head and discharge. However, only under favourable field conditions can the established formulae for some types of weirs and flumes be applied accurately. If these structures are used to measure flow directly from water level readings, it is important that care be taken in their construction and operation and that the most suitable formulae be used [1-6].

Under less favourable conditions, in-place calibration is necessary to establish the extent of the departures from the standard formulae or to develop the head-discharge relationship. It is particularly important at low flow to measure periodically the discharge by other means in order to detect changes in the discharge coefficient caused by sediment deposits in the pool or growth of algae on the weir or flume.

The material in this *Guide* is limited to the general considerations involved in the selection and use of weirs and flumes at gauging stations. Specific information on their geometries and head-discharge formulae are presented in the WMO *Use of Weirs and Flumes in Stream-gauging* [7].

12.4.1 *Scope*

Weirs and flumes for use at gauging stations may be catalogued into three groups:

(*a*) Thin-plate weirs generally used on small, clear-flowing streams or small research watersheds;
(*b*) Flumes used on small streams and canals conveying sediment and debris or in other situations where the head loss associated with thin-plate weirs is unacceptable; and
(*c*) Broad-crested, triangular-profile, and round-shaped weirs used on larger streams.

Weirs and flumes may be free-flowing or submerged. In the first case, the discharge is a function of the headwater elevation, and accurate calibrations are possible. For submerged conditions, the discharge is a function of both the headwater and tailwater elevations, and less accuracy is obtained by use of laboratory calibrations. At many sites, weirs or flumes are used to measure only the lower range of discharge, and the stage-discharge relationship for the upper range of discharges is determined by direct methods.

12.4.2 *Selection of structure*

Choice of a measuring structure depends on costs, the characteristics of the stream and channel at the site, the range of discharges, the accuracy desired, and the potential head loss. Criteria to be considered in choosing a structure include:

(*a*) Cost is usually the major factor in deciding whether or not a measuring structure is to be built. The cost of the structure is affected most by the width of the stream and the type or condition of the bed and bank material. Stream width governs the size of the structure, and bed and bank material govern the type of construction that must be used to minimize leakage under and around the structure;

(*b*) Channel characteristics and flow conditions influence the design of the measuring structure. Factors controlling velocity or Froude number, sediment loads, and the stability of the bed need to be considered in the structure design; and

(*c*) The range of discharge, range of stage, the desired sensitivity, and the allowable head loss must also be considered in structure design and positioning. Submergence by high flows or from backwater influence both the design and elevations of the structure. The sensitivity, i.e., the change in stage corresponding to change in discharge at very low flows, may dictate whether a V-crest or flat crest is appropriate.

12.4.3 *Measurement of head*

The head over the structure is usually measured at a distance upstream from the structure equal to about three times the depth of water, h_{max}, on the control at the maximum stage for which the section control is effective. Some special weir shapes and all flumes require that stage be measured at specific distances from the control section that differ from the general rule of three times h_{max}. The locations for the gauge or gauge intake for these special cases are described in the WMO *Use of Weirs and Flumes in Stream-gauging* [7]. The zero of the gauge should be set at crest elevation and should be checked regularly.

12.4.4 *Operation of measuring structures*

Both the channel and structure are subject to changes with time that may affect the head-discharge relationship. Sand, rocks or debris may be deposited in the approach section or on the structure itself. Algae may grow directly on the crest of the structure during summer, and ice may form on the structure during winter.

For optimum accuracy the approach channel to weirs should be kept clean and free from any accumulation of silt and vegetation. The structure must be kept clean and free of debris, algae and ice. Damage to critical parts of the structure should be repaired. The datum of the gauge should be checked periodically. Periodic discharge measurements should also be made to define possible changes in the original calibration.

12.5 Stage-discharge relationships

The stage-discharge relationship for most gauging stations is defined by plotting the measured discharges as the abscissa and the corresponding stage as the ordinate [8].

The shape of the discharge relationship is a function of the geometry of the downstream elements of the channel that act as the control. When plotted on rectangular coordinate paper, the relationship is generally concave downwards; when plotted on logarithmic coordinate paper, the medium- and high-stage sections of the relationship is often approximately linear if the stage represents the effective head on the control for medium and high stages. Because only the linear section of the stage-discharge relationship can be conveniently expressed by a mathematical equation, the relationship is generally used in graphical or tabular form.

At many sites, the discharge is not a unique function of stage, and additional variables must be measured continuously to obtain a discharge record. For example, in situations where variable backwater at the gauge is caused by a downstream tributary or by tidal effect or by downstream reservoir operation, an auxiliary stage gauge must be installed to measure continuously the fall of the water surface in the gauged reach of the channel. Where flow is unsteady and the channel slopes are flat, the rate of change of stage can be an important variable, and a given discharge that occurs on a rising stage will have a lower gauge height than the same discharge occurring on a falling stage.

12.5.1 *Stability of stage-discharge relationships*

The stability of a stage-discharge relationship is directly related to the stability of the control. For natural section controls, a rock-ledge outcrop will be unaffected by high velocities. Boulder, gravel, and sandbar riffles are likely to shift. Boulder riffles are the most resistant to movement, and sandbars are the least. Of the natural channel controls, those found in sand-channel streams are the most likely to change as a result of velocity-induced scour and deposition.

The growth of aquatic vegetation on section controls increases the stage for a given discharge, particularly in the low-flow range. Vegetal growth on the bed and banks of channel controls also affects the stage-discharge relationship by reducing velocity and the effective waterway area. In temperate climates, accumulation of water-logged leaves on section controls during autumn may clog the interstices of alluvial riffles and raise the effective elevation of natural section controls. The first ensuing stream rise of any significance usually clears the control of leaves.

Ice cover also affects the stage-discharge relationship of a stream by causing backwater that varies in effect with the quantity and nature of the ice. If the section control remains open and if the gauge is not too far from the control, there will probably be little or no backwater effect even though the entire pool is ice covered. The only effect of the ice cover will be to slow the velocity of approach, and that effect will probably be minor. However, if the gauge is a considerable distance upstream from the riffle, surface ice on the pool may cause backwater when the covered reach of the pool becomes a partial channel control.

Surface ice forming below a section control may jam and dam water sufficiently to cause backwater effects at the control. Anchor ice may build up the bed or control to the extent that a higher than normal stage results from a given discharge. The magnitudes of ice effects can be determined accurately only by measuring the discharges, observing the corresponding stages, and analysing the differences between the observed stage and the discharge corresponding to the open-water stage-discharge relationship.

The various additional conditions that have to be taken into account in making discharge measurements under ice conditions and the procedures for making such measurements are described in section 11.2.5.

Artificial controls eliminate or alleviate many of the undesirable characteristics of natural section controls. Not only are they physically stable, but they are less subject to the cyclic or progressive growth of aquatic vegetation. Algal slimes that sometimes form on artificial controls can be removed with a wire brush, and the controls can be self-cleaning with regard to fallen leaves. In moderately cold climates, artificial controls are less likely to be affected by the formation of winter ice than are natural controls. However, even when the artificial control structure is unchanged, the stage-discharge relationship may be affected by changes in the velocity of approach caused by scour and/or fill, or by vegetal growth in the approach channel.

12.5.2 *Frequency of discharge measurements*

Factors to be considered in scheduling the number and distribution of discharge measurements within the year include:

(a) Stability of stage-discharge relationship;
(b) Seasonal discharge characteristics and variability; and
(c) Accessibility of the gauge in various seasons.

Many discharge measurements are necessary at a new station to define the stage-discharge relationship throughout the entire range of the stage. Periodic measurements are then necessary to define changes in the stage-discharge relationship. A minimum of ten discharge measurements per year is recommended.

Adequate definition of discharge during flood and under ice conditions is of prime importance. It is essential that the measurement programme provides for non-routine measurement of discharge at these times.

Where it is important to record streamflow continuously throughout the year, discharge measurements should generally be made more frequently when the stream is under ice cover.

During freeze-up and break-up periods, measurements should be obtained as often as possible because of the extreme variability of flow. In midwinter, the frequency of the measurements will depend on climate, accessibility, size of stream, winter runoff characteristics, and the required accuracy. In very cold climates, where discharge follows a smooth recession curve, fewer measurements are required than for a stream in a climate of alternate freezing and melting.

References

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CHAPTER 13

SEDIMENT DISCHARGE

13.1 General [E09]

Sediment is transported by flowing water in different ways. The sediment grains may be moved by saltation, rolling, or sliding on or near the bed or may be swept away from it and kept in suspension. The type of movement experienced by the grains depends upon the physical characteristics (size and form of particles, specific weight, etc.) and upon the grain-size composition of the sediment, as well as upon flow velocities and depths. The different phases of sediment transportation generally occur simultaneously in natural streams, and there is no sharp line of demarcation between them. For convenience, sediment discharge is divided into two categories: suspended-sediment and bed-material discharge. The latter consists of grains sliding, rolling, or saltating on or near the bed.

This chapter provides guidance on the collection of sediment-discharge data. For each phase of transport, a more in-depth discussion of this topic can be found in the WMO *Manual on Operational Methods for Measurement of Sediment Transport* [1].

13.2 Selection of site

The same criteria used for the selection of a site for a water-discharge measurement should be used in selecting a site for measuring sediment transport (sections 11.2.1 and 12.2).

13.3 Measurement of suspended-sediment discharge

13.3.1 *Sampling instruments and in situ gauges* [C10]

Several types of suspended-sediment samplers are in use, e.g. instantaneous, bottle, pumping, integrating. However, only some of them are designed so that the velocity within the cutting circle of the sampler intake is equal to the ambient stream velocity. This feature is essential so that the samples obtained are truly representative of the suspended-sediment discharge at the point of measurement. The well-designed sampler faces the approaching flow, and its intake protrudes upstream from the zone of disturbance caused by the presence of the sampler.

Instantaneous samples are usually taken by trap samplers consisting of a horizontal cylinder equipped with end valves that can be closed suddenly to trap a sample at any desired time and depth. The very simple bottle sampler is corked or provided with an entrance of variable diameter, up to the full opening. As soon as the bottle is opened and air within the bottle is being displaced by the sample, bubbling takes place at the entrance, which slows the filling process. Consequently, bottle-sampling is not actually instantaneous.

The pumping sampler sucks the water-sediment mixture through a pipe or hose, the intake of which is placed at the sampling point. By regulating the intake velocity, the operator can obtain a sample that is representative of the sediment concentration at the point of measurement. The integrating sampler consists of a metallic streamlined body equipped with tail fins to orient it into the flow. The sample container is located in the sampler body. An intake nozzle of variable diameter projects into the current from the sampler head. An exhaust tube, pointing downstream, permits the escape of air from the container. Valve mechanisms enclosed in the head are electrically operated by the observer to start and stop the sampling process.

A relatively new method of *in situ* determination of suspended-sediment concentration is the application of optical or nuclear gauges. The working principle of these instruments is that a visible light of X-ray emitted by a source with constant intensity is scattered and/or absorbed by the suspended-sediment particles. The decrease of intensity measured by a photoelectric or nuclear detector situated at constant distance from the source, is proportional to the sediment concentration, if other relevant characteristics of water and sediment (chemical, mineral composition, etc.) remain unchanged.

The overall design of suspended-sediment samplers should be checked by towing them in still water at a known velocity or by holding them in flowing water of known velocity. The optical and nuclear gauges must be calibrated by simultaneous and repeated sampling in sediment-laden flumes and natural streams.

13.3.2 ***Measurement procedure***

Samples of suspended sediment in streams are taken in the discharge-measuring cross-sections, but not necessarily in the velocity-measuring verticals. In lakes, the locations of sampling verticals are scattered over an area, because here the measurements are usually aimed at the determination of distribution of sediment concentration in time and space. The samplers are suspended in the water on a rod or on a wire.

In streams, there are two methods that give comparative results:

(*a*) The cross-section is divided into three to 10 sub-sections of about equal discharge. A depth-integrated sample (section 17.2.3.1) is taken at each vertical in the centroid of each sub-section by lowering the sampler from the stream surface to the bed and back at a uniform transit rate. This gives a discharge-weighted sample for each centroid;

(*b*) The stream width is divided into six to 10 equal distances separated by the verticals and one depth-integrated sample is taken at each vertical at a constant transit rate. In the latter case, all samples can be composited into a single representative discharge-weighted sample [2].

By using a point sampler, samples may also be taken at evenly-spaced points at each vertical mentioned above, and the sediment concentrations obtained are weighted by the ratio of the velocity at the given point to the mean velocity in the vertical. In practice this procedure can be combined with the mid-section method of discharge measurement (section 11.2.4) because the velocity measuring and sampling verticals coincide.

The optical and nuclear sediment gauges may be used both for point- and depth-integrating measurements, provided the electrical signals from the detector are summarized by a scalar. Depending upon the statistical characteristics of counting by a particular instrument, the usual counting period is three to five minutes.

13.3.3 *Determination of sediment concentration*

Suspended-sediment samples are usually processed and analysed in special laboratories where, after a settling time of one to two days, the water is carefully drained off and the remaining sediment is oven dried at a temperature of about 110°C, and weighted. If the sediment is separated by evaporation, a correction must be made of dissolved solids. The concentration of suspended sediment is expressed in g m^{-3} or in kg m^{-3}. The Table below gives recommended sample sizes necessary to have a measurable quantity of sediment.

Volumes of samples required for suspended sediments

Expected concentration of suspended sediment, g m^{-3}	*Volume of sample, litres*
> 100	1
50 - 100	2
20 - 30	5
< 20	10

Sediment samplers have been standardized in some countries to have a container capacity of one litre or less. In such cases, sampling should be repeated until the required volume of sediment sample is obtained [2].

The intensities of light or X-ray indicated by the submerged photoelectric or nuclear probes of *in situ* gauges should be divided by the intensity measured in clear water and the sediment concentration corresponding to this ratio is read from the calibration curves of these instruments.

13.3.4 *Computation of suspended-sediment discharge*

For the first method of concentration (section 13.3.2), the weighted mean sediment concentration $\overline{c}_s$ in kg m^{-3} for the entire cross-section is computed as:

$$\bar{c}_s = \frac{\Sigma\, c_q\, q_p}{\Sigma\, q_p} \qquad (13.1)$$

where q_p is the partial discharge in the sub-section in $m^3\ s^{-1}$, and c_q is the discharge-weighted concentration in the vertical at the centroid of the sub-section in kg m^{-3} [3].

For the second method, the concentration of the composite sample is the weighted mean concentration in the entire cross-section. The suspended sediment daily discharge Q_s, is computed as:

$$Q_s = 86.4\,\bar{c}_s\, Q \qquad (13.2)$$

where Q_s is in tons per day and Q is the stream discharge in $m^3\ s^{-1}$.

13.3.5 *Continuous record of suspended-sediment discharge*

A continuous record of suspended-sediment discharge may be computed from a record of stream discharges and systematic samples of suspended-sediment concentration. The samples should be taken daily during periods of low and mean flow and more frequently during floods. The most valuable information concerning the time-variation of concentration and its peak values can be obtained by the continuous recording of signals supplied by the photoelectric or nuclear suspended-sediment gauges during flood periods. The peak in concentration usually precedes peak flow, and loops can be observed on plots of the water discharge versus sediment discharge, similar to those in stage-discharge rating curves during floods.

The samples or observation records are collected at a single vertical in the cross-section, preferably using the depth-integrating procedure. The relation between the concentration at this vertical and the mean concentration in the section must be established by detailed measurements of the distribution of sediment in the cross-section, as outlined in section 13.3.2. This relation is not necessarily linear and constant throughout the year, nor in all ranges of sediment concentration.

13.4 Measurement of bed-material discharge

13.4.1 *Instrumentation* **[C12]**

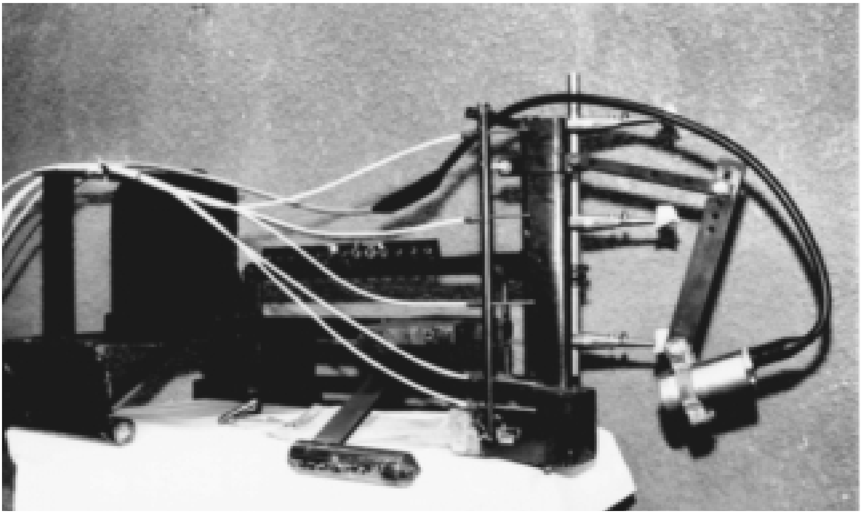
The field measurement of bed-material discharge is difficult because of the stochastic nature of the sediment movement and because the phenomenon takes place in the form of ripples, dunes, and bars. No single apparatus has proved to be completely adequate for trapping the largest and smallest sediment particles with the same efficiency, while remaining in a stable, flow-oriented position on the stream bed, and still not altering the natural flow pattern and sediment movement. Available samplers can be classified into three types: basket, pan, and pressure-difference [3].

Basket samplers are generally made of mesh material with an opening on the upstream end, through which the water-sediment mixture passes. The mesh should pass the suspended material but retain the sediment moving along the bed.

Pan samplers are usually wedge-shaped in longitudinal section and are located so that the point of the wedge cuts the current. The pan contains baffles and slots to catch the moving material.

Pressure-difference samplers are designed to produce a pressure drop at the exit of the sampler which is sufficient to overcome energy losses and to ensure an entrance velocity equal to that of the undisturbed stream. A perforated diaphragm within the sampler forces the flow to drop its sediment into the retaining chamber and to leave through the upper exit.

Because of several uncertainties involved in sampling, it is necessary to determine an efficiency coefficient for each type of sampler. The calibration generally takes place in a laboratory flume, where the bed-material discharge can be directly measured in a sump at the end of the flume, although uniform-transport conditions over the width and length of the flume are difficult to maintain. Even under favourable conditions, efficiency factors are not easily determined because they vary according to the grain-size composition of the bed material, the degree of fullness of the sampler, etc. An efficiency of 60 to 70 per cent can be regarded as satisfactory.



Delft-Nile sampler consisting of a bed-load and suspended-load sampler as well as an underwater video camera.

13.4.2 *Measurement procedure*

Bed-material discharge is determined from the amount of sediment trapped per unit time in a sampler located at one or more points on the stream bed. There should generally be three to 10 measurement points in a cross-section. In determining the distribution of sampling points, it should be noted that, except during flood periods, bed-material transport takes place in a part of the stream width only.

The inclusion of a zero measurement in the computation of bed-material discharge can lead to uncertainties in the result even though the sampling point may be situated between two moving strips of the stream bed. Uncertainties can also occur if a measured rate of transport is extended over a segment of the cross-section with low or zero sediment movement.

On gravel-bed streams, of which partial bed-material movement is most characteristic, different types of acoustic detectors can help to solve this problem. Submerged to a depth near the bed, these detectors pick up the sound of moving gravel, indicating the movement of bed material at this particular point. Moreover, the intensity of the sound and that of the sediment transport may be correlated.

The samplers are lowered to the bottom and held in position by a rod or a wire. The duration of the sampling period is usually a few minutes, depending on the dimensions of the sampler and on the intensity of the sediment transport. When low-flow velocities exist near the bed, the downstream forces are reduced, and the sampler tends to dive into the stream bed and scoop up bed material that is not in transport. A similar tendency can develop during an abrupt or incautious lifting of the sampler.

Measurements should be made at various stream discharges so that a rating may be prepared showing the relationship between stream discharge and bed-material discharge. Due to the highly complex mechanism and random nature of sediment transport and to the errors of sampling, one single catch at a measuring point can provide a very uncertain estimate of the true bed-material transport. Therefore, repeated sampling should be carried out at each point. The number of repetitions depends on the local circumstances. However, statistical analyses of field data resulting from up to 100 repetitions have shown that only the bed-material discharge can be measured with restricted accuracy, unless an impracticably large number of samples are taken at each point.

13.4.3 *Computation of bed-material discharge*

The sediment collected in the sampler is dried and weighed. The dry weight, when divided by the time taken for the measurement and the width of the sampler, gives the bed-material discharge per unit width of stream at the point of measurement, q_b. A curve showing the distribution of *qb* in the stream width can be constructed, based on data obtained at the sampled points. The area enclosed between this curve and the water-surface line represents the total daily bed-material discharge over the entire cross-section Q_b. The value of Q_b can also be computed by using the measured q_b data as:

$$Q_b = 86.4\left[\frac{q_{b1}}{2}x_1 + \frac{q_{b1}+q_{b2}}{2}x_2 + \mathrm{K} + \frac{q_{bn-1}+q_{bn}}{2}x_{n-1} + \frac{q_{bn}}{2}x_n\right] \quad (13.3)$$

where Q_b is in tons per day, qb is in kg s^{-1} m^{-1} and x is in metres. The variable x represents the distance between sampling points, between a marginal point and the edge of the water surface, or that of the moving strip of stream bed.

The existence of dams trapping most of the sediment transported by upstream river reaches offer the possibility of estimating the annual or seasonal sediment discharge by successively surveying suitable selected profiles of the reservoir and by computing the volumes occupied by the trapped sediment. This method, combined with regular suspended-sediment sampling upstream and downstream of the dam, can provide acceptable estimates of bed-material discharge.

13.4.4 *Continuous record of bed-material discharge*

A continuous record of bed-material discharge can be obtained by relating bed-material discharge to stream discharge or other hydraulic variables with available records. This relationship can be assumed approximately linear for water discharges above the limiting value corresponding to the beginning of sediment movement because the tractive force of the flow increases in direct proportion to the increase in stream discharge. Bed-material transport is of primary interest in all investigations concerning stream bed changes.

References

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2. International Organization for Standardization, 1977: *Liquid Flow Measurement in Open Channels: Methods of Measurement of Suspended Sediment.* ISO 4363, Geneva.
3. International Organization for Standardization, 1977: *Liquid Flow Measurement in Open Channels: Bed Material Sampling.* ISO 4364, Geneva.

CHAPTER 14

ICE ON RIVERS, LAKES, AND RESERVOIRS

14.1 General

Observations of ice conditions on rivers, lakes, and reservoirs are of great interest in regions where ice formation affects navigation or results in damage to structures, and where ice jams may form (even to the extent of damming a major river). The obstruction of streamflow by ice can also cause serious local flooding. Long-term data on ice conditions in rivers are extremely valuable in designing various structures, in studying processes of ice formation and dissipation, and in developing methods of ice forecasting.

14.2 Elements of ice regime

The most important elements of ice regime to be recorded are the following:

(*a*) Dates on which flows of floating ice are first observed each winter;
(*b*) Ratio of the surface area of drifting ice to the open-water surface (ice cover ratio);
(*c*) Ratio of the surface area of drifting ice to the stationary ice surface;
(*d*) Dates on which ice becomes immovable;
(*e*) Thickness of ice;
(*f*) Features of ice destruction;
(*g*) Dates of ice break up;
(*h*) Dates on which the ice on rivers and reservoirs has completely vanished.

14.3 Methods of observation

Many of the elements given in section 14.2 cannot be measured instrumentally and must be evaluated subjectively and recorded in descriptive language. For this reason, it is very important that observers be well trained and that instructions be clearly prepared.

The thickness of ice is measured by means of an auger and a ruler at representative sites. To minimize errors caused by spatial variability in ice thickness, measurements should be made at a minimum of three points spaced over a distance of at least five metres, and the measurements should be averaged. The depth of any snow on top of the ice should also be measured.

The kilometre signs of navigable rivers or dykes may be used to identify the locations at which ice surveys are routinely conducted. Particularly dangerous conditions (e.g., ice jams) must be identified in relation to other landmarks (e.g., bridges, river regulation structures, and harbours).

Determining some of the characteristics of ice phenomena can be made by means of regular photogrammetric surveys from a location on the shore or by aerial photography. In the case of large rivers, reservoirs, or lakes, aircraft observations of ice formation or breakup are of great value. They are also useful in the case of ice gorges when flood warnings are required.

For surveying ice conditions over a reach, a strip width, s, and a flying height, h_f, can be determined as a function of focal length, L_f, of the camera being used and the effective width, l, of the film frame, $h_f = s(L_f/l)$. Because L_f is a camera constant that is approximately equal to 1.0, the strip width is approximately equal to the flying height. By repeat aerial photography at intervals of a few minutes, the velocity of the ice drift can be determined along with the density of cover. If the average ice thickness is known, the ice discharge (throughput) can also be calculated.

TV and infrared remote-sensing data from meteorological and earth-resource satellites are also useful for estimating ice conditions on lakes and reservoirs [1].

14.4 Times and frequency of observations

Observations of the state of the ice are made at times when the water level is observed, while ice thickness and snow depth on major rivers, lakes, and reservoirs should be measured at intervals of five to 10 days during the critical periods of ice formation and break up. Aircraft observations should be made, as required, to meet special purposes.

14.5 Accuracy

The measurements of ice cannot be very accurate because of difficult conditions. However, uncertainty of ice thickness measurement should not exceed 10-20 millimetres or five per cent, whichever is greater.

Reference

1. Prokacheva V. G., 1975: Otsenka prigodnosti televizionnoj informatsii meteorologiceskih ISZ ‘Meteor’ dlya opredeleniya ledovoj obstanvki na ozerah i vodokhraniliscakh (Estimate of the suitability of television data from the ‘Meteor’ meteorological satellite for determining ice conditions on lakes and reservoirs). *Proceedings of the State Hydrological Institute,* No. 205, pp. 115-123.

CHAPTER 15

SOIL-MOISTURE MEASUREMENT

15.1 **General**

Instruments and methods for observing soil moisture can be divided into two groups:

(*a*) Methods based on the determination of soil-water content; and
(*b*) Methods that measure soil-water potential.

Soil-water content is expressed as a ratio of the mass of water contained in a sample of soil either to the dry mass of the soil sample or to the original volume of the sample. These two expressions are linearly related by a coefficient known as the dry bulk density of the soil being sampled.

Soil-water potential expresses the potential energy of the water contained in the soil and is composed of gravitational, pressure, and osmotic components. In most cases, the soil-water mixture can be considered locally homogeneous, and the osmotic potential becomes negligible. The gravitational potential represents the work required to raise water from a given point in the soil to a reference elevation, which is usually the soil surface. Because gravitational potential can be computed, the problem of measuring soil-moisture potential is constrained to a measurement of its pressure component. Several methods, both direct and indirect, are used to measure the pressure potential. The more commonly used methods are discussed below.

Regardless of the type of method applied, it is essential in every instance to determine the soil moisture at many test points in an area under examination because of its high spatial variability. A statistical analysis of the variability of the soil moisture observed at the test points makes it possible to calculate the error of the average. Such analysis permits the determination of the required number of test points for a prespecified accuracy of the mean. For a more detailed discussion of soil-moisture measurement see the WMO *Snow Cover Measurements and Areal Assessment of Precipitation and Soil Moisture* [1].

15.2 **Gravimetric method**

The gravimetric method is the only direct method of measuring soil moisture. It involves collecting a soil sample, weighing the sample before and after drying it, and calculating its moisture content. The soil sample is considered to be dry when its weight remains constant at a temperature of 105°C. Many different types of sampling equipment, as well as special drying ovens and balances, have been developed for this method.

The gravimetric method is the most accurate method of measuring moisture content in the soil and is required for calibrating the equipment used in all other methods. However, it cannot be used to obtain a continuous record of soil moisture at any one location because of the necessity of removing the samples from the ground for laboratory testing.

15.2.1 *Sample collection*

The procedure for collecting a sample for the gravimetric method depends on whether the soil-moisture determination is to be based on the dry mass of the sample or on its volume. For the dry-mass determination, the sample can be disturbed, but for the volumetric determination, it cannot.

Soil sampling is fraught with difficulties if the soil is very dry or very wet and if it contains stones, rocks, and other items that preclude easy cutting by the sampling equipment.

The technique and equipment used for sample collection should be such that the samples do not lose or gain moisture or otherwise become altered or contaminated during sampling and transportation. When sampling through a wet layer into a dry layer, care must be taken to keep the sampling equipment as dry as possible and to prevent water from running down the hole into the drier material. If there is free water in the soil, the measured moisture content will probably be less than the correct value because some water will drip off as the sample is removed from the ground, or some may be squeezed out by compaction during sampling.

When dry, hard, fine-textured sediments are encountered, it is difficult to drive the core barrels or to rotate the augers. When dry, coarse-textured sediments are sampled, the sample may slide out at the end of the core barrel or auger as it is withdrawn. Stony soils are very difficult to sample, especially volumetrically, because of the likelihood of hitting a stone with the cutting edges of the equipment and because representative samples must be large. Soils that contain a considerable amount of roots and other organic matter also present difficulty.

The amount of soil taken for the gravimetric moisture determination of a gravel soil needs to be substantially more than for non-gravel soils and depends proportionally on the size and content of the gravel. Moisture is determined as a percentage by mass (weight). If multiplied by bulk density, moisture as a percentage of volume is obtained.

In soil-moisture sampling, it is essential that all sampling operations, as well as the transfer of samples to cans, and the weighing of the moist samples be done as rapidly as possible to minimize moisture losses. Many difficulties in the use of sampling equipment may be avoided if the equipment is kept clean and free of moisture and rust.

15.2.2 ***Description of samplers***

15.2.2.1 *Auger samplers*

The simplest equipment for soil-moisture sampling is the hand auger. Hand augers, with shaft extensions of aluminium pipe, have been used in sampling to depths as great as 17 metres. One of the most useful types of hand augers consists of a cylinder 76 millimetres in diameter and 230 millimetres long, having a 1.4 metre extension pipe on the top and two curved, cutting teeth on the bottom. Because the barrel is a solid cylinder, the sample is not as likely to become contaminated from the side of the test hole. Thus, a good, representative, but disturbed, sample is obtained by using this equipment. For ease in sampling at depths greater than 1.5 metres, 0.9 metre extensions of 19-millimetres aluminium pipe are added, as needed.

To obtain a sample by the hand-auger method, the auger is turned by its handle and forced downward into the material to be sampled. Usually about 80 millimetres of the material may be penetrated before the cylinder barrel is filled. The auger is then raised to the surface, and the barrel is struck with a rubber hammer to jar the sample loose.

15.2.2.2 *Tube or core-barrel samplers*

A soil-sampling tube, core barrel, or drive sampler offers an advantage in soil moisture sampling because volumetric samples can be obtained for calculating moisture content by volume. Core samplers provide uncontaminated samples if the equipment is kept clean. Oil should never be used on the samplers, and they should be kept free of dirt, rust, and moisture. A two-person crew is normally recommended for deep sampling, and depths of 20 metres may be sampled. It is recommended that the volume of the soil core be at least 100 cm^3.

The open-drive sampler consists of a core barrel 50 millimetres in inside diameter and 100 millimetres long, with extension tubes 25 millimetres in diameter and 1.5 metres long for sampling at depth. Brass cylinder liners, 50 millimetres in length, are used to retain the undisturbed core samples. The samples are removed from the core barrel by pushing a plunger. A light drill rod or 15 millimetres pipe may be used for extensions.

A simple and economical sampler for obtaining volumetric core samples from shallow depths consists of a thin-walled brass tube 50 millimetres in diameter and 150 millimetres long mounted on the end of a 90 centimetre T-handle of 19 millimetre pipe. Samples are collected by a downward thrust on the handle. After removing the sampler from the hole, samples are pushed out of the core barrel by the central plunger. Because the inside diameter of the core barrel is known, volumetric samples may be obtained easily by cutting off predetermined lengths of the core as it is removed from the sampler.

15.2.3 *Laboratory procedure*

First, the wet soil samples are weighed individually in their transport containers. The containers are then opened and placed in a drying oven that is capable of maintaining a temperature of 105 ± 0.5°C. For samples that contain peat or significant amounts of gypsum, the oven temperature should be 50 ± 0.5°C, which will then require a longer time for the sample to reach a dry state.

After drying, the samples are reweighed in their containers. The difference in the wet and dry weights for a sample is the measure of its original water content.

Other drying processes that are faster than the standard oven may be used, for example, alcohol roasting, infrared lamps, and microwave ovens.

If the samples contain gravel and stones, the above procedure can be modified if the weights or volumes of the gravel and/or stones can be determined separately.

15.3 Electrical-resistance method [C60]

The electrical resistance of a block of porous material in moisture equilibrium with the soil can provide a measure of soil moisture. Two electrodes are fixed in the block, which is made of such materials as plaster of Paris, nylon, or fibreglass. The contact resistance remains constant, and once the block has been placed in the soil and has reached moisture equilibrium, it adjusts to further changes in soil moisture after a brief time lag. Changes in moisture content cause changes in electrical resistance, which are measured by a meter at the surface. The resistance read on the meter is converted to moisture content by means of a calibration. The calibration is prepared by correlation with moisture content values determined by the gravimetric method (section 15.2) for each layer at each observation site.

Soil-moisture blocks are generally considered most dependable in the low moisture content range. Their suitability for measuring moisture content is restricted by hysteretic effects and by the fact that calibration depends on the density and temperature of the soil. The suitability of such blocks for obtaining quantitative results for application in water-budget studies is doubtful.

15.4 Neutron method [C58, E55]

The neutron method indicates the amount of water per unit volume of soil. The soil volume measured by this method is bulb-shaped and has a radius of one to four metres, according to the moisture content and the activity of the source.

This method is based on the principle of measuring the slowing of neutrons emitted into the soil from a fast-neutron source [2]. The energy loss is much greater in neutron collisions with atoms of low atomic weight and is proportional to the number of such atoms present in the soil. The effect of such collisions is to change a fast neutron to a slow neutron. Hydrogen, which is the principal element of low atomic weight found in the soil, is largely contained in the molecules of the water in the soil. The number of slow neutrons detected by a counter tube after emission of fast neutrons from a radioactive source tube is electronically indicated on a scale.

15.4.1 *Instruments*

A typical set of equipment consists of a portable battery-powered or spring-wound timer that has a time-accounting range of 0.5 to 5 minutes and weighs approximately 16 kilograms, and a moisture probe containing a 100 millicurie fast-neutron source of americium-241 and finely ground berryllium (half-life, 458 years). The probe has a length of about 400 millimetres, a diameter of about 40 millimetres, and a weight of 20 kilograms when complete with a lead and paraffin shield that is 150 millimetres in diameter and 100 millimetres long. These probes have been used with up to 60 metres of cable.

The source and detector are lowered into the soil through a hole cased with aluminum tubing, and readings can be taken at any depth except close to the surface. The inside diameter of the tube should be only slightly larger than the diameter of the probe. The tube should be installed by augering the soil inside the tube, if possible, to ensure close contact between the outside surface of the tube and the soil.

Similar gauges have been developed to make measurements in the surface layers of the soil. In this case, the equipment is placed on the ground surface and gives the moisture content of a semispherical volume of 15 to 40 centimetre radius.

15.4.2 *Access tubes*

The installation of access tubes must be performed carefully to prevent soil compaction and to ensure soil contact around the outside of the tubes, i.e. no voids in the soil should be created outside the tubes during their installation. Access tubes may be installed:

(*a*) By inserting the tubes into prepared holes of the same or slightly smaller diameter (the holes can be prepared by using either a hand-powered or a motorized auger); or

(*b*) By driving the tubes into the soil with a hammer and then removing the soil from inside the tubes with an auger.

The bottom ends of the tubes should be sealed to prevent infiltration of groundwater. The top ends of the tubes should be sealed with a cap or a stopper when not in use.

15.4.3 *Calibration*

The probe should be calibrated by gravimetric sampling (section 15.2) in the type of soil that is to be tested and in the size and type of casing into which the probe is to be lowered. Sufficient samples should be taken around the test hole to define the soil moisture profile. It is difficult to obtain a good calibration in heterogeneous soil or when soil moisture is changing rapidly with depth. An approximate calibration can also be carried out in the laboratory by using a container filled with soil material. The type and size of casing and the method of installation of the access tube have a considerable effect on the readings, and new calibration curves should be obtained for each type of installation.

15.4.4 ***Measurements and accuracy***

The access tubes must be kept free of excess moisture or erroneous readings will result.

After lowering the probe to the proper depth in the access tube, the number of counts over a known time period is determined. The average count is converted to soil moisture content by using the calibration curve. The accuracy of a determination depends primarily on:

(*a*) The validity of the calibration curve; and
(*b*) The number of counts per determination.

Because of the randomness of the emission and the impact of neutrons, random count errors can occur. Timing errors may be kept to a minimum by using a standard-count timing cycle of two minutes.

Salt concentrations in the range ordinarily found in soil moisture do not materially affect data obtained by the neutron method, but at salt concentrations equal to sea water, there is an appreciable effect. There is some evidence of a temperature effect. Readings close to the surface are affected by the position of the probe with respect to the air-soil interface. Proximity of the interface causes lower counts than would be indicated for the same moisture content at a greater depth.

When the error sources are minimized, the accuracy of an individual determination can reach 0.5 to one per cent. For repeated determinations over time, such as might be performed in a water-balance study, the changes in water content of soil can be even more accurate because of the elimination of systematic errors.

15.5 **Gamma-ray attenuation**

The intensity of a gamma ray that passes through a soil section undergoes an exponential decrease that principally depends on the apparent density of the soil, on the water contained in the soil, and on the coefficients of attenuation of the soil of the water, which are constants. The method consists of concurrently lowering a gamma-ray source (generally Cesium 137) and a gamma-ray detector (scintillator-photomultiplier) down a pair of parallel access tubes that have been installed in the soil. At each measurement level, the signal can be translated into the apparent wet density of the soil or, if the apparent dry bulk density of the soil is known, the signal can be converted into a measure of the volumetric soil-moisture content.

The measuring equipment permits tracking of the evolution of wet density profiles and of the volumetric soil-moisture at several tens of centimeters of depth below the soil surface if the dry density does not vary with time.

The method has the advantage of having a high spatial resolution (it measures over a slice of soil 20 to 50 millimetres in thickness with the access tubes being separated by about three metres). However, the measurements are not specific to water alone. The apparent variations in dry density can confound the measurements of soil moisture.

Some complex equipment has two energy sources with different intensities of gamma rays, which permit the joint study of the variations in both apparent density and soil moisture. Such equipment is used primarily in laboratories and not under field conditions.

15.6 **Dielectric methods**

The apparent dielectric constant (permittivity) of a volume of soil varies with the amount of moisture contained in the soil. The soil is a complex mixture of particles of differing chemical compositions in a matrix of air and water. The dielectric constants of soil particles range from about two to seven, while those of air and water are one and 80, respectively. Thus, if the dry bulk density of a soil remains constant, i.e. the percentage of the soil comprised of the matrix remains constant, its apparent dielectric constant will be a function of the amount of moisture in the matrix. This fact permits the conversion of measurements of apparent dielectric constant into determinations of volumetric soil-moisture content.

The two main dielectric methods are:

(*a*) Time domain reflectometry (TDR); and
(*b*) The capacitance method.

Some remote-sensing methods, primarily the use of active microwaves, also take advantage of this principle to estimate the moisture context of soils close to the surface.

15.6.1 ***Time domain reflectometry***

The speed of a micowave pulse between a pair of wave guides that have been placed in the soil is a function of the apparent dielectric permittivity of the soil-water-air mixture between the wave guides [3]. As the pulse speed increases, the permittivity decreases, which indicates a decrease in the moisture content of the soil.

A TDR installation consists of:

(*a*) A TDR device, which contains a pulse generator, an electronic timing device, and usually microelectronics for storing a calibration relationship and converting the pulse speed into a soil-moisture determination;
(*b*) One or more pairs of wave guides; and
(*c*) Cables for connecting the wave guides to the TDR device.

The wave guides are metal tubes, generally 0.15 to 0.6 metre in length, and the cables may be several metres long. The wave guides can be driven vertically into the soil or horizontally into a wall of a pit dug into the soil. The horizontal installation may cause considerable disturbance of the soil surrounding the wave guides, thereby leading to erroneous determinations of soil moisture.

The installation of the wave guides can be temporary or permanent. Multiplexing instrumentation permits the automatic, sequential scanning of several pairs of wave guides.

The TDR method is fast and measurements are almost instantaneous. In mineral soils, the accuracy of TDR is good, and it can be improved by specific calibration of each soil. Calibration is essential for soils with significant organic content. In saline soils, significant energy losses limit the utility of the TDR method.

In soils that are completely frozen, TDR is not useful for soil-moisture determination because the permittivities of ice and of dry soils are approximately equal. However, TDR can be useful in the study of freezing and thawing of soils and snow.

15.6.2 *Capacitance method*

A capacitance sensor consists of the electrodes imbedded in the soil — an electronic oscillator, a frequency meter, and connecting cables. The electrodes and their adjacent soil form a capacitor with a capacitance that is a function of the permittivity of the soil and thus, also of the soil moisture contents (section 15.6.1). The varying capacitance can be measured by the frequency changes of the electronic signal across the capacitor. A soil-dependent calibration is required to convert capacitance to moisture content.

Various designs of this methodology are available. Depending on their geometry, the electrodes may be burried in the soil, installed on the tip of a probe and driven into the soil, or inserted into an access tube.

Generally, the sensor is equipped with a temperature correction mechanism to compensate for the effects of temperature on the relationship of water content to permittivity.

Measurements are fast and easy, but they are very sensitive to installation because the sphere of influence of the capacitor is relatively small. Calibration must be carried out with great care for each probe and each soil if accurate determinations of water content are to be obtained.

15.7 **Remote sensing**

Remote sensing is the only way to obtain measurements that contain area-integrated information on the water content of a field. The principles, features, and applications of this not yet fully operational approach are briefly outlined here. Further details and more complete surveys are provided by Schmugge in *Hydrological Forecasting* [4].

Most techniques for remote sensing of soil moisture are based on some relationship between the soil-water content and another soil property, e.g. the dielectric constant, that can be monitored by means of electromagnetic radiation emitted or reflected from the soil. In principle, the entire electromagnetic spectrum can be used. Because most remote sensors operate from aircraft or spacecraft, insufficient atmospheric transmissivity renders wavelengths of the X-ray range, as well as certain regions in the far and middle infrared regions, unsuitable.

Particularly effective for measuring areal soil moisture are microwaves in the wavelength range between 50 and 500 millimetres. This is because they have minimum atmospheric attenuation and because there is a large difference between the dielectric constants of water and dry soil, which results in a high sensitivity for water (section 15.6).

Microwave radiation is used passively (radiometry) or actively (radar). In the passive microwave technique, radiometers are used to measure the thermal emission of microwaves from the ground. The intensity of this radiation is proportional to the so-called brightness temperature, which is the product of surface temperature and emissivity. The latter depends on the dielectric constant and thus on water content.

In the active microwave technique (radar), an artificial radiation source, an emitter, is used and the intensity of radiation reflected back from the soil is measured. The reflectivity of the soil, which like the emissivity depends on the dielectric constant, is then used to infer the areal soil-water content.

A definite advantage of active, in comparison with passive microwave sensors, is their superior spatial resolution, because the ground can be scanned with an angularly-confined radiation beam. For passive microwave sensors, the spatial resolution is limited by the ratio of the wavelength and the observation distance to the antenna size. Given the latter, finer resolution can be obtained only by reducing the wavelength at the expense of a shorter soil penetration or sampling depth or by lowering the flying altitude with the expense of more flights.

Two important factors, other than soil moisture, that influence soil emissivity and reflectivity are surface roughness and vegetation. Although these factors can be accounted for by relatively simple linear regression models that incorporate an empirical roughness parameter and the vegetation moisture content , they reduce the sensitivity of the method by increasing the relative background emissivity.

15.8 **Tensiometric method** **[C62]**

A tensiometer consists of a porous point or cup (usually ceramic) connected through a tube to a pressure-measuring device. The system is filled with water, and the water in the point or cup comes into equilibrium with the moisture in the surrounding soil. Water flows out of the point as the soil dries and creates greater tension, or flows back into the point as the soil becomes wetter and has less tension. These changes in pressure or tension are indicated on a measuring device. Multiple tensiometers located at several depths permit the computation of a soil-moisture profile.

Tensiometers provide data on soil-water potential (pressure components). If a tensiometer is used for moisture determinations, a calibration curve is needed. The calibration curve may be a part of the soil-moisture retention curve, but it is recommended that field data from the gravimetric method (section 15.2) and tensiometer readings be used for the calibration. Even so, the moisture data are only approximate, because of the hysteresis between the wetting and drying branches of the soil-moisture retention curve. The range of use is restricted to zero to 0.8 bars (zero to eight metres of negative hydraulic head). Therefore, the method is suitable only for wet regions.

The different components of a tensiometer include the porous cup, the connecting tube and/or the body tube, and the pressure sensor. The porous cup is made of a porous, rigid material (usually ceramic). The pores of the cup wall are small enough to prevent the passage of air. A semi-rigid connecting tube and/or a rigid body tube are used to connect the tensiometer cup to the pressure sensor.

The pressure measuring device is usually a Bourdon-tube vacuum gauge or a mercury manometer. The tensiometer may also be attached to an electrical pressure transducer to maintain a continuous record of tension changes. Because the system is under a partial vacuum during unsaturated soil conditions, it is necessary that all parts or joints be impermeable to air. For field use, Bourdon vacuum gauges are more convenient than mercury manometers, but they have a lower accuracy. Electrical pressure transducers are both convenient and precise.

The tensiometer response time is much faster with pressure transducers that have small volume displacements than with other pressure sensors. The disadvantage of the cost can be reduced by using only one electrical pressure transducer connected to several tensiometers via a scanning device. Another solution consists of using a measuring apparatus that briefly samples the pressure in the tensiometer by means of a needle. This needle perforates a special bulb on the tensiometer tube only during the moment of the measurement. A single needle apparatus can be used to sample numerous tensiometers placed in the soil. However, unlike the system described above, this type of tensiometer cannot be used to record changes of pressure potential.

Tensiometers should be filled with previously de-aired water. Then it is possible to remove air trapped inside the system by using a vacuum pump. Tensiometers are generally inserted vertically into the soil in pre-augered holes of the same diameter as the porous cup. The centre of the porous cup is located at the depth where pressure measurement is required.

Tensiometers are affected by temperature fluctuations that induce thermal expansion or contraction of the different parts of the system and that influence the pressure readings. In the field, protection from solar radiation is recommended for tensiometers that are above ground to minimize this influence. Similarly, tensiometers used in the winter should be protected against frost damage to the water tube and the pressure sensor. Tensiometers need to be purged periodically to remove accumulated air from the system.

A tensiometer reading indicates the pressure in the porous cup minus the pressure difference caused by the water column between pressure sensor and porous cup. So, the pressure potential of the soil water at the depth of the cup is the pressure sensor reading plus that of this water column. If the pressure is expressed in terms of suction, i.e. atmospheric pressure minus gauge pressure, then the pressure potential of the soil equals the sensor reading minus the pressure difference caused by the water column in the tube. Corrected pressure potential of the soil can be generated directly with pressure transducer systems.

It is difficult to state the precision of a tensiometer measurement of soil-water pressure potential. The accuracy of a measurement is influenced by temperature, the accuracy of the pressure sensor, and the quantity of air accumulated within the system. Moreover, the response time of tensiometers can cause erroneous measurements if the soil-water potential is changing quite rapidly in time. In this case, equilibrium between the soil water and the tensiometer water cannot be obtained. Recent studies have shown that semi-permeable plastic points provide much faster response than ceramic points [5].

The tensiometer is probably the easiest to install and the most rapidly read of all soil-moisture measuring equipment. However, tensiometers are not suitable for installation at depths greater than three metres. At normal atmospheric pressures, the method is limited to a range of pressure potential down to about -85 kPa. Tensiometers require frequent servicing to obtain reliable measurements under field conditions.

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CHAPTER 16

GROUNDWATER

16.1 **General** **[E65]**

Fluctuations in groundwater levels reflect changes in groundwater storage within aquifers. Two main groups of fluctuation can be identified: long term, such as those caused by seasonal changes in natural replenishment and persistent pumping, and short term, as for example, those caused by the effects of brief periods of intermittent pumping and tidal and barometric changes. Because groundwater levels generally respond rather slowly to external changes, continuous records from water level recorders are often not necessary. Systematic observations at fixed time intervals are frequently adequate for the purposes of most national networks. Where fluctuations are rapid, a continuous record is desirable, at least until the nature of such fluctuations has been resolved.

Groundwater investigations may be divided into three main stages:

(*a*) Reconnaissance, with the objective of a preliminary appraisal of the available water resources;
(*b*) General investigations, to obtain information for planning future urban, industrial, and agricultural development; and
(*c*) Intensive studies of the aquifer(s). This level of the investigation requires the greatest effort and is necessary for areas of present or potential intensive development.

During each stage of the groundwater investigation, the information required includes:

(*a*) Spatial and temporal variations of the piezometric heads, resulting from natural and man-made processes;
(*b*) Hydraulic constants of the aquifer;
(*c*) Geometry of the aquifers and aqueducts;
(*d*) Rates of natural replenishment and outflow;
(*e*) Rates of abstraction and artificial recharge; and
(*f*) Water quality.

The data on piezometric heads and water quality are obtained from measurements at observation wells and analysis of groundwater samples. Observation wells are either existing wells, carefully selected from those already drilled in the area, or are drilled and specially constructed for the purposes of the study. One of the main costs in groundwater studies is drilling observation wells. Whenever possible, existing wells should be carefully selected and incorporated into the observation network.

16.2 Installation of observation wells

Since ancient times, wells have been dug into water-bearing formations. Existing wells may be used to observe the static water table, provided that the well depth encompasses the expected range of the seasonal water level fluctuations and that the geological sequence is known. An examination should be made of existing wells to ascertain which, if any, would be suitable as observation wells. Existing pumped wells can also be incorporated into the network if the annular space between the outer casing of the well and the pump column allow free passage of a measuring tape or cable for measuring the water level. Whenever existing drilled or dug wells are used as observation wells, the water level in those wells should be measured after the pump has been turned off for a sufficient time to allow recovery of the water level in the well. Abstractions in the vicinity of an observation well should also be stopped for a time long enough for the depth of the cone of depression at the observation well to recover. If new wells are required, the cost makes it necessary to plan the network carefully.

In those parts of aquifers with only a few pumped or recharge wells that have non-overlapping cones of influence, it is generally preferable to drill special observation wells far enough from the functioning wells in order to avoid their influences.

The principal advantage of dug wells is that they can be constructed with hand tools by local skilled labourers. Depths of three to 15 metres are common, but such wells exist as deep as 50 metres or more. Dug wells may be constructed with stone, brick, or concrete blocks. To provide passage of the water from the aquifer into the well, some of the joints are left open and inside corners of the blocks or bricks are broken off.

When the excavation reaches the water table, it is necessary to use a pump to prevent water in the well from interfering with further digging. If the quantity of water entering the well is larger than the pump capacity, it is possible to deepen the well by drilling. The technique of excavating wells to the water table and then deepening the well by drilling is common practice in many parts of the world. The finished well should be protected from rain, flood, or seepage of surface waters, which might pollute the water in the well and hence the aquifer. The masonry should extend at least 0.5 of a metre above ground level. The top of the well should be provided with a watertight cover and a locked door for safety purposes. A reference mark for measuring depth to water (levelled to a common datum) should be clearly marked near the top of the well.

Where groundwater can be reached at depths of five to 15 metres, hand boring may be practical for constructing observation wells. In clays and some sandy looms, hand augers can be used to bore a hole 50 to 200 millimetres in diameter that will not collapse if left unsupported. To overcome the difficulty of boring below the water table in loose sand, a casing pipe is lowered to the bottom of the hole, and boring is continued with a smaller diameter auger inside the casing. The material may also be removed by a bailer to make the hole deeper.

In areas where the geological formations are known in advance and which consist of unconsolidated sand, silt, or clay, small-diameter observation wells up to 10 metres in depth can be constructed by the drive-point method. These wells are constructed by driving into the ground a drive point fitted to the lower end of sections of steel pipe. One section is a strainer (filter) consisting of a perforated pipe wrapped with wire mesh protected with a perforated brass sheet. Driven wells, 35 to 50 millimetres in diameter, are suitable for observation purposes.

To penetrate deep aquifers, drilled wells are constructed by the rotary or percussion-tool methods. Because drilling small-diameter wells is cheaper, observation wells with inner diameters ranging from 50 to 150 millimetres are common. Hydraulic rotary drilling, with bits ranging in diameter from 115 to 165 millimetres, is often used. The rotary method is faster than the percussion method in sedimentary formations except in formations containing cobbles, chert, or boulders. Because the rock cuttings are removed from the hole in a continuous flow of the drilling fluid, samples of the formations can be obtained at regular intervals. This is done by drilling down to the sampling depth, circulating the drilling fluid until all cuttings are flushed from the system, and drilling through the sample interval and removing the cuttings for the sample. Experienced hydrogeologists and drillers can frequently identify changes in formation characteristics and the need for additional samples by keeping watch on the speed and efficiency of the drill.

The percussion-tool method is preferred for drilling creviced-rock formations or other highly permeable material. The normal diameter of the well drilled by percussion methods ranges from 100 to 200 millimetres to allow for the observation well casing to be 50 to 150 millimetres in diameter. The percussion-tool method allows the collection of samples of the excavated material from which a description of the geological formations encountered can be obtained.

In many cases, the aquifer under study is a confined aquifer separated by a much less permeable layer from other aquifers. Upper aquifers penetrated during drilling must be isolated from the aquifer under study by a procedure known as sealing (or grouting). The grout may be clay or a fluid mixture of cement and water of a consistency that can be forced through grout pipes and placed as required. Grouting and sealing the casing in observation wells are carried out for the following reasons:

(*a*) To prevent seepage of polluted surface water to the aquifer along the outside of the casing;
(*b*) To seal out water in a water-bearing formation above the aquifer under study; and
(*c*) To make the casing tight in a drilled hole that is larger than the casing.

The upper three metres of the well should be sealed with impervious material. To isolate an upper aquifer, the seal of impervious material should not be less than three metres long extending above the impervious layer between the aquifers.

In consolidated rock formations, observation wells may be drilled and completed without casings. Figure 16.1 shows a completed well in a rock formation. The drilled hole should be cleaned of fine particles and as much of the drilling mud as possible. This cleaning should be done by pumping or bailing water from the well until the water clears.

Casing is installed in wells in unconsolidated deposits. The main features of such an installation are shown in Figure 16.2. It should be noted that:

(*a*) The normal diameter of the casing in observation wells is 50 millimetres;
(*b*) At the bottom of the hole, a blank length of casing (plugged at the lower end) is installed. This blank casing should be at least three metres long and serves to collect sediment from the perforated part of the casing. This is referred to as the debris sump;
(*c*) A perforated length of casing, known as the strainer or screen, is secured to the debris sump and ensures free interchange of water between the aquifer and the observation well. In observation wells, a perforated or slotted length of casing about two metres long serves this purpose;
(*d*) The blank casing above the screen should be long enough to protrude above ground level by about one metre. The top of this blank casing forms a convenient reference point for the datum of the observation programme;
(*e*) Centering spiders ensure proper positioning of the screen column in the drilled hole;
(*f*) In aquifers with fine or silty sand, the mesh jacket and slotted casing should be protected from clogging by fine material. Graded coarse material should be packed around the screen to fill the annular space between the screen and the wall of the drilled hole. In the case of a 150 millimetre hole and 50 millimetre casing pipe, the normal thickness of the gravel packing should be approximately 45 millimetres but should not be less than 30 millimetres thick. The material may be river gravel, ranging from one to four millimetres in diameter. The gravel should be placed through a guide pipe of small diameter, introduced into the space between the casing and the wall of the hole. The amount of gravel that is used should be sufficient to fill both the annular space and the bottom of the hole, i.e., the whole length of the debris sump as well as the length of the screen and at least 500 millimetres of the casing above the perforation;

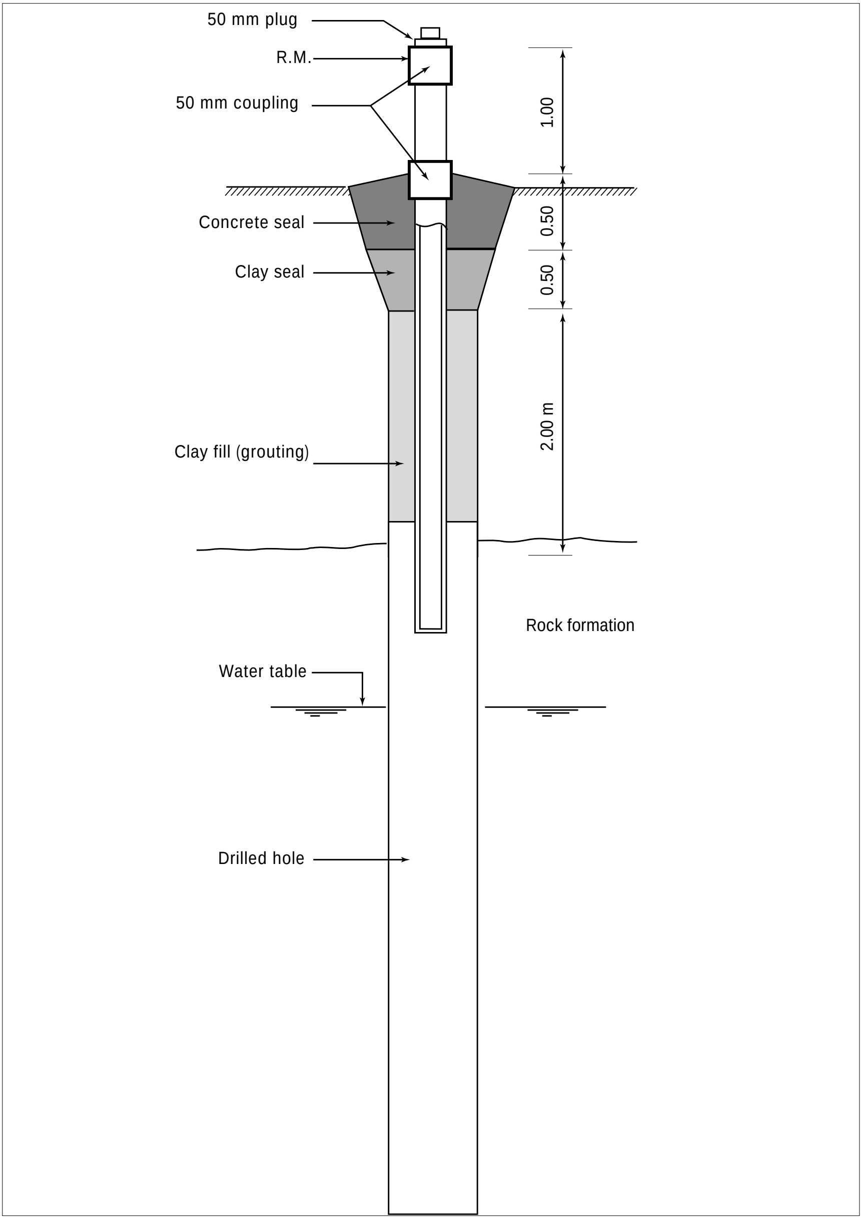

Figure 16.1 — Observation well in a rock formation.

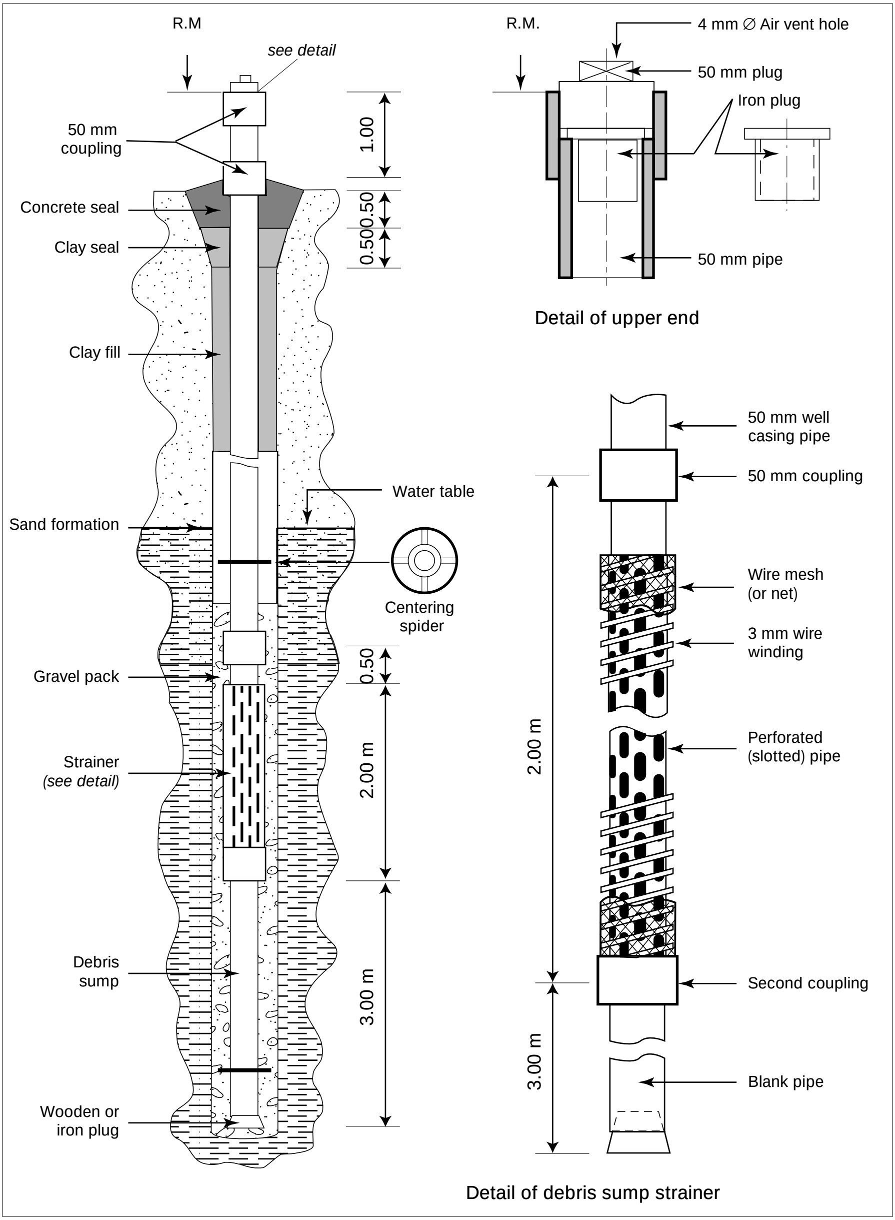

Figure 16.2 — Observation well in a sand formation.

(*g*) At ground level, a pit should be excavated around the casing. The recommended dimensions of the pit are 800 by 800 millimetres at ground level going down as a cone with a lower base approximately 400 by 400 millimetres at a depth of one metre. Clay grout should be placed around the casing to a depth of two metres to make the casing tight in the drilled hole and to prevent seepage of polluted surface water into the aquifer. The pit should be filled partly by a clay seal and the upper part with concrete. The concrete should be poured to fill the pit and form a cone around the casing to drain precipitation and drainage water away from the well;

(*h*) The upper end of the protruding casing above the concrete cone should be closed for security purposes. Figure 16.1 shows details of the installation of the well. The outer 50 millimetre plug is screwed to the casing by using a special tool, and the iron plug inside the casing can be lifted by the observer using a strong magnet.

The part of the casing extending above ground level should be painted a bright colour to make it easy to detect from a distance. Depth to water table is measured from the edge of the casing (after removal of plugs). This reference mark should be levelled to a common datum for the area under investigation.

Observation wells should be maintained by the agency responsible for the monitoring or investigation. The area around the well should be kept clear of vegetation and debris. A brass disc may be anchored in the concrete seal at ground level bearing the label “observation well” and the name of the agency or organization. This brass disc may also serve as a bench mark for survey purposes. If the protruding part of the well casing should be replaced because of damage, then the levelling of the new reference mark is simplified by the proximity of the bench mark. Pre-existing wells that serve as observation wells should be maintained and labelled in the same manner as wells drilled specifically as observation wells.

In the area under study, several aquifers at different levels may be separated by impervious layers of different thicknesses. In such cases, it is advisable to observe the following routine (Figure 16.3):

(*a*) A large diameter well should be drilled, by the percussion-tool method, until the lowest aquifer is penetrated;

(*b*) A small-diameter observation pipe with a proper screen is installed in the lowest aquifer;

(*c*) The outer casing is lifted to reach the bottom of the impervious layer above this aquifer. The top of the lower aquifer is then sealed by cement or other suitable grout;

(*d*) A small-diameter observation pipe with a screen is then lowered to the next higher aquifer that is again sealed off by grouting from the aquifer lying above it; and

(*e*) Steps (*c*) and (*d*) are repeated for each additional aquifer that was penetrated.

In this case, the sealing of each of the aquifers should be done very carefully to prevent damage to the water-bearing formation either by the interchange of water

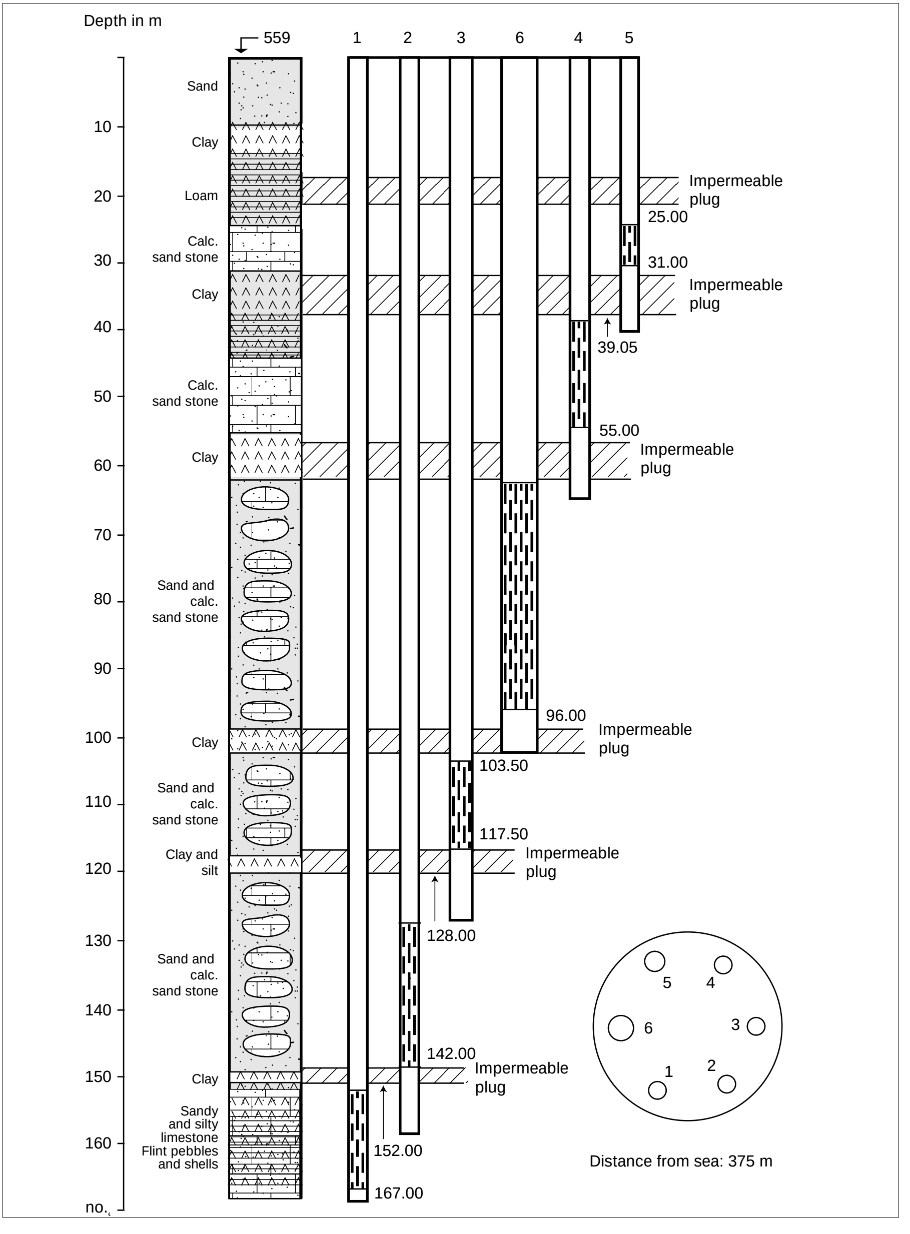

Figure 16.3 — Schematic vertical cross-section of an observation well in a multiple aquifer system.

with different chemical properties or by loss of artesian pressure. If the geology of the area is well-known and the depth to each of the aquifers can be predicted, it may be advisable to drill and construct a separate well in each aquifer. Such boreholes are spaced only a few metres apart. This procedure may prove to be more economical.

Pumping wells incorporated into the observation network should be maintained by the owners of the well.

16.3 Testing of observation wells

The response of an observation well to water level changes in the aquifer should be tested immediately after the construction of the well. A simple test for small-diameter observation wells is performed by observing the recharge of a known volume of water injected into the well, and the subsequent decline of water level is measured. For productive wells, the initial slug of water should be dissipated within three hours to within five millimetres of the original water level. If the decline of the water level is too slow, the well must be developed to remove clogging of the screen or slots and to remove as much as possible of the fine materials in the formation or the pack around the well. Development is achieved by alternately inducing movement of the groundwater to and from the well.

After cleaning the well, the depth from the reference mark to the bottom of the well should be measured. This measurement, compared with the total length of casing, shows the quantity of sediment in the debris sump. This test should be repeated occasionally in observation wells to check the performance of the screen. If the measurement of the bottom of the well shows that debris fill the whole column of the sump and the screen, then the water level in the well might not represent the true piezometric head in the aquifer. The reliability of such an observation well should be considered questionable.

To aid in the determination of changes in lithology, geophysical (electrical) logs are made in open, small-diameter, deep boreholes before the casing is inserted. These logs consist of two records: resistivity and self-potential (spontaneous potential). A log of the intensity of the natural gamma radiation can also be used to check the clay plugs above the aquifer under study and to help check the seals of the upper aquifers. The quality of water in the well should be determined from the samples of water taken at the end of the well-development process.

16.4 Sealing and filling of abandoned wells

Observation wells and pumping wells may be abandoned for the following reasons:

(*a*) Failure with respect to either the quantity or quality of water;
(*b*) Drilling of a new well to replace an existing one; and
(*c*) Observation wells that are no longer needed for investigative purposes.

In all these cases, the wells should be closed or destroyed in such a way that they will not act as channels for the interchange of water between aquifers when such interchange will result in significant deterioration of the quality of water in the aquifers penetrated.

Filling and sealing of an abandoned well should be performed as follows:

(*a*) Sand or other suitable inorganic material should be placed in the well at the levels of the formations where impervious sealing material is not required;

(*b*) Impervious inorganic material must be placed at the levels of confining formations to prevent water interchange between different aquifers or loss of artesian pressure. This confining material must be placed at a distance of at least three metres in either direction (below and above the line of contact between the aquifer and the aquiclude);

(*c*) When the boundaries of the various formations are unknown, alternate layers of impervious and previous material should be placed in the well;

(*d*) Fine-grained material should not be used as fill material for creviced or fractured rock formations. Cement or concrete grout should be used to seal the well in these strata. If these formations extend to considerable depth, alternate layers of coarse fill and concrete grout should be used to fill the well;

(*e*) In all cases, the upper five metres of the well should be sealed with inorganic impervious material.

16.5 **Instruments and methods of observation** **[C65]**

Direct measurement of groundwater levels in observation wells can be accomplished either manually or with automatic recording instruments. The following descriptions relate to principles of measurement of groundwater levels. The references include descriptions of certain instruments.

16.5.1 ***Manually-operated instruments***

The most common manual method is by suspending a weighted line (for example, a graduated flexible steel or plastic-covered tape or cable) from a defined point at the surface, usually at the well head, to a point below the groundwater level. On removal of the tape, the position of the groundwater level is defined by subtracting the length of that part of the tape which has been submerged from the total length of the tape suspended in the well. This wetted part can be identified more clearly by covering the lower part of the tape with chalk before each measurement. Colour changing pastes have been used to indicate submergence below water, although such substances containing toxic chemicals should be avoided. Several trial observations may have to be made unless the approximate depth to water surface is known before measurement. As depth to water level increases, the length of tape to be used increases, and the weight and cumbersome nature of the instrument may be difficult to overcome. Depths to water surface of up to 50 metres can be measured with ease and up to 100 metres or more with greater difficulty. At these greater depths, steel tapes of narrower widths or lightweight plastic-covered tapes can be used. Depths to water level can be measured to within a few millimetres but the accuracy of measurement by most methods is usually dependent on the depth.

Inertial instruments have been developed so that a weight attached to the end of a cable falls at constant velocity under gravity from a portable instrument located at the surface. On striking water, a braking mechanism automatically prevents further fall. The length of free cable, equivalent to the depth to water level, is noted on a revolution counter. The system is capable of measurement within one centimetre, although with an experienced operator this may be reduced to 0.5 centimetre.

The double-electrode system employs two small adjacent electrodes incorporated into a single unit of 10 to 20 centimetres in length at the end of the cable. The system also includes a battery and an electrical current meter. Current flows through the system when the electrodes are immersed in water. The cable must have negligible stretch and plastic-coated cables are preferred to rubber sheathed. The cable is calibrated with adhesive tapes or markers at fixed intervals of one or two metres. The exact depth to water level is measured by steel rule to the nearest marker on the cable. Measurement of water level up to about 150 metres can be undertaken with ease and up to 300 metres and more, with some difficulty. The limits to depths of measurement are essentially associated with the length of the electrical cable, the design of the electrical circuitry, the weight of the equipment (particularly the suspended cable), and the effort in winding-out and winding-in the cable. The degree of accuracy of measurement depends on the operator's skill and on the accuracy with which markers are fixed to the cable. The fixed markers should be calibrated and the electrical circuitry should be checked at regular intervals, preferably before and after each series of observations. This system is very useful when repeated measurements of water levels are made at frequent intervals during pumping tests.

In deep wells that require cable lengths in the order of 500 metres, the accuracy of the measurement is approximately ± 15 centimetres. However, measurements of change in water level, where the cable is left suspended in the wells with the sensor near the water table, are reported to the nearest millimetre.

The electrochemical effect of two dissimilar metals immersed in water can be applied to manual measuring devices. This results in no battery being required for an electrical current supply. Measurable current flow can be produced by the immersion in most groundwaters either of two electrodes (e.g., magnesium and brass) incorporated into a single unit, or of a single electrode (magnesium) with a steel earth pin at the surface. Because of the small currents generated, a microammeter is required as an indicator. The single-electrode system can be incorporated into a graduated steel tape or into a plastic-covered tape with a single conducting-cable assembly. The accuracy of measurement depends upon the graduations on the tape, but readings to within 0.5 centimetre can be readily achieved.

A float linked to a counterweight by a cable that runs over a pulley can be installed permanently at an observation well. Changes in water level are indicated by changes in the level of the counterweight or of a fixed marker on the cable. A direct reading scale can be attached to the pulley. The method is generally limited to small ranges in fluctuation.

When artesian groundwater flows at the surface, an air-tight seal has to be fixed to the well head before pressure measurements can be undertaken. The pressure surface (or the equivalent water level) can be measured by installing a pressure gauge (visual observations or coupled to a recording system) or, where practicable, by observing the water level within a narrow-diameter extension tube made of glass or plastic, fitted through the seal directly above the well head. Where freezing may occur, oil or an immiscible antifreeze solution should be added to the water surface.

All manual measuring devices require careful handling and maintenance at frequent intervals otherwise their efficiency may be seriously impaired. The measurement of groundwater level by manual methods requires the skill of a trained operator.

16.5.2 *Automatic recording instruments*

Many different types of continuous, automatically-operated water-level recorders are in use. Although a recorder can be designed for an individual installation, emphasis should be placed on versatility. Instruments should be portable, easily installed, and capable both of recording under a wide variety of climatic conditions and of operating unattended for varying periods of time. They should also have the facility to measure ranges in groundwater fluctuation at different recording speeds by means of interchangeable gears for time and water level scales. Thus, one basic instrument, with minimum ancillary equipment, can be used over a period of time at a number of observation wells and over a range of groundwater fluctuations.

Experience has shown that the most suitable analogue recorder currently in operation is float actuated. The hydrograph is traced either onto a chart fixed to a horizontal or vertical drum or onto a continuous strip chart. To obtain the best results with maximum sensitivity, the diameter of the float must be as large as practicable with minimum weight of supporting cable and counterweight. As a generalization, the float diameter should not be less than about 12 centimetres, although modifications to certain types of recorders permit using smaller-diameter floats. The recording drum or pen can be driven by a spring or by an electrical clock. The record can be obtained by pen or by weighted stylus on specially prepared paper. By means of interchangeable gears, the ratio of drum movement to water level fluctuation can be varied and reductions in the recording of changes in groundwater levels commonly range from 1:1 up to 1:20. The tracing speed varies according to different makes of instruments, but the gear ratios are usually so adapted that the full width of a chart corresponds to periods of one, two, three, four, five, 16, or 32 days. Some strip-chart recorders can operate in excess of six months.

Where float-actuated recorders have lengths of calibrated tape installed, a direct reading of the depth (or relative depth) to water level should be noted at the beginning and at the end of each hydrograph when charts are changed. This level should be checked against manual observations at regular intervals. The accuracy of reading intermediate levels on the chart depends primarily upon the ratio of drum movement to groundwater level fluctuations, and therefore is related to the gear ratios.

The continuous measurement of groundwater level in small-diameter wells presents problems because a float-actuated system has severe limitations as the diameter of the float decreases. Miniature floats or electrical probes of small diameter have been developed to follow changes in water level. The motivating force is commonly provided by a servo-mechanism (spring or electrically driven) located in the equipment at the surface. The small float is suspended in the well on a cable stored on a motor-driven reel that is attached to the recorder pulley. In the balanced (equilibrium) position, the servo-motor is switched off. When the water table in the well moves down, the float remains in the same position and its added weight unbalances the cable (or wire), causing the reel to move and, by this small movement, causing an electrical contact to start the small motor. The reel operated by this motor releases the cable until a new equilibrium is reached, and the motor is switched off.

When the water level in the well rises, the cable is retrieved on the reel until the new equilibrium is reached. This movement of the cable on or off the reel actuates the pen of the recorder, and water level fluctuations are recorded. The servo-motor, which rotates the cable reel, may be activated by an electrical probe at the water table in the well. This attachment consists of a weighted probe suspended in the well by an electric cable stored on the motor-driven reel of the water level recorder. Water-level fluctuations in the well cause a change in pressure that is transmitted by a membrane to the pressure switch in the probe. The switch actuates the reel motor, and the probe is raised or lowered, as required, until it reaches a neutral position at the new water level.

Float and float-line friction against the well casing can affect the recording accuracy of water level recorders, especially in deep wells. The largest error is caused by float line drag against the well casing. A small-diameter float may be provided with sliding rollers (fixed at both ends of the float) to reduce friction against the casing. Round discs (spiders) with small rollers attached to the cable at 10 metre intervals keep the cable away from the well casing and significantly reduce friction. Figure 16.4 shows some details of this device. The sensitivity of water level recorders with attachments for small-diameter floats may be six millimetres of water level movement, but the switching mechanism of the float may not be this sensitive. The

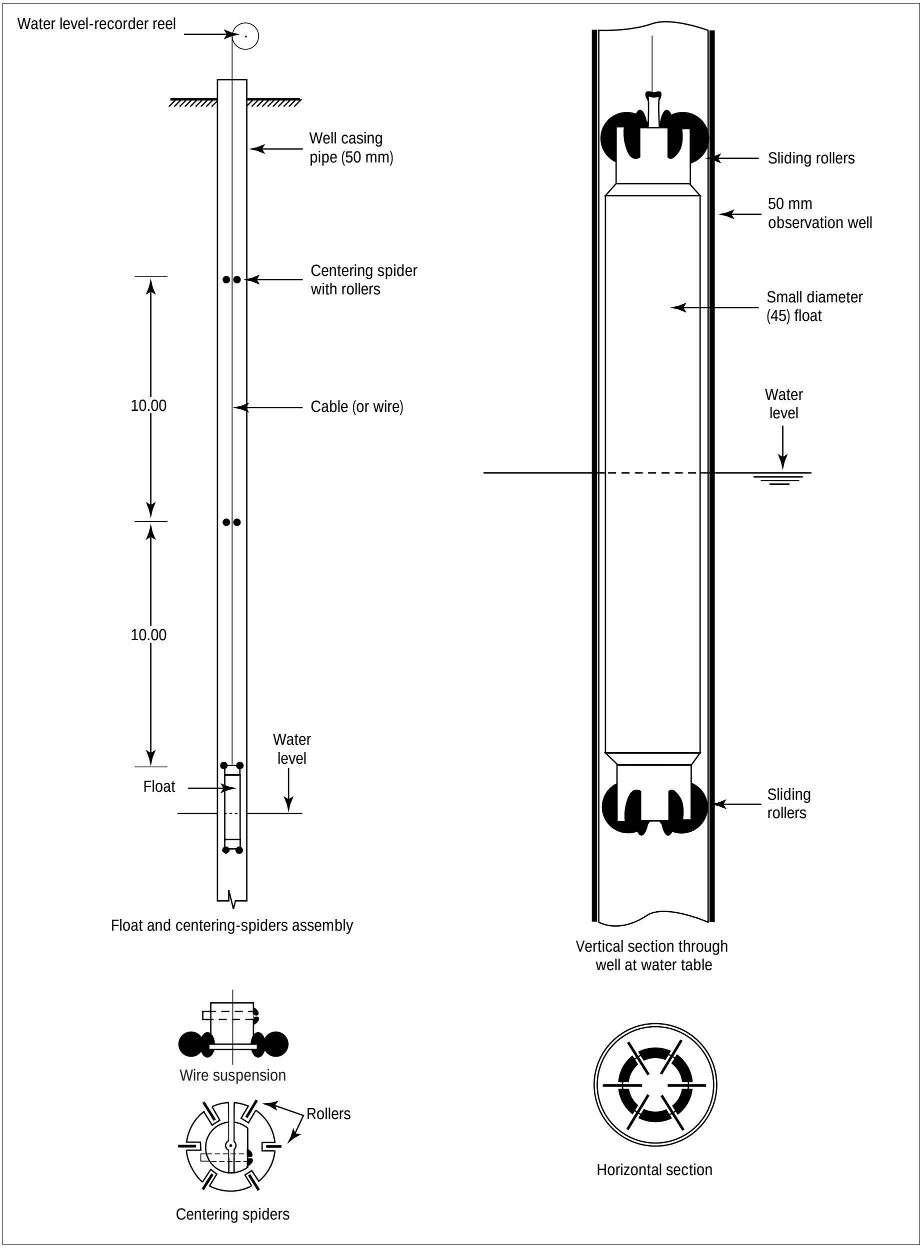

Figure 16.4 — Small-diameter float with sliding rollers.

accuracy of the mechanism is decreased by weak batteries. To avoid this effect, the batteries should be replaced after a maximum of 60 to 90 days of normal use.

An alternative approach is an electrode suspended in an observation well at a fixed distance above the water level. At specified time intervals, the probe electrically senses the water level and the movement occurs by a servo-mechanism at the surface. The depth to water level is then recorded. This system can be adapted to various recording systems.

Although these instruments have particular value in small diameter wells, they can be installed in wells of any diameter greater than the working diameter of the probe.

In some research projects, instruments have been designed to measure fluctuations in groundwater level by more sophisticated techniques than those described above, such as capacitance probes, pressure transducers, strain gauges, and sonic and high-frequency wave reflection techniques. At present, these instruments are expensive when compared with float-actuated recorders, have limitations in application, particularly in the range of groundwater fluctuations, and commonly require advanced maintenance facilities. Float-actuated systems are considered more reliable and more versatile than any other method, although future developments in instrument techniques in the sensor, transducer and recording fields may provide other instruments of comparable or better performance at competitive costs.

Analogue-to-digital stage recorders used for stream discharge measurements (section 10.2.2) can be readily adapted to the measurement of groundwater levels.

Automatic recording instruments require comprehensive and prompt maintenance otherwise records will be lost. Simple repairs can be undertaken on the site, but for more serious faults, the instrument should be replaced and repairs should be undertaken in the laboratory or workshop. Adequate protection from extremes of climatic conditions, accidental damage, and vandalism should be provided for these instruments. Clockwork is particularly susceptible to high humidity, thus adequate ventilation is essential, and the use of a desiccant may be desirable under certain conditions.

16.5.3 *Water samplers for unpumped wells*

The simplest device for lifting samples of water from a well is a bailer, consisting of a length of tube with a ball valve at the bottom. The bailer is suspended on a cable and lowered into the well. The ball valve allows water to enter the tube and, when lifted, prevents water from escaping the bailer. This allows samples to be taken from the uppermost layer of water in the well. Water will enter the bailer at any deeper point of the water column in the well, but may be mixed with the upper water when lifted.

To allow sampling at any depth below the water table, water samplers with spring operated valves have been developed. The sampling tube, attached to a suspension cable is lowered to the desired depth. Depth readings are taken from a counter. While descending the well, the tube is open at both ends, allowing free flow of water through the sampler. Upon reaching the required depth, a weight is dropped, sliding along the suspension cable, to strike a release trigger that closes the sampling chamber. The sampler is lifted to the surface and the chamber is opened by depressing the valve trigger.

16.5.4 *Salinity and temperature loggers* **[C67]**

The electrical conductivity of water increases with increasing salinity. Thus, it is common to determine the concentration of dissolved minerals by measuring the electrical resistance of the water. The instrument used for measuring resistance may be a very simple transportable small resistance bridge that measures *in situ* the resistance of a water sample pumped or bailed from the well.

In cases where a measurement of salinity at a certain point below the water table is required (e.g., in the screened part of the observation well casing) or if a chemical log of the whole column of water in the well is required (e.g., seawater-freshwater interface research), an electric salinity logger is used. This consists of a dip-cell attached to a cable. Two electrodes contained in the dip cell pass an electric current via the intervening water. The electrical resistance of the water is indicated by a resistance meter connected to the end of the cable at the surface.

The resistance changes with changes in water temperature. Therefore, the temperature is measured simultaneously by a thermistor contained in the dip-cell. The concentration of dissolved minerals at each level in the well is calculated by using a calibration curve drawn through points of measured resistance corresponding to respective known concentrations of KC1. The resistance is calculated at a temperature of 25°C, by using the following equation:

$$R_{25} = \left(R_{\Theta} - r\right)\left(1 - 0.02\,\Delta\;\Theta\right) \tag{16.1}$$

where R_{25} is the resistance of sample at 25°C, R_{Θ} is the resistance indicated by meter at a measured temperature of 0 °C, r is the resistance of the instrument system (cell + cable, etc.), Θ is the measured temperature in °C, and $\Delta = 25° - \Theta$.

16.6 Groundwater quality monitoring [E65]

The quality of groundwater is subject to change and deterioration as a result of the activities of man. Localized point sources of pollution include cesspools and septic tanks, leaks in municipal sewers and waste ponds, leaching from garbage dumps and sanitary landfills, runoff from animal feedlots, industrial waste discharges, cooling water returned to recharge wells, and leaks from tankers or pipelines. Larger geographical areas may suffer degradation of groundwater quality because of irrigation water returns, recharge into aquifers of treated sewage or industrial effluents, and intrusion into fresh water aquifers from neighbouring sea water or other highly saline aquifers.

Water samples can be collected from flowing wells and from pumping wells. Portable pumps are available for sampling non-pumping wells. When samples from specific depths are desired, these can be taken by grab samplers in open wells. However, these samplers often need to have smaller external diameters to fit into the well casings. In some cases, selected zones in a well can be isolated temporarily for sampling with mechanical or inflatable packers.

Samples and water levels from perched layers, saturated regions sitting on less permeable layers in the unsaturated zone, can often be obtained by the use of piezometers. These are tubes with a porous region near the bottom that can be pushed or driven into the soil to the desired depth. Other samples from the unsaturated zone can be obtained by embedding a porous ceramic cup in good contact with the soil, or with a bed of fine sand to ensure good contact, with a vacuum tube leading to the bottom (section 15.4). Soil water is drawn into the cup by suction and is raised into a sample bottle in the vacuum line. If the installation is below the level from which suction can lift the sample, the material can be sucked from the porous chamber through a check-valve into a second chamber, from which it can then be forced to the surface by releasing nitrogen into the chamber.

The basic variables for the definition of surface-water quality (section 17.5.2) also apply in groundwater quality monitoring except for turbidity, which normally is not a problem [1-7].

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CHAPTER 17
WATER QUALITY

17.1 General

This chapter discusses general aspects of water quality sampling and specific aspects related to the sampling of rivers, streams, lakes, and reservoirs. Specific aspects of sampling the quality of precipitation and groundwater are discussed in sections 7.9 and 16.6, respectively. More detailed discussions can be found in the WMO *Manual on Water Quality Monitoring — Planning and Implementation of Sampling and Field Testing* [1] and in the *GEMS/Water Operational Guide* [2].

17.2 Sampling methods [E05]

Sampling is the process of collecting a representative quantity of water from a river, lake, or well. Archived data are no better than the confidence that can be placed in the representativeness of the sample.

Sampling methods are determined by a number of factors including the type of material being sampled, the type of sample, and the quality parameter being analysed, which in turn determine the equipment and procedures to be used.

17.2.1 *Types of water samples*

17.2.1.1 *Grab samples*

Grab samples are appropriate when it is desired to characterize water quality at a particular time and location, collect variable sample volumes, or deal with a stream that does not flow continuously. They are also used to establish the history of water quality based on relatively short time intervals.

A discrete grab (or spot) sample is taken at a selected location, depth, and time, and then analysed for the constituents of interest.

A depth-integrated grab sample is collected over the depth of the water column at a selected location and time.

17.2.1.2 *Composite samples*

A composite sample is obtained by mixing several discrete samples of equal or weighted volume in one container, an aliquot of which is then analysed for the constituents of interest, or by continuously sampling the flow over a period of time.

A composite sample provides an estimate of average water quality condition over the period of sampling. An obvious advantage is in the economy of reducing the number of samples to be analysed. On the other hand, composite samples cannot detect changes in parameters occurring during the sampling period.

There are two main types of composite samples, sequential and flow proportional.

A sequential composite is constituted by continuous, constant sample pumping, or by mixing equal water volumes collected at regular time intervals.

A flow-proportional composite is obtained by continuous pumping at a rate proportional to the flow, mixing equal volumes of water collected at time intervals that are inversely proportional to the rate of flow, or by mixing volumes of water proportional to the flow collected at regular time intervals.

17.2.2 ***Collecting a representative water sample***

For sampling at sites located on a uniform, well mixed reach of stream, the collection of depth-integrated samples in a single vertical may be adequate. For small streams, a grab sample taken at the centroid of flow is usually adequate.

In other cases, it may be necessary to sample the channel cross-section at a specified number of points and depths. The number and types of samples taken will depend on the width, depth, discharge, the amount of suspended sediment being transported, and on the aquatic life present. Generally, the more points that are sampled in the cross-section, the more representative the composite sample will be. Three to five verticals are usually sufficient, and fewer are necessary for narrow or shallow streams.

One common method is the equal-width-increment method, in which verticals are spaced at equal intervals across the stream. The equal-discharge-increment method requires detailed knowledge of the streamflow distribution in the cross-section to subdivide the cross-section into verticals spaced in proportion to the incremental discharges.

17.2.3 ***Field sampling equipment and techniques***

17.2.3.1 *Grab samplers*

Grab samplers may be classified as those appropriate only for non-volatile constituents, or those that can be used for dissolved gases and other volatile constituents. Both discrete (surface or specific depth) and depth-integrating types of samplers are available. Both may be used to collect water for the determination of non-volatile constituents. A multiple sampler can also be used for this purpose.

An approximate depth-integrated sample may be taken by lowering an open sampling apparatus to the bottom of the water body and raising it to the surface at a constant rate so that the bottle is just filled on reaching the surface. A sampling iron can be used for this purpose. A sampling iron is a device, sometimes made of iron, used to hold sample bottles. The sample bottles are placed in the sample iron and are secured by the neck holder. In some cases, sampling irons may have provisions for additional weights to ensure a vertical drop in strong currents.

A very simple method is to take a clear plastic tube, weighted at one end, with an internal diameter designed to give a sufficient sample volume, e.g. 4 l, and lower the weighted end to the desired depth, pinch off the tube at the surface, raise the tube, and drain the contents into a sample container.

Depth integration may not be possible in shallow streams where the depth is insufficient to permit integration. In such cases, care must also be taken not to disturb the river bottom when taking a sample. One suggestion in such cases is to dig a hole in the bottom, let the stream settle, and sample down to the top of the hole.

Discrete samplers are used to collect water samples at a specific depth. An appropriate sampler is lowered to the desired depth, activated, and then retrieved. Van Dorn, Kemmerer, and pump samplers are frequently used for this purpose:

(*a*) Van Dorn bottle — The Van Dorn bottle is designed for sampling at a depth of two metres or greater. The sampler, shown in its two configurations in Figure 17.1, is available in both polyvinyl chloride and acrylic plastic materials so that it may be used for general or trace-metal sampling. The horizontal configuration should be used when samples are taken at the bottom, at the sediment-water interface, or when samples are required from a narrow band of the depth profile, e.g. chemocline, thermocline. Sampler volumes from two to 16 litres are available;

(*b*) Kemmerer sampler — The Kemmerer sampler is one of the oldest types of messenger-operated vertical samplers. It is commonly used in water bodies with a depth of one metre or greater. The Kemmerer sampler, which is shown in Figure17.2, is available in brass and nickel-plated brass for general water sampling. For trace metal sampling, Kemmerer samplers are made of polyvinyl chloride and acrylic plastic with silicone rubber seals. Both metal and plastic samplers are available in volumes ranging from 0.5 to eight litres;

(*c*) Pumps — Three types of pumps, such as diaphragm, peristaltic, and rotary, are available to collect samples from specified depths. In general, diaphragm pumps are hand-operated and the peristaltic and rotary pumps require a power source, and consequently, they have limited field utility. Peristaltic pumps are not recommended for the collection of samples for chlorophyll analysis, because damage to the algal cells may occur. All pumps must have an internal construction that does not contaminate the water sample. Input and output hoses must also be free of contaminants.

The Van Dorn samplers have an advantage over the Kemmerer bottle in that their lids do not lie in the path of the flow of water through the sampler, which can cause eddies and disturbance.

A multiple sampler (Figure 17.3) permits the simultaneous collection of several samples of equal or different volumes at a site. Each sample is collected in an

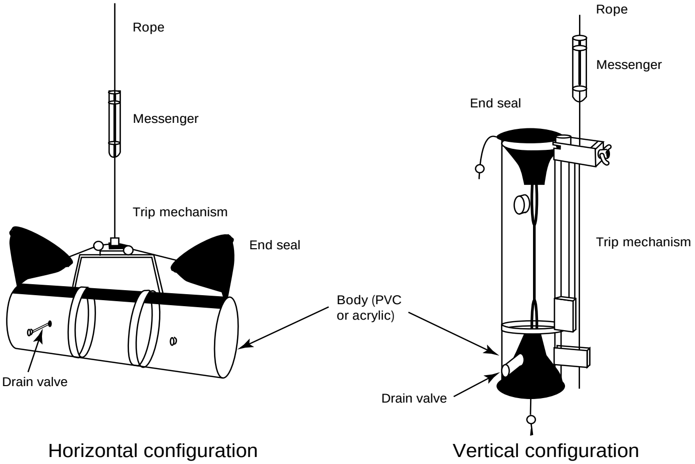

Figure 17.1 — Van Dorn bottle.

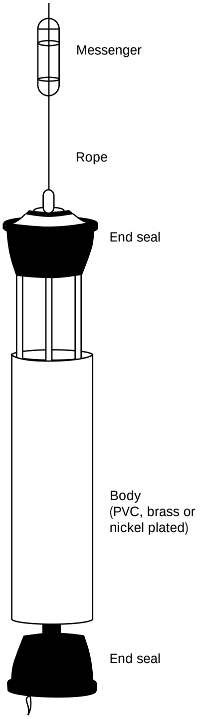

Figure 17.2 — Kemmerer sampler.

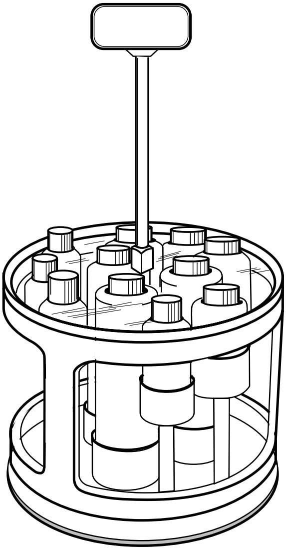

Figure 17.3 — Multiple sampler.

individual bottle. When the samples are of equal volume, information concerning the instantaneous variability between the replicate samples can be obtained. The sampler may be altered to accommodate different sizes and numbers of bottles according to the requirements of specific programmes. This may be done by changing cup sizes, length of cup sleeves, and the configuration and size of openings in the clear acrylic top.

17.2.3.2 *Dissolved-oxygen sampler*

A typical sampler for dissolved-oxygen concentration and biochemical oxygen demand (BOD) is illustrated in Figure 17.4. These must be pulled up open, thus some mixture with upper layers is possible. If certain grab samplers are fitted with bottom drain tubes, they may be used by running the sample into the bottom of the analysis container. The samples should be collected in narrow-mouthed BOD bottles that have bevelled glass stoppers to avoid entrapment of air in the samples. Sampling of shallow streams is not advisable with this sampler. In this case, sample agitation (bubbling) should be minimized by gently tilting a BOD bottle downstream.

17.2.3.3 *Automatic samplers*

Automatic samplers range from elaborate instruments with flexible sampling programmes, which require external power and permanent housing, to simple, portable,

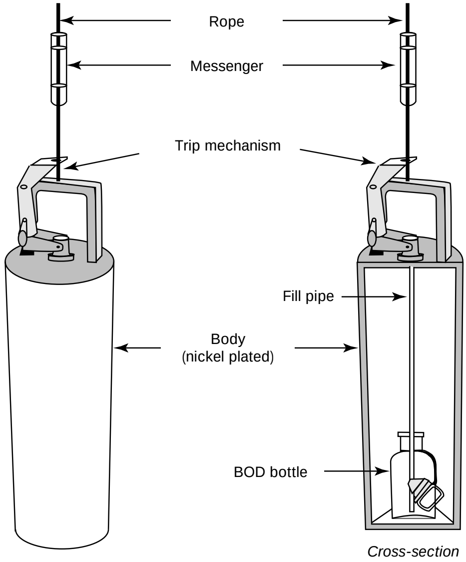

Figure 17.4 — Dissolved-oxygen sampler.

self-contained devices, such as a submerged bottle with a rate of filling determined by a slow air bleed.

These devices can sometimes be programmed to sample over extended periods of time, but to meet the suggested maximum time of 24 hours from sampling to analysis, 24-hour samplers are most common. They reduce costly personnel requirements if frequent sampling is required. If the site has automatic flow-measurement capability, some automatic samplers can provide flow-proportional samples. Both composite- and individual-sample models are available.

17.2.3.4 *Sampling procedures as influenced by station location and season*

In the field, various sampling situations require different sampling techniques. Shallow water samples are handled in a manner different from that used at deep water sites. Field technicians must be equipped to handle these situations. Some of the practical sampling considerations related to location and season of sampling are outlined in the following sections. Detailed procedures for sampling are given in the WMO *Manual on Water Quality Monitoring — Planning and Implementation of Sampling and Field Testing* [1].

Sampling from bridges is often preferred because of the ease of access and safety under all conditions of flow and weather. However, vehicular traffic on bridges is another potential hazard that should be considered (section 18.3).

Boats provide more flexibility and reduce the time of travel between sampling points. The sampling point must be identified by triangulation from landmarks, and there are navigation, high flow, and storm hazards to consider (section 18.5).

Aircraft, including helicopters, are expensive but are fast and flexible. Tests have shown that the disturbance of water under helicopters does not significantly affect even dissolved-oxygen water samples.

Bankside sampling should only be used where no alternative is possible. The sample should be taken in turbulent water or where the water is fast and deep. A sampling iron is often used when water samples are collected from shores, stream banks, and wharves.

Sampling of ice and snow under winter conditions requires somewhat different techniques. The safety precautions outlined in section 18.9.3 should be followed. Overlying snow should be removed from the ice surface to provide a suitable working area.

17.3 **Preparation for field trips**

17.3.1 ***General preparation***

(*a*) Obtain specific instructions on sampling procedures;
(*b*) Prepare an itinerary according to the sampling schedule (see also section 21.3);
(*c*) Prepare lists of required equipment and materials;
(*d*) Ensure that all sample bottles have been cleaned in accordance with standard procedures;
(*e*) Ensure that the laboratory has prepared the chemical reagents and standards needed for the trip; and
(*f*) Prepare a checklist (section 17.3.3).

17.3.2 ***Selection of sample volumes***

The volumes of the particular samples required depend on the type and number of parameters to be analysed, the analytical method, and the expected concentrations of the constituents in the water. Laboratory personnel will specify the sample volume required. The required sample volume can be determined by listing all of the parameters that are preserved in the same way, totalling the volume needed for preparation and analysis, and then multiplying by two for duplicate and three for triplicate analyses.

The following points should be kept in mind:

(*a*) When contact with air is to be avoided, the sample container should be completely filled;
(*b*) When samples require vigorous shaking before taking aliquots for analysis, the container should not be completely filled;
(*c*) Where both requirements must be met, completely fill the bottle, but add pieces of clean, sterile inert solid such as beads; and

(*d*) When the sample contains discrete particles, e.g., undissolved materials, bacteria, and algae, a volume of sample larger than usual may be needed to minimize errors.

17.3.3 *Checklist prior to field trip*

(*a*) Check and calibrate meters (pH, specific conductance, dissolved oxygen, turbidity) and thermometers;
(*b*) Replenish supplies of reagents for dissolved-oxygen determinations as well as reagents for chemical preservation;
(*c*) Obtain fresh buffer solutions. The pH values for the buffers should be close to the values expected in the field;
(*d*) Obtain KCl solution for pH probes;
(*e*) Obtain road maps, station-location descriptions, field sampling sheets, sampling bottles, labels, samplers, preservation reagents, pipettes, and equipment manuals;
(*f*) Obtain writing materials, extra rope, and a comprehensive tool box;
(*g*) Obtain electrical cables if the equipment has in-field charging capabilities;
(*h*) Obtain distilled water and clean beakers for pH, blanks, and buffer measurements;
(*i*) If field filtering is required, obtain filtering apparatus;
(*j*) If microbiological sampling is to be done, obtain sterile bottles and ice chests. Ice chests are recommended for all sample storage; and
(*k*) Check the contents of the emergency first-aid kit.

17.4 Field filtration and preservation procedures

17.4.1 *Filtration*

Sample filtration is recommended for separation of dissolved from particulate matter. Centrifuging requires more equipment, settling requires more time, and both cannot be easily calibrated and may increase contamination hazards. The filtration should be carried out in the field during or immediately after sample collection and must be followed by appropriate sample preservation procedures.

The total concentrations of metals may be determined by using a second unfiltered sample collected at the same time. This sample will undergo a complete digestion in the laboratory that converts the metals to water-soluble compounds.

Samples requiring analysis for organic constituents are filtered immediately after collection by using a glass fibre filter or a metal membrane. The filtrate may be analysed for dissolved organic constituents, and the filter supporting the particulate fraction is available for particulate-organic analysis.

The absorption of dissolved substances on the filter material can be a serious problem. Various suggestions have been made as to the best materials to use, e.g. organic filters (polycarbonate, cellulose acetate) for mineral substances and glass fibre filters for organic compounds.

The filter and filtration apparatus require laboratory pre-treatment and should be rinsed with a portion of the collected sample before the filtrate is collected, i.e. by discarding the first 150 to 200 millilitres of filtrate. Either an electrical or a manual pump must be used to create the vacuum in the filtration apparatus. If an electrical pump is employed, filtration will require access to electrical services or the operation of a mobile power unit. Vacuum may cause changes in the pH due to loss of carbon dioxide, and result in the precipitation of some metals. For this reason and to reduce losses due to adsorption on the walls of the container, metal samples are often acidified.

17.4.2 ***Preservation techniques***

Between the time that a sample is collected in the field and is analysed in the laboratory, physical, chemical, and biochemical changes may take place. Consequently, this time should be minimized to the extent practicable, or sample preservation must be practiced.

For several determinants, preservation is not possible, and the measurements must be made in the field. Even when the constituent is reasonably stable, it is usually necessary to preserve the samples. This is done by various procedures, such as keeping the samples in the dark, adding chemical preservatives, lowering the temperature to retard reactions, freezing samples, extracting them with different solvents, using field column chromatography, or by a combination of these methods.

Limited knowledge is available on the preservation of water samples, and any recommendations should be regarded as tentative until their efficiency has been experimentally tested.

17.4.2.1 *Containers*

The use of appropriate containers is very important in preserving the integrity of the sample.

Sample bottles are usually provided by the analytical laboratory. The two major types of container materials are plastic and glass. Borosilicate glass is inert to most materials and is recommended when glass containers are required, such as when collecting samples to be analysed for organic compounds. Polyethylene is inexpensive and adsorbs fewer metal ions. It is used for samples that will be analysed for inorganic constituents, e.g., major ions and metals. Polyethylene containers should not be used to trace organic samples, such as pesticides and some volatile substances, that can diffuse through plastic walls. Light-sensitive samples require opaque or nonactinic glass containers. Narrow-mouthed bottles with pointed glass stoppers are used for dissolved gases. Containers for microbiological samples must withstand sterilization, either by autoclaving or with ethylene oxide.

Bottle caps are a potential source of problems. Glass stoppers may seize up, particularly with alkaline samples. Cap liners other than Teflon may introduce contaminants or absorb trace samples.

The smaller the concentrations in the sample of the species to be determined, the more important these aspects become.

Many publications contain recommendations on which type of container should be used for particular determinants.

17.4.2.2 *Chemical addition*

This method is used for most dissolved metals and phenoxy acid herbicides. Some samples for biological analysis also require chemical preservation.

As a general rule, it is preferable to use relatively concentrated solutions of preserving agents. Corrections for the dilution of the sample by the small volume of preserving agent will then be small or negligible.

Potential interference of the preservative with the analysis requires that procedures be carefully followed. For example, an acid can alter the distribution of suspended material and can lead to dissolution of colloidal and particulate metals. Thus the order of first filtration and then acidification becomes very important.

17.4.2.3 *Freezing*

Freezing is acceptable for certain analyses, but is not a general preservation technique because it can cause physical-chemical changes, e.g., the formation of precipitates and loss of dissolved gases that might affect the sample composition. Also, solid components of the sample change with freezing and thawing, and a return to equilibrium followed by high-speed homogenization may be necessary before any analysis can be run.

Never freeze water samples in glass bottles.

17.4.2.4 *Refrigeration*

Refrigeration at 4°C or in ice is a common preservation technique. It has the advantage that no substance is added to the sample that could interfere with future analyses. However, it does not maintain the complete integrity of all constituents. In some cases it may affect the solubility of some constituents and cause them to precipitate. Refrigeration is often used in conjunction with chemical addition.

When glass containers are filled to the brim, they should be stored at a lower temperature, down to 4°C, to avoid development of high expansion pressures during warming.

17.4.2.5 *Practical aspects of preservation*

An important practical aspect of preservation is a consistent routine to ensure that all samples requiring preservation receive the immediate treatment they need. This is particularly important when a chemical preservative is added, because such additions may not produce an easily detectable change in sample appearance. It may be advisable to mark or flag each preserved sample to ensure that none is forgotten or treated more than once.

Safe and accurate field addition of chemical preservatives also requires special precautions. Precalibrated and automatic pipettes ensure accurate field addition, as well as eliminate the safety hazard of pipetting acids by mouth. It is often convenient to add the preservative in the laboratory before the sample containers are taken to the field. Another alternative is to use colour-coded or labelled, sealed vials containing premeasured preserving agents. Although more expensive, this method has the advantage of simplifying the field procedure and lessening the possibility of error and contamination.

17.5 **Field measurements**

17.5.1 ***Automatic monitoring***

One type of monitoring requires that the water be pumped and that the measurements be made on shore. Other instruments use probes immersed in the body of water and make the measurements *in situ.* A more recent type is a self-contained, battery-operated instrument that can be operated as much as 300 metres below the surface.

Currently, automatically measured parameters include pH, temperature, specific conductance, turbidity, dissolved oxygen, chloride, redox potential, stage, sunlight intensity, and ultraviolet absorbance.

17.5.2 ***Field-measured parameters***

Conductivity, pH, dissolved oxygen, temperature, turbidity, colour and transparency can change on storage of a sample, and should therefore be measured in the field as soon as possible after sample collection.

The sample collector should also look out for any unusual features of the body of water being sampled or any changes from previous sampling periods. These qualitative observations might include unusual colour, odour, surface films, and floating objects. Any special environmental conditions, such as rainfall, heavy winds, storm runoff, or ice break-up, should be noted.

17.5.2.1 *pH measurement*

In unpolluted natural waters, the pH is largely controlled by a balance between carbon dioxide, carbonate, and bicarbonate ions. The concentration of carbon dioxide can be altered by exchanges at the air-water interface and by photosynthesis and decay processes.

Changes in the pH are caused by acid rain, industrial wastes, mine drainage, or leaching of minerals. The pH is an important criterion of the quality of water, because it affects the viability of aquatic life and many uses of the water.

Optimally, the pH is determined *in situ*. The preferred method of measurement is electrometric because of its ease and accuracy. The pH is proportional to the electromotive force or electrical potential between a hydrogen-ion-responsive, glass-membrane electrode immersed in the sample and a reference electrode. There are many portable battery-powered pH meters on the market today. The investigator should select the one that best suits the situation. Digital meters are preferable because analogue meters (e.g., pointer on a scale) are sometimes difficult to read while taking *in situ* measurements, for example in a boat on rough water.

The pH may also be determined colorimetrically by using pH indicators and buffer standards for visual or colorimeter comparison. This method is generally less accurate than electrometric methods and is limited to waters with a low content of coloured substances and with little turbidity.

In the field, the instrument should be recalibrated before each reading with appropriate buffer solutions and according to the instructions in the operating manual. Adjust the temperature of the buffer solutions and electrodes by submerging the bottles of buffer and electrodes in the water sample. Extreme care must be taken to prevent the water from entering the buffer bottles or the filling hole of the reference electrode. An equivalent procedure is to measure the temperature of the buffer, to calibrate the meter, and then to readjust the temperature compensation to the temperature of the sample. If the electrodes have not been used recently or have been allowed to dry for several days, they may require l0 to 20 minutes to stabilize.

Protect the meter from extreme temperature changes during measurement because these affect the stability of the electronic system and the precision of the measurement.

When combined electrode assemblies have been stored dry for a long period, the glass membrane should be soaked in a 3 mol/l KCl solution for 12 to 24 hours before use. Meters may have a probe-storage reservoir that should be filled with electrolyte. Glass electrodes that have not been conditioned before use may not stabilize properly and may require frequent recalibration.

If the pH meter shows a drift and the probe has been stored and correctly conditioned, the probe itself may require topping up with additional 3 mol/l KCl solution. The most common cause of trouble with combined electrode assemblies is a blockage in the diaphragm. If this occurs, as indicated by persistent drifting, soak the electrode in ammonium hydroxide. As with any piece of equipment, the probe should be protected from dirt, freezing temperatures, and rough handling at all times.

17.5.2.2 *Conductivity measurement*

Most inorganic salts, acids, and bases dissociate into ions in water. Many organic substances dissociate little or not at all. Although not specific for individual substances, changes in conductivity can indicate saline intrusion and other sources of pollution. The relationship between conductivity and the concentration of dissolved solids is usually linear for most natural waters. Changes in this relationship indicate changes in the proportions of different salts and therefore changes in the sources of dissolved substances entering the water body.

In situ conductivity measurement is preferable. Conductivity is temperature dependent. If the measurement is not automatically corrected for temperature, the temperature at the time of measurement should be recorded.

The instrument should be recalibrated in the field before each reading. The KCl standard solutions, with the specific conductance closest to the values expected in the field, should be used. Do not use the same water sample in which the pH was measured to measure the specific conductance, as KCl diffuses from the pH electrode. Rinse sample containers and the probe several times with the water sample.

Equipment for measuring conductivity must receive the same care and maintenance required by all sensitive instruments. Accurate readings require that the meter be protected from dirt, shocks, and freezing temperatures.

The accuracy of measurement will depend upon the type of instrument, the way in which it has been calibrated, and the actual conductivity value of the sample. If care is taken in selecting and calibrating the instrument, an uncertainty of ± 5 per cent of full scale should be possible over a temperature range of 0° to 40°C with automatic temperature compensation. For this reason, the instrument should be selected with some knowledge of the likely range of conductivity of the samples to be investigated. For example, the conductivity of inland waters will be in the order of 0.01 to 0.02 μS m^{-1}, and it would be unwise to use an instrument that was intended for use in saline conditions of 2.5 to 3.0 μS m^{-1}.

17.5.2.3 *Dissolved-oxygen measurement*

Dissolved-oxygen concentration is important for the evaluation of surface water quality and of waste treatment process control.

Dissolved oxygen (DO) should be measured *in situ* because concentrations may show a large change in a short time if the sample is not adequately preserved. Even when the sample is preserved, it is advisable to run the analysis within three to six hours from the time of sampling. Dissolved-oxygen concentrations may be determined directly with a DO meter or by a chemical method, such as the Winkler analysis. For very precise measurements, the potentiometric method should be considered.

Collect three water samples with the dissolved-oxygen sampler (section 17.2.3.2). Measure the dissolved-oxygen concentration of the samples by using a dissolved-oxygen meter or a Winkler chemical analysis. The recorded DO value will be the average of at least two readings that are within 0.5 mg/l of each other.

Dissolved-oxygen meters work on one of two principles, polarographic or potentiometric. The instruments respond to activity of oxygen, not concentration. Thus, fresh water saturated with oxygen gives the same reading as salt water saturated with oxygen at the same pressure and temperature, although the solubility of oxygen in salt water is less. The processes are also temperature dependent and most instruments include methods for temperature compensation.

The meters can be used under conditions that interfere with iodometric methods (for example the Winkler analysis), such as samples that are highly coloured or turbid or contain readily oxidizable or other interfering substances, such as sulfite, thiosulfate, polythionate, mercaptans, or free chlorine. This method also can be used to give a continuous record if needed and can be used in conjunction with BOD measurements.

The Winkler analysis method can be used to determine dissolved-oxygen concentrations in the field or laboratory with high precision. There are a number of modifications of this iodometric method, particularly the Alsterberg-azide modification that prevents interference by nitrite ions.

The Hach method is used for determining dissolved-oxygen concentrations in the field. It involves the same chemical reactions as Winkler titration. The reagents, except for the titrant, are contained in individual “powder pillows” premeasured for the required concentrations.

This method can be used when results within ± 0.5 to 1.0 mg l^{-1} of the true value are sufficient for the purposes of the study.

It is possible to obtain accuracies of less than one per cent of full scale for dissolved-oxygen concentrations. However, it is more realistic to expect three per cent over a 10°C temperature range. In general, if the sample has a relatively high dissolved-oxygen concentration, the accuracy is adequate, but in some cases where the dissolved-oxygen concentration is very low, it is important to use a newly made and carefully calibrated probe.

17.5.2.4 *Temperature measurement*

Temperature measurements may be taken with a great variety of thermometers. These include alcohol-toluene, mercury-filled, bimetallic strip, or electrical thermometers. The last category includes thermocouples and less portable varieties, such as thermistors, quartz and resistance thermometers. Some meters, such as those used to measure dissolved oxygen and specific conductance, have temperature-measuring capabilities.

If a thermometer is used, rinse the thermometer by pouring a portion of the water sample over it. Immerse the thermometer in the sample for approximately one minute or until the reading stabilizes. Do not place the thermometer in any of the sample bottles being shipped to the laboratory. Record the value in degrees Celsius on the field sheet.

In general, the accuracy of water-temperature measurements of 0.1°C will not be exceeded. However, in many circumstances, an uncertainty of 0.5°C can be tolerated and there are many instances where statistical temperature data are quoted to the nearest 1°C. Thus, it is important to specify the operational requirements so that the most suitable thermometer can be selected.

17.5.2.5 *Turbidity measurement*

Turbidity is an optical measure of suspended sediment such as clay, silt, organic matter, plankton and microscopic organisms in a water sample. Turbidity affects virtually all uses of water and adds to the cost of water treatment.

Whenever possible, turbidity should be measured *in situ*. Turbidity can be measured by visual methods (in Jackson turbidity units or JTU) or nephelometric methods (in nephelometric turbidity units or NTU).

To use the Jackson Candle Turbidimeter, the distance through the suspension at which the outline of the standard candle becomes indistinct is compared with standard suspensions.

Nephelometric methods are preferred because of their greater precision, sensitivity, and application over a wide turbidity range. They measure light scattering by the suspended particles. However, instruments of different design may give different results for the same sample. Colour in the sample can cause errors, as will variations in the light source. Both problems can be minimized by using an instrument that simultaneously measures the scattered and transmitted light, with both scattered and transmitted beams traversing the same path length.

To operate the turbidity meter, prepare calibration curves for each range of the instrument by using appropriate standards. Test at least one standard in each range to be used, making certain that the turbidity meter gives stable readings in all sensitivity ranges. Shake the sample vigorously before analysis. Readings should always be made after the same time period following the homogenizing of the sample (e.g. 10 seconds) to ensure uniform data. It is important to pour off the sample quickly and to measure the turbidity of the sample in triplicate.

The performance of a given turbidimeter will depend on the frequency of calibration with a formazin standard and the way that the sample is presented to the instrument. As a general guide, nephelometers used under laboratory conditions should be accurate to within ± 1 formazin turbidity unit (FTU) in the range 0 to 10 FTU, and to ± 5 FTU in the range 0 to 100 FTU at 95 per cent confidence level. The uncertainty of absorption meters will vary considerably, but should give at least ± 10 per cent of full scale for any given range of turbidity.

In practice, the performance of turbidimeters depends, to a large extent, on their optical configuration and, in the case of instruments that accept a flowing sample and give a continuous reading, on their ability to withstand fouling of optical surfaces by algal growth and sediment buildup, which would otherwise result in calibration drift and insensitivity.

17.5.2.6 *Colour measurement*

The true colour is observed after filtration or centrifugation. Colour results from the presence of metallic ions, humus and peat materials, plankton, and industrial wastes.

Colour is important for potable water supplies, washing or processing water, or recreational purposes.

The hues ordinarily present in natural waters can be matched by mixtures of chloroplatinic acid and cobaltous chloride hexahydrate. Because this method is not convenient for field use, colour may be obtained by visually comparing standard glass colour discs with tubes filled with the sample.

Waters mixed with certain industrial wastes may be so different in hue from platinum-cobalt mixtures that comparison is inappropriate or impossible. In this case, a filter photometer may suffice, although a double-beam spectrophotometer would be preferable if the samples can be taken to the laboratory.

17.5.2.7 *Transparency measurement*

Transparency of water is determined by its colour and turbidity. A measure of transparency can be obtained from depth in metres at which a 20-30 centimetre diameter disc — called a Secchi disc and usually painted in black and white quadrants — disappears when lowered slowly and vertically into the water. Standard type on white paper is sometimes used instead of the disc. The measurement is usually made in lakes and other deep water bodies and is useful in assessing biological conditions.

17.5.2.8 *General summary of field procedures*

Regardless of the specific parameters of interest, a routine should be followed at each sampling station. The following is a general summary of procedures to be followed at each station:

(*a*) Calibrate meters;
(*b*) Standardize sodium thiosulphate when using Winkler analysis for dissolved oxygen;
(*c*) Run field or *in situ* measurements for pH, conductivity, dissolved oxygen, temperature, and turbidity;
(*d*) Rinse all bottles with sampled water except for those that contain preservatives or those used for dissolved oxygen and bacteria analyses;
(*e*) Collect and preserve samples according to the instruction manual;
(*f*) Complete field sheet accurately according to the instruction manual;
(*g*) Put bottles in appropriate shipping containers; and
(*h*) Label boxes and complete field sheets with all required information.

17.6 **Radioactivity measurement**

17.6.1 ***Sources of radioactivity in water***

Radioactivity in water may be of natural or anthropogenic origin. The main natural sources are the weathering of rocks containing radioactive minerals and fallout of cosmic-ray nuclides. The major sources of man-made radioactivity are uranium mining, the nuclear-power industries, nuclear-weapons testing, and the peaceful applications of nuclear materials and devices.

The principal radionuclides introduced naturally into surface and groundwater are uranium, radium-226, radium-228, radon, potassium-40, tritium, and carbon-14. All but the last two derive from radioactive minerals. In areas where radioactive minerals are abundant, natural uranium is the major radioactive constituent present in water. Tritium and carbon-14 are produced by the interaction of cosmic-ray neutrons with nitrogen in the upper atmosphere. The tritium is eventually rained out as tritiated water, and the radiocarbon is incorporated into atmospheric carbon dioxide. Both radionuclides are also produced by thermonuclear weapons testing. Tritium is also an activation product, and since 1970, the nuclear-power industry has probably been the largest source of tritium. Strontium-90 and Cesium-137 are the major man-made radioisotopes of concern in water.

Dissolved and particulate radioactivity in water is controlled by the same mechanisms that affect other constituents in the geohydrologic environment. The geochemical behaviour of a daughter element may be grossly different from that of the radioactive parent, although its occurrence, distribution, and transport may be governed by the parent.

The International Commission on Radiological Protection recommends maximum permissible body burdens for various radioisotopes, from which maximum permissible concentrations in water are derived.

17.6.2 *Collection and preservation of samples*

Acceptable containers are polypropylene, polyethylene, or Teflon. They should be pretreated by filling them with concentrated nitric acid for a day, rinsing with detergent, and then rinsing several times with purified water. The principal problem encountered in preserving these samples is adsorption on the walls of the container or on suspended matter.

Samples are collected in four litre bottles. To keep metals in solution and minimize adsorption, two millilitres of concentrated HCl per litre of sample, or nitric acid to one per cent concentration, are added, and then the bottles are shipped to the laboratory.

One procedure is to sample for radioactivity measurements monthly and then to analyse an annual composite sample. This is made up by mixing, in a separate bottle, 400 millilitre aliquots from each monthly sample. If a significant level of radioactivity over background levels is found, the samples making up the composite are analysed individually to locate the sample(s) that has (have) the higher than expected radioactivity level.

Detailed instructions for the analysis of radioisotopes associated with water quality are given in the U.S. Geological Survey *National Handbook of Recommended*

Methods for Water Data Acquisition [3]. Recommended containers and preservation methods are included.

17.7 Sampling for biological analysis

17.7.1 *Microbiological analysis*

The presence of living fecal coliform bacteria indicates inadequately treated sewage. The complete absence of coliforms and especially of fecal coliforms is mandated by the World Health Organization for any drinking water supply. Other micro-organisms responsible for human diseases are sometimes found in water, for example the cholera and typhoid agents, salmonella, pseudomonas, and certain single-celled animals, such as those that cause amoebiasis.

In order to reflect accurately microbiological conditions at the time of sample collection, it is very important that all water samples submitted for microbiological analysis be collected as aseptically as possible.

Microbiological samples are usually collected in sterile 200 or 500 millilitre wide-mouthed glass or nontoxic plastic bottles with screw caps. Plastic containers should be checked to make sure that they do not shed microscopic particles capable of confusing some kinds of bacterial counts. Metal and certain rubber containers may exert a bacteriostatic effect. If capped, the bottle cap should have an autoclavable silicone rubber liner. If stoppered, the bottle mouth should be covered with sterile heavy-duty paper or with aluminum foil secured with either string or an elastic band.

Whenever possible, water samples should be analysed immediately after collection. If immediate processing is impossible, then samples should be stored in the dark, in melting ice. Storage under these conditions minimizes multiplication and die-off problems up to 30 hours after collection. Samples should never be frozen.

If samples are suspected of containing concentrations greater than 0.01 mg l^{-1} of heavy metals, such as copper, nickel or zinc, their bacteriostatic or bactericidal effects should be minimized by the addition of 0.3 millilitre of a 15 per cent solution for each 125 millilitres of sample of a sequestering agent, such as ethylene diaminetetracetic acid (EDTA) [4].

Residual chlorine would not often be expected in natural waters, but if present, it should be destroyed by the addition of 0.1 millilitre of a 10 per cent solution of sodium thiosulfate for each 125 millilitres of sample.

17.7.2 *Macrobiota*

There are several categories of multicellular species that may be monitored for a number of different reasons.

Fish, as the peak of the aquatic food chain, are indicative of a variety of water quality condition, dependent on their type and age. Benthic macro-invertebrates (organisms living on or near the bottom that are retained by a standard sieve) are indicators of recent pollution events because of their low mobility and sensitivity to stress. Periphyton are sessile plants, growing attached to surfaces, and those that grow in the mat attached to it are some of the primary producers of aquatic organic matter, particularly in shallow areas. Macrophytes are large plants, often rooted, that cover large areas in shallow water and may interfere with both navigation and recreational uses of a water body. Plankton are small free-floating plants and animals. Phytoplankton are primarily algae whose growth is an indirect measure of, among other things, the concentration of nutrient chemical constituents. Zooplankton are found at all depths in both standing and flowing waters.

Many of these organisms can be troublesome in water treatment. For example, algae clog filters, consume extra chlorine, adversely affect odour and taste of water, and some are toxic. Others species may be carriers of disease-causing organisms, such as the snails that carry guineaworm larvae or schistosomes.

Fish can be collected actively, with seines, trawls, electro-fishing, chemicals, and hook and line, or passively, with gill nets, trammel nets, hoop nets, and traps.

Macroinvertebrates may be sampled qualitatively by many methods, depending on their habitats and other parameters. In addition to nets, two methods are multiple-plate samplers and basket samplers. These are left suspended in place by floats for periods of four to eight weeks, and then are carefully raised to the surface with a net underneath for dislodgement of the specimens.

Plankton can be collected by using the water samplers described in section 17.2. There are also specially designed samplers, such as the Juday plankton trap, which encloses about five litres of sample at the desired depth and filters out the plankton. It is rather expensive and awkward to handle from a boat. Zooplankton require large samples, and a metered nylon net can be employed. Periphyton can be sampled by exposing anchored or floating slides at the site for at least two weeks.

For macrophytes, a garden rake can be used in shallow water, and dredges can be used in deeper water. From a boat, a cutting knife on the end of a pole or a simple grapple can be used. For some purposes, the self-contained underwater breathing apparatus has been found to be useful.

It is recommended that a suitable stain such as rose bengal be added before any fixatives. At a later date, the preserved animals can be picked out by personnel with less biological training because the colour causes them to stand out against the background.

Tables recommending methods for the preservation of specimens of macrobiota are included in the Table below. Some practitioners prefer the use of lugol solution rather than formaldehyde for periphyton and planktons.

17.8 **Biochemical oxygen demand**

The discharge of polluting organic matter to a water body instigates a natural purifying action through the process of biochemical oxidation. Biochemical oxidation is a

Techniques generally suitable for the preservation of samples

Biological analysis — The biological parameters to be determined are generally numerous and may sometimes vary from one biological species to another. For this reason, it is impossible to draw up an exhaustive checklist of all the precautions that should be taken to preserve samples for this type of analysis. The information below, therefore, only relates to certain parameters generally studied for various animal or vegetable groups. It should be noted that before carrying out any detailed study, it is essential to choose the parameters of interest.

1	*2*	*3*	*4*	*5*	*6*
Counting and identification					
Benthic macroinvertebrates	P or G	Addition of ethanol	Laboratory	1 year	
Fish	P or BG	Addition of 10% (m/m) formaldehyde, 3 g of sodium borate decahydrate and 50 ml of glycerol per litre	Laboratory	1 year	This analysis should preferably be carried out as soon as possible
Macrophyton	P or G	Addition of 5% (m/m) formaldehyde	Laboratory		
Periphyton	P or opaque G	Addition of 5% (m/m) neutral formaldehyde and storage in the dark	Laboratory	1 year	
Phytoplankton	P or opaque G	Addition of 5% (m/m) neutral formaldehyde or mentholate and storage in the dark	Laboratory	6 months	
Zooplankton	P or G	Addition of 5% (m/m) formaldehyde or a lugol solution	Laboratory		
Fresh and dry mass					
Benthic macroinvertebrates					Do not freeze to -20°C

(*continued*)

Macrophytes	P or G	Cooling to between 2 and 5°C	On the site or in the laboratory	24 hours	The analysis should be carried out as soon as possible and not later than 24 h.
Pheriphyton					
Phytoplankton					
Zooplankton					
Fish			On site		
Mass of ash					
Benthic macroinvertebrates		Filtration and cooling to between 2 and 5°C	Laboratory	6 months	
Macrophytes	P or G	Freezing to -20°C	Laboratory	6 months	
Periphyton		Freezing to -20°C	Laboratory	6 months	
Phytoplankton		Filtration and freezing to -20°C	Laboratory	6 months	
Calorimetry					
Benthic macroinvertebrates	P or G	Cooling to between 2 and 5°C then filtration and storage in a desiccator	Laboratory	24 h	The analysis should preferably be carried out as soon as possible and in all cases within 24 h
Phytoplankton					
Zooplankton					
Toxity tests	P or G	Cooling to between 2 and 5°C	Laboratory	36 h	The preservation period will vary according to the method of analysis
		Freezing to -20°C	Laboratory	36 h	

microbial process that utilizes the polluting substances as a source of carbon, while consuming dissolved oxygen in the water for respiration. The rate of purification depends on many conditions, including the temperature and the nature of the organic matter.

The amount of dissolved oxygen consumed by a certain volume of a sample of water, for the process of biochemical oxidation during a period of five days at 20°, has been established as a method of measuring the quality of the sample, and is known as the biochemical oxygen demand test or BOD. Oxidation is by no means complete in five days and for some purposes longer periods of incubation may be used. The incubation period may be indicated by a suffix, e.g., BOD_5 or BOD_{20}, and the results are expressed as milligram oxygen per litre of sample.

BOD is defined as the total amount of oxygen required by micro-organisms to oxidize decomposable organic material. The rate of biochemical oxidation is proportional to the remaining amount of unoxidized organic material. Thus, the BOD test is used to estimate the amount and rate of de-oxygenation that would occur in a watercourse or lake into which organic material is discharged. However, the predictions of the effects of such discharge are more complicated and may involve many other factors not involved in the determination of BOD. For example, suspended organic material can be deposited onto a stream bed in a slow moving stream just downstream from the source of discharge, where it may have a considerable effect on the local dissolved-oxygen content. The presence of benthos, rooted plants, and planktonic algae also influence, on a daily basis, the dissolved-oxygen regime.

Serious complications in the BOD test can also occur as a result of the presence of nitrifying bacteria that will oxidize ammonia and organic nitrogen compounds to nitrite and nitrate.

Industrial effluents may also present problems because of potentially high concentrations of pollutants, which may suppress biochemical oxidation in the receiving water under natural conditions. In these circumstances, the sample may have to be diluted with pure water and “seeded” with sewage effluent that contains the active micro-organisms required to start the biochemical oxidation process. Special sample preparation techniques may have to be developed to suit the sample to be tested.

17.8.1 *Methods of measurement*

Several methods have been developed for the measurement of BOD. The one most commonly used is the dilution method, but manometric techniques, while still mainly used for research, may have advantages in some circumstances, for example the control of sewage effluent.

Ideally, the sample should be analysed immediately after it has been taken from the effluent, watercourse, or lake. If this is not possible, the sample must be kept at a temperature of 3° to 4°C to slow down the biochemical oxidation processes.

If the BOD of a sample is estimated to be greater than about 7 mg l^{-1}, appropriate dilution and/or seeding of the sample are necessary. An excess of dissolved oxygen must be present in the sample at the end of the test period for the BOD value to be valid.

BOD is calculated from the measurement of volumetric dilution of the sample and the difference between the dissolved-oxygen concentrations of the sample (section 17.5.2.3) before and after a five-day incubation period. During this period, a temperature of 20°C should be maintained, and atmospheric oxygen should be excluded from the sample, which should be kept in the dark to minimize the effect of photosynthetic action of green plants. However, the oxygen consumed by the respiration of algae is included in the test.

For samples in which nitrification may occur during the test, allylthiourea (ATU) is added to the sample prior to incubation. In this case, the resulting apparent BOD is indicative of carbonaceous polluting matter only.

The rate of biochemical oxidation can be estimated on the basis of incubating five identical BOD samples and measuring the dissolved oxygen in the first bottle on day 1, a second bottle on day 2, a third bottle on day 3, a fourth bottle on day 4, and the fifth on day 5. The logarithm of BOD should plot against time as a straight line. Extrapolation of the straight line to ultimate time results directly in an estimate of the ultimate carbonaceous BOD, which is a measure of the total amount of oxygen required to oxidize decomposable organic material.

17.8.2 ***Accuracy***

The BOD test is rather inexact. If statistical significance is to be made of the results, several samples must be diluted and incubated (and seeded, if necessary) under identical conditions, and an average BOD is calculated. To achieve higher accuracies, it has been suggested that the manometric test should replace the dilution method. It should be borne in mind that the two methods are not always directly comparable [5]. The manometric method can give an indication of the biological oxidizability of a sample in a period shorter than five days.

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CHAPTER 18

SAFETY CONSIDERATIONS

18.1 General practices [A00]

Hydrological measurements are made under an extremely wide range of conditions, many of which are potentially hazardous to the personnel taking them. Knowledge of the hazards and the means by which they can be minimized are essential for hydrological personnel. A number of agencies have produced detailed and informative safety manuals. Familiarization with this material is highly recommended to all hydrologists and technicians.

Each country or state will have safety standards and practices as well as laws and regulations governing safety. These may cover many of the activities outlined in this chapter, and personnel must be familiar with and take account of all that are applicable.

Each person has the responsibility to themselves and to their companions to work as safely as possible. Organizations have the responsibility to promote an awareness of hazards and work practices to minimize them and to provide an appropriate level of safety equipment and training [1-4].

18.2 Safety at recording stations

18.2.1 *Access*

Well-constructed footpaths, steps, ladders, and the like are essential for safety on steep riverbanks. These need to be constructed for safe access in wet weather and possibly darkness. When construction of a station begins, the access should have been completed first.

18.2.2 *Platforms*

High platforms and catwalks should have a non-slip surface, such as fine wire mesh fastened over timber planks. Handrails should also be fitted.

18.2.3 *Wells*

Some water level recording stations have deep wells that must be entered occasionally for maintenance. Hazards exist due to the possibility of falling and the presence of gases. All wells should have at least a simple rope, pulley, and winch system installed so that a person can be rescued from the bottom of the well.

Persons descending wells that are deep, or in any way suspected to contain gas, must wear a safety harness attached to a rescue system, with one or more people in attendance at the top. A safety helmet should also be worn.

The hazards of slipping can be minimized by having properly constructed ladders and by maintaining all equipment in good condition. A number of gases including carbon dioxide, methane, and hydrogen sulphide may be present in a well. They are produced from decomposing organic material and may displace air, leading to an oxygen deficiency as well as toxicity and flammability. These dangers can occur with quite low concentrations, and reaction to the gases may be quite rapid, with a person becoming unconscious after only one or two inhalations of a toxic gas.

Precautions include proper ventilation in all wells over six metres in depth, opening wells for ventilation prior to entry, forbidding flames or smoking, use of gas monitoring equipment, and the routine use of safety harnesses and rescue equipment. All efforts should be made to exclude or remove organic matter from wells.

18.3 Safety precautions when working from bridges

The main hazards in carrying out measurements or sampling from bridges are in being struck by passing traffic or being tipped over the side of the bridge by undue force or weight on the suspended equipment.

18.3.1 *Traffic hazard*

Bridges with a pedestrian lane may provide a good margin of safety. In other circumstances, it is imperative to warn motorists with adequate signs and, if practical, flashing lights. Personnel should wear fluorescent or brightly-coloured clothing, and portable traffic markers may be deployed to shift traffic flow away from the work area. If it is necessary to interfere with traffic, arrangements must be made with the local authorities.

18.3.2 *Hazards from suspended equipment*

The potential leverage on equipment, such as gauging frames, means that they are prone to being tipped over the side of the bridge if the suspended equipment should become caught on riverborne debris or on boats passing below. Take extra care against these dangers during floods.

Gauging cranes or frames need to be suitably counterbalanced or tied down. The overturning moments of vehicle-mounted cranes should be calculated and shear-pins incorporated in the equipment, if necessary, to prevent capsizing. Over navigable water, the presence of all cables should be indicated by attaching marker flags.

18.4 Safety precautions while wading

18.4.1 *General*

Where it is possible to wade streams, hydrological measurements may be made more simply and directly than by other means. However, it becomes hazardous when the depth or velocity, or both, are excessive.

18.4.2 *Assessing the situation*

Personnel need to exercise caution and be experienced to decide whether wading should be carried out in a particular situation. As a general guide, if the product of the depth in metres and the velocity in metres per second exceed 1.0, the stream is unlikely to be safe to wade. A person's build and attire will influence this. Waders have more drag than bare legs or a wetsuit.

18.4.3 *Wearing of lifejackets*

Correctly fastened lifejackets of an appropriate size and design should generally be worn in flowing water above crotch level, where there is a possibility of entering such water, or where conditions could otherwise become hazardous.

18.4.4 *Safety lines and taglines*

When making discharge measurements, a rope or line strung across the stream can be useful as a support. It can also double as a line for measuring distance and should be securely anchored at both ends to sustain the weight and drag of a person against the river's flow.

18.4.5 *Wading technique*

One should select a crossing with negotiable depths, velocities, and bed material, plan a route diagonally downstream, and walk across with short steps, facing the opposite bank, and side-on to the current. It can be helpful to use a wading rod (without current meter) on the upstream side to probe the depth and give support. It is preferable to brace against the current, remain calm, and do not hurry. If the crossing becomes too difficult, one should retreat, possibly by stepping backward until it is possible to turn around, and perhaps try an easier crossing.

18.4.6 *Mishap technique*

If one begins to be swept downstream, one should go with the current and head towards the bank, propelling oneself with the arms outstretched and pushing with the feet. If the bed is rocky, the natural reaction to put the feet down should be avoided as they may be caught between the rocks. If this occurs, the current can easily push a person underwater with fatal results.

If the water is deep and if it is necessary to swim some distance, waders may need to be removed. The best way is to work them down to the hips and pull the feet out one at a time. One should avoid turning them inside out and should refrain from this operation where the water is shallow and the waders are likely to become snagged. Wader straps should be fastened so that they can readily be undone.

It is possible to trap air in waders so that they aid buoyancy, either by wearing a belt tightly fastened around the waist or by quickly assuming a floating position on one's back with the knees drawn up.

18.4.7 *Responsibility*

Personnel must not be obligated to wade streams in situations where they feel unsafe. Experience and confidence are important factors but must be tempered with sensible caution.

18.5 Safety precautions while working from boats

18.5.1 *General*

Many types of boats are used for hydrological purposes, each having their own safety requirements. These must always be observed, as boating is inherently dangerous. The boat operator must be familiar with all operating and emergency procedures, and all regulations governing the intended operations. Craft must be in good repair, adequate for the conditions that could be encountered, and must not be overloaded.

18.5.2 *Lifejackets and safety equipment*

Lifejackets must be worn at all times in small craft and, in larger craft, there must be sufficient lifejackets on board for all passengers and crew.

Each boat must carry a full inventory of safety equipment that is appropriate to the type of craft and the conditions that could be encountered. These items may include all or some of the following: life-raft, flares, lifebelts, bailer, bilge pumps, safety harnesses, and survival equipment. Suitable radiocommunications equipment should be installed whenever practical. Each boat must have a rope attached to the bow for mooring and handling, as well as an adequate anchor and sufficient rope for the bottom conditions and depths to be encountered. Auxiliary motive power and fuel should be aboard if at all practical.

18.5.3 *Use of taglines*

Measuring lines or taglines are frequently used for measuring the distance across a river. These need to be of an adequate size and type of material to prevent stretch, and hold the necessary flags. However, the lighter the cable, the less tension is necessary in its rigging, and thus handling will be easier and safer.

Other lines may be rigged to moor the boat at the desired measurement points, and the same factors apply. Depending on the current, these may need to be rather more substantial. All lines must be flagged with sufficient large brightly-coloured markers across navigable waters at intervals that make the line very evident to river users. Colour itself must not be relied upon as many people are colour-blind. Where possible, boats working with such wires should be equipped with a bright flashing light. Appropriate local authorities and all likely river users should be notified of the hazards.

Such lines may not be left unattended, and personnel on-site should be equipped with wire cutters to be used, if necessary, to prevent an accident.

18.5.4 *Use of dinghies*

In rivers, one should row using the ferry-glide technique, heading diagonally upstream into the current. The rower is then facing in the direction of travel downstream, and steerage around any obstacles can be accomplished.

Personnel should be competent at rowing, oars should be of a suitable length (approximately 1.5 times the width between rowlocks), and secure rowlocks of the closed type are recommended. Inflatable dinghies are relatively safe with their built-in buoyancy. In the event of overturning, they can be righted by threading the bow rope around one rowlock, standing on the opposite side, and pulling hard on the rope to overturn it again. Aluminium dinghies are light, durable, and easy to row. Their lightness makes them prone to being blown with the wind, and they are unsuitable for windy conditions. If they become swamped, two people can remove most of the water by depressing the stern until the bow is well out of the water and then quickly raising the stern. It can then be bailed out by a person alongside. When partly bailed out, boarding can be accomplished over the stern with a second person holding the bow down, and the remaining water can then be bailed out. Wooden and fibreglass dinghies are often too heavy for this technique, but may float higher when swamped, thus allowing the use of a bailer.

18.6 Safety precautions when working with cableways

Before using any cableway, one should check the condition, looking for signs of anchorage movement, changed sag, vandalism or other damage to the cable, backstays, anchorages, cable hardware, and cable-car. Manned cableways normally require regular inspections and the issue of a certificate of fitness. The certificate should be current.

When using cable-cars, all personnel must be instructed never to touch the cable with the hands, whether moving or stopped, because of the danger of being run over by the cable-car wheels. The appropriate pulling device must be used instead. The maximum design load of the cableway must not be exceeded, and wire cutters should be carried to cut the suspension wire if it becomes fouled in the river. The wire should be cut close to the reel, and personnel should hold tightly to the cable-car during the rebound.

Unmanned cableways generally have powered or manual winches on the bank, and these need ratchets and brakes that lock firmly. As with all winches, long hair and loose clothing must be fastened back to avoid being caught.

All cables and wires should be installed and used with due regard for the safety of river traffic and aircraft, particularly helicopters. Where appropriate, they must be marked with suitably durable and visible markers to indicate their presence to operators and pilots.

18.7 Safety precautions when handling equipment

18.7.1 *Surveying*

Overhead electrical wires are a hazard when using survey staves, particularly metal ones. Staves should have signs warning of this hazard affixed to the back of them at eye level.

18.7.2 *Chainsaws*

Operators should wear suitable close-fitting clothing and safety equipment including hard hat, ear protection, eye protection, and strong work boots with steel toe-caps.

The saw should be started while held on the ground, and cutting should be carried out in a position with firm footing, clear of obstructions and other people, and with a safe exit from falling timber or rolling branches.

Kickback can occur when the chain recoils upward from striking an obstacle. It can recoil far faster than a person's reaction time and may cause them to lose their grip. Lacerated left hands are common in this situation. In order to reduce the likelihood of this happening, operators should maintain a firm grip with a straight wrist and good footing, cut at peak revolutions, and keep the nose of the bar away from obstructions.

18.7.3 *Electrical equipment*

All electrical equipment used outdoors or in damp conditions must be powered from an isolating transformer or an earth-leakage current-tripping device. All electrical leads should be routed to prevent damage from abrasion and contact with water. Leads must be kept in good repair, and any frayed or damaged connections should be properly repaired.

Circuits should not be overloaded, and repairs that should be done by a qualified electrician should not be attempted.

18.7.4 *Power tools*

Power tools should be used for their intended purposes only and always in accordance with the manufacturer's specifications. Personnel should be properly instructed in the use of these items. The use of some air- or power-operated tools may require authorization by government organizations. Safety goggles should always be used with all cutting, grinding, or drilling equipment.

18.7.5 *Protective clothing and safety equipment*

Personnel must be supplied with all safety and protective items required for the conditions and equipment being used.

18.7.6 *Radioactive equipment*

Some items, such as soil-moisture meters and geophysical instruments, incorporate radioactive sources. These instruments will be appropriately marked and must be handled and stored with special care in accordance with the relevant regulations. Radiation emitted by the source can be hazardous to health. The radioactive material will usually be sealed within a stainless steel pellet. As part of the equipment, this pellet will normally be surrounded by a material, such as plastic, steel, or lead to absorb radiation. It must be ensured that the source is within this absorber when the equipment is not in operation. Do not handle the pellet under any circumstance. If it needs to be moved, use long-handled tongs or similar equipment.

Keeping a good distance is normally adequate protection. With some sources, significant exposure only occurs closer than 10 centimetres. Others require considerably more than this. It is imperative that personnel determine the type and other details of the source being used and that they acquaint themselves with the recommended procedures and instructions for that source.

All instructions, procedures, and regulations must be rigorously followed, and the equipment should be handled with the utmost care at all times.

18.7.7 *Safety aspects of groundwater monitoring*

Pumps and airlift equipment for sampling, testing, or developing wells should be used in accordance with safety procedures for those types of equipment. Safe practices around drilling rigs are essential, and manuals of drilling practice should be consulted.

Entry of large-diameter wells for sampling should be avoided because of the potential presence of gases, as described in section 18.2.3. Safety harnesses should be worn when working above large-diameter wells.

18.8 Safety precautions when handling chemicals

All chemicals, such as those used for the preservation of water samples, cleaning fluids, and tracers, must be stored and handled with care. Avoid inhalation of vapours or direct contact with skin, eyes, and clothing. Any spills must be cleaned up immediately by dilution with large quantities of water, neutralization, or mopping up of the chemical followed by disposal of the material. Gloves, aprons, and suitable clean-up materials should be available for this purpose.

No pipetting should be done orally, except possibly when potable waters are the only substances being used. Skin that has been in contact with acids, bases, or other corrosive substances should be washed immediately with plenty of water. A neutralizing solution may be applied if applicable, to be followed by a second washing with soap. If any chemicals enter the eyes, they should be rinsed immediately with plenty of water. Rinse around the eyes as well. It may be necessary to hold the eyelids open during the washing procedure. Continue rinsing for several minutes. All eye injuries must be treated professionally.

Precautions must be taken as waters may contain a variety of toxic or bacterially hazardous substances. These may be derived from a wide range of sources, such as wastewater or effluent discharges, leachate from landfills, leakages from storage tanks, washing of agricultural spray tanks, and chemical or oil spills.

Any unusual appearance, colour, films, frothing, odours or vapours must be treated as suspicious, and adequate precautions must be taken. Many toxic substances can enter through the skin and, in the case of vapours, through the lungs.

Precautions may include gloves, waterproof overalls and aprons, hats, and eye protection. Where toxic vapours might be present, work only in well-ventilated areas or use self-contained breathing apparatus. Food should be kept away from samples and sampling locations. Always wash hands thoroughly before handling food. Smoking while sampling or near samples should be prohibited. If flammable compounds are suspected to be present, keep sparks and heat sources away and store samples in special explosion-proof refrigerators.

When measuring or sampling waters with high concentrations of toxic substances, such as leachate from landfills, or with suspected radioactivity, special considerations are required and the appropriate specialists should be consulted.

18.9 Special precautions for cold conditions

18.9.1 *Hypothermia (exposure)*

Hypothermia is a condition of lowered body temperature caused by exposure to cold, and results in rapidly progressing mental and physical collapse. Its onset is caused by cold temperatures aggravated by wet clothes, wind, hunger, and exhaustion. It often occurs in conditions where its early symptoms may not be recognized.

Early symptoms of exposure may include signs of tiredness, cold and exhaustion, lack of interest, lethargy, clumsiness and stumbling, slurring speech, and irrational behaviour. These signs constitute a medical emergency and require immediate action to prevent further heat loss and to effect rewarming. The victim may not complain and possibly deny that there is a problem. Later symptoms indicating a very serious emergency include obvious distress, a cessation of shivering despite the cold, collapse, and unconsciousness.

Rewarming must be started immediately when symptoms become evident. The victim's body will probably be incapable of generating sufficient warmth to accomplish this, and warmth must be applied gradually to the torso, but not to the limbs and extremities. Warming the extremities will increase blood circulation to these cooler parts of the body and reduce the temperature of the body's core still further.

Requirements for rewarming are shelter, dry clothes, insulation (such as a sleeping bag), and warmth applied to the vital organs of the body. This can be applied by close body contact of a warm companion in the sleeping bag also. No alcohol, rubbing, or rapid reheating is to be applied. Warm sweet drinks are valuable, but not to an unconscious person.

With warmth and shelter, patients often appear to recover quickly, but a resumption of cold conditions can bring upon collapse. Full recovery can take up to two days.

Hypothermia can be prevented by adequate shelter and clothing of adequate insulation and windproofing. One should avoid prolonged wet conditions and have food and shelter available, such as a tent or bivouac.

18.9.2 *Frostbite*

Exposure to extreme cold causes freezing of the outer parts of exposed tissues, such as toes, fingers, ears and nose. Affected parts become numb, dull white in colour, and waxy in appearance. Superficial frostbite can be treated by applying a hand or other parts of the body, without rubbing. Do not rewarm by direct heat or rubbing or give alcohol. More serious frostbite requires medical treatment.

Prevention involves wearing adequate foot, hand, face and ear protection, avoiding tight-fitting clothing or boots, keeping hands and feet dry, and constantly monitoring for signs of numbness. Constant movement or wriggling of toes and fingers to stimulate circulation is a short-term remedy that should be followed by reducing exposure to the cold.

18.9.3 *Working on ice-covered lakes and streams*

Travel and work on ice should be done with great caution, keeping weight to a minimum. If one falls through the ice, outstretch arms onto solid ice, kick to keep the body level, crawl forward on the stomach until hips reach the ice, then make a quick full-length roll onto the ice. Keep rolling until safe. If the ice is too thin for support, make way to shore by breaking the ice with one hand while supporting oneself with the other.

Rescuers should try to reach the victim with a pole, board, or rope. Going out to the ice edge should only be done as a last resort. If it becomes necessary, carry a long pole or slide along in a prone position. If there is a rope available, secure it to an object on shore. Dry and rewarm a person who has fallen through the ice as soon as possible to prevent hypothermia. Considerable risk may be involved in taking measurements through ice. Drilling or breaking a hole may significantly reduce the strength of the ice. Ice in a stream is likely to be of variable thickness, and its strength cannot be estimated from its apparent thickness near the edges. Areas with rapids or flow disturbances, such as bridge piers, are likely to have thinner ice due to the water movement. In advancing across an ice-covered stream, it is advisable to test the ice with an ice chisel every few steps. Hard ice will give a resounding ring, and soft ice will give a dull thud. A safety rope should be employed when there is any doubt, along with a companion on the bank with suitable rescue equipment.

18.9.4 *Working in mountainous areas*

The weather in mountainous areas can change rapidly, causing problems for the unwary or ill-equipped. The colder the climate, the greater the potential problems and the more clothing, supplies and safety equipment are required.

Personnel need to be experienced or be with someone who is, and the party's travel plans should be known to an appropriate person who could initiate assistance should this become necessary. Adequate waterproof, windproof, and warm clothing should be worn and carried, as well as sufficient food and survival equipment for the extremes of the climate. If working from a helicopter, ensure that each person has this equipment with them even if they are dropped off only for a short while, as cloud or other conditions may prevent its return.

One should not venture onto hard snow without an ice axe, climbing rope, crampons, and knowledge of their use. It is important to be wary of avalanches, particularly just after snowfalls or rain, to be aware of the various causes of unstable snow conditions, and to seek advice from experienced persons. Whatever the snow conditions, travel on or below steep slopes should be avoided. If caught in an avalanche, one should make every effort to stay on top to avoid being buried, cover the nose and mouth to prevent suffocation, and if buried, try to make an air space in front of the face and chest.

18.9.5 *Cold-water survival*

Hypothermia will result very rapidly from immersion in cold water. Its onset can be delayed by staying still and having sufficient coverage of clothing to reduce water movement against the body with its accompanying heat loss. It usually helps to keep as much of the body as possible out of the water, as it loses heat much more quickly to water than to air of the same temperature.

It is preferable to keep the head above water and to draw the legs up in contact with the groin area to reduce heat losses. A lifejacket is invaluable in assisting with this, and it will also provide insulation to the core portions of the body. A number of people should huddle together, holding on to each other facing inwards with the sides of the chests pressed together to reduce heat loss. Children should be held in the centre of such a group.

Treatment involves rewarming of the vital organs of the body prior to warming the limbs and extremities, as described in section 18.9.1.

18.10 Special precautions for hot conditions

18.10.1 *Heat stroke (hyperthermia)*

Heat stroke is caused by exposure to high temperatures that cause the body temperature to rise above 40°C. Adverse response to high heat varies among people depending on their acclimatization, fitness, and most importantly, body hydration. With the onset of excessive heat, the body loses heat primarily by the evaporation of water through sweating and respiration. If this loss of water is not replenished, the cooling mechanisms are inhibited and heat builds up. Symptoms include headache, chilling, nausea, rapid pulse, muscle pains, loss of coordination, and more severely, delirium and convulsions. If not treated, death follows.

Treatment involves immediate cooling by placing the victim in the shade, removing clothes, and spraying with cold water while fanning vigorously. Give fluids when fully conscious.

Precautions include being physically fit, moderating exercise, drinking moderate amounts regularly and often, avoiding alcohol and caffeine, avoiding working in the hottest part of the day, wearing lightweight, light-coloured, loose-weave clothing and a wide-brimmed hat, and adding extra salt to meals.

18.10.2 *Sunburn*

Excessive exposure to the sun can cause severe burns, particularly to light-skinned people. It will cause severe pain, damage to the skin, and possibly heat stroke. Prolonged exposure to the sun’s ultraviolet rays can cause skin cancer, with the greatest risks being to those people with fair skin.

Precautions include wearing protective clothing with attention to head covering. Sunscreen lotions should be applied to exposed skin. Confine exposure to the sun to short periods each day with gradual increases to build tolerance.

18.11 Travel and transport

18.11.1 *General*

Modes of travel and transport for hydrological work are many and varied in accordance with the great ranges of terrain, climate, and routes travelled. Safety aspects of travel, taking into account all of the variations in these factors, is a large topic in itself and is not just confined to hydrological work. Accordingly, it is only covered briefly here, and hydrologists are urged to seek out manuals and advice for local conditions and modes of travel.

18.11.2 *Helicopters*

On the ground the noise, wind, and urgency associated with helicopters tend to mask the dangers presented by the main and tail rotors. These have killed and maimed many people. One must not approach or leave the helicopter without the pilot's knowledge and approval, and this should be done within the pilot's field of vision. One should approach and leave the aircraft on the downslope side for maximum clearance from the main rotor and should never walk around the tail.

Personnel should keep away from the landing pad and keep it clear of equipment. All equipment and loose articles should be kept well clear of the effects of rotor wash or heavily weighted down. Long objects, such as survey staves, should be carried horizontally at waist level to avoid contact with the rotors. The aircraft should be loaded under the supervision of the pilot, whose attention should be drawn to hazardous cargo, such as batteries and fuel.

Cableways and aerial wires are particularly hazardous to helicopter operations, and personnel should make the pilot aware of any that are known and assist in looking out for others.

18.11.3 *Motor vehicles*

In much hydrological work, frequent travel by motor vehicle means potential for serious accidents. Travel on remote back-country roads is common, and this provides additional hazards to those on highways.

The most common causes of accidents relate to excessive speed. This is no less true of back-country roads, which are often narrow and winding and have loose surfaces. The best drivers tend to accelerate smoothly, corner carefully and brake gently, being considerate of their vehicle, their passengers, and other road users.

18.12 Survival kits and rations

Emergency survival kits should be carried by personnel in remote areas. The components of these kits will vary greatly depending upon the climate, conditions and mode of travel, but should include food, water, cooking and heating equipment, shelter, such as a tent or bivouac, sleeping bags, lighting, medical supplies, adequate clothing for the worst possible conditions, and signalling equipment, such as a mirror, flares and two-way radio.

First-aid training should be given to all field personnel, and each person should be supplied with an adequate first-aid kit and manual.

Topics to be covered should include rescue breathing, cardio-pulmonary resuscitation, unconsciousness, bleeding, fractures, shock, eye injuries, poisoning, and burns.

18.13 **Other hazards**

Field personnel should be familiar with, and always on the lookout for, other hazards posed by their working environment. These include, for example, poisonous plants, stinging or biting insects, dangerous animals, quicksand, electrical storms, and so forth. Also, bodily contact or ingestion of some waters may pose significant health risks. In some localities, there may be a possibility of attack by other people, who may be engaged in illegal or warlike activities, for example. Employers have a responsibility to ensure that their staff are never unknowing to any such risks.

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PART C

COLLECTION, PROCESSING, AND DISSEMINATION OF HYDROLOGICAL DATA

CHAPTER 19

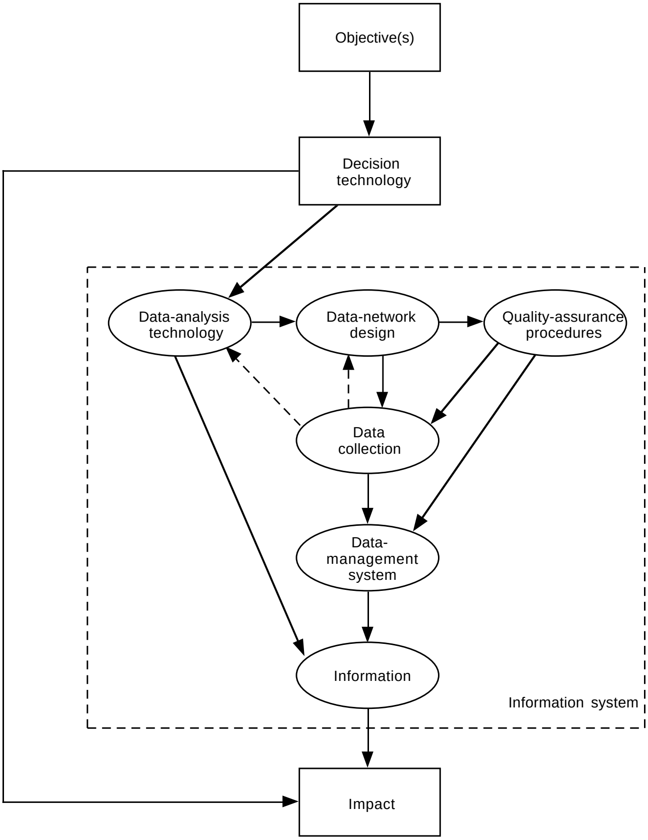
THE ROLE OF HYDROLOGICAL DATA IN AN INFORMATION SYSTEM

19.1 Information systems

Part B of this *Guide* deals with the field activities of operational hydrology. However, the data that are generated by the field activities are of little or no value if they cannot be readily and confidently accessed by the potential data users. Operational hydrology within a given Hydrological Service can be considered as an information system providing a conceptual basis for the development of proper approaches which ensure that the right data are available in the right form at the right place and time. The Figure below depicts the elements of a hydrological information system. Ideally, the information system is imbedded in a natural sequence of actions and decisions that begins with the perception of an opportunity and culminates in the implementation of decisions that maximize the net positive impacts of the opportunity.

The Figure joins the sequence at the stage where the opportunity is converted into an objective or set of objectives that are used to direct subsequent decision making. Once the objectives have been chosen, appropriate decision technologies are selected to address those objectives. The selection of decision technologies entails the choice of the relevant variables and parameters that describe both the hydrology and the socio-economic setting of the opportunity, the specification of the means by which the variables will be synthesized to determine subsequent actions, and a definition of the process for dealing with the inherent uncertainties in the variables and parameters. With the decision technologies firmly in mind, the designer of the information system can specify the procedures to be used to analyse the hydrological data. These data-analysis technologies may be any one or a combination of models that account for the probabilistic, stochastic, or deterministic natures of the hydrological phenomena of interest. Part C of this *Guide* discusses many of these data analysis technologies.

In an ideal setting, each of the steps described above should be taken prior to designing a hydrological-data network. The design of a data network answers the following questions: what is to be measured? where is it to be measured? when is it to be measured? and how accurately is it to be measured? Aspects of several of these questions are discussed briefly in Part B. Expanded guidance concerning network design is provided in Chapter 20.



Components of a hydrological information system.

The actual data collection can begin at this point in the sequence, and it is also at this point that feedback, represented as dashed arrows in the Figure, begins to take place. All of the previous steps have been based on a specific level of knowledge about the hydrologic conditions of interest. As data are collected, this level increases, and new data-analysis techniques and new network designs may become appropriate. Guidance on data collection is given in Chapter 21.

From the Figure, it is possible to see that quality assurance is an integral phase of the information system that is relevant throughout the continuum from field activities to the dissemination of data and information. Because of its pervasive nature, quality-assurance guidance can be found in various locations in Chapters 21 through 25.

No discussion of information systems is complete without mention of data-management systems. The information contained in a robust data-management system is available, not only for the uses for which the data were collected originally, but also for a multitude of uses that may never have been anticipated. But with robustness comes a price tag. The first part of the price is that the options inherent in robust systems tend to make it difficult to use, as more training is required.

This part of the cost can be minimized by user-friendly systems designs. The second cost factor is the potential loss of information that robustness entails. Because a data-management system cannot be all things to all people, compromises must be made, which usually result in data compaction and loss of data attributes. To ameliorate this loss, subsystems that retain more objective-specific data can be appended to the robust, central system. Such systems are discussed in Chapters 24 and 25.

The ultimate product of the information system is obtained by processing the data through the same data-analysis technology that was initially crucial in the design of the data network. The sequence culminates by integrating the hydrological information into the decision process for which it was designed to have an optimal impact. The key to obtaining this optimality is the compatibility among the decision technology, the data-analysis technology, and the data network.

A well designed information network contains synergism that is derived in three ways. Firstly, information is a commodity that is not destroyed by its use. Thus, if properly preserved, it can be made available at minimal cost for many uses not anticipated at the time of its collection. Secondly, information can be used to improve understanding of hydrological processes. By improving process understanding, both the information content of the existing data and all future data are increased. Thirdly, synergism evolves by taking advantage of the accomplishments of others. New approaches and technologies for the design of information systems, like the data they contain, are recyclable commodities.

19.2 **Computer technology**

The joint WMO/FAO *Guidelines for Computerized Data Processing in Operational Hydrology and Land and Water Management* [1] describe the concepts, terminology, and application of computerized data processing.

Computers have taken an increasingly important role in all aspects of data collection and processing. With current technology, the primary data-processing function can be successfully performed on a personal computer at the Field Office. However, the ability to collect large volumes of data can result in a large volume of incorrect and misleading records being accumulated. Quality control through the use of computers is essential. Well-developed operating systems and recorder software, with appropriate field check observations, form the first component of the primary data-processing system. The ability to review the record in the field is highly desirable. The ability to compare records from neighbouring stations and to view a trace of the record on a graphics screen is essential in evaluating the validity of the collected record.

In Section G of the *HOMS Reference Manual* [2], there are a number of components that describe computer-based data-collection, processing, and storage systems.

19.3 Staff and training

Whatever the level of technical sophistication of a data-collection authority, the quality of its staff will always remain its most valuable resource. Careful recruitment, training, and management is the key to attaining and maintaining the appropriate personnel.

The WMO has published a set of *Guidelines for Education and Training of Personnel in Meteorology and Operational Hydrology* [3]. UNESCO has published a document on *Curricula and Syllabi in Hydrology* [4]. With respect to data collection and processing, employee education, although costly and time consuming, can be a sound investment that results in greater productivity and effectiveness. A carefully structured training programme is essential for all personnel engaged in data collection because they are in a strong position to influence the standard of the final data. Formal training should aim at providing both a general course in first principles, plus training modules to teach in-house procedures. All material should be relevant and current. Section 2.4 provides additional information on different aspects of training in hydrology.

Where processing is not carried out by the data collector, it is important that data processors be trained in data-collection techniques to ensure that data are processed according to the intent of the collector. It is a good practice to give processing staff periodic field experience to build a physical association with the data and their origins. Such knowledge on the part of the processor can allow interim interpretations of incorrectly presented data, pending confirmation from the collector.

It is essential to establish the principle that the person collecting the data has the primary responsibility for its quality. One method of honouring this principle is to involve the collector in the processing as much as possible, and to ensure that feedback is obtained by returning the published data to the collector for assessment. At the processing stage, staff should recognize that they also have a responsibility to maintain the quality and integrity of the data.

Data processing is often routine in nature and well suited to the application of automation and technology. For this reason, it is important that special attention be given to the care of human resources, and that the system be structured to foster interest, involvement, professionalism, and a sense of achievement. Data-processing staff should be given the opportunity to contribute ideas which may increase the effectiveness of the processing system.

Staff safety is also an integral component of any profession, and the duties undertaken by data collectors and processors require the establishment of safety standards. These are primarily discussed in Chapter 18. However, the possibility of repetitive strain injury in data-processing staff can be often caused by routine and the repetitive nature of some aspects of their jobs. This problem should be addressed from both a staff safety and a management point of view.

References

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2. World Meteorological Organization, 1988: *Hydrological Operational Multipurpose System (HOMS) Reference Manual.* Second edition, Geneva.
3. World Meteorological Organization, 1984: *Guidelines for Education and Training of Personnel in Meteorology and Operational Hydrology.* Third edition, WMO–No 258, Geneva.
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CHAPTER 20

DESIGN AND EVALUATION OF HYDROLOGICAL NETWORKS

20.1 General concepts of network design

A hydrological-data network is a group of data-collection activities that are designed and operated to address a single objective or a set of compatible objectives. Frequently, the objective(s) is(are) associated with a particular use that is anticipated for the data being collected in the network — for example, for a water-resources assessment, a development plan, or a project design. A particular hydrological station or gauge may be included in more than one network if its data are being used for more than one purpose. In most parts of the world this is more commonly the case than not. On the other hand, a single network may consist of several types of stations or gauges if they are all contributing information to the network's objective. For example, both raingauges and stream gauges might be included in a flood-warning network.

The term network is frequently used in a less rigorous sense. It is often possible to hear of surface-water network, groundwater network, precipitation network, or water quality network when the speaker is referring to an aggregation of gauges and stations that have no coherence in their objectives. Data-collection sites included in a network under this looser definition may even have disparate uses for the data being collected. This disparity of usage is more than just a semantical oddity. It can cause confusion and false expectations when network analysis and design are being discussed among programme managers and hydrologists.

Ideally, a network design would be based on a maximization of the economic worth of the data that are to be collected. However, such is not the case in the real world. In the majority of the cases in water-resources decision making, the economic impacts of hydrological data are never considered. Decisions are made based on the available data, and the option of delaying the decision to collect more data is frequently not explored. However, several examples that are exceptions to this general rule are contained in the WMO *Cost-benefit Assessment Techniques and User Requirements for Hydrological Data* [1] and in *Economic and Social Benefits of Meteorological and Hydrological Services* [2].

In lieu of complete economic analyses, network designs are usually based on surrogate measures of the economics or on guidance such as that presented subsequently in this chapter.

20.1.1 *Definition of network design*

A complete network design answers the following questions pertaining to the collection of hydrological data:

(*a*) What hydrological variables need to be observed?
(*b*) Where do they need to be observed?
(*c*) How often do they need to be observed?
(*d*) What is the duration of the observation programme? and
(*e*) How accurate should the observations be?

To answer these questions, network design can be conceptualized as a pyramid, as shown in Figure 20.1. The base of the pyramid is the science of hydrology. Without a thorough understanding of the hydrological setting of the area in which the network is to be established, there is little chance that the resulting network will generate information in an effective manner. Hydrological understanding comes from both education and experience, but there is no substitute for experience when initiating a hydrological network in an area where little or no historical data are available.

The right-hand side of the pyramid deals with quantitative methods for coping with hydrological uncertainty. Because of measurement errors and errors caused by sampling in space and time, there will always be hydrological uncertainty. Perfect hydrological information can never exist. Probabilistic descriptions of these errors are the most effective means of dealing with the resulting uncertainty. Probability theory provides the theorems and the language for doing so and also yields the

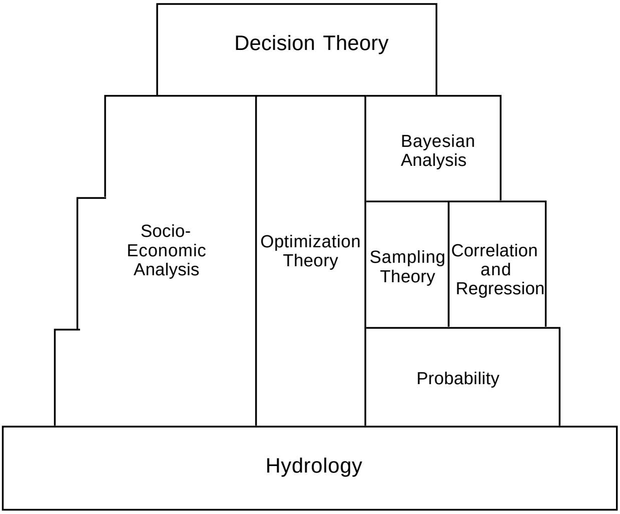


Figure 20.1 — The basic building blocks of network design.

understanding that is necessary for appropriate use of the tools of statistics. In Figure 20.1, statistical tools are represented by sampling theory and by correlation and regression analyses, which are commonly used in quantitative network-design approaches. However, there are many other branches of statistics that may be found useful in network analysis and design. The capstone of uncertainty is Bayesian analysis, which pertains to the level of uncertainty in the descriptions of hydrological uncertainty. In other words, the probabilistical descriptions of uncertainty, based on statistics of finite samples of hydrological data, are uncertain in themselves. Reduction of uncertainty about uncertainty is a key aspect of taking full advantage of the information contained in the data that the network will generate.

The column in the middle of the structure, labelled optimization theory, is often included taxonometrically as a part of socio-economic analysis. However, even in the absence of socio-economics, optimization theory is often used in hydrological network design. Thus, it is included here as a separate component of the structure. A suite of mathematical programmes, each with its own utility and shortcomings, comprises optimization theory, which is often referred to as operations research. The context of the network-design problem determines which, if any, of the mathematical programmes can be used in a given situation. Often, the choice between two or more network designs must be made on the basis of judgement because appropriate optimization tools either do not exist or are too consuming of computer resources to be efficient.

Atop the pyramid is decision theory, which is a formal mechanism for integrating all of the underlying components. The application of decision theory in network design is not required — it is not even possible in most circumstances. However, an understanding of its pretexts and premises can make a network designer more cognizant of the impacts of his or her final decisions.

The left-hand side of the pyramid represents a rather amorphous group of technologies under the heading of socio-economic analysis. In addition to social sciences and economics, this part of the network-design structure also encompasses policy science and even politics. The latter plays a very important role in the realization of the potential benefits of water and, thus, also in the ultimate value of the data from the network. The left-hand side is the part of the structure that usually receives the least consideration in the design of the data network. This is probably attributable to two causes: the subject matter is difficult to treat in an objective, mathematical way; and to do so in a substantive manner requires the synthesis of inputs from many disciplines beyond those of hydrology and water-resources engineering. Thus, a network design that includes a significant socio-economic analysis will probably be both expensive and time consuming. Nevertheless, it is wise to keep in mind the influence that the data have on the real world when designing a network — even if this must be done subjectively.

20.1.2 *Surrogate approaches*

Since full-scale and complete network design is either impossible or impractical in today's world, approaches that substitute surrogate measures, objectives, or criteria are actually used to answer the questions that comprise network design. For example, a common substitution is to maximize information content from a network in lieu of optimizing the economic value of the data. Studies have shown that, if information is used properly, it can be expected to contribute to the economic worth resulting from a decision. The more information, the better the decision. However, the economic impact of information is not linearly related to its magnitude and the marginal worth of additional information decreases with the amount of information that is available. Thus, the use of this surrogate criterion can lead a Hydrological Service in the right direction if only sparse hydrological information is available, but its use can cause the collection of excess data if the region of interest already has a reasonably adequate information base.

Among the basic analytical techniques that take advantage of surrogates in the design of networks are cartographic analysis, correlation and regression methods, probabilistic modelling, deterministic modelling, and regionalization techniques. Each method has particular applications and the choice depends on the limitations of available data and the type of problem under consideration. Quite often the different techniques are combined in certain applications. The WMO *Casebook on Hydrological Network Design Practice* [3] presents applications of these techniques as a means of determining network requirements. Other examples are contained in other publications [4-6].

20.1.3 *The basic network*

The worth of the data that derive from a network is a function of the uses that subsequently are made of them. Nevertheless, many of the uses of hydrological data are not apparent at the time of the network design and, therefore, cannot be used to justify the collection of specific data that ultimately may be of great value. In fact, few hydrological data would be collected if *a priori* economic justifications were required. However, modern societies have developed a sense that information is a commodity that, like insurance, should be purchased for protection against an uncertain future. Such an investment in the case of hydrological data is the basic network, which is established to provide hydrological information for unanticipated future water-resources decisions. The basic network should provide a level of hydrological information at any location within its region of applicability that would preclude any gross mistakes in water-resources decision making. To accomplish this aim, at least three criteria must be fulfilled:

(*a*) A mechanism must be available to transfer the hydrological information from the sites at which the data are collected to any other site in the area;

(*b*) A means for estimating the amount of hydrological information (or, conversely, uncertainty) at any site must also exist; and

(*c*) The suite of decisions must include the option of collecting more data before the final decision is made.

20.1.3.1 *The minimum network*

In the early stages of development of a hydrological network, the first step should be the establishment of a minimum network. Such a network should be composed of the minimum number of stations which the collective experience of hydrological agencies of many countries has indicated to be necessary to initiate planning for the economic development of the water resources.

The minimum network is one that will avoid serious deficiencies in developing and managing water resources on a scale commensurate with the overall level of economic development of the country. It should be developed as rapidly as possible by incorporating existing stations as appropriate. In other words, a minimum network will provide the basic framework for network expansion to meet future needs for specific purposes. It is emphasized that a minimum network will not be adequate for the formulation of detailed development plans and will not meet the numerous requirements of a developed region for the operation of projects and the management of water resources.

20.1.3.2 *Expanding the information base*

Once the minimum network is operating, regionalized hydrological relationships, interpreted information, and models can be formulated for estimating general hydrological characteristics, including rainfall and runoff at any location in the area. The basic network of observing stations should be adjusted over time until regional hydrological relationships can be developed for ungauged areas that provide the appropriate level of information. In most cases, this adjustment will result in increases in the densities of hydrologic stations. However, this is not always the case. Since models are used to transfer the information from the gauged sites to the ungauged, the goodness of the model is also a factor in determining the density of the basic network. If a model is particularly good, it can distil the information from the existing data better than a poorer model, and the better model would require less data to attain a given level of regional information than would the poorer one. In an extreme situation, the regional model might be so good that the level of data collection in the basic network could be reduced.

Owing to the broad dependence on the stations in the basic network, it is very important that the records from all of these stations be of high quality. Even if the installation of a station is adequate, its records may be of little value if it is not operated correctly. Continuous operation may be difficult — especially over a period of

20 years or more. A minimum network, in which stations are abandoned or irregularly observed, will have its effective density reduced and is, therefore, no longer an adequate minimum network. For that reason, care should be taken not only in establishing, but also in providing for the continuing operation of these stations and for monitoring the reliability and accuracy of the collected records.

Economics, as well as technical considerations, are involved in the design and implementation of basic networks, and the number of stations requiring observation over an indefinitely long period cannot be excessive. Consequently, a sampling procedure may be adopted to maximize the cost effectiveness of the basic network. One such approach categorizes the stations as either principal or base stations, or secondary stations. The secondary stations are operated only long enough to establish a stable relationship (usually by means of correlations) with one or more of the base stations. A new secondary station can then be established with the equipment and funds that had been in use at the discontinued site. Records can be reconstructed at the discontinued site by means of the base-station records and the inter-station relationship. At times, it may be necessary to re-establish secondary stations if it is believed that the conditions either at the secondary site or at its related base station(s) have changed.

The perpetual nature of the principal stations in the basic network provides a basis for monitoring long-term trends in hydrological conditions in the region. This is particularly important in light of potential changes in the hydrological cycle that could be caused by land-use changes or by increases in stratospheric greenhouse gasses.

20.1.4 *Integrated network design*

The hydrological cycle is a continuum, and its inter-connections permit the partial transfer of information obtained in one part of the cycle to another. The efficiency of such transfers is proportional to the degree of hydrological understanding that is captured in the models that are used to route the water (and the information) between the parts of the cycle. For example, precipitation records on or near a gauged drainage basin permit the reconstruction of streamflow records during periods when the stream-gauge malfunctions if a valid precipitation-runoff model has been calibrated during times when all gauges were functioning properly. A groundwater observation well may perform a similar role for malfunctions of the stream gauge if the well is monitoring the water table of an aquifer that is directly connected to the stream.

To date, little has been done to include these interactions in network designs in an explicit manner. Ideally, the complementarity between the raingauges and the stream gauges that are operated in a flood-forecasting network could be used in designing a network for water-resources assessment, for example. If the economic tradeoffs between the two networks could be defined, they could be optimized together and peak efficiencies in information generation could be attained for both. In spite of this technological shortcoming, networks should be designed iteratively, and the outcomes of an existing design should become starting points for subsequent designs. By extension of the above example, this can be illustrated. The flood-forecasting network will probably have stream gauges and precipitation gauges at rather specific locations to meet its information needs. Because the water-resources assessment will generally have less specific requirements for its information sources, it will be likely that many of the gauges of the flood-forecasting network can be incorporated into the assessment network and used as initial given conditions for its design. This iterative approach is particularly useful when designing generalized networks, like the basic network on the basis of networks, with more restrictive information demands. Networks with more restrictive demands include bench-mark stations, representative basins, and networks for operational purposes.

20.1.4.1 *Stations for operational purposes*

Stations may be established for such specific purposes as reservoir operation, irrigation, navigation, water quality monitoring, flood forecasting, or research. Bench-mark or reference stations would also belong to this category. The length of operation of special stations is related to the purpose for which they were installed.

In some cases, the specific purpose to be served may require observations on only one particular aspect of an element, or be confined to one season of the year. For example, a hydrometric station may consist of a crest gauge for recording only the maximum flood peak or a storage gauge for measuring the total precipitation during a season. Although such stations may perform a valuable function, they do not provide the data required for general hydrologic analyses. Consequently, such stations may or may not be included in a basic hydrological network.

20.1.4.2 *Bench-mark stations*

Each country and each natural region of large countries should contain one bench-mark station to provide a continuing series of consistent observations on hydrological and related climatological variables. Hydrological bench-mark stations should be established in areas which are relatively uninfluenced by past or future anthropogenic changes. Since long records are the essence of a bench-mark station, consideration should be given to existing stations if they meet the other requirements. Climatological bench-mark stations are known as reference stations.

20.1.4.3 *Representative basins*

A representative basin is desirable in each natural region — especially in those regions where great economic growth is expected or where the hydrological problems are particularly difficult. In their simplest form, they permit to study simultaneous precipitation and runoff, thus helping to make up for deficiencies in short periods of observation and low densities of minimum networks.

20.1.5 *Conducting a network analysis*

Figure 20.2 lays out the steps that should be taken in conducting a review and redesign of an existing hydrological network. Such reviews should be conducted periodically to take advantage of the reduction in hydrological uncertainty brought about by the added data since the last network analysis and to tune the network to any changes in the socio-economic environment that may have transpired. The steps of the analysis are discussed individually below.

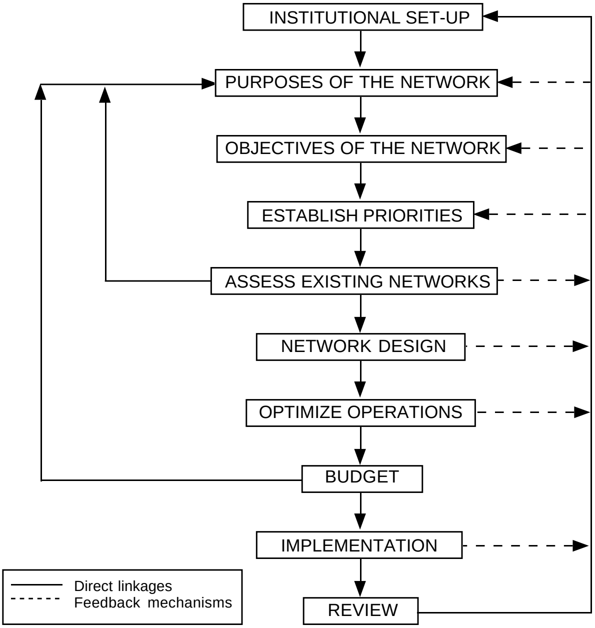


Figure 20.2 — A framework for network analysis and redesign.

Institutional set-up

The roles and aims of all of the organizations involved in various aspects of water-resources management should be defined and identified (particularly legislative responsibilities). Communication links between these organizations should be improved to ensure coordination/integration of data-collection networks.

Purposes of the network

The purposes of the network in terms of the users and uses of the data should be identified. Data users and uses can vary temporally and spatially. There is also a need to identify potential future needs and incorporate these into the design as well.

Objectives of the networks

Based on the purpose of the network, an objective or set of objectives can be established in terms of the information required. An indication of the consequences of not being able to provide this information may prove useful later.

Establish priorities

If there is more than one objective, priorities need to be set for later evaluation. If all objectives can be met within the budget, then this is not needed. However, if they cannot, then the lower-priority objectives may not be met fully.

Assess existing networks

Information on the existing network should be compiled and interpreted to determine if the current networks fulfil the objectives. This may include comparisons with other basins and/or networks.

Network design

Depending on the available information and the objectives defined, the most appropriate network-design technique or techniques should be applied. This may be simple hydrological characteristics, regression relationships, or more complex network analysis using generalized least squares (NAUGLS) methods.

Optimize operations

A significant portion of the cost of data collection is contained within the operational procedures. This includes the types of instruments, frequencies of station visits, and structure of field trips. The minimum-cost operational procedures should be adopted.

Determine costs

Based on the identified network and operational procedures, the cost of the operation of the network can be established. If this is within the budget, the next step can be followed. If not, either additional funding must be obtained or the objectives and/or priorities need to be examined to determine where costs may be reduced. The process adopted should allow the designer to express the impact of insufficient funding in terms of not meeting objectives or reduced information and net impacts.

Implementation

The re-designed network needs to be implemented in a planned manner. This will include both short- and long-term planning horizons.

Review networks

Since a number of the above components are variable in time, a review can be required at the instigation of any particular component — for example, changes in users or uses or changes in the budget. To be ready to meet such changes, a continuing review process is essential.

20.2 Density of stations for a minimum network

As stated in section 20.1.3.1, the minimum network is one that will avoid serious deficiencies in developing and managing water resources on a scale commensurate with the overall level of economic development and environmental needs of the country. It should be developed as rapidly as possible, incorporating existing stations, as appropriate. In other words, such a network will provide the framework for expansion to meet the information needs of specific water uses.

The concept of network density is intended to serve as a general guideline if specific guidance is lacking. As such, the design densities must be adjusted to reflect actual socio-economic and physio-climatic conditions. Computer-based mathematical analysis techniques should also be applied, where data are available, to optimize the network density required to satisfy specific needs. For example, the network analysis using generalized least squares (NAUGLS) developed by the U.S. Geological Survey [7] offers a promising approach for optimizing the stream gauges in a basic network for regional information.

In the following sections, minimum densities of various types of hydrological stations are recommended for different climatic and geographic zones. These recommendations have been revised for this edition of the *Guide* on the basis of the review of Members' responses for the WMO basic network assessment project (BNAP) [8]. It is impossible to define a sufficient number of zones to represent the complete variety of hydrological conditions. A limited number of larger zones have been defined in a somewhat arbitrary manner.

The simplest and most precise criterion for the classification of zones would be on the basis of the areal and seasonal variation of rainfall. Each country could present a good map of annual precipitation and a minimum network would be developed from this. But this would not help the various countries that need a network most as they have very few prior records, and the establishment of a good precipitation map is impossible. One must consider, as a special category, the countries with very irregular rainfall distribution. It is not advisable to base the classification on this one characteristic.

Population density also affects network design. It is almost impossible to install and operate, in a satisfactory way, a number of stations where population is sparse. For example, to set up more than two gauges on a catchment of 1 000 km^2, when the population of the area is only 100 people, is almost impossible, especially if this population is not permanent. Besides, it is difficult even to find observers in thinly-populated areas where access is poor. Sparsely-settled zones, in general, coincide with various climatic extremes, such as arid regions, polar regions, or tropical forests. The use of totalizers (storage gauges) is recommended in such cases because they need little maintenance and infrequent visits.

On the other extreme, densely-populated urban areas need a very dense raingauge network for both temporal and spatial resolution of storms and for design, management, and real-time control of the storm-drainage systems and for other engineering applications.

From these considerations, some general rules have been adopted for the definition of density norms. Six types of physiographic regions have been defined for minimum networks:

(*a*) Coastal;
(*b*) Mountainous;
(*c*) Interior plains;
(*d*) Hilly/undulating;
(*e*) Small islands (surface areas less than 500 km^2); and
(*f*) Polar/arid.

For the last type of region, it is necessary to group together the areas in which it does not seem currently possible to achieve completely acceptable densities because of sparse population, poor development of communications facilities, or for other economic reasons.

20.2.1 ***Minimum densities for climatological stations***

The following kinds of data are collected at a climatological station in the basic network: precipitation, snow survey, and evaporation. It is understood here that evaporation or snow-measuring stations, particularly the former, will generally measure temperature, humidity, and wind because these meteorological elements affect evaporation and melting.

20.2.1.1 *Precipitation stations*

The minimum densities for precipitation stations are provided in Table 20.1. These densities are not applicable to the great deserts (Sahara, Gobi, Arabian, etc.) and great ice fields (Antarctic, Greenland, and the Arctic islands) that have no organized hydrographic networks. In these regions, precipitation is not studied by raingauge networks of standard type, but by special stations and methods of observation.

If one follows certain principles of installation and use, the small number of stations in the minimum network can furnish the most immediate needs. In general, precipitation gauges should be as uniformly distributed as is consistent with practical needs for data and the location of volunteer observers. In mountainous regions, attention must be given to vertical zonality by using storage gauges to measure precipitation at high altitudes. Snow surveys may be used to supplement the network, but they should not be counted as part of the network.

The minimum network should consist of three kinds of gauges:

(*a*) Standard gauges — These gauges are read daily for quantity. Besides daily depth of precipitation, observations of snowfall, the depth of snow on the ground, and the state of the weather are to be made at each standard precipitation station;

(*b*) Recorders — In developing networks, it is advisable to aim to have at least 10 per cent of such stations in cold climates. The greatest density of recording stations should be achieved in those areas subject to intense, short-duration rainfalls. Such stations will provide valuable information on the intensity, distribution, and duration of precipitation.

For urban areas where the time resolution needed for rainfall measurements is of the order of one to two minutes, special attention should be paid to the time synchronization of the raingauges. For reliable measurements, tipping-bucket raingauges with an electronic memory (or another computer readable medium) are recommended.

In assigning priorities to locations for recording-raingauge installations, the following types of areas should be given priority: urban areas (population in excess of 10 000) where extensive drainage systems are likely to be constructed, river basins in which major river control systems are anticipated or in operation, large areas inadequately covered by the existing network, and special research projects.

(*c*) Storage gauges (totalizers) — In sparsely settled or remote regions, such as in desert or mountainous terrain, storage gauges may be used. These gauges are read monthly, seasonally, or whenever it is possible to inspect the stations;

TABLE 20.1

Recommended minimum densities of precipitation stations

Physiographic Unit	*Minimum densities per station (area in km^2 per station)*	
	Non-recording	*Recording*
Coastal	900	9 000
Mountainous	250	2 500
Interior plains	575	5 750
Hilly/undulating	575	5 750
Small islands	25	250
Urban areas		10-20
Polar/arid	10 000	100 000

Location of precipitation gauges relative to stream-gauging stations — To ensure that precipitation data are available for extending streamflow records, for flood-forecasting purposes, or for hydrologic analysis, coordination of the locations of the precipitation gauges with respect to those of the stream gauges is of great importance. Precipitation gauges should be located so that basin precipitation can be estimated for each stream-gauging station. These will usually be located at or near the stream gauge and in the upper part of the gauged drainage basin. A precipitation gauge should be located at the site of the stream gauge only if the observations will be representative of the general area. There can be cases in which it is desirable to locate the precipitation gauge some distance away from the stream gauge, as for instance when the stream gauge is in a narrow, deep valley.

20.2.1.2 *Snow surveys*

Where applicable, observations of snowfall, water equivalent of snow, and depth of snow on the ground should be made at all precipitation stations in the minimum network.

The water equivalent of snow at the time of maximum accumulation is an indication of total seasonal precipitation in regions where winter thaws and winter snow melt are insignificant. In such regions, surveys of the snow cover on selected courses may be useful in estimating seasonal precipitation at points where the normal observations are unavailable. Such snow-cover surveys will also provide useful information for river forecasting and flood studies.

Snow-cover surveys are conducted by special teams equipped with simple instruments for sampling the accumulated snow and for determining its depth and water equivalent (Chapter 8). The number of the snow courses, their locations, and lengths will depend upon the topography of the catchments and the purposes for which the data are being collected. The full range of elevation and the types of exposure and vegetation cover in the area of interest should be considered in selecting representative courses. It has been suggested that one course for 2 000 to 3 000 km^2 is a reasonably good density for less homogeneous regions, and one course for 5 000 km^2 in homogeneous and plain areas. However, each case must be considered on its own merits, and these generalities must not be applied indiscriminately.

In the early stages of network development, snow-cover surveys will usually be made only once a year, near the expected time of maximum accumulation. It will be desirable, later on, to extend the operation to include surveys at regular intervals throughout the snowfall season. As soon as it becomes feasible, the snow-cover observations should be augmented by observations of related meteorological factors, such as radiation, soil temperature, and wind velocity.

20.2.1.3 *Evaporation stations*

Evaporation can be estimated indirectly in the water-budget, energy-budget and aerodynamic approaches, and directly by extrapolation from pan measurements (Chapter 9). An evaporation station consists of a pan of standard national designs where daily observations of evaporation are made, together with daily observations of precipitation, maximum and minimum water and air temperatures, wind movement, and relative humidity or dewpoint temperature. The norms recommended for a minimum network of evaporation stations within areas of uniform physiography are given in Table 20.2.

Evaporation plays an important role for long-term studies of the water regime of lakes and reservoirs and for water management. In such cases, the number and distribution of evaporation stations are determined according to the area and configuration of the lakes and the climatic region or regions involved.

TABLE 20.2

Minimum density of evaporation stations

Physiographic unit	*Minimum density per station (area in km^2 per station)*
Coastal	50 000
Mountainous	50 000
Interior plains	50 000
Hilly/undulating	50 000
Small islands	50 000
Polar/arid	100 000

20.2.2 *Minimum densities for hydrometric stations*

20.2.2.1 *Streamflow stations*

The main objective of the stream-gauging network is to obtain information on the availability of surface-water resources, their geographical distribution, and their variability in time. Magnitude and frequency of floods and droughts are of particular importance in this regard.

The minimum densities for streamflow stations are given in Table 20.3. These norms are not applicable to the great deserts with no defined stream networks (such as the Sahara, Gobi, Arabian and Korakorum deserts) and great ice fields (Antarctic, Greenland, Arctic islands).

TABLE 20.3

Recommended minimum densities of streamflow stations

Physiographic unit	*Minimum density per station (area in km^2 per station)*
Coastal	2 750
Mountainous	1 000
Interior plains	1 875
Hilly/undulating	1 875
Small islands	300
Polar/arid	20 000

In general, a sufficient number of streamflow stations should be located along the main stems of large streams to permit interpolation of discharge between the stations. The specific location of these stations should be governed by topographic and climatic considerations. If the difference in flow between two points on the same river is not greater than the limit of error of measurement at the station, then an additional station is unjustified. In this context, it must also be stressed that the discharge of a small tributary cannot be determined accurately by subtracting the flows at two mainstream gauging stations which bracket the mouth of the tributary. Where the tributary flow is of special interest in such a case, a station on the tributary will be required. It will usually take its place as a secondary station in the minimum network. The streamflow stations may be interspersed with stage stations (section 20.2.2.2).

Wherever possible, the base stations should be located on streams with natural regimes. Where this is impractical, it may be necessary to establish additional stations on canals or reservoirs to obtain the necessary data to reconstruct the natural flows at the base stations. Computed flows past hydroelectric plants or control dams may be useful for this purpose, but provisions will have to be made for calibration of the control structures and turbines and for the periodic checking of such calibrations during the life of the plants.

Stations should be located on the lower reaches of the major rivers of the country, immediately above the river mouths (usually above tidal influence), or where the rivers cross borders. Stations should also be located where rivers issue from mountains and above the points of withdrawal for irrigation water. Other hydrometric stations are situated at points, such as where the discharge varies to a considerable extent, below the points of entry of the major tributaries, at the outlets from lakes, and at those locations where large structures are likely to be built.

To ensure adequate sampling, there should be at least as many gauging stations on small streams as on the main streams. However, for small streams, a sampling procedure becomes necessary as it is impracticable to establish gauging stations on all of them. The discharge of small rivers is strongly influenced by local factors. In highly developed regions, where even the smallest watercourses are economically important, network deficiencies are keenly felt even on streams draining areas as small as 10 km^2.

Stations should be installed to gauge the runoff in different geologic and topographic environments. Because runoff varies greatly with elevation in mountains, the basic network stations must be located in such a way that they can, more or less evenly, serve all parts of a mountainous area, from the foothills to the higher regions. Account should be taken of the varying exposure of slopes, which is of great significance in rough terrain. Similarly, consideration should be given to stations in districts containing numerous lakes, whose influence can be determined only through the installation of additional stations.

20.2.2.2 *River stages*

Stage (height of water surface) is observed at all stream-gauging stations to determine discharge. There are places where additional observations of water level only are needed as part of a minimum network:

(*a*) At all major cities along rivers, river stages are used for flood forecasting, water supply, and transportation purposes; and
(*b*) On major rivers, at points between stream-gauging stations, records of river stage may be used for flood routing and forecasting purposes.

20.2.2.3 *Lake and reservoir stages*

Stage, temperature, surge, salinity, ice formation, etc., should be observed at lake and reservoir stations. Stations should be established on lakes and reservoirs with surface areas greater than 100 km^2. As in the case of rivers, the network should sample some smaller lakes and reservoirs as well.

20.2.2.4 *Sediment discharge and sedimentation*

Sediment stations may be designed either to measure total sediment discharge to the ocean or to measure the erosion, transport and deposition of sediment within a country, basin, etc. In designing a minimum network, emphasis should be placed on erosion, transport, and deposition of sediment within a country. An optimum network would contain a sediment station at the mouth of each important river discharging into the sea.

Sediment transport by rivers is a major problem in arid regions, particularly in those regions underlain by friable soils and in mountainous regions where, for engineering applications, the amount of sediment loads should be known.

Although the densities given in Table 20.4 serve as guides in considering a basic network, the designer must be forewarned that sediment-transport data are much more expensive to collect than other hydrological records. Consequently, great care must be exercised in selecting the number and location of sediment-transport stations. Emphasis should be placed on those areas where erosion is known to be severe. After a few years of experience, it may be desirable to discontinue sediment measurements at those stations where sediment transport no longer appears to be of importance.

Sediment-transport data may be supplemented by surveys of sediment trapped in lakes or reservoirs. Echo sounding devices are useful for this purpose. However, information obtained in this way is not considered a substitute for sediment-transport measurements at river stations.

20.2.2.5 *Water quality stations*

The usefulness of a water supply depends, to a large degree, on its chemical quality. Observations of chemical quality, for the purposes of this *Guide*, consist of periodic

TABLE 20.4
Recommended minimum densities for sediment stations

Physiographic unit	*Minimum density per station (area in km^2 per station)*
Coastal	18 300
Mountainous	6 700
Interior plains	12 500
Hilly/undulating	12 500
Small islands	2 000
Polar/arid	200 000

sampling of water at stream-gauging stations and analyses of the common chemical constituents.

The number of sampling points in a river depends on the hydrology and the water uses. The greater the water quality fluctuation, the greater the frequency of measurement required. In humid regions, where concentrations of dissolved matter are low, fewer observations are needed than in dry climates, where concentrations, particularly of critical ions such as sodium, may be high.

As a minimum network, records of water quality should be obtained at the densities shown in Table 20.5. Additional guidance on water quality monitoring is provided in section 20.4.

20.2.2.6 *Water temperature*

The temperature of water should be measured and recorded each time a hydrometric station is visited to measure discharge or to obtain a sample of the water. The time of day of the measurement should also be recorded. At stations where daily stage observations are made, temperature observations should also be made daily. These

TABLE 20.5
Recommended minimum densities for water quality stations

Physiographic unit	*Minimum density per station (area in km^2 per station)*
Coastal	55 000
Mountainous	20 000
Interior plains	37 500
Hilly/undulating	47 500
Small islands	6 000
Polar/arid	200 000

observations, whose cost is negligible, may provide data which are useful in studies of aquatic life, pollution, ice formation, sources of cooling water for industry, temperature effects on sediment transport, or solubility of mineral constituents.

20.2.2.7 *Ice cover on rivers and lakes*

Regular observations of ice cover should include:

(*a*) Visual observations of various processes of ice formation and of ice destruction, with recording of date of first occurrence of floating ice, date of total cover, date of break up of the ice, and date at which ice has vanished completely. These observations should be made on a daily basis;

(*b*) Simultaneous measurement of ice thickness at two or three points near each selected hydrometric station should be made once every five to 10 days. The location of measurement points is chosen from detailed surveys of ice cover made at the beginning of the observing period of the stations.

20.3 **Groundwater observations**

While one aim of a groundwater observation programme is adequate national coverage, the regional density of observation wells will depend upon the characteristics of the hydrological units, the properties of the water-bearing material, and the importance of, and need for, the development of groundwater resources. Thus, studies of changes in groundwater level must be included in appraisals of groundwater, and networks must be designed to consider purposes other than measurement of groundwater levels, such as chemical changes, evaluation of natural and artificial replenishment, monitoring of pollution, and salt-water intrusion.

The purposes for which a network of observation wells may be established include the following:

(*a*) Determination of the depth to water table in large underdeveloped areas and of aquifer thickness and age;
(*b*) Determination of the direction of groundwater flow;
(*c*) Evaluation of the components of the groundwater balance;
(*d*) Determination of contacts with mineralized bodies of groundwater, especially the sea water/fresh water interface;
(*e*) Safeguarding water supplies against mineralization and pollution;
(*f*) Calibration of models of groundwater basins;
(*g*) Determination of safe field and exploitable reserves;
(*h*) Evaluating proposed water projects;
(*i*) Forecasting water levels and chemical composition under alternative schemes for managing the aquifer;
(*j*) Supervision of water exploitation and of artificial replenishment; and
(*k*) Assessment of environmental impacts of water projects.

The observations, measurements, and other activities should be planned according to the aims and purposes for which the network is designed. Water level measurements are but one of many parameters required to develop predictive models of the groundwater systems.

While minimum densities for groundwater have not been developed, other guidance on station location and sampling may be provided. The spacing of observation wells in a groundwater network depends on:

(*a*) The size of the area;
(*b*) The hydrological complexity of the area;
(*c*) The objectives of the network; and
(*d*) Financial limitations.

If several aquifers at different depths below land surface with different piezometric heads and salinities are under investigation, separate small-diameter boreholes should be installed in each aquifer (section 16.2). These boreholes may be only a few metres apart. The spacing may be different for each aquifer.

The observation wells in the network should be laid out according to a general geometrical pattern (a checkerboard or triangular pattern). However, the design must be flexible enough to allow the utilization of existing wells and accessibility for measurements.

A basic or minimum national network in underdeveloped areas should be dense enough to observe all main aquifers, the definition of which is based initially on available geological information. The following criteria should be considered in establishing the initial network in underdeveloped aquifers:

(*a*) The distance between two observation wells must be similar to the distance over which the geological configuration of the aquifer can be extrapolated;
(*b*) This distance will vary from place to place. The maximum distance between wells in extremely large areas in a basic network should not exceed 40 kilometres;
(*c*) Full use should be made of hydrogeological information from wells drilled for other purposes, such as oil exploration;
(*d*) Existing wells should be incorporated in the network to reduce the cost of drilling and installation of additional observational wells;
(*e*) In alluvial terraces of lower reaches of rivers, the hydraulic connection between the groundwater and the water level fluctuations in the river should be investigated. Full use should be made of existing hydrometric stations on rivers to reduce costly installations to a minimum; and
(*f*) In areas with phreatic aquifers in which the depth to the water table from the land surface is small, the density of the basic network should be increased by installing one observation well every five to 20 km^2. For intensive studies and for aquifer-management purposes, the density should be increased.

More intensive studies of groundwater regime, and therefore additional data, will be required where there is intensive development or overdevelopment of the aquifer, intensive irrigation or drainage systems, and special purposes to be served, such as study of salt water intrusion or groundwater networks connected with large engineering projects.

20.4 Specific requirements for water quality

There are several approaches to water quality monitoring. Monitoring can be accomplished through a network of strategically located long-term stations, by repeated short-term surveys, or by the most common approach, a combination of the two. In addition to the basic objectives of the programme, the location of stations should take into account the following factors:

(*a*) Existing water problems and conditions;
(*b*) Potential growth centres (industrial and municipal);
(*c*) Population trends;
(*d*) Cimate, geography and geology;
(*e*) Accessibility:
(*f*) Available manpower, funding, field and laboratory data handling facilities;
(*g*) Interjurisdictional considerations;
(*h*) Travel time to the laboratory (for deteriorating samples); and
(*i*) Safety of personnel.

The design of a sampling programme should be tested and assessed during its initial phase to ensure the effectiveness and efficiency with respect to the objectives of the study.

20.4.1 *Water quality parameters*

The parameters that characterize water quality may be classified in several ways, including physical properties (e.g., temperature, electrical conductivity, colour, turbidity), inorganic chemical components (e.g., dissolved oxygen, chloride, alkalinity, fluoride, phosphorous, metals), organic chemicals (e.g., phenols, chlorinated hydrocarbons, polycyclic aromatic hydrocarbons and pesticides), and biological components, both microbiological, such as faecal coliforms, and macrobiotic, such as worms, plankton and fish, which can indicate the ecological health of the aquatic environment.

A second classification is done according to the importance attached to the parameter. This will vary with the type of water body, the intended use of the water and the objectives of the monitoring programme. Water quality variables are sometimes grouped within two categories:

(*a*) Basic variables (Table 20.6);
(*b*) Use-related variables:
  (i) Drinking water supplies;
  (ii) Irrigation; and
  (iii) General quality for aquatic life.

TABLE 20.6
GEMS/WATER basic variables

	Rivers	*Lakes and reservoirs*	*Groundwaters*
General water quality:			
Water discharge/level	x	x	x
Total suspended solids	x	-	-
Temperature	x	x	x
pH	x	x	x
Electrical conductivity	x	x	x
Dissolved oxygen	x	x	x
Transparency	-	x	-
Dissolved salts:			
Calcium	x	x	x
Magnesium	x	x	x
Sodium	x	x	x
Potassium	x	x	x
Chloride	x	x	x
Fluoride	-	-	x
Sulphate	x	x	x
Alkalinity	x	x	x
Nutrients:			
Nitrate plus nitrite	x	x	x
Ammonia	x	x	x
Total phosphorus, dissolved	x	x	-
Total phosphorus, particulate	x	x	x
Total phosphorus, unfiltered	x	x	-
Silica reactive	x	x	-
Organic matter:			
Chlorophyll *a*	x	x	-

A third classification that is highly relevant to sampling procedures is done according to stability:

(*a*) Conservative (does not change materially with time);
(*b*) Non-conservative (changes with time, but can be stabilized for at least 24 hours by appropriate treatment); or
(*c*) Non-conservative (changes rapidly with time and cannot be stabilized).

The first two groups can be measured by representative water samples subsequently analysed in the laboratory. The third group needs to be measured *in situ*.

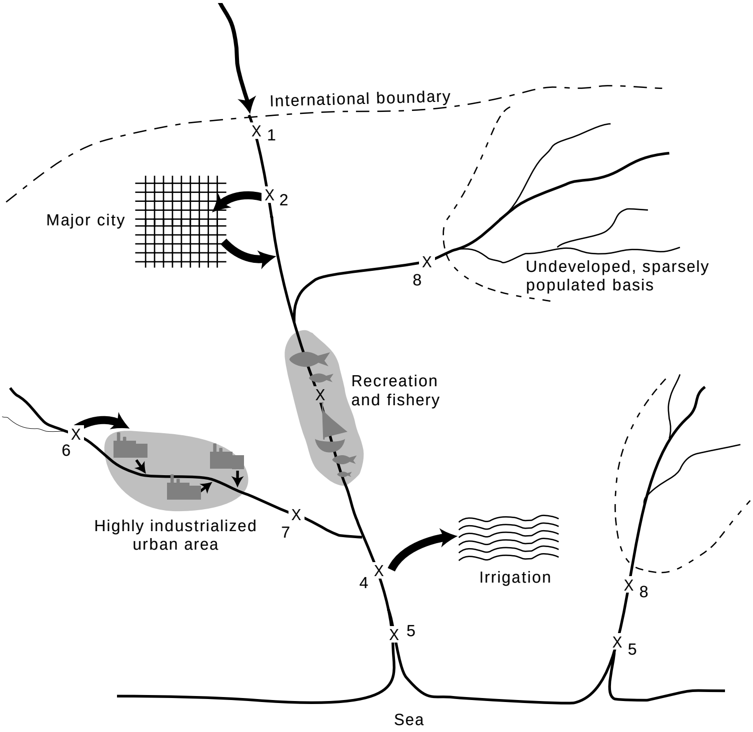
20.4.2 ***Surface-water quality***

Sometimes the programme objectives will precisely define the best locations for sampling in a river or lake system. For example, in order to determine the effect of an effluent discharge on a receiving stream, sampling locations upstream and downstream of the discharge would be required. In other cases, both location and frequency of sampling will be determined by anti-pollution laws or by a requirement for a specific use of a water body. For example, a permit to discharge surface waters may outline details of monitoring, such as location, number of samples, frequency and parameters to analyse.

Sampling strategies are quite different for different kinds of water bodies and media, e.g. water, sediment, or biota. Rivers mix completely within distances ranging from several kilometres to a few hundred kilometres of any point source of pollution. Lakes may be vertically stratified because of temperature or inflows of high-density saline water. Groundwater tends to flow very slowly, with no surface indication of the changes in its solutes taking place below.

If the objective concerns the impact of human activities on water quality in a given river basin, the basin can be separated into natural and altered regions. The latter can be further subdivided into stationary zones (over periods longer than 10 years, say), and those in which the impact is variable, such as agricultural, residential, and industrial zones. In acid-deposition studies, an important factor is the terrain sensitivity to the deposition. Figures 20.3 and 20.4 give some examples on how sampling stations could be located to meet specific objectives on river and lake systems.

The next step in choosing sampling locations is to collect relevant information about the region to be monitored. The information sought includes geological, hydrological, and demographic aspects, as well as the number of lakes and streams, sizes and locations of aquifers, locations of existing water quality or stream gauging stations, flow rates, climatic conditions in the catchment area, historical developments, present and potential municipal and industrial centres, current water intakes and waste outlets, natural salt springs, mine drainage, irrigation schedules, flow regulation (dams), present and planned water uses, stream or lake water quality

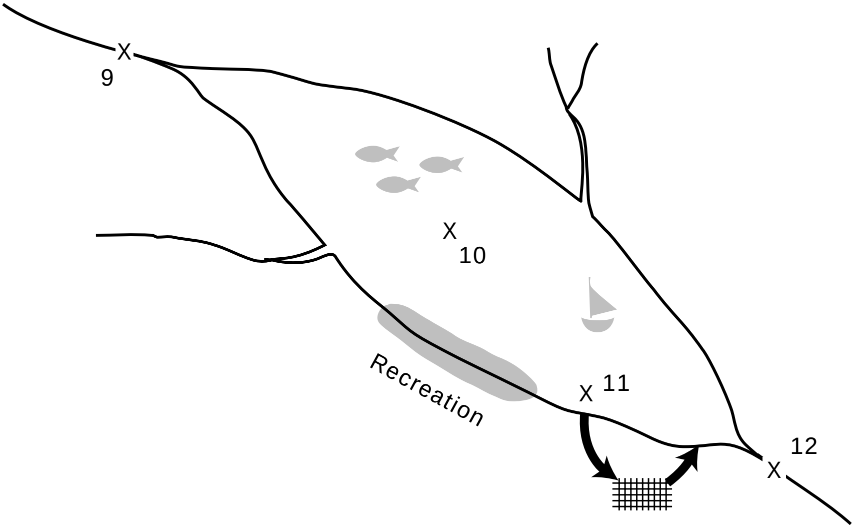


Station	*Criteria*
1	Immediately downstream of an international boundary
2	Diversion for public supply of large town
3	Important fishing, recreation and amenity zone
4	Diversion for large-scale agricultural irrigation
5	Fresh water tidal limit of major river
6	Diversion for large industrial supply
7	Downstream of industrial effluent discharges and important tributary influencing main river
8	Baseline station, water in natural state

Figure 20.3 — Monitoring site: rivers.

objectives or standards, accessibility of potential sampling sites (land ownership, roads, airstrips), availability of services such as electricity, and existing water quality data. Figure 20.5 shows the steps to be followed in selecting sampling sites.

The distance downstream to the point of complete mixing is roughly proportional to the stream velocity and to the square of the width of the channel. Rivers



Station	*Criteria*
9	Principal feeder tributary
10	General water quality of lake
11	Water supply for major city
12	Water leaving lake

Figure 20.4 — Monitoring site: lakes.

are usually sufficiently shallow that vertical homogeneity is quickly attained below a source of pollution. Lateral mixing is usually much more slowly attained. Thus, wide swift-flowing rivers may not be completely mixed for many kilometres downstream from the input point.

Various protocols are recommended to determine representative sampling in the cross-section of the river, e.g., six samples analysed in duplicate, at three positions across the river and two depths or mid-depth samples at the quarter points, or other equal distance points across the width of the river. If a representative sample cannot be obtained, it is advisable to select another site, either immediately upstream or downstream. The other alternative is to obtain a flow-weighted composite sample from samples collected on cross-section verticals.

Longitudinal mixing of irregular or cyclic discharges into a river will have a secondary influence on the location of a sampling site. Their effects need to be taken into account in deciding the frequency of sampling and interpreting data.

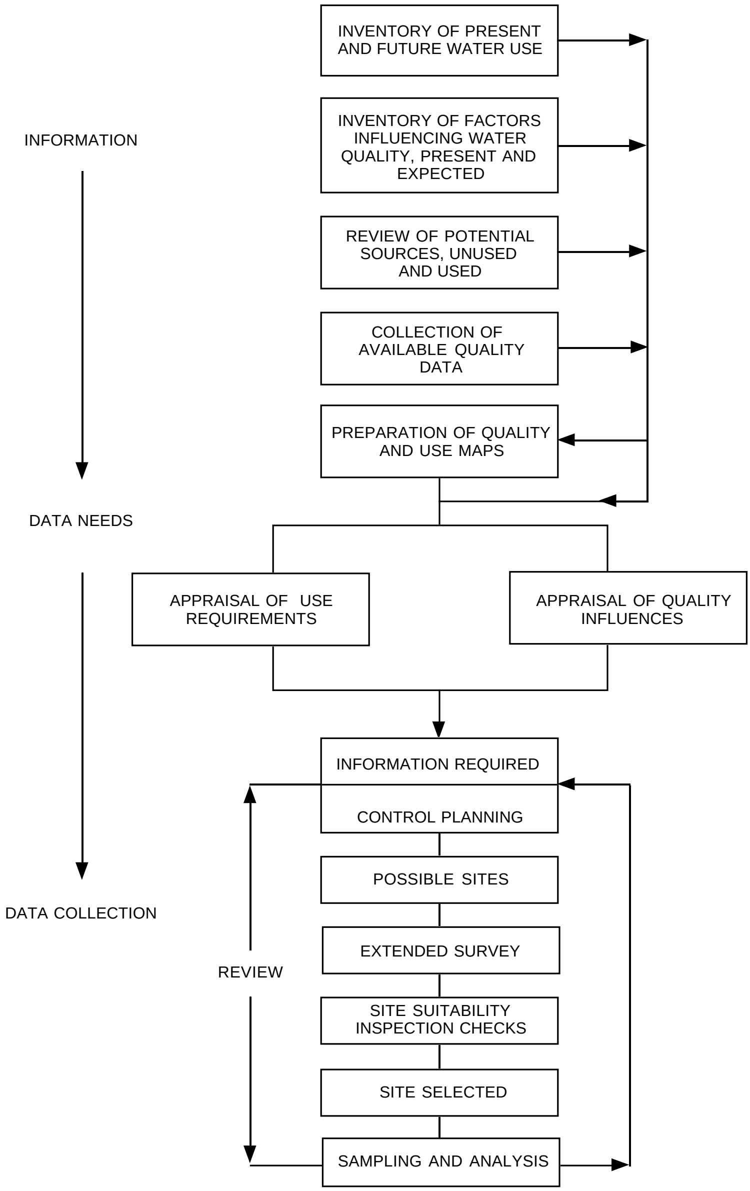


Figure 20.5 — Scheme for the selection of water quality sampling sites.

Sampling frequency depends on the purpose of the network, on the relative importance of the sampling station, on the range of measured values, on the time variability of the parameter of interest, and on the availability of resources. In the absence of sufficient background information, an arbitrary frequency based on knowledge of local conditions is chosen. After sufficient data have been collected, the frequency may be adjusted to reflect the observed variability. The frequency is also influenced by the relative importance of the station and whether or not the concentrations approach critical levels for some substances measured.

For lake stations, the recommended practice is to sample five consecutive days during the warmest part of the year and five consecutive days every quarter. Special cases include temperate-zone lakes that experience stratification. These should be sampled at least six times a year, together with the occasional random sample, to cover the following periods: during open water prior to summer stratification, during mixing following summer stratification, under ice, and during the periods of snow melt and runoff. Similarly, additional samples of rivers should be taken, if possible, after storm events and during snow melt and runoff.

When parameters are plotted against time, some cyclic variation may be apparent amidst the random fluctuations. The detection of cyclic events requires a sampling interval no longer than one-third of the shortest cycle time and sampling over a period at least ten times longer than time of the longest cycle. Therefore long-period cycles will not be verified in the initial surveys, but become apparent during the operation of the network. In order to detect the cyclic variations, some random sampling is desirable, e.g., on different days of the week or different hours of the day.

20.4.3 *Precipitation quality*

In general, sampling sites should be selected to give accurate and representative information concerning the temporal and spatial variation of chemical constituents of interest. Important factors to take into consideration are prevalent wind trajectories, sources for compounds of interest, frequency of precipitation events (rain, snow, hail), and other meteorological processes that influence the deposition. There are also local criteria to be considered:

(*a*) No moving sources of pollution, such as routine air, ground, or water traffic, should be within 1 000 metres of the site;

(*b*) No surface storage of agricultural products, fuels, or other foreign materials should be within 1 000 metres of the site;

(*c*) Samplers should be installed over flat undisturbed land, preferably grass-covered, surrounded by trees at distances greater than five metres from the sampler. There should be no wind-activated sources of pollution nearby, such as cultivated fields or unpaved roads. Zones of strong vertical eddy currents, eddy zones leeward of a ridge, tops of wind-swept ridges and roofs of buildings, particularly, should be avoided because of strong turbulence;

(*d*) No object taller than the sampler should be within five metres of the site;

(*e*) No object should be closer to the sampler than a distance of 2.5 times the height by which the object extends above the sampler. Particular attention must be given to overhead wires;

(*f*) The collector intake should be located at least one metre above the height of existing ground cover to minimize coarse materials or splashes from being blown into it;

(*g*) Automatic samplers require power to operate lids and sensors, and in some cases for refrigeration in the summer and thawing in the winter. If power lines are used, they must not be overhead. If generators are used, the exhaust must be located well away and down-wind from the collector; and

(*h*) To address issues on a continental scale, sites should preferably be rural and remote, with no continuous sources of pollution within 50 kilometres in the direction of the prevalent wind direction and 30 kilometres in all other directions.

It may not be possible to meet all of these criteria in all cases. The station description should refer to these criteria and indicate the exact characteristics of each location chosen as a sampling site.

In the case of large lakes, the precipitation over the lake may not be as heavy as along the shores and the proportion of large particles may be smaller. In order to sample in the middle of a lake, the sampler can be mounted on a buoy, rock, shoal or small island.

Event sampling is the preferred method for sampling precipitation. Each rain shower, storm, or snowfall constitutes an event. The analysis of event-precipitation samples enables pollutants associated with a particular storm to be determined, and a wind-trajectory analysis can determine probable sources. However, this sampling regime is very sensitive. The same statistical considerations concerning frequency of sampling apply here as for surface-water sampling.

20.4.4 ***Sediment quality***

Most of the selection criteria outlined in previous sections also apply to sampling for sediments. Therefore only additional special recommendations will be described here.

For rivers where sediment-transport data are required, it is necessary to locate the sampling sites near a water quantity gauging station so that accurate stream-discharge information is available at all times. Sampling locations immediately upstream from confluences should be avoided because they may be subjected to backwater phenomena. In streams too deep to wade, locate sampling sites under bridges or cableways. When sampling from bridges, the upstream side is normally preferred. Sampling in areas of high turbulence, such as near piers, is often unrepresentative. Attention also must be paid to the accumulation of debris or trash on the piers, as this can seriously distort the flow and hence the sediment distribution. An integrated sample obtained by mixing water from several points in the water column according to their average sediment load can be considered as a representative sample as long as there is good lateral mixing.

The best places to sample bottom deposits in fast-flowing rivers are in shoals, at channel bends, and at mid-channel bars or other sheltered areas where the water velocity is at its minimum.

Sampling sites should be accessible during floods, since sediment-transport rates are high during these times.

For identification of peak pollution loads in rivers, two cases must be considered:

(*a*) For pollution from point sources, sampling should be done during low-flow periods, when pollution inputs are less diluted;

(*b*) When pollutants originate from diffuse sources such as runoff from the land of agricultural nutrients or pesticides, sampling must be focused on flood periods during which the pollutant is washed out of the soil.

If one of the objectives is to quantify the transport of sediment in the river system, it should be noted that peak concentrations of sediment do not necessarily correspond with times of peak flow. Also, a series of high flow rates will lead to progressively lower sediment peaks — an exhaustion effect arising from the depletion of material available for resuspension.

For lakes, the basic sampling site should be located at the geographic centre of the lake. If the lake is very large (area >500 km^2), several base stations may be needed. If various sediment types must be sampled, then data from acoustic surveys (echo-sounders) can be used both to identify the type of surficial material (sand, gravel or mud) and to indicate the presence of layering below the surface.

Secondary sampling sites should be located between the base station and major tributary inlets or pollutant sources. A common strategy is to place points down the long axis of the lake with occasional cross lines. Three to five stations should usually give a good approximation to the sediment quality of an average size lake. For statistical validity, however, a larger number of sampling sites will probably be required.

Sampling frequency in lakes is affected by the generally low concentrations of suspended sediment. Sediment traps should be operated during the periods of maximum and minimum algal productivity and at times of high input of sediment from rivers.

Repeat sampling of bottom sediments in lakes need to take into account the rates of sediment accumulation. Basins in cool temperate climates often have accumulation rates in the order of 0.1-0.2 millimetre per year. A resampling period of five years would then be too soon to provide worthwhile new information, unless the presence of a new pollutant is to be tested.

20.4.5 ***Groundwater quality***

A great deal of hydrogeological information may be necessary to plan the sampling strategy for aquifers. Water levels, hydraulic gradients, velocity, and direction of water movements should be known. An inventory of wells, boreholes, and springs fed by the aquifer should be drawn up, and details of land use should be recorded.

Groundwater samples are taken from drainage water, open wells, and drilled wells. Wells should be sampled only after they have been pumped long enough to ensure that a fresh sample has been obtained. This is particularly necessary where a well has a lining subject to corrosion.

An existing well is a low-cost choice, although they are not always at the best location or made of non-contaminating materials. A well that is still in use and pumped occasionally is preferable to one which has been abandoned. Abandoned or unused wells are often in poor condition with damaged or leaky casings and corroded pumping equipment. It is often difficult to measure their water levels, and they may be safety hazards.

Changes in groundwater can be very slow and are often adequately described by monthly, seasonal, or even annual sampling schedules.

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CHAPTER 21
COLLECTION OF DATA

21.1 Site selection

Once the network design phase has been completed, the operational requirements have established the general location of the data-collection sites, and the types of instrumentation have been identified, the best specific site within the general location is selected to meet the requirements of the instrumentation as outlined in Part B of the *Guide*. Modifications to the site may be necessary to ensure the quality of the data, e.g., clearing and control stabilization.

When a site has been selected and the instrumentation has been installed, two types of data will be collected at the site — descriptive details of the site and its location, and the hydrological observations that it has been established to measure.

Once established, the installation should be operated and maintained to its predetermined standard. In general, this involves the execution of an adequate schedule of inspection and maintenance to ensure continuity and reliability of data, and the development of routine check measurements and calibrations to ensure data of the required accuracy.

21.2 Station identification

Two aspects should be considered to ensure the historical documentation of a data-collection site's details — the institution of an identification system, and the archival of descriptive information.

21.2.1 *Identification of data-collection sites*

Every permanent site should be given a unique identifier that will be used to denote all data and other information pertinent to the site. Such identifiers are usually numeric, but they may also be alphanumeric.

Frequently, more than one service or agency may be operating data-collection sites within the same region or country. The acceptance by all parties of a single, unique system of site identification will facilitate data interchange and the multiparty coordination of data-collection activities. The region chosen should be determined by drainage basin(s) or climatic zones, and a portion of a site's identification should reflect its location within the region.

The site identification can be simply an accession number, i.e., a sequential number assigned as stations are established. Site identification in NAQUADAT, the Canadian National Water Quality Data Bank, represents a sophisticated system designed for computer processing. It has a 12-digit alphanumeric code, that is the key element in storing and retrieving data in the computer system. This number is composed of several subfields [1]:

(*a*) Type of water — a two-digit numerical code indicating the type of water sampled at any given location, such as streams, rivers, lakes, or precipitation. The meaning of this code has been extended to include other types of aquatic media. A list of all currently assigned codes is given in Table 21.1;
(*b*) Province, basin, and sub-basin — three pairs of digits and letters identifying the province, basin, and sub-basin;
(*c*) Sequential — a four-digit number assigned usually by a regional office.

TABLE 21.1
NAQUADAT codes for types of aquatic media

Type	*Code*	*Subtype*	*Code*
Surface water	0	Stream-channel	0
		Lake	1
		Estuary	2
		Ocean-sea	3
		Pond	4
		Impounded reservoir	5
		Harbour	6
		Ditch	7
		Runoff	8
		Unknown	9
Groundwater	1	Well-sump	0
		Spring	1
		Piezometer well	2
		Tile drain	3
		Bog	4
		Household tap	8
		Unknown	9
Waste-treated and untreated	2	Industrial	0
		Municipal	1
		Mining	2
		Livestock waste	3
		Unknown	9

Table 21.1 (*continued*)

Precipitation	3	Rain	0
		Snow	1
		Ice (precipitated)	2
		Mixed precipitation	3
		Dry fallout	4
Treated supply	4	Municipal	0
		Industrial	1
		Mining	2
		Private (individual)	3
		Other communal works	4
		Municipal distribution	5
		Municipal treatment plant (intermediate)	6
		Treatment residue or sludge	7
		Other	9
Sediments, soils	5	Stream channel	0
		Lake bottom	1
		Stream bank	2
		Lake bank	3
		Contaminated by soil	4
		General soil	5
		Effluent irrigation soil	6
		Sludge conditioned soil	7
		Other	8
Industrial waste water	6	Storm water	0
		Primary influent	1
		Primary effluent	2
		Final effluent	3
		Sludge	4
		Special problem	5
		Other	6
Municipal waste water	7	Raw	0
		Primary lagoon effluent	1
		Secondary lagoon effluent	2
		Conventional primary effluent	3
		Conventional secondary effluent	4
		Advanced waste water treatment effluent	5

Table 21.1 (*continued*)

Municipal waste water (*contd.*)	7	Disinfected effluent	6
		Raw sludge	7
		Digested sludge	8
		Other	9
Miscellaneous waste water	8	Raw	0
		Primary lagoon effluent	1
		Secondary lagoon effluent	2
		Conventional primary effluent	3
		Conventional secondary effluent	4
		Advanced waste water treatment effluent	5
		Disinfected effluent	6
		Raw sludge	7
		Digested sludge	8
		Other	9
Aquatic biota	9	To be categorized later (e.g., fish, phytoplankton, benthos, macrophytes, periphyton, zooplankton)	

Source: World Meteorological Organization, 1988: *Manual on Water Quality Monitoring — Planning and Implementation of Sampling and Field Testing.* Operational Hydrology Report No. 27, WMO–No. 680, Geneva.

For example, station number 00BCO8NA0001 indicates that the sampling site is on a stream, in the province of British Columbia, in basin 08, and sub-basin NA, and the sequence number is 1. Station 010N02IE0009 is on a lake, in the province of Ontario, in number 02 basin and in IE sub-basin and the sequential number is 9.

WMO has accepted a coding system for station identification [2] that is similar to (*b*) and (*c*) of the NAQUADAT system.

Another well known coding system for sampling points is the River Mile Index used by the Environmental Protection Agency of the United States as part of the STORET system. In this system, the location of a sampling point is defined by its distance and hydrological relationship to the mouth of a river system.it includes major and minor basin codes, terminal stream numbers, the direction and level of streamflow, the mileages between and to confluences in the river system, and a code to identify the stream level on which the point is located.

21.2.2 *Descriptive information*

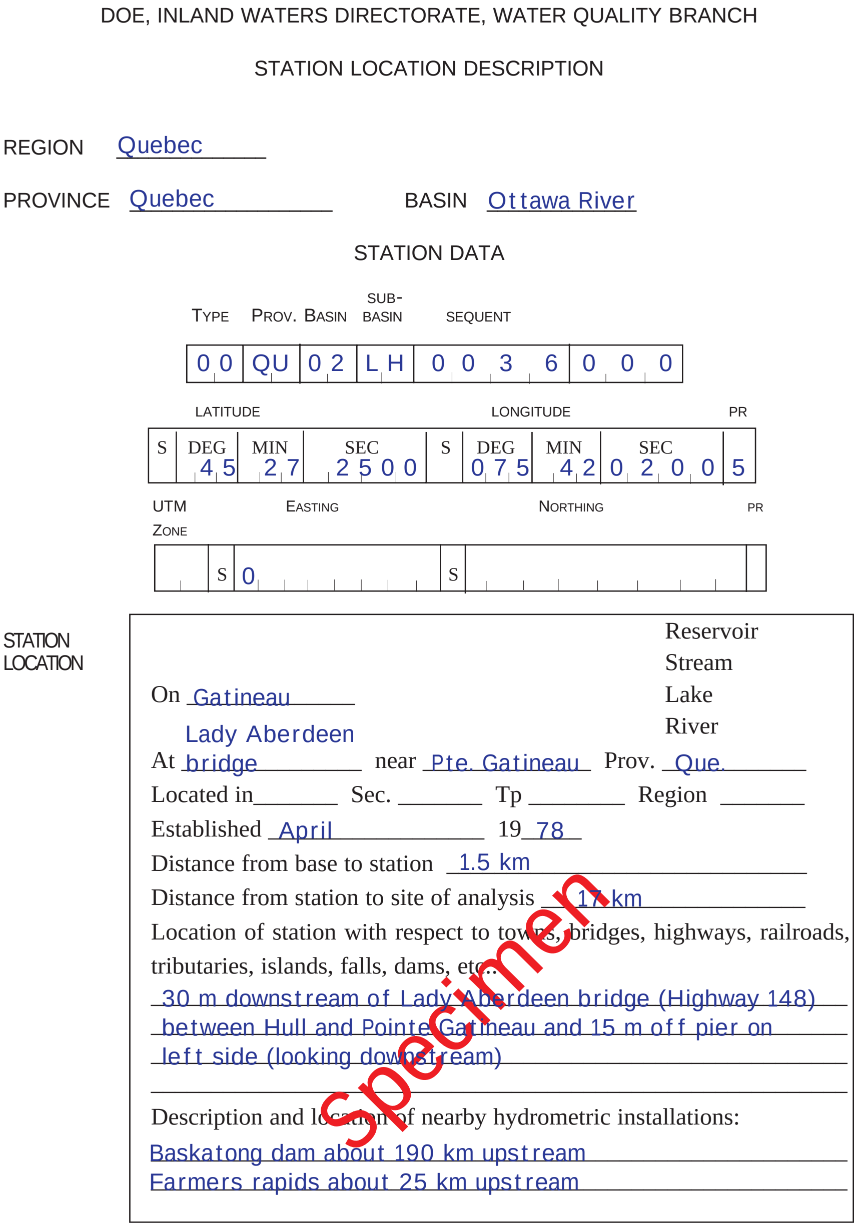
In many instances the value of the data will be enhanced if the user can relate it to the details of the history of its collection. To this end, a station registration file should record the details of each station. The level of detail will of course vary with the parameter monitored. Typical information would include the station name and location details, the station type, the associated stations, establishing/operating/owner authorities, the elevation details, the frequency of observation, the operating periods, and the details of installed equipment. Additional items specific to the station type should also be included. Selected information from this text file should be attached routinely to any data output (Chapter 25).

A historical operations file of more detailed information should also be prepared for release as required (Chapter 25). Again, the level of detail will vary with the type of observations being recorded. A stream station may include details such as climate zone and rainfall and evaporation notes, geomorphology, landforms, vegetation, land use and clearing, and station details. Typical components of such a file would include the station description, a detailed sketch of the site, a map showing the location of the site within the region, and a narrative description of the site and region. Some examples of the format of such files can be found in [3] and [4]. Figure 21.1 is an example of one format.

21.2.2.1 *Station description*

An accurate description of the sampling location includes distances to specific reference points. It is important that these reference points be permanent and clearly identified. For example, “5 metres north-west of the willow sapling” is a poor designation for a data site. An example of a useful description is “30 metres downstream from Lady Aberdeen Bridge (Highway 148), between Hull and Pointe Gatineau and 15 metres off the pier on the left side looking downstream”. The date that the station was first established and data collection was commenced should also be recorded.

For streamflow and water quality data stations, location information should also include descriptions of the water body above and below the station. These should include water depths, a description of the banks on either side of the water body, and the bed material. A description of the water body should include any irregularities in morphology that might affect the flow of water or its quality. Such irregularities may include a bend in a river, a widening or narrowing of the channel, the presence of an island, rapids or falls, or the entry of a tributary near the station. A description of the banks should mention slope, bank material, and extent of vegetation. Bed or sediment material may be described as rocky, muddy, sandy, vegetation-covered, etc.. Station-location descriptions should mention seasonal changes that may hinder year-round data collection. Additional information in the case of lakes could include surface area, maximum depth, mean depth, volume, and water residence time.



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STATION LOCATION DESCRIPTION

REGION Quebec

PROVINCE Quebec BASIN Ottawa River

STATION DATA

TYPE	PROV.	BASIN	SUB-BASIN	SEQUENT	
0 0	QU	0 2	L H	0 0 3 6	0 0 0

LATITUDE				LONGITUDE				PR
S	DEG	MIN	SEC	S	DEG	MIN	SEC	
	4 5	2 7	2 5 0 0		0 7 5	4 2	0 2 0 0	5

UTM ZONE		EASTING		NORTHING	PR
	S	0	S		

STATION LOCATION

Reservoir
Stream
Lake
River

On Gatineau

At Lady Aberdeen bridge near Pte. Gatineau Prov. Que.

Located in ________ Sec. ________ Tp ________ Region ________

Established April 19 78

Distance from base to station 1.5 km

Distance from station to site of analysis 17 km

Location of station with respect to towns, bridges, highways, railroads, tributaries, islands, falls, dams, etc...

30 m downstream of Lady Aberdeen bridge (Highway 148)
between Hull and Pointe Gatineau and 15 m off pier on
left side (looking downstream)

Description and location of nearby hydrometric installations:

Baskatong dam about 190 km upstream
Farmers rapids about 25 km upstream

Figure 21.1 — Station-location forms.

STATION DESCRIPTION

Direction of flow:

South-east

Description of channel above station:

Permanent log boom on right, gradual curve to left

Description of channel below station:

Gradual widening before emptying into Ottawa r.; main current on left, slight backwater on right

Description of left bank:

Approx. 3 m drop to river; slope allows only shrubby vegetation

Description of right bank:

Edge of park land; gentle slope

Bed: rocky, gravel, sandy, clean, vegetated:

Probably wood chips, muddy

Approximate dimensions and descriptions of lakes and/or reservoirs:

None

OBSERVATIONS

Natural conditions and/or control installations which may affect flow regimes:

Baskatong dam

Farmers rapids

Sources of chemical or physical inputs:

Logs, local sewage input

Figure 21.1 — Station-location forms (*continued*).

Additional information about conditions, either natural or man-made, which may have a bearing on the data should be recorded. Past and anticipated land disturbances and pollution sources should be mentioned, e.g., forest fires, road construction, old mine workings, and existing and anticipated land use.

21.2.2.2 *Detailed sketch of station location*

A sketch of the location and layout of the station (including distances expressed in suitable units) with respect to local landmarks and permanent reference points should be prepared (Figure 21.2). Sampling or measuring sites and equipment locations should be prominently shown on the sketch.

21.2.2.3 *Map*

A large-scale map (Figure 21.3) that locates the site with respect to roads, highways, and towns should be included. The combination of the map and the sketch of the station location should provide complete location information. An investigator travelling to the site for the first time should have enough information to locate the station confidently and accurately.

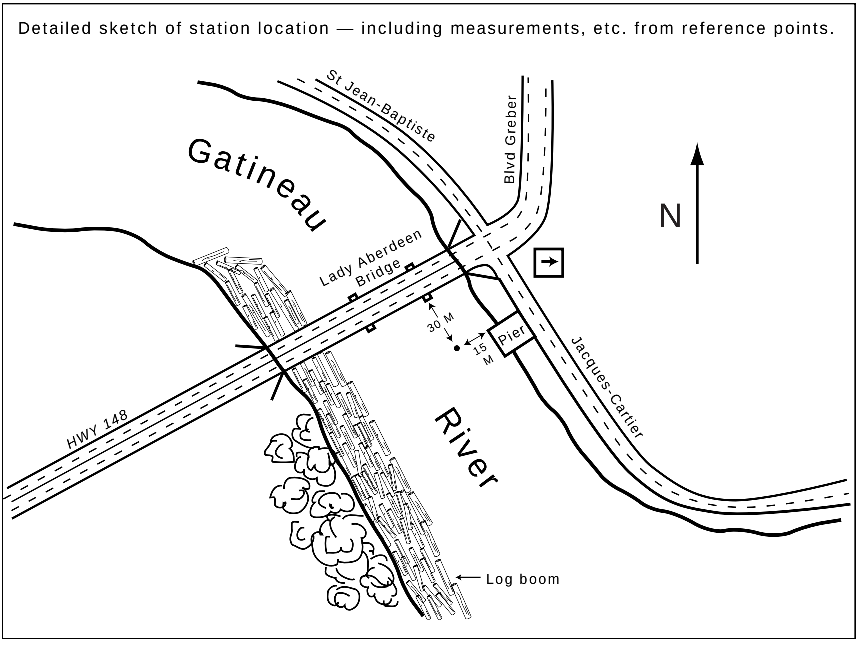


Figure 21.2 — Sketch of station layout.

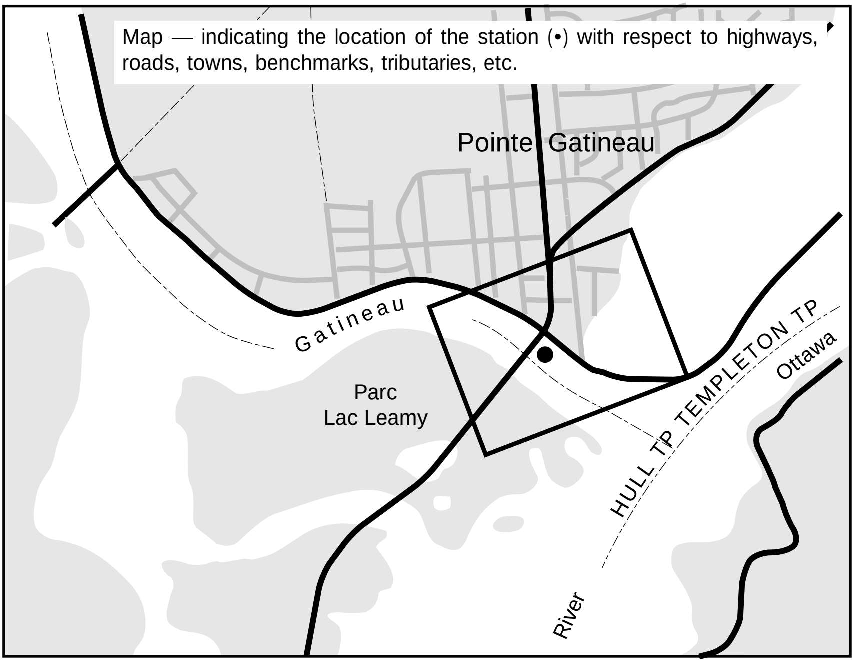


Figure 21.3 — Station-location map.

21.2.2.4 *Coordinates*

Geographical coordinates are recorded as latitude and longitude, universal transverse mercator (UTM) coordinates, and, if the site is on a stream, its distance upstream from a reference point, such as a reference station or a river mouth. National grid references, if available, should also be provided. For the international GLOWDAT (i.e., GEMS/WATER data bank [3] station) one entry is the WMO code for the octant of the globe for the northern hemisphere: 0, 1, 2 and 3 for 0-90 degrees W, 90-180 W, 180-90 E and 90-0 E, respectively [5]. Correspondingly, for the southern hemisphere the codes are: 5, 6, 7, and 8 for 0-90 W, 90-180 W, 180-90 E and 90-0 E [3].

Latitude and longitude values should be obtained from 1:50 000 or 1:250 000 topographical maps. Points on a 1:250 000 map can be located to about ± 200 metres and on a 1:50 000 scale to about ± 40 metres [3]. If available, navigational charts can be used to provide more accurate values than the topographical maps.

21.2.2.5 *Narrative description*

For streamflow and water quality sites, it is recommended that the narrative description begin with the name of the river, stream, lake, or reservoir followed by its location (e.g., upstream or downstream) and its distance (to 0.1 kilometre or better) from the nearest town, city, important bridges, highways, or other fixed landmarks. The name of the province, territory, or other geopolitical division should also be included.

Information concerning changes at the site, including instrumentation changes, should be added to the narrative description to provide a historical description of the site and the region that it represents. Chapter 25 contains a suggested format for such information.

21.3 Frequency and timing of station visits

The frequency and timing of readings and thus visits to the site should be determined by the anticipated data usage and should be adequate to define the observations over time. Station visits will, thus, be for purposes of observation or collection of data and for maintenance of the site.

When the variable of interest at the site is changing rapidly, visits to manual stations must be more frequent if a valid record is to be maintained. Under such conditions, it may be more efficient to install automatic recording equipment if funds and trained staff are available. This applies particularly to rainfall and stage data, where more frequent observations are desirable for hydrological purposes during storms and flood periods, as well as in tidal reaches of rivers.

21.3.1 *Manual stations*

There is considerable merit in encouraging that observations at climatological and hydrometrical stations be taken at specified synoptic hours. In WMO [6], the time at which three-hourly and six-hourly weather observations are taken at synoptic stations are 0000, 0300, 0600, 0900, 1200, 1500, 1800, and 2100 UTC. In most countries, such stations are the key stations of the meteorological and climatological observation programmes. If the observer is to take three observations per day, the synoptic hours most conveniently related to normal times of rising and retiring and that nearest noon should be specified. For stations at which only one or two observations per day are taken, it should be possible to select synoptic hours for the observations. It is recommended that all observers making only one observation per day should have a common observation time, preferably in the morning.

While it is desirable to have regular observations at synoptic hours, in some cases, this will not be possible. In these cases, it is important that observations be taken at the same time each day and that this time be recorded in UTC or local standard time using 24-hour clock designations. If “summer time” (daylight saving time) is introduced for part of the year, arrangements should be made to have observations taken at the same hour, by UTC, as in the period prior to and following “summer time”.

The designated time of the observation should be the end of the time at which the set of observations is taken at a station. The set of observations should be taken, if possible, within the 10-minute period prior to the stated observational time. However, it is important that, whether the observation is taken at a standard time or not, the actual time of observation must be recorded carefully. In tidal reaches of rivers, the times of observation should be related to the tidal cycle.

21.3.2 *Recording stations*

The frequency and timing of visits to recording stations will be constrained by the length of time that the station can be expected to function without maintenance. For example, some continuous rainfall recorders record on a weekly strip chart and, thus, require weekly visits to remove and replace charts. Other instruments have much larger data storage capabilities and, therefore, require less frequent visits. A balance must be achieved between the frequency of the visits and the resultant quality of the data collected. Too long of a time between visits may result in frequent recorder malfunction and, thus, in loss of data, while frequent visits are both time consuming and costly. Various studies have been carried out on the cost effectiveness and efficiency of data collection. Further details are found in the WMO *Economic and Social Benefits of Meteorological and Hydrological Services* [7].

The frequency of the visits may also be determined by accuracy requirements of the data. Some data-collection devices may suffer a drift in the relationship between the variable that is recorded and that which the recorded value represents. An example of this is a non-stable stage-discharge relationship. In such cases, visits to the station are required periodically in order to recalibrate the equipment or the measurement equations.

The introduction of data loggers and telephone/satellite data transmission may have a significant impact on station inspection/data-collection frequencies (section 21.5.3). However, it should be noted, that in order to ensure the quality of the data, regular station maintenance is necessary.

21.4 **Maintenance of collection sites**

The following maintenance activities should be conducted at data-collection sites at intervals determined to ensure that the quality of the data being recorded is adequate. These activities should be conducted primarily by the observer responsible for the sites. However, they may occasionally be performed by an inspector (section 22.1.1).

All collection sites:

(*a*) Service the instruments;
(*b*) Replace or upgrade instruments, as required;
(*c*) Retrieve or record observations;

(*d*) Perform the recommended checks on retrieved records;
(*e*) General check of all equipment (e.g., transmission lines, etc.);
(*f*) Check and maintain the site to the recommended specifications;
(*g*) Check and maintain access to the station;
(*h*) Record, in note form, all of the above activities;
(*i*) Comment on changes in land use or vegetation; and
(*j*) Clear debris and overgrowth from all parts of the installation.

Streamflow collection sites:

(*a*) Check the bank stability, as necessary;
(*b*) Check the level and condition of gauge boards, as necessary;
(*c*) Check and service the flow-measuring devices (cableways, etc.), as necessary;
(*d*) Check and repair control structures, as necessary;
(*e*) Regularly survey cross-sections and take photographs of major station changes after events or with vegetation or land-use changes;
(*f*) Record, in note form, all of the above activities and their results; and
(*g*) Inspect the area around or upstream of the site, and record any significant land use or other changes in related hydrological characteristic.

Further details are found in the WMO *Manual on Stream Gauging* [8]

Flood gauging cannot be programmed as part of a routine inspection trip because of the unpredictable nature of floods. A flood-action plan should be established prior to the beginning of the storm season and should include priority sites and types of data required. If flood gaugings are required at a site, the preparations must be made during the preceding dry season so that all is ready should high flow occur. Preparations include:

(*a*) Upgrade site access (helipad, if necessary);
(*b*) Equip a temporary camp site with provisions; and
(*c*) Store and check gauging equipment.

21.5 **Observations**

The components of data collection are listed in Table 21.2.

21.5.1 ***Manual stations***

At the very minimum, observers should be equipped with field notebooks and/or station journals in which the original observations are recorded as they are taken. Forms should also be provided to permit the observer to report observations daily, weekly, fortnightly, or monthly, as required. The field notebook or station journal should be retained by the observer in the case of the loss of the report in transit.

TABLE 21.2
The components of data collection

Data collection		
Data capture		*Transmission*
Sensing	*Recording*	
1. Visual Water level gauge, land use, site description, soil texture, etc.	1. Field notebook Text descriptions and element or parameter values	1. Manual Field observers Postal service Telephone
2. Mechanical Raingauge, thermometer, current meter, soil penetrometer	2. Field data sheet Purpose designed for particular text descriptions and element or parameter values May be pre-coded for subsequent computer input purposes	2. Automatic (Telemetry) Telephone Dedicated land line Radio Satellite
3. Electrical Thermistor, radiometer, pressure transducer, conductivity probe	3. Charts Strip charts with element value continuously recorded by pen tracing	
	4. Computer compatible media (*a*) Manually recorded Mark sense forms Multiple choice forms (*b*) Automatically recorded Cassette Paper tape Solid state memory	

NOTE: The table applies to elements or parameters observed in the field. There are notable groups of data, e.g., in soils and water quality, where laboratory analysis of physical samples are performed. Here the data-collection system almost invariably is:
(*a*) Mechanical sampling;
(*b*) Notebook/data sheet field entries.

The report forms should be designed to permit easy copying of the results from the field notebook or station journal. A good approach is to have the report form identical to a page in the notebook or journal. At least, the various elements should be in the same columns or rows in both. Space should be allowed in the journal and, perhaps, in the report form for any conversions or corrections that may have to be applied to the original readings.

Alternatively, an observation notebook with carbon paper between successive sheets will permit easy preparation of an original form for dispatch to the central office, and a copy for the local station record. This is not a satisfactory procedure where the notebook is to be carried into the field as moisture can easily make the entries illegible. In the case of automatic data processing, the report forms may also be coding forms suitable for direct conversion to computer medium. Data may also be keyed directly into a computer that is either portable or permanently located at the collection site.

The value of data can be greatly enhanced — or devalued — by the standard of the accompanying documentation. Observers should be encouraged to comment on any external influences that may affect observations, whether they be related to equipment, exposure, or short-term influence. In addition, input formats and forms should be flexible enough both to allow comments to be appended and for these comments to be accessible with the final data. It is important that published comments are expressed in standard terminology, and it is preferable that correct vocabulary be employed in the field report.

There is also reason for setting up the processing system so that quality coding or tagging is carried out as the observations are made. This is particularly applicable to manual observations because it encourages that judgements be made while the conditions are being observed. Recent advances that will minimize errors in processing data from field measurement books include optical readers and portable field computers that will allow the direct input of observations into a computer storage. Such devices allow for automatic data quality checks.

Field observations that may assist in interpreting water quality should be entered on the report. These observations may include unusual colour or odour of the water, excessive algal growth, oil slicks, surface films, or heavy fish kills. Such observations may prompt the field investigator to take additional observation-based samples, in addition to those required by the routine schedule. The types of samples and their preservation should be consistent with the types of analysis that the investigator thinks is warranted by the prevailing conditions. If additional samples are collected at sites other than the established station, the description of their locations should be recorded accurately. This kind of information and the additional samples may prove very useful in the interpretive phase of the study.

21.5.2 ***Recording stations***

At automatic recording stations, observations are recorded in graphical or digital form. However, the following observations should be recorded at the time of any visits for data retrieval or station maintenance:

(*a*) Site identification number;
(*b*) Observations from independent sources at the time of collection (e.g., gauge boards, total rainfall collected);
(*c*) Specific comments relating to the recording mechanism, including its status, current observation, and time.

Each inspection should be recorded by completing a station-inspection sheet. Final extraction of observations from the recorded data should be performed at computing facilities. However, the data collector should check the recorded data by eye during field collection or by use of a field computer if the data have been collected in a computer-compatible form. Comments should be written on the chart or noted on the inspection sheet if any errors are detected.

With graphical recorders, observations are collected continuously, and processing of the data in the office is required. Data loggers, however, will record data at specific time intervals (as requested by the user). Intelligent loggers will also allow for data compaction and variability of observation times. In the case of multiparameters being observed, the coordination of observations can also be performed by the intelligent field logger. For example, rainfall data can be recorded at a five-minute interval or at every tip of a bucket for stage data when the level alters by more than one centimetre, and water-quality parameters when stream height alters by 10 centimetres and/or on a 21 hourly basis (section 6.2.4).

As with graphical recorders, independent field observations should be made and recorded during each site visit.

After a station has been in operation for a reasonable period, the frequency and timing of inspections should be re-assessed in light of the capabilities of the instrumentation and the requirements for data at that site. In some cases, consideration should be given to the real-time collection of data via various communications options as a cheaper method of data collection than regular site visits (section 21.6).

21.5.3 ***Real-time reporting***

There are many recording and non-recording stations from which real-time data are required, for example in the operation of reservoirs, flood-warning and forecasting situations, and in some instances as a cost-effective method of data collection.

Real-time data collected by field observers must be reported by a transmission facility to the agency. Similarly, recording stations must report via some transmission facility. Recording devices may have the advantage of being able both to transmit data at prescribed intervals/parameter changes and be interrogated by the collecting agency to determine the current situation or reset observation intervals. Intelligent loggers can also provide information on the current available storage capacity of the logger and the condition of the available power supply. Automated quality-control processes can be developed in these situations.

21.5.4 *Additional instructions for observers*

Clearly written instructions must be provided to all observers. These should contain guidance and directions on the following matters:

(*a*) A brief description of instruments, with diagrams;
(*b*) Routine care and maintenance of instruments and actions to be taken in the event of serious breakage or malfunctioning;
(*c*) Procedures for taking observations;
(*d*) Times of routine observations;
(*e*) Criteria for the beginning, ending, and frequency of special non-routine observations (e.g., river-stage observations while water level is above a predetermined height);
(*f*) Procedures for making time checks and putting check observations on charts at stations with recording instruments;
(*g*) Completion of field notebooks or station journals;
(*h*) Completion of report forms, including methods of calculating means and totals with appropriate examples; and
(*i*) Sending of reports to the central office.

Such written instructions should be supplemented by verbal instructions by the inspector to the observer at the time of installation of instruments and at regular intervals thereafter.

The instructions should emphasize the importance of regular observations with perhaps a brief account of how the observed data are used in water-resource development, hydrological forecasting, or flood-control studies. Any special observations that may be required during special periods, e.g., during floods, or any special reports that are to be filed should be specifically discussed. Observers should be urged not to forget to fill in the spaces for station names, dates, and their signature. The necessity of reporting immediately any instrument failure or significant modification of the observing site should be emphasized.

Observers at stations equipped with automatic recording instruments must be provided with instructions on the method of changing charts and taking check observations. These instructions must stress the importance of annotating the chart with all information that might be required for later processing. This would include station identification, time on, time off, check-gauge readings, and any other entries that would make the record more easily interpreted at a later time.

At stations with full-time personnel, the staff should be sufficiently well trained to abstract data from charts of autographic instruments. For such stations, carefully worded instructions on the method of abstracting data from the charts and on the completion of report forms must be provided. However, at many ordinary stations, where observers may not be thoroughly trained, it may be undesirable to require observers to undertake the relatively complex job of data abstraction from charts. In such cases, charts should be forwarded to a central office for the processing of the data.

In many countries, gauges have been introduced for water level, water quality, and precipitation measurements that produce data as digital output. In such cases, instructions to observers need only contain information on routine maintenance, check observations, and methods of forwarding the recording device to the central office for machine processing.

21.6 Transmission systems

21.6.1 *General*

During recent years, the demands from users of hydrological data have become more and more complex so that systems that include automatic transmission of hydrological observations have been incorporated into national networks. This has also led to the need for developing codes to facilitate the formatting of observations for the transmission and dissemination of forecasts. Hydrological codes HYDRA (hydrological data) and HYFOR (hydrological forecasts) are discussed in section 4.4. The following is a list describing different possibilities for transmission systems (additional details can be found in section 6.2.4):

(*a*) Manual — The observer at the station mails data or initiates radio or telephone call to the central office on pre-arranged criteria;

(*b*) Manual/semi-automatic — Central office manually interrogates the remote automatic station by telephone, radio or radio telephone, or satellite, and receives single discrete values as often as interrogated. It is possible to have automatic telephone-dialling equipment in the central office that can make calls in series;

(*c*) Automatic timed — Automatic equipment at stations programmed to initiate transmission of a single, instantaneous observation and/or past observations held in a storage register;

(*d*) Automatic event indicator — Station transmits automatically, by radio, telephone, or satellite, a specified unit of change of a variable (for example, each centimetre change in the stage of a river); and

(*e*) Automatic — Data are transmitted by the station and recorded at the central office on a continuous basis.

21.6.2 *Transmission links*

The possible choices of transmission links include:

(*a*) Dedicated land-lines — Used where relatively short distances are involved and commercial lines are not readily available. Land-lines are typically able to transmit frequencies of up to 3 000 Hz without special techniques;

(*b*) Commercial telephone and telegraph lines — Telephone and telegraph systems can be used whenever feasible. Equipment is available that permits unattended reception of observations at the central office. Measurements and commands can be transmitted to and from the remote site;

(*c*) Direct radio links — These must be used when requirements cannot be met by those facilities provided by land-lines, or when distances or natural obstacles prevent the economic installation of wires. Distances of several kilometres to hundreds of kilometres may be spanned by radio transmitters, depending upon the carrier frequency and the transmitter power. At the higher frequencies, the transmitter and receiver must have a clear line-of-sight transmission path. This limits the range without repeater stations to about 50 kilometres. In all cases, the installation and operation of radio transmission links is subject to national and international regulations; and

(*d*) Satellite links — Data transmission from satellites can take place in two ways: transmission of data, as observed by sensors in the satellite (such as imagery) or the use of the satellite to relay data observed at remote ground stations to central receiving locations. At the present time, the science of observation and transmission or retransmission from satellites is developing rapidly, e.g., through the WMO Global Telecommunication System of the World Weather Watch. The data involved are available either directly from the spacecraft or through central data banks.

21.6.3 *Factors affecting the choice of transmission systems*

When considering the possibility of including automatic transmission of data in any measuring system, consideration should be given to the following:

(*a*) Speed with which data are required. This depends upon the following factors:
  (i) The speed with which changes in the measured variable take place;
  (ii) The time between the observation and receipt of the data by conventional means, versus automatic transmission systems;
  (iii) The urgency of having this information available for warnings or forecasts;
  (iv) The benefits of forecasts from telemetered data and economic losses due to lack or delay of forecasts;
  (v) The advantages of radio and satellite transmission versus land-lines in times of storms and floods when these disasters can destroy the more conventional means of telecommunications at the time that the information is most urgently needed;

(*b*) Accessibility of the measurement sites for quality control and maintenance;

(*c*) Reliability of the recording device. When local climatic conditions are rigorous, the operation of on-site mechanical equipment is difficult. Under these situations, it may be more reliable to transmit information electronically to a central climate-controlled office and to record it. This system also permits a continuous check of this operation of the sensors;

(*d*) Staffing for operational, maintenance, and logistic problems. It is important for these aspects to be considered in the planning process and to recognize that each individual project will have its own particularities. Careful attention should be given to the costs and benefits of all the alternatives before any final decision is made. When designing a system for the automatic transmission of data, the main components to consider for staffing purposes are:
   (i) Sensors and encoding equipment;
   (ii) The transmission links; and
   (iii) Receiving and decoding equipment.

It is necessary to consider these components jointly in the design stage. This is essential because the special characteristics of any one component can have serious consequences on decisions regarding the others.

21.7 Water quality monitoring

Chapter 17 provides details of instrumentation and field practices for the collection of water quality data. However, the sampling locations, the sampling times, the parameter identifications, and the corresponding values must be recorded and coherence must be maintained throughout the handling of the data. If any one of these essential items is lacking, then the whole effort is wasted.

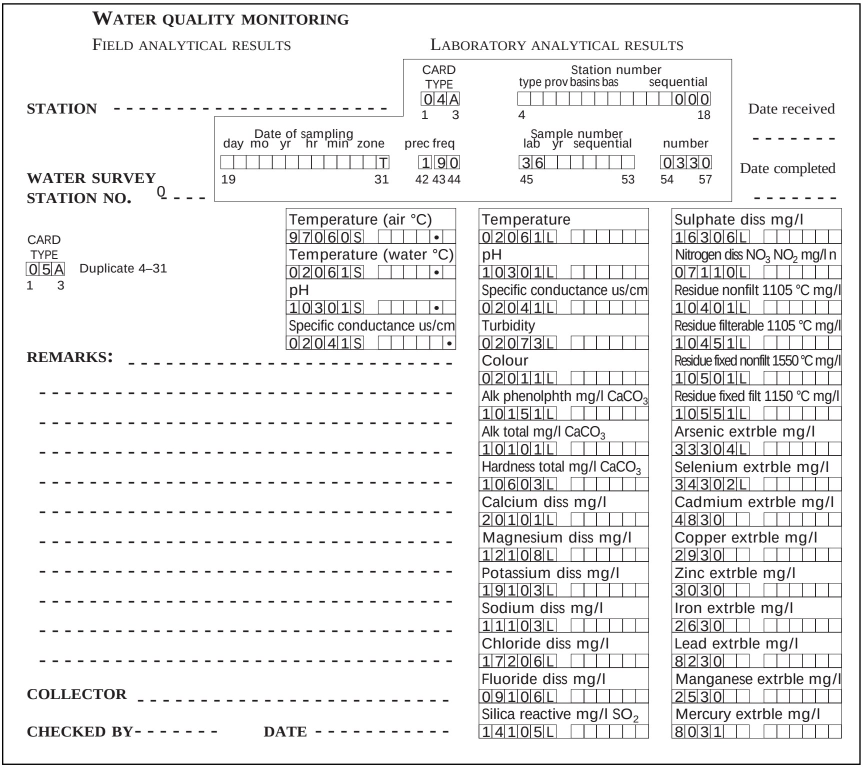
21.7.1 *Station identification*

The importance of an accurate written description of each station location and the conditions under which the samples are collected are discussed in detail in section 21.2.2.

21.7.2 *Field sheets for water quality monitoring*

Perhaps one of the most important steps in a sampling programme is the recording on the field sheets of observations, sampling date, time, location, and the measurements made. All field records must be completed before a station is left. Additional instructions are contained in section 21.5.

Two examples of a systematic format for recording field analyses and observations are provided in Figures 21.4 and 21.5. The formats shown in these figures are appropriate for those groups that use computer systems for storing their results. The format of Figure 21.4 can be used by any group collecting water quality work. Both



WATER QUALITY MONITORING

FIELD ANALYTICAL RESULTS

LABORATORY ANALYTICAL RESULTS

CARD TYPE 0 4 A (1 3)

Station number: type prov basins bas sequential 0 0 0 (4 18)

STATION -

Date received - - - - - - -

Date of sampling: day mo yr hr min zone T (19 31)

prec freq 1 9 0 (42 43 44)

Sample number: lab yr sequential 3 6 (45 53)

number 0 3 3 0 (54 57)

Date completed - - - - - - -

WATER SURVEY STATION NO. 0 - - -

CARD TYPE 0 5 A (1 3) Duplicate 4–31

Temperature (air °C)	9 7 0 6 0 S •
Temperature (water °C)	0 2 0 6 1 S •
pH	1 0 3 0 1 S •
Specific conductance us/cm	0 2 0 4 1 S •

Temperature	0 2 0 6 1 L
pH	1 0 3 0 1 L
Specific conductance us/cm	0 2 0 4 1 L
Turbidity	0 2 0 7 3 L
Colour	0 2 0 1 1 L
Alk phenolphth mg/l $CaCO_3$	1 0 1 5 1 L
Alk total mg/l $CaCO_3$	1 0 1 0 1 L
Hardness total mg/l $CaCO_3$	1 0 6 0 3 L
Calcium diss mg/l	2 0 1 0 1 L
Magnesium diss mg/l	1 2 1 0 8 L
Potassium diss mg/l	1 9 1 0 3 L
Sodium diss mg/l	1 1 1 0 3 L
Chloride diss mg/l	1 7 2 0 6 L
Fluoride diss mg/l	0 9 1 0 6 L
Silica reactive mg/l SO_2	1 4 1 0 5 L

Sulphate diss mg/l	1 6 3 0 6 L
Nitrogen diss NO_3 NO_2 mg/l n	0 7 1 1 0 L
Residue nonfilt 1105 °C mg/l	1 0 4 0 1 L
Residue filterable 1105 °C mg/l	1 0 4 5 1 L
Residue fixed nonfilt 1550 °C mg/l	1 0 5 0 1 L
Residue fixed filt 1150 °C mg/l	1 0 5 5 1 L
Arsenic extrble mg/l	3 3 3 0 4 L
Selenium extrble mg/l	3 4 3 0 2 L
Cadmium extrble mg/l	4 8 3 0
Copper extrble mg/l	2 9 3 0
Zinc extrble mg/l	3 0 3 0
Iron extrble mg/l	2 6 3 0
Lead extrble mg/l	8 2 3 0
Manganese extrble mg/l	2 5 3 0
Mercury extrble mg/l	8 0 3 1

REMARKS: -

COLLECTOR -

CHECKED BY - - - - - - - **DATE** - - - - - - - - - - -

Figure 21.4 — Field sheet for use with NAQUADAT or similar computer system.

formats can be adapted to fit situations specific to a particular need. The following information is usually recorded:

(*a*) Sampling site and date;
(*b*) Field-measured parameters;
(*c*) Instrument calibration;
(*d*) Sampling apparatus used and procedures;
(*e*) Quality control measures used; and
(*f*) General remarks and field observations.

21.7.3 *Transportation of water quality samples*

Once collected, some water samples must be transported to the laboratory. The mode of transportation will depend on the geographic location and on the maximum permissible time lapse before analysis for each constituent. The field investigator is

STATION NO.____________________
DESCRIPTION:____________________
____
DATE OF SAMPLING DY ________ MO ________ YR ________
TIME OF SAMPLING HR ________ MI ________ TIME ZONE ________
SAMPLED BY ____________________

FIELD MEASURED PARAMETERS
Water temp. °C ________ Air temp. °C ________
pH ________ Specific cond. ________ Diss. oxygen ________ Turb. ________
Depth of water ________ Depth at which sample taken ________
Ice thickness____________________
Other ____________________
Remarks ____________________
____

INSTRUMENT CALIBRATION
Diss. oxygen meter model ________ Winkler calibration ________ mg/L
Meter reading before adjustment ____________________
Conductivity meter model ____________________
pH meter model ________ Calibration butters used ________
Remarks ____________________
____

WATER QUANTITY MEASUREMENT DATA
Location description ____________________
____
Description of gauge ____________________
____
Stage height ____________________
Time ____________________

Figure 21.5 — General format for a field-sampling sheet.

SAMPLING APPARATUS USED AND PROCEDURES

____

____

____

____

____

SAMPLE SPECIFICS

	Container material	Volume collected	Preservation	Quality control
Major ions				
Metals				
Organics				
Pesticides & herbicides				
Mercury				
Phenols				
Nutrients				
BOD & COD				
Others				

QUALITY CONTROL REMARKS ____

____

____

GENERAL REMARKS ____

____

MODE OF TRANSPORT ____

Figure 21.5 — General format for a field-sampling sheet (*continued*).

responsible for delivering the samples to the airline, bus, train, or postal terminal on schedule so that there will be minimal delay in sample transport. Logistics for sample transport and storage should be determined before fieldwork is initiated.

21.7.4 *Field quality assurance in water quality monitoring*

A field quality assurance programme is a systematic process that, together with the laboratory and data-storage quality assurance programmes, ensures a specific degree of confidence in the data. A field quality assurance programme involves a series of steps.

All equipment should be kept clean and in good working condition, with records kept of calibrations and preventive maintenance, standardized and approved methodologies, such as those recommended in this *Guide* should be used by field personnel.

The quality of data generated in a laboratory depends on the integrity of the samples that arrive at the laboratory. Consequently, the field investigator must take the necessary precautions to protect samples from contamination and deterioration. Further details on field quality assurance are available in Chapter 17 or in the WMO *Manual on Water Quality Monitoring — Planning and Implementation of Sampling and Field Testing* [9].

21.8 **Special data collection**

21.8.1 *Requirement*

Data concerning severe storms and floods are very important in determining design criteria for many types of hydraulic structures. In general, regular observation networks do not provide enough detailed information on storm-rainfall distribution, or on flood-peak discharges of tributary streams. In addition, during severe floods, permanent stream gauge installations are sometimes overtopped or washed away, and the record is lost. For these reasons, very valuable information can be obtained by a field survey crew in the area of a storm flood just following a severe occurrence. In addition, data from instruments, such as weather radar, are often valuable in hydrological studies (section 7.6).

21.8.2 *Bucket surveys of storm rainfall*

Measurements of rainfall from private, non-standard raingauges, and estimates that can be made from various receptacles such as pails, troughs, barrels, etc. (provided these can be verified to have been empty prior to the storm) can be used to augment rainfall data from the regular observing network. Eyewitness reports can be obtained of time of beginning and ending of rain and of periods of very heavy rain. Care must be taken in interpretation of bucket-survey data, and where discrepancies exist between data from a bucket survey and the regular observation network. Greater weight should usually be given to the latter.

21.8.3 *Weather-radar and satellite data*

Data from weather radars and satellites are valuable in determining the intensity and areal distribution of rainfall and times of beginning and ending of precipitation over a specific river basin. For record purposes, these data can be collected on photographic film or in digital form by a computer linked to the radar. Film data may be collected continuously, at timed intervals, or as selected individual photographs. Photographs of video integrator processor (VIP) displays that depict several levels of contoured echo intensity simultaneously, or the entire uncalibrated weather radar display, could be included. The hydrometeorological application of filmed data, however, is limited because of the time for film development and the laborious task of manual processing, whereas digitizing of radar data allows rapid and innumerable investigations through computer processing. These digitized data can be readily transmitted to forecast offices over teletypewriter or computer networks.

21.8.4 *Extreme river stages and discharges*

Extreme events during floods and droughts should be documented at both regular gauging stations and at non-gauged locations.

Highwater marks along rivers are useful in delineating flooded areas on maps, in the design of structures such as highway bridges, and for estimation of flood slopes. These marks, if taken carefully, may also be used with other data to compute the peak discharge of the stream by indirect methods (section 11.6).

Field surveys to measure minimum streamflow at non-gauged locations provide valuable data at a very economical cost. These measured discharges can be correlated with the simultaneous discharges at index gauging stations to determine the low-flow characteristics at the ungauged sites.

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CHAPTER 22

DATA REVIEW AND CODING

22.1 Quality control and error detection

Quality control begins with the selection and maintenance of the instrumentation and the data-collection site. The purpose of quality control is to ensure the highest possible standard of the primary data before they are given to users.

22.1.1 *Inspection of stations*

It is essential for the maintenance of good quality observations that stations be inspected periodically to ensure the correct functioning of instruments and the maintenance of a high standard of observations. The gauge datum of hydrometric and groundwater stations should be checked at least once annually. These inspections may be independent of routine inspection and maintenance visits. In some countries, it may be possible to have inspections made by regional offices at least once a year, with less frequent visits being made by an inspector from the central office.

For a stream gauging station, such inspections include the stability of the rating curve, the inspection duties listed below, and a review of the relationships between the gauges and permanent level reference points to verify that no movements of the gauges have taken place. Since a minimum of ten discharge measurements per year at a stream gauging station is recommended, it follows that most stations would be inspected at an equal frequency. Every stream gauging station should be inspected at least twice a year. The inspection programme should also provide for visits by a well-trained technician or inspector immediately after every severe flood in order to check the stability of the river section and the gauges. In some instances, the observer should be trained to undertake such inspection duties so that this can occur during data-collection and observation visits (section 21.4).

The duties of the inspector are to:

(*a*) Note and record any change in the observation site (a sketch map and photographs are useful);
(*b*) Make local arrangements for the improvement or restoration of the observation site (e.g., removal of trees affecting raingauge catch);
(*c*) Check the instruments and make any necessary field repairs or adjustments;
(*d*) Inspect the observer's record book;

(*e*) Instruct the observer, as required, on observation procedures and routine instrument maintenance;
(*f*) Emphasize the importance of promptly filing complete and accurate returns to the observer; and
(*g*) Brief the observer on any special observations that may be required (e.g., more frequent readings during storm and flood periods).

In order to perform duty (*e*) effectively, the inspector must be kept advised of errors made by observers, especially of any recurring errors made by a particular observer. Such advice should be forwarded regularly to the inspector by the officers responsible for the preliminary checking and error detection procedures. Results of these inspections should be included in the station description files (section 21.2.2).

22.1.2 ***Preliminary checking of data***

The difference between preliminary checking and error detection is rather arbitrary. Procedures included under preliminary checking in one country may be thought of as error detection in another. Also the extent of the use of computers in processing the data may change the definition of preliminary checking. For instance, for data collected manually and later transferred to machine-readable form (computer disk, magnetic tape, or sheets readable by optical scanning), the term preliminary checking will be used to cover those procedures performed prior to transcribing the data into machine-readable form. For data collected directly in digital, machine-readable form, there may be little checking prior to the first machine processing other than verifying the proper identification of the storage medium (identification of site of collection, proper beginning and ending dates of this unit of data, and proper identification of the type of data involved, such as items sampled and frequency of sampling). Under such conditions, the quality control of data by means of a computer is the only possible method.

For data collected manually, preliminary checking should generally include the following steps:

(*a*) Log in data at the time of the receipt of the report form;
(*b*) Ensure completeness and correctness of the information, i.e., dates, station name, and station identification if required in subsequent machine processing;
(*c*) Ensure completeness of the data;
(*d*) Check the observer’s arithmetic; and
(*e*) Compare the observer’s report with the recorded data.

In many countries, this last step may be done by machine methods. Corrections should be entered legibly and in ink of a different colour from that used in the completion of the original form, making sure that the original entry is not erased or made illegible.

Certain preliminary checks should also be applied to data from continuously recording gauges. The times recorded at the beginning and end of the chart, and at any time check in between, should be checked against the time-scale on the chart to determine if time corrections need to be applied, or to determine the magnitude of the time correction. An attempt should be made to determine whether a time correction is due to clock stoppage or whether it can reasonably be prorated over the chart period. In addition, check observations by recording instruments should be entered on the chart to permit corrections to the recorded data, if necessary.

In some cases of manually-collected data, computations are made from the observed data before the data are ready for transfer to a machine-readable form. Frequently, these computations are too complex to be done by the observer, and they must be done in a central office. An example is the calculation of lake evaporation from pan evaporation and auxiliary data. In some countries, such calculations may be made by machine (computer or calculator) methods.

At times, data will be missing from observers' reports. The missing observations may be estimated or interpolated. For example, during the recession of water level on a river in a dry season, interpolation of 10 to 30 days of data may be justified if precipitation and temperature observations indicate no significant rainfall or snow melt. In the case of daily precipitation data, it may be possible to estimate missing observations for one or two days if the storm producing the precipitation yielded fairly uniform amounts at surrounding observation stations. All interpolated or estimated values should be clearly indicated as such, both on the original records and in publications, and care should be taken to make sure that conditions permit reasonably accurate interpolation.

22.1.3 *Error detection*

The efficiency of quality-control procedures depends greatly on machine processing facilities being available. An outline of general principles and practices involved in data processing by machine methods is given in the WMO *Guide to Climatological Practices* [1]. The procedures outlined below assume that machine-processing facilities are available. Where such equipment is not available, the procedures can be undertaken by hand by using clerical and technical staff. Even when machine methods are used on manually-collected data, adjustments to original observations should be made with great caution by experienced technicians or professional personnel.

Techniques for quality control of data differ for various elements. The basis of most quality-control procedures for manually-collected temperature and precipitation data are machine-tabulated arrays of daily data by district or region. From such arrays, it is easy to detect by eye those stations at which the data are consistently credited to the wrong day or to gross errors in temperature or precipitation measurements.

However, caution must be exercised in changing reported data. A study of the original report from the station, a check of the history of the station (as to the quality of its record), and an appraisal of the factors that produced the event (to ensure the data in question may not be a natural anomaly) are necessary before an apparent error is corrected. The alteration should be coded to indicate that a change to the raw data has been made and that all of the above information must be documented.

Another method that can be used for checking the relative fluctuations of an observed element over a period is the use of various types of mathematical relationships (e.g., polynomials). The computed value is compared with the observed value at the time. If the difference between the two does not exceed the previously determined tolerance, the data are considered to be correct. If the limits are exceeded, then further investigation is warranted.

Since streamflow data are continuous in time and correlated in space, it is possible for the reliability of the observation to be checked by interpolation and statistical methods. Checking for internal consistency between observed discharges may also be undertaken by means of:

(*a*) Qualitative assessment of the correspondence between discharges at adjacent stations;
(*b*) Qualitative assessment of the correspondence between the discharge and its value during the previous measure;
(*c*) Approximate check of the value of the discharge by seeing that it falls within the range of previous values for the given phase in the regime of the river; and
(*d*) Approximate assessment of the correspondence between the measured value and the regular variations during the previous period.

Computerized quality control of the primary data is objective and makes possible a thorough control of individual reports. Computerized quality control of the primary data therefore makes superfluous any further control of the results derived from the analysis of such primary data.

It should be stressed that the only absolutely reliable method for deciding whether to accept or reject unusual results is to consider carefully the conditions under which the observations were obtained.

22.1.4 ***Results of quality control***

For data collected manually and later transcribed to machine-readable form, errors detected by either preliminary checking or error-detection procedures should be dealt with as follows:

(*a*) The correction should be made legibly on the original form and initialled by the official making the correction;

(*b*) The machine-readable form containing the erroneous data should be corrected, and the correction should be carried through to any existent copies of the observation and to data that may have been derived from the erroneous observations;

(*c*) The station observer should be advised of the error. If the error is of a systematic type caused by the malfunctioning of instruments or the failure to follow correct observing procedures, the problem should be remedied through a visit by the inspector (section 22.1.1); and

(*d*) A note of the error should be made in a log-book or station description file (section 21.2.2) so that a running check can be kept on observational quality at all stations and so that the inspection staff can be advised of observations stations with frequent errors.

For data collected in machine-readable form, errors detected and verified must be corrected in the summaries produced by the machine computations. The originally recorded machine-readable form should not be altered, but symbols or notations should be included on the output to indicate the items rejected on the basis of the automatic or semi-automatic editing processes. For instance, for records of river stages automatically punched at uniform time intervals, a sequential test difference may be used to draw attention to recorded values that change more than a given test difference. After manual inspection of such values, some will be rejected while others will be accepted. A subsequent operation would revise and code (section 22.3) the summary results accordingly, but the original recorded values would not be altered. All such corrections should be fully documented.

22.2 Validation procedures

This first level involves the collector in the detailed checking, assessment, and preparation of the data. It gives the collector an opportunity to improve the standard of the data prior to its submission to the processing system.

Standard checks should be applied to test the data. These usually involve the application of check readings for errors in time and magnitude. Instrument calibration tests are examined and assessed for consistency and drift. A visual examination is made of sequential readings, or of the recorded trace in the light of expected patterns or the simultaneous behaviour of related variables that have also been recorded.

On the basis of this assessment, the observer will apply quality codes or verify those recorded on site. The codes indicate if the record is considered good quality, or if faulty, the degree of confidence expressed in terms of the data accuracy.

At this stage, any detailed documentation substantiating the interpretation should be attached to the data for the benefit of future users.

22.2.1 *General procedures*

It should be recognized from the outset that data-validation techniques can never be made fully automatic. While some variables have strictly limited ranges of validity that the computer can check, most time-series variables have asymptotic probability distributions that only allow the computer to recognize a value as being suspect. The most extreme values may prove to be correct and, if so, are vitally important for all hydrological-data applications. For such variables, therefore, the computer should only be used to accept or to query data, but not to reject it. The computer must refer the suspect values to analysis by experienced human judgement.

The advantages of computer validation techniques are that they are objective and uniform. Data from all sources are subjected to the same scrutiny. The computer also allows the use of complex checking algorithms impossible to implement by manual techniques. These algorithms may be complex in terms of the mathematical content or in the amount and type of control data that are used. A further advantage is the elimination of tedious manual checking of data. The computer permits the specialist to devise sets of validation rules that will report only those data considered in need of closer inspection.

Validation outputs should clearly indicate, normally by the use of flags or codes, both the values queried and the reasons for the queries. As a further aid to any subsequent error-correction process, some systems also provide a computer estimated expected value. When deciding on the complexity of a validation procedure to be applied to any given variable, the accuracy to which the variable can be observed and the ability to correct detected errors should be kept in mind.

It is common to perform validation of data batches at the same time as updating the database files — normally on a monthly, semi-annual, or annual basis.

One important organizational aspect of validation is the possibility of splitting data validation tasks between field centres equipped with data-entry microcomputers and the central data-processing computer. Since most microcomputers have standard data entry software packages that incorporate data validation options, no software development effort is required. Field validation checks could include absolute checks for dates and variable codes, and relative checks for range and rate of change. Tables and plots of input data could also be made for manual checking. Such a system would reduce considerably the error rate of data arriving at the centre where more elaborate validation, e.g., inter-station consistency checks, could be performed. Perhaps a more significant advantage of this procedure is that the responsibility for the major part of the validation process is assigned to the observers themselves.

22.2.2 *Combined techniques*

These techniques rely upon the computer to format the input data to facilitate manual checking. The two formats are tabular summaries and plots.

Tabular summaries may bring together data from selected stations, adjacent stations for the same variable, or adjacent stations for interrelated variables.

There is no doubt that visual checking of plotted time-series of data by experienced personnel is a very rapid and effective technique for detecting data anomalies. For this reason, most data-validation systems incorporate a facility to produce time-series plots on computer screens, printers, and plotters. If the original time-series data were derived from a chart, it may be compared directly with the plot. Particularly helpful for this comparison is the scaling of printed plots to match that of the original chart, which allow checks to be performed by overlaying the two traces. This checking technique detects errors due to data entry. Overlays may also be made of traces from adjacent stations, which is a very simple but effective way of monitoring interstation consistency.

Time-series plots may contain just the observed traces, but, more usefully, should also show upper and lower bounds (statistical confidence limits or previously recorded extremes) to assist in the manual interpretation process. The plots may be made in the units observed, or the computer may be programed to transform values. The most common example of this technique is the use of logarithmic plots of river flows and groundwater levels. Figure 22.1 shows a logarithmic plot of daily river flows on which the previously recorded maxima and minima have been superimposed.

To identify long-term trends in time-series, double-mass plots are readily computed and plotted for selected stations. Figure 22.2 shows a typical double-mass plot for checking long-term rainfall consistency.

Plots may also be prepared to allow manual checking of spatial variation. A simple means is to plot station positions, together with their identification numbers and data values. Such a technique is used widely for monthly and annual checking of rainfall and groundwater data on an areal basis. More complex software can interpolate data in space and plot isolines.

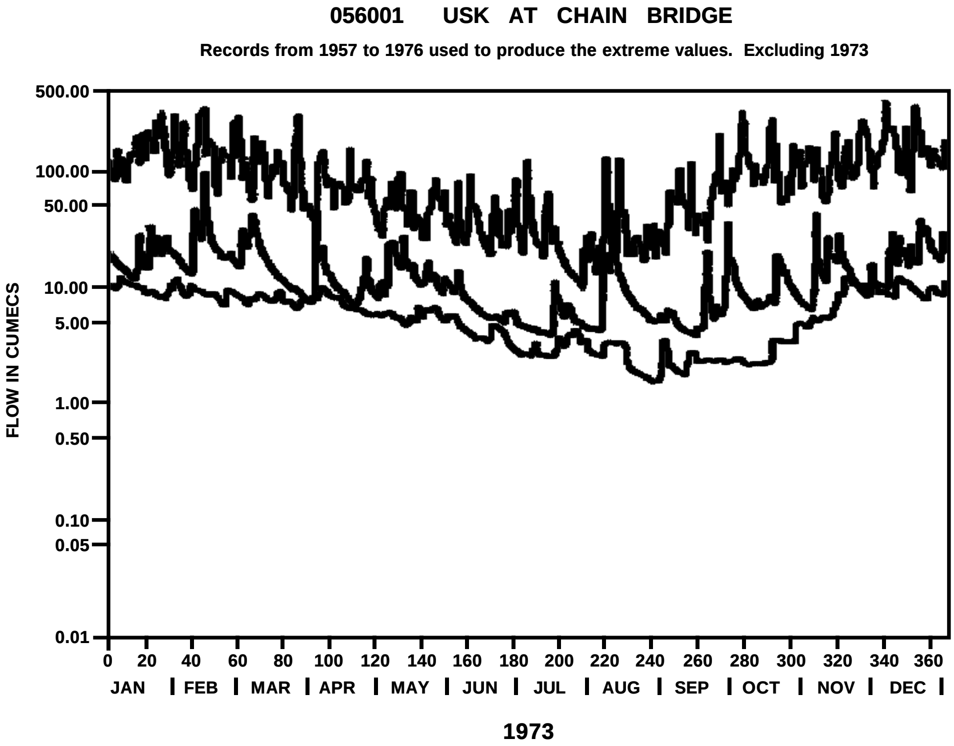
In order to review the wide range of techniques available for automated-validation systems it is useful to refer to absolute, relative, and physio-statistical errors.

Absolute checking implies that data or code values have a value range that has zero probability of being exceeded. Thus, geographical coordinates of a station must lie within the country boundary, the day number in a date must lie in the range 1-31, and in a numeric-coding system the value 43A cannot exist. Data failing these tests must be incorrect. It is usually a simple task to identity and remedy the error.

Relative checks include the following:

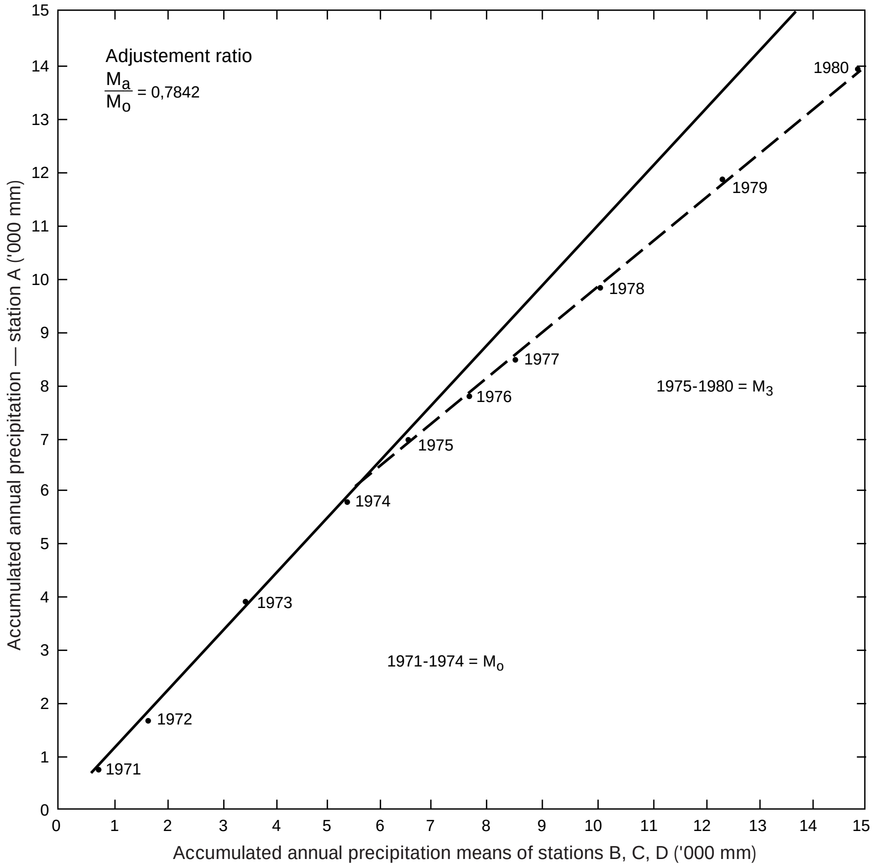
(*a*) Expected ranges of variables;
(*b*) Maximum expected change in a variable between successive observations; and
(*c*) Maximum expected difference in variables between adjacent stations.

It can be appreciated that the definition of acceptable ranges requires that a manageable number of queries be generated. During the early stages of database



Source: World Meteorlogical Organization/Food and Agriculture Organization, 1985: *Guidelines for Computerized Data Processing in Operational Hydrology and Land and Water Management*. WMO–No. 634, Geneva.

Figure 22.1 — Logarithmic plot of river flows with extremes values.



Source: World Meteorological Organization/Food and Agriculture Organization, 1985: *Guidelines for Computerized Data Processing in Operational Hydrology and Land and Water Management.* WMO–No. 634, Geneva.

Figure 22.2 — Double-mass plot. Double-mass curve showing the relationship of annual precipitation at Station A to the mean of three nearby stations. Note the abrupt change that occurred in 1975.

development, it is advisable to make tolerance limits fairly broad. These limits can be tightened as better statistics are obtained about the variation of individual variables.

While requiring much background analysis of historical records, the expected ranges for relative checks (method (*a*)) should be computed for several time intervals including the interval at which the data are observed. This is necessary because the variance of data decreases with increasing time aggregations. Daily river levels would first be compared with an expected range of daily values for the current time period, e.g., the current month. Because there is a possibility that each daily value could lie within an expected range, but that the whole set of values was consistently (and erroneously) high or low, further range checks must be made over a longer time period. Thus, at the end of each month, the average daily values for the current month should be compared with the long-term average for the given month. In a similar way, at the end of each hydrological year, the average for the current year is compared with the long-term annual average. This technique is of general applicability to all hydrological time-series data.

The method of comparing each data value with the immediately preceding observation(s) (method (*b*)) is of particular relevance to variables exhibiting significant serial correlation, e.g., most types of water-level data. An example of the application of this technique to stage data is presented below. Where serial correlation is very strong (e.g., groundwater levels), multi-period comparisons could be performed as described for method (*a*) above. Daily groundwater observations could first be checked against expected daily rates of change, and the total monthly change could subsequently be compared with expected monthly changes.

Method (*c*) is a variation of method (*b*), but it uses criteria of acceptable changes in space rather in time. This type of check is particularly effective for river-stage (and flow) values from the same watershed, although with larger watersheds some means of lagging data will be necessary before interstation comparisons are made. For other hydrological variables, the utility of this technique depends upon the density of the observation network in relation to the spatial variation of the variable. An example is the conversion of rainfall totals to dimensionless units by using the ratio of observed values to some long-term average station value. This has the effect of reducing differences caused by station characteristics.

Physio-statistical checks include the use of regression between related variables to predict expected values. Examples of this type of checking is the comparison of water levels with rainfall totals and the comparison of evaporation-pan values with temperature. Such checks are particularly relevant to observations from sparse networks, where the only means of checking is to compare with values of interrelated variables having denser observation networks. Another category of physio-statistical checks is used to verify that the data conform to general physical and chemical laws. This type of check is used extensively for water quality data.

Most of the relative and physio-statistical checks described above are based upon the use of time series, correlation, multiple regression, and surface-fitting techniques [2].

22.2.3 ***Specific validation procedures***

In most instances the general procedures described above provide a sufficiently high capability to detect suspect data. However, some of these procedures have been adapted and extended in a more specific manner to match the characteristics of certain data types.

22.2.3.1 *Climatological data*

When considering general quality-control procedures, it was noted that validation of climatological data by methods of interstation comparison was questionable in many cases because of the sparsity of the climatological stations. Thus, the basic validation techniques applied are range checks, rates of change checks, and, of particular importance, consistency checks between related variables observed at the same site. For example, all reported psychrometric data should be checked or re-computed to see that the dry bulb temperature exceeds or equals a reported wet-bulb or dew-point temperature and, depending on which data are available, the dew-point temperature and/or relative humidity should be computed and checked against the reported value. Similarly, empirical relationships between evaporation-pan or lysimeter data and other observed variables could give broad indications of suspect data at the validation stage. More sophisticated adjustments for the evaluation of evaporation and evapotranspiration are normally made in subsequent primary-processing stages.

For all climatological data, station and variable codes should be tested for validity, and, where relevant, sensor-calibration values and ranges should be output with suspect values.

Comprehensive details of climatological quality-control procedures are presented in the WMO *Guide to Climatological Practices* [1].

22.2.3.2 *Rainfall data*

Because rainfall is a very important and a highly variable hydrological phenomenon, there are many rainfall stations and hence large amounts of data. Most countries now have well established systems for quality control and archiving of rainfall data. A system used by the Meteorological Office in the United Kingdom for the processing of daily rainfall is described in the WMO *Guide to Climatological Practices* [1]. The errors occurring in the collection and processing of rainfall data are almost universal, so this system should serve as a model for many environments.

The reliability of a system that uses interstation comparisons is related to the network density. In areas having sparse coverage of raingauges, there is an increasing tendency to install rainfall radar (section 7.6). Areal values derived from such installations provide excellent data for both validation and rainfall data for areas having no rainfall stations. Another application of radar data for validation purposes is encountered in areas subject to intense localized thunderstorms, e.g., most tropical countries.

22.2.3.3 *Snow and ice data*

While the water equivalent of falling snow caught in raingauges may be validated along with rainfall data. Other snow and ice variables are more difficult to treat.

Data on the extent of snow cover may be validated only by a time-consuming manual synthesis of field observations, aerial-survey data, and satellite imagery (section 7.5). Techniques to perform automated interpretation of satellite imagery for snow extent (and even depth and water equivalent) are being developed. While these techniques show promise, there are still problems both of differentiating between snow and cloud cover and of insufficient image resolution. Further, unless a geographical information system is used, data on extent may be stored only as manually-abstracted catchment-area totals.

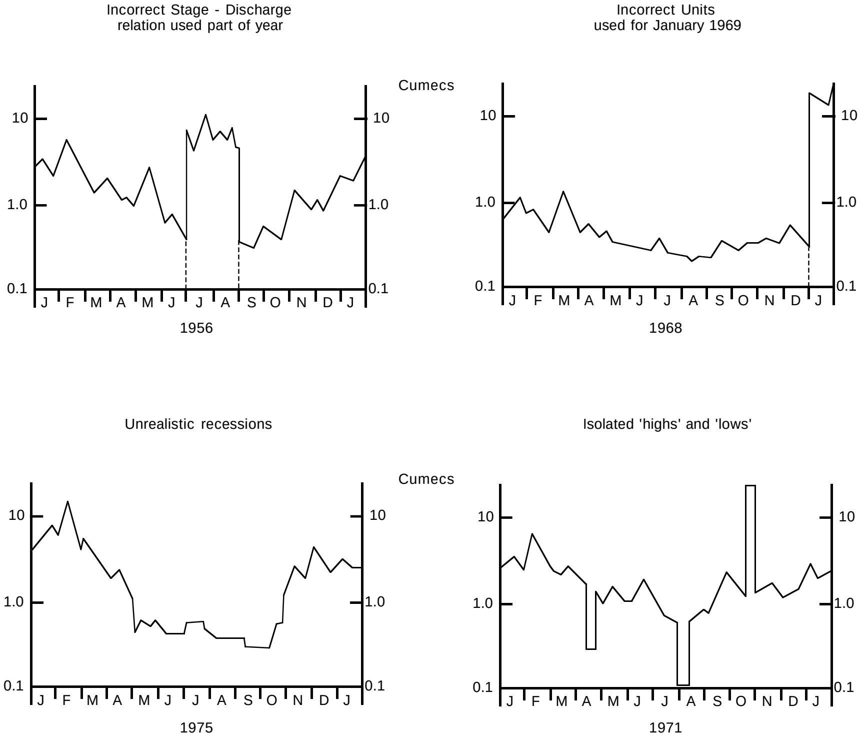
Data on snow depth and water equivalent demand much manual validation and verification by integrating data from snow courses, snow gauges, and conventional precipitation gauges. The large spatial variation in snow cover makes interstation comparisons difficult. However, there are techniques to estimate the statistical reliability of snow-course observations under conditions of melting snow. Degree-day factors are widely used for correlation purposes, and, where snow melt represents a significant proportion of river flow, established relationships between runoff and snow-water equivalents may be used. Air (and water) temperature relationships are valuable not only for the computation of degree-day factors, but also for the validation of ice-cover and thickness data and in the forecasting of ice formation and break-up dates.

Snow and ice data, whether quantitative or qualitative, are important validation data for a wide range of other hydrological variables. For example, anomalous river-stage data during the winter months may be explained and possibly corrected if background data indicated the nature and extent of ice conditions.

22.2.3.4 *Water level data*

The techniques of tabular and plotted data, range, and rate-of-change checks described above are used extensively for water level data.

The overlaying of adjacent station plots is of general utility, but the overlaying of river-stage data from stations on the same river system is a particularly useful validation process. An interesting plotting format is shown in Figure 22.3 which, although it depicts flow, is equally valid for water level data. The plot covers a 13-month period and is designed to reveal any discontinuities that may appear between successive annual updates of a master database.



Incorrect Stage - Discharge relation used part of year

Incorrect Units used for January 1969

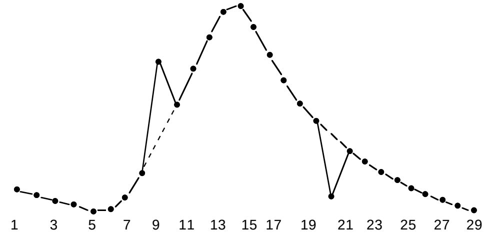
Unrealistic recessions

Isolated 'highs' and 'lows'

Source: World Meteorological Organization/Food and Agriculture Organization, 1985: *Guidelines for Computerized Data Processing in Operational Hydrology and Land and Water Management.* WMO–No. 634, Geneva.

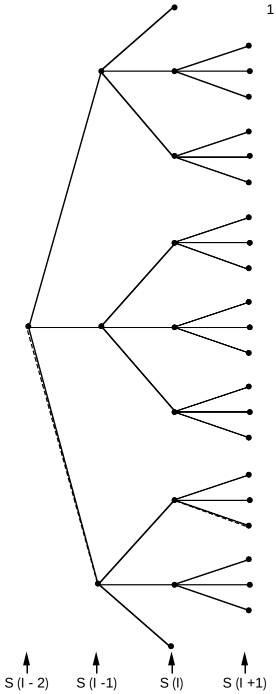
Figure 22.3 — Time-series plots for checking streamflow data.

When the sampling interval is relatively short, for example the 15-minute standard on many digital recorders, more sophisticated pattern-recognition techniques may be used. Such a technique, developed for stage data by the U.K. Institute of Hydrology [3], recognizes patterns that are considered acceptable and others that are considered suspect, as indicated in Figure 22.4. The pattern check is applied successively to every sequence of four 15-minute stage values for each gauge. The relevant pattern code and the four suspect readings are printed out to a query file every time a suspect pattern is detected by the system. To avoid suspect patterns being printed out unnecessarily (for example when the digital recorder is hunting at



Points 9 and 20 show improbable departures from the trend which should be queried by the Quality Control routine.

Action taken in the trend test



CASE	ACTION TAKEN
1	accepted
A	query S(I)
B	query S(I-1)
C	accepted
D	query S(I-1)
E	accepted (becomes case 20, 21, 22)
F	accepted
G	accepted
H	accepted (becomes case 2, 3, 4)
I	query S(I-1)
J	accepted
K	accepted
L	query S(I)
M	query S(I-1)
N	accepted (becomes case 20, 21, 22)
O	accepted
P	accepted
Q	accepted (becomes case 2, 3, 4)
R	query S(I-1)
S	accepted
T	query S(I-1)
U	query
V	accepted

NOTE: Configurations to be queried should be selected on the basis of known or expected behaviour at individual stations or groups of stations.

Source: World Meteorological Organization/Food and Agriculture Organization, 1985: *Guidelines for Computerized Data Processing in Operational Hydrology and Land and Water Management.* WMO–No. 634, Geneva.

Figure 22.4 — Pattern-recognition technique for checking water levels.

small variations in water level) a minimum acceptable error limit should be included in the routine. If the difference between successive stage readings is less than this minimum, the suspect values are not reported.

22.2.3.5 *River-gauging data*

A useful checking procedure for river-gauging data is to plot the average water level during the gauging and the vertical depths on a trace of the cross-section. These data should be available from the station-description file or one of the associated files. Profile differences may be caused by observer or data-entry error or may be genuine changes in the bed level, but should be queried. From this same set of information, the computer may be programed to evaluate the cross-sectional area associated with each vertical.

The remaining validation processes depend on the level of aggregation of input data, e.g., basic field data or manually-computed velocities. Velocities may be included as annotations to the cross-section plot. The user must decide if the checking procedures are simply to establish the accuracy of the data-entry operation, or whether a system is being developed to compute flow. In the latter case, the flow computations are normally performed to check the manual values derived for immediate use in the field or field office.

If measurements are made to establish or verify a rating curve, the computed flow should be plotted (manually or automatically) on the existing rating curve to identify suspect values or rating shifts in accordance with the confidence intervals of the measurements.

For all measurements, the validation program should check for the use of valid station, current-meter, propeller, and method-of-analysis codes and, where possible, for valid combinations of these. It is also useful for any plots or printouts to contain this information and any relevant calibration coefficients.

Additional information on aspects of discharge measurement are available in the *Manual on Stream Gauging* [4].

22.2.3.6 *Water quality data*

The very wide range of water quality variables has resulted in the use of relatively simple validation procedures for water quality data. Such criteria are normally absolute checks of analysis codes, relative checks of expected ranges and physiochemical checks of determinant relationships. If range checks are being devised in the absence of historical data, it should be noted that the valid ranges of many variables will be associated with the purpose for which the sample was taken, and the location of the sampling point. Thus, the levels of dissolved salts found in water samples taken from drinking water sources will be less than those found in effluents or in brackish or marine water bodies.

Physio-chemical tests are very effective and, hence, widely used for water quality data. Examples of typical physio-chemical tests performed for normal and specific (effluent) samples are shown in Table 22.1.

TABLE 22.1

Checking water quality data against physio-chemical laws

1. Dissolved solids

All results expressed in mg/1 should comply with the check:

$$0.1 \times \text{TDS} > [\text{TDS - (Na+K+Mg+Ca+C1+SO}_4\text{+4,42NO}_3\text{+0.61 (Alk)+}$$
$$\text{3,29NO}_2\text{+S}_1\text{O}_2 + \text{F)]}$$

NO_2, S_1O_2 and F are optional, i.e., validation check can be used without them, but they should be included, if available.

2. Ion balance

(*a*) Standard requirements (eight to 12 ions)
Ions should be converted to me/1 and subjected to the check:

$$\left[\frac{\text{Cations} - \text{Anions}}{\text{Cations} + \text{Anions}}\right] \times 100 < 3\%$$

where Cations = $Na+K+Mg+Ca+NH_4$
and Anions = $C1+SO_4+NO_3+HCO_3+NO_3+PO_4 + F$

PO_4, NH_4, NO_2 and F are optional, i.e., the balance can be checked without them;

(*b*) Minimum requirements (six ions)
This rough check can be used where only major ions have been measured. Results should be converted to me/1 and be subjected to the check:

$$\left[\frac{\text{Cations} - \text{Anions}}{\text{Cations} + \text{Anions}}\right] \times 100 < 10\%$$

where Cations = Na + Mg + Ca
and Anions = $C1 + SO_4 + HCO_3$.

3. Conductivity

0.55 conductivity (µs/cm) < TDS < 0.7 conductivity (µs/cm)
where TDS = Total Dissolved Solids

Table 22.1 *(continued)*

General checks for water quality	
Total solids	> total dissolved solids
Total solids	> settleable solids
200	> % satn of dissolved oxygen
20	> mg/1 dissolved oxygen
BOD_5 (total)	> BOD_5 (filtrate)
BOD_5 (total)	> BOD_5 (settled)
COD	> BOD
Total oxidized nitrogen	> nitrate
Total hardness	> temporary hardness
Total cyanide	> cyanide (excluding ferrocyanide)
Total phenols	> monohydric phenols
Total phenols	> polyhydric phenols
Total dissolved chromium	> chromate
Oil (total)	> oil (free)
Oil and grease	> oil (free)
Total oxidized nitrogen	= nitrate + nitrite
Total hardness	= Ca + Mg
Total phenols	= monohydric + polyhydric phenols

Source: World Meteorological Organization/Food and Agriculture Organization, 1985: *Guidelines for Computerized Data Processing in Operational Hydrology and Land and Water Management.* WMO–No. 634, Geneva.

If some variable values have been determined in the laboratory and all of the relevant associated data are available to the computer, they may be recomputed for verification purposes. All water quality data and the station, variable, and analysis codes may be checked for validity, and, where possible, for validity of their combination.

22.2.3.7 *Sediment data*

As with water quality data, mass-balance calculations may be performed if sufficient data exist. If a sediment rating curve exists for the section sampled, the departure of the sampled value from the curve may be estimated for its statistical significance and/or plotted for manual scrutiny.

22.2.4 ***Missing data***

The usefulness of data is, to a great degree, dependent on its completeness. Time spent on the estimation of missing record during the pre-processing stage may pay large dividends when the final data are used or analysed. It is also appropriate that these first estimates be made by the data collector with the benefit of local knowledge.

It is often the case, however, that faulty records can only be reconstructed with the expenditure of large amounts of time, or that recovery requires access to processed data from another source covering the same period. In this event, it may not be practical to delay the transmission of the remaining data for processing. A decision must be made as to whether the onus for the initial estimation of the missing record stays with the collector, or whether it could be synthesized more efficiently later in the process by using tertiary-processing routines.

22.3 **Coding data**

Coding systems should be comprehensive and flexible, and data collectors should be encouraged to make full use of their options. In addition to the application of codes to guide the processing, comments should be included at this stage. These comments give a general description of the data within defined time periods and should be attached automatically when data are presented to users.

The main objective of using codes is to make the files more compact and less ambiguous. The steps involved in devising and utilizing codes are:

(*a*) Define the data that require coding. These are normally descriptive data items that are used frequently (e.g., the names of locations, variables, analysis methods, measurement units, and data quality indicators);

(*b*) Decide when coding should be performed. To satisfy the objective of common recording and data-entry documents, coding should be performed at the time of data logging by the hydrological observer or the laboratory technician. Alternatively, though much less desirable, data may be coded as it is entered into the computer. This slows down the data-entry process and requires a more technically skilled operator;

(*c*) Consider the adoption of existing (national or international) coding systems for some data items. Schedules of variable codes, laboratory analysis methods, and measurement-unit codes have been developed by several countries. The adoption of such coding systems facilitates the interchange of data and reduces the need to devote resources to developing new coding lists;

(*d*) Obtain or prepare coding lists, incorporate the codes into the reporting and data-entry forms and the computer systems, and include coding instructions (and relevant coding lists) into technician instruction sheets; and

(*e*) Train observers in the use of codes, monitoring completed forms very closely for the initial period after introducing or modifying the coding system. This should be done for several months to allow for technician familiarization with the codes.

Most codes used for hydrological purposes are numeric. However, different combinations of alphabetic and numeric codes are also used. Alphabetic or alphanumeric codes are widely used for borehole logs and in other fields that use more descriptive data, such as soil land-use classification. The typical usage of codes in hydrological systems are described below and in the *NAQUADAT Dictionary of Parameter Codes* [5].

22.3.1 *Location codes*

Codes normally exist for basin or sub-basin, and it is very useful to incorporate them into the station description data file (section 21.2). This allows rapid identification of all stations (or stations measuring selected variables) in a single basin or group of basins.

For additional information on station numbering, see section 21.2.

22.3.2 *Variable (parameter) codes*

This heading covers the largest group of codes. The range of hydrological and related variables that may need to be included in a comprehensive database is enormous. Fortunately, several hydrological agencies have prepared and published variable-code lists (Environment Canada [5] and the U.K. Department of Environment [6]). The code lists normally comprise a four- or five-digit code for the variable, a text definition of the variable, and possibly some abbreviations or synonyms. One feature that varies between the lists is whether the measurement units and/or analyses techniques (particularly for laboratory derived data) are included in the definition or are themselves coded. Thus, in one system variable code 08102 is dissolved oxygen measured in mg/l using a dissolved-oxygen meter, whereas another system describes the same variable as 0126 (dissolved oxygen) with measurement unit code 15, where 0126 and 15 are entries in the relevant code lists for mg/l and metre, respectively.

The purposes and uses of these code lists result in the appellation, data dictionaries. Table 22.2 shows an extract from a dictionary of hydrological codes, while Table 22.3 shows an extract from a water quality dictionary. The first example uses separate variable and unit codes, while the second has a single variable code to cover the whole dictionary definition. This water quality dictionary also gives details of the applicability of the analysis to samples taken from groundwater (G), lakes (L), and rivers (R), and a target accuracy for the indicated analysis method.

The comprehensive nature of such dictionaries and the work involved in their preparation indicates the advisability of trying to use the existing codes.

22.3.3 *Data-qualification codes*

It is usual, and highly recommended, to have a set of codes available for the hydrological observer and the laboratory technician to qualify unusual or uncertain data so that future data usage may be weighted accordingly. There are basically two groups of qualifications — the first can be viewed as the current status (reliability) of the data value and the second indicates some background conditions that may cause a non-normal status. For both groups, the code used is normally a single alphabetic character, also known as a flag. Flags for the status of the data are typically:

E — estimated value, with an implication of a satisfactory estimate;
S — suspect value, thought to be incorrect but no means to verify;
G — value greater than calibration or measurement limit (value set to limit);

L — value less than the detection limit (value set to limit); and
V — value outside normally accepted range but has been checked and verified.

Flags for background conditions may be:

I — presence of ice (or ice damming);
S — presence of snow;
F — presence of frost;
D — station submerged (during flood events);
N — results from a non-standardized (quality controlled) laboratory; and
P — results from a partially quality controlled laboratory.

TABLE 22.2

Extract from a dictionary of hydrological codes

Codes		*Preferred title and synonyms*	*Unit*
DET	UNIT		
2000	110	RIVER FLOW	$m^3 s^{-1}$
2001	110	RIVER FLOW HOURLY MEAN	$m^3 s^{-1}$
2002	110	RIVER FLOW DAILY MEAN	$m^3 s^{-1}$
2003	110	RIVER FLOW DAILY MEAN (0000-2400)	$m^3 s^{-1}$
2004	110	RIVER FLOW MONTHLY MEAN	$m^3 s^{-1}$
2005	110	RIVER FLOW ANNUAL MEAN	$m^3 s^{-1}$
2006	110	RIVER FLOW ANNUAL MEAN (Oct.-Sept.)	$m^3 s^{-1}$
2008	110	RIVER FLOW DAILY MAX	$m^3 s^{-1}$
2009	110	RIVER FLOW MONTHLY MAX	$m^3 s^{-1}$
2010	110	RIVER FLOW MONTHLY MAX DAILY MEAN	$m^3 s^{-1}$
2011	110	RIVER FLOW ANNUAL MAX	$m^3 s^{-1}$
2012	110	RIVER FLOW MONTHLY MIN DAILY MEAN	$m^3 s^{-1}$
2013	21	RUNOFF DAILY TOTAL	mm
2014	21	RUNOFF MONTHLY TOTAL	mm
2015	18	WATER LEVEL REL. O.D.	m
2016	18	WATER LEVEL REL. O.D. DAILY MEAN	m
2017	18	WATER LEVEL REL. O.D. MONTHLY MEAN	m
2018	18	WATER LEVEL REL. O.D. ANNUAL MEAN	m
2019	18	WATER LEVEL REL. O.D. DAILY MAX	m
2020	18	WATER LEVEL REL. O.D. MONTHLY MAX	m
2021	18	WATER LEVEL REL. O.D. DAILY MIN	m
2024	21	RAINFALL HOURLY TOTAL	mm

NOTE: O.D. is Ordonance Datum, the national zero elevation.

TABLE 22.3

Extract from a dictionary of water quality determinand codes

Code	*Determinand*	*Abbreviation*	*Units*	$G^1L^2R^3$	*Concentration Accuracy Targets*	*Method of Analysis*
18130	Aldrin	Aldrin	ug/l			Gas-liquid chromatography
10101	Alkalinity total	Alk Tot	mg/l CACO3	+ + +	0.02	Potentiometric titration
10102	Alkalinity total	Alk Tot	mg/l CACO3	+ + +	0.02	Colourimetric titration
	Anionic tensides	Tens An	MBAS	+ + +	0.1 mg/l Lauryl	
33103	Arsenic	AS	mg/l AS	+ - +	0.005 mg/l	Colourimetry
33104	Arsenic	AS	mg/l AS	+ - +	0.005 mg/l	Flameless atomic absorption
56101	Barium	BA	mg/l BA	+ - -	0.1 mg/L	Atomic absorption
56102	Barium	BA	mg/l BA	+ - -	0.1 mg/l	Flame emission
06510	Benzo G.H.I., perylene	P A H	ug/l	+ + +		Fluorescence spectrophotometry
	3,4 Benzofluoranthene		mg/l			
	11,12 Benzofluoranthene		mg/l			
	3,4 Benzopyrene		mg/l			
08201	Biochemical oxygen demand	BOD	mg/l 02	- - +	2 mg/l	5 day
05101	Boron	B	mg/l B	+ - +	0.1 mg/l	Mannitol potentiometric method
05102	Boron	B	mg/l B	+ - +	0.1 mg/l	Curcumin method
05103	Boron	B	mg/l	+ - +	0.1 mg/l	Fluorimetry
05105	Boron	B	mg/l	+ - +	0.1 mg/l	Colourimetry carminic acid
48101	Cadmium	CD	mg/l CD		0.001 mg/l	Atomic absorption
20101	Calcium	CA	mg/l CA	+ + +	1 mg/l	Edta titration
20103	Calcium	CA	mg/l CA	+ + +	1 mg/l	Atomic absorption
20105	Calcium	CA	mg/l CA	+ + +	1 mg/l	Flame emission
08301	Chemical oxygen demand	COD	mg/l 02	+ + +	20 mg/l	K2CR07 method
17201	Chloride	CL	mg/l CL	+ + +	1 ml	Titration
17203	Chloride	CL	mg/l CL	+ + +	1 ml	Colourimetry
17205	Chloride	CL	mg/l CL	+ + +	1 ml	Specific ion electrode
17207	Chloride	CL	mg/l CL	+ + +	1 ml	Ion exchange
06711	Chlorophyll A	CHLORO A	mg/l	- + +	0.005 mg/l	Colourimetry
24101	Chromium hexavalent	CR HEX	mg/l CR	- - +	0.005 mg/l	Colourimetry

Table 22.3 (*continued*)

Code	*Determinand*	*Abbreviation*	*Units*	$G^1L^2R^3$	*Concentration Accuracy Targets*	*Method of Analysis*
24002	Chromium total	CR TOT	mg/l CR	- - +	0.005 mg/l	Atomic absorption
29101	Copper	CU	mg/l CU	- - -	0.005 mg/l	Colourimetry
29105	Copper	CU	mg/l CU	- - +	0.005 mg/l	Atomic absorption-solvent extraction
29106	Copper	CU	mg/l CU	- - +	0.005 mg/l	Atomic absorption-direct aspiration
06606	Cyanide	CN	mg/l CN	- - +	0.005 mg/l	Colourimetry
18010	DDD	DDD	ug/l			Gas-liquid chromatography
18020	DDE	DDE	ug/l			Gas-liquid chromatography
18000	DDT	DDT	ug/l			Gas-liquid chromatography
18150	Dieldrin	Dieldrin	ug/l			Gas-liquid chromatography
	Dissolved carbon dioxide	CO2	mg/l	+ + -	1 mg/l	
08101	Dissolved oxygen	DISS 02	mg/l 02	+ + +	0.2 mg/l	Winkler method
08102	Dissolved oxygen	DISS 02	mg/l 02	+ + +	0.2 mg/l	Dissolved oxygen meter
02041	Electrical conductivity	ELEC COND	usie/cm	+ + +	1.0 MSM at 20 Deg. C	Conductivity meter
36011	Faecal coliform bacteria	FAEC COL	No/100 ml	+ + +	N.A.	Multiple tube
36012	Faecal coliform bacteria	FAEC COL	No/100 ml	+ + +	N.A.	Membrane filter count
36101	Faecal streptococci	FAE STREP	No/100 ml	+ + +	N.A.	Multiple tube fermentation
36102	Faecal streptococci	FAE STREP	No/100 ml	+ + +	N.A.	Membrane filter
	Fluoranthene		mg/l			
09104	Fluoride	F	mg/l F	+ - -	0.1 mg/l	Colourimetry
09105	Fluoride	F	mg/l F	+ - -	0.1 mg/l	Specific ion electrode
09106	Fluoride	F	mg/l F	+ - -	0.1 mg/l	Electrode potential method
	Hexachloro cyclohexane isomers	BHC	ug/l			Gas liquid chromatography
01000	Hydrogen sulphide	H2S	mg/l H2S	+ + +	0.05 mg/l	
	Indero 1,2,3-C,D pyrene		mg/l			
97167	Instantaneous discharge	INST DISCHG	m^3/s	+ - +		Gauge height
	Instantaneous discharge	INST DISCHG	m^3/s	+ - +		Other methods
26002	Iron total	FE	mg/l FE	+ + +	0.1 mg/l	Colourimetry
26004	Iron total	FE	mg/l FE	+ + +	0.1 mg/l	Atomic absorption — direct
26005	Iron total	FE	mg/l FE	+ + +	0.1 mg/l	Aspiration

Table 22.3 (*continued*)

Code	*Determinand*	*Abbreviation*	*Units*	$G^1L^2R^3$	*Concentration Accuracy Targets*	*Method of Analysis*
82101	Lead	PB	mg/l PB		0.001 mg/l	Atomic absorption — solvent
82102	Lead	PB	mg/l PB		0.001 mg/l	Extraction
03101	Lithium	LI	mg/l LI	+ + +	0.1 mg/l	Atomic absorption
12102	Magnesium	MG	mg/l MG	+ + +	1 mg/l	Colourimetry
12103	Magnesium	MG	mg/l MG	+ + +	1 mg/l	Atomic absorption
25101	Manganese	MN	mg/l MN	+ + +	0.01 mg/l	Atomic absorption
25104	Manganese	MN	mg/l MN	+ + +	0.01 mg/l	Edta titration
25105	Manganese	MN	mg/l MN	+ + +	0.01 mg/l	Colourimetry
80111	Mercury	HG	mg/l HG		0.001 mg/l	Atomic absorption — direct
28101	Nickel	NI	mg/l NI	- - +	0.005 mg/l	Aspiration
28102	Nickel	NI	mg/l NI	- - +	0.005 mg/l	Atomic absorption — solvent
07506	Nitrogen ammonia	NH3	mg/l N	+ + +	0.1/0.01 mg/l	Extraction
07553	Nitrogen ammonia	NH3	mg/l N	+ + +	0.1/0.01 mg/l	Atomic absorption
07554	Nitrogen ammonia	NH3	mg/l N	+ + +	0.1/0.01 mg/l	Atomic absorption — direct aspiration
07555	Nitrogen ammonia	NH3	mg/l N	+ + +	0.1/1 0.1 mg/l	Atomic absorption — solvent
07105	Nitrogen, nitrate + nitrite	NO3NO2	mg/l N	+ + +	0.1/1 0.1 mg/l	Extraction
	Nonionic tensides	TENS NON		- - +	0.1 mg/l Lissapol	Ion selective electrode
07001	Organic nitrogen Kjeldahl	N KJEL	mg/l N	- + +	X	Titration
07004	Organic nitrogen Kjeldahl	N KJEL	mg/l N	- + +	0.1 mg/l	Nesslerization
15254	Orthophosphate sol	PO4-P SOL	mg/l P	- + +	0.1 mg/l	Colourimetry
	Reactive				0.02/0.002 mg/l	Colourimetry
18165	PCB’s total	PCB	ug/l			
	Permanganate value	PERM V	mg/l	+ - +		Kjeldahl method
10302	PH	PH	pH	+ + +	2 mg/l	Colourimetry
06532	Phenols	PHENOLS	mg/l	+ - +	0.1 pH units	Colourimetry
15403	Phosphorus total	P Total	mg/l P	- + +	0.002 mg/l	
	Phytoplankton genus +	PHYTOP		- + -		Gas-liquid chromatography
	species				N A	
19103	Potassium	K	mg/l K	+ + +		pH meter
19105	Potassium	K	mg/l K	+ + +	0.1 mg/l	Colourimetry
	Primary productivity	PRIM PROD	mg 02/l	- + +	0.1 mg/l	

Table 22.3 (*continued*)

Code	*Determinand*	*Abbreviation*	*Units*	$G^1L^2R^3$	*Concentration Accuracy Targets*	*Method of Analysis*
34102	Selenium	SE	mg/l SE	+ + +	A02 0.3 mg/l	
14101	Silica reactive	SI REAC	mg/l SI 02	- + -	0.001 mg/l	
11103	Sodium	NA	mg/l NA	+ + +	0.1/0.01 mg/l	Flame photometry
11105	Sodium	NA	mg/l NA	+ + +	1 mg/l	Atomic absorption — direct
16301	Sulphate	SO4	mg/l SO4	+ + +	1 mg/l	Aspiration
16302	Sulphate	SO4	mg/l SO4	+ + +	2 mg/l	
16303	Sulphate	SO4	mg/l SO4	+ + +	2 mg/l	Flameless atomic absorption
16306	Sulphate	SO4	mg/l SO4	+ + +	2 mg/l	Colourimetry
10401	Suspended solids	SUSP SOL TOT	mg/l	- - +	2 mg/l	Flame photometry
02061	Temperature	TEMP	Deg C	+ + +	2 mg/l	Atomic absorption — direct
02062	Temperature	TEMP	Deg. C	+ + +	0.5 Deg. C	Aspiration
06001	Total organic carbon	TOC	mg/l C	+ + +	0.5 Deg. C	Gravimetric method
02076	Transparency	TRANS	metre	- + +	1 mg/1	Turbidmetric method
10504	Volatile suspended solids	SUSP SOL VOL	mg/l	- - +	0.5 metre	Titration

1. Determination to be done on groundwater marked as +.
2. Determination to be done on lakes marked as +.
3. Determination to be done on rivers marked as +.

Flags should be entered if they are present and will be stored with the data to which they relate. The computer data-validation procedures performed on the input data may generate more status flags, and the same codes may be used.

22.3.4 *Missing data codes*

It is extremely important to differentiate between data that are missing and data that were recorded as having a zero value. If the data field for a missing numeric value is left blank, most computers automatically infill a (misleading) zero. Because a character value is not allowed in a numeric data field, this missing data problem cannot be overcome by inserting ‘M’ (for missing). One possibility is to put the code M as a separate data-status flag, but in systems where flags are not used, some physically impossible data value, e.g., - 999, are entered in the data field to indicate a missing value to the processing system. If required, this value may be decoded to a blank or a “-” on output.

22.3.5 *Transmission codes*

All systems for the transmission of data make use of some form of coding methods, the purpose of which is to ensure that the information is transmitted quickly and reliably. In the case of fully automated systems, the information must necessarily be put into coded form before being processed. For this reason, the codes are composed of standard code forms, which enable the information to be transmitted and given in a form compatible with processing. Such processing is usually preceded by quality control. Transmission codes are discussed in detail in section 4.4.

References

1. World Meteorological Organization, 1983: *Guide to Climatological Practices.* Second edition, WMO–No. 100, Geneva.

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CHAPTER 23

PRIMARY DATA PROCESSING

23.1 General

Data processing entails transforming the raw data into forms that enable ready manipulation and efficient storage for prospective users. Data typically enter the system via key punching of manuscript records, by mechanical conversion of analogue records, or in a digital form. Raw data are commonly compressed or reformatted into their most usable forms, and they should be subjected to a variety of quality checks at appropriate stages.

Regardless of the type of data being processed or the path that its processing takes, a basic requirement is to maintain a standard of operation that will not degrade the quality of the data.

The processing system should be integrated, and it should be reviewed periodically to ensure its continuing effectiveness in the light of new systems, technology, and data-user requirements. Some elements that should be considered are noted briefly below.

The system should aim at minimizing duplication of effort, avoiding unnecessary processes, monitoring progress and completion, and ensuring that interrelated activities are coordinated effectively. The system should be structured to include checks at appropriate stages. It should encourage broad patronage by allowing rapid, easy access to the data, and it should be geared to update data at routine, short intervals.

The system should have sufficient flexibility to allow easy correction, addition, or upgrading of faulty sections of the data. At the same time, it must be protected by a high level of security to ensure that any alterations to the database are legitimate and authorized. All original versions of a data set, plus the corrected version, should be archived. This allows the pedigree of any set of data to be checked.

At a more technical level, great care should be taken in setting up the computer algorithms for data compaction, computation, and checking. They have a direct effect on the quality of the stored data. Once in place, algorithms tend to be taken for granted, and an inadequate routine can degrade the database for long periods of time without detection. Similarly, any enhancements to the software should be dated and documented after testing to assist tracing periods of incorrect processing. For a more concise presentation, the various components of a complete data-processing system are shown in the Table below.

The components of data processing

Data processing							
Data preparation	*Data entry (input)*	*Validation*	*Primary processing*	*Database updating*	*Secondary processing*	*Retrieval*	*Output*
Prepare punching documents by: 1 Transcription Field notebook entries Non-standard data formats 2 Coding Reduction/ standardization of input data	1. Puncing document a. Direct keying through VDU b. Keying onto computer-compatible media Punched cards Key-to-tape Key-to-disk 2. Charts and maps Direct input by digitizer 3. Computer-compatible media a. Tapes/cassette b. Diskettes c. Solid state memory d. Communication lines (telemetered data) e. Mark sense/ optical character readers	1. Range checks 2. Sum checks 3. Interstation consistency checks	1. Standardization of units 2. Calculation of derived parametres 3. Further coding of input to reduce storage requirements 4. Arranging data in database format	1. Add new data sets to existing database 2. Report any errors	1. Programs for routine reports 2. Statistical summaries 3. Infilling missing data values 4. Interpolation or aggregation of data	1. Selection of data by: a. Parameter type b. Parameter value c. Location d. Period of record e. Time interval of record 2. Selection of output device	1. Printers 2. Plotters 3. VDU 4. Computer storage media 5. Microfilm 6. Telemetry
	Error correction						

Section H of the *HOMS Reference Manual* contains components describing primary processing systems for several types of data. These include climatological, precipitation, water level, discharge and water quality data.

Finally, overall security of the database should be ensured against loss or corruption.

23.2 **Data entry**

23.2.1 ***Key stroking***

The basic choice lies between off-line or on-line systems, and within either system, whether or not data should be validated during the entry process.

Off-line systems provide key-stroked data on a computer-compatible medium that is transferred to the input device of the main processing computer. Off-line systems produce disks, diskettes, or 9-track magnetic tapes containing the data or can be connected via a modem or local area network to the main processing centre. Associated with this shift in storage medium, there has been increasing use of microprocessor-based intelligent data-entry equipment, which has allowed data to be subjected to specified initial validation checks as it is entered (i.e., data entry under computer control). The data are then transferred to a temporary storage area from which they may be recalled for further editing. Once data-checking procedures have been completed, the data sets may be output to disk, diskette, or tape and sent for processing or be transferred electronically for processing.

The main advantages of off-line data-entry systems are that they can be located remotely from the main electronic-data-processing (EDP) computer, and that they release the central machine for more complex data-processing tasks. The decentralization of the data-entry function is recommended, and it is suggested that, as far as possible, those responsible for data collection should also be responsible for data preparation, including the initial data-validation stages. Data volumes collected by hydrological observers are not very high in conventional EDP terms, because most of their time may be spent travelling between stations to collect relatively few data values. It is both practical and highly recommended that by the provision of simple microcomputer facilities at field centres, hydrological observers could supervise themselves, under computer control, in the entry of the data. The computer-controlled forms can be generated from standard microcomputer data-entry packages or can be derived from software developed centrally for the specific purposes of hydrological-data entry. When specifying such systems, a high priority should be given to ensuring disk format compatibility.

The tasks of distributed data-entry centres are:

(*a*) To key stroke locally completed data forms, preferably under computer control;

(*b*) To check and correct keyed data. This may be performed by visual inspection of data printouts and/or the use of simple data-validation programes (section 22.2) developed centrally;

(*c*) To copy the corrected data onto disk or other computer medium and send it to the central office or transmit it via modem or other connection;
(*d*) To receive and respond to queries from the central office after the execution of more sophisticated data-validation routines on the main EDP machine. If necessary, the original data set may be edited and a new copy forwarded.

When centralized data-entry systems are preferred or where there still remain significant volumes of data to be entered centrally, larger off-line data-entry systems can be utilized. Because such systems are normally manned by experienced operators, the standard punch/verify type of data entry should be used. The data-validation checks performed by computer-controlled data-entry techniques can cause delays in system response, unnoticeable to most operators, but disruptive to the data-entry speed of experienced operators. Furthermore, because such operators usually have no hydrological background, they would have no means of interpreting warning or error messages arising from tests of hydrological validity. In effect, the functions of data entry and data validation would be split between the central data-preparation service and the central hydrological office. This again points to an advantage of distributed data-entry systems, where for smaller scale operations, the two functions could be combined.

Disks and/or tapes generated from off-line systems arrive at the main EDP machine for input and are submitted to comprehensive sets of data-validation routines.

On-line data-entry systems enable data to be input directly to the main EDP machine through VDU terminals. This type of data entry is suited to small EDP systems, but for larger applications, it should be minimized as much as possible because on-line terminals should be devoted to the execution and control of more complex data-processing operations or to software development. However, the ability to perform on-line data editing is very useful when a small number of data items need to be corrected after a validation run. For limited edits, this procedure is much simpler than requesting the off-line systems to prepare new data sets. The development of powerful personal computers, which can be attached by a local area network to the main computer, has greatly increased the flexibility of these systems.

Whatever data-entry system is used, it is essential that clear guidance is given, preferably on the data form itself, on the way in which data entry should be performed. There should be no ambiguity about what must and what must not be entered nor about the format of the data contained in each data field.

23.2.2 ***Processing of charts***

The primary decision is whether charts will be digitized by automatic techniques or weather computations will be performed manually and the processed data entered into the database. If small numbers of charts are involved, the design of computer systems for automated chart digitization may not be worthwhile. However, studies should be made by system designers to balance the cost and accuracy of manual and automatic techniques. The case for automatic techniques is assisted if the necessary software can be purchased to suit available computer hardware, and also if the digitizing equipment forms part of a larger map analysis system. Automated chart analysis generally implies the use of a digitizer with a hand-held cursor used to trace the chart. Good quality digitizers are expensive compared to other basic components of computer hardware, and the analysis software may cost a similar amount. A higher degree of training is necessary to operate a digitizer than to abstract charts manually.

It should be noted that charts having non-rectilinear grids cannot be analysed directly by using software developed for normal orthogonally gridded charts. Such charts are found on some climatological and water-pressure recorders.

At a higher level of sophistication, in the digitization process, is the use of scanners that automatically follow the chart trace. These are extremely sophisticated pieces of equipment and are usually only purchased by the larger water-sector authorities.

To a large extent, the need for automation is governed by the complexity of the chart. If the majority of charts are derived from groundwater-level recorders, manual abstraction techniques can be fast and accurate. If, however, there are many rainfall-recorder charts, manual analysis becomes slow and liable to error. Charts taken from instruments having reversing-pen movements present particular problems in manual interpretation.

Whether manual or automatic methods are used, the abstraction technique must be determined. The technique of data abstraction at change points between which variations can be linearly interpolated can provide adequate results. This technique reduces the digitizing effort, particularly on charts where there are prolonged periods with little or no parameter change, e.g., rainfall charts in dry spells, groundwater charts, river-flow recessions. Furthermore, data aggregations may subsequently be made to any time base without significant loss of information.

For rainfall charts where traces can be very dynamic, it may be preferable to abstract in continuous-trace mode and develop software to eliminate points that may be interpolated acceptably. The data-compression technique should not sacrifice any of the original data content (section 24.2.4).

Even at stations where digital recorders have been installed, many hydrological services still maintain chart recorders. The reason is that the chart gives the observer an immediate visual appreciation of current and antecedent conditions. If charts serve only as control and backup functions, the development of specific chart processing systems becomes superfluous, as the archive data will be derived from the digital record.

Digitizers are normally operated on-line in small (micro/mini) based EDP systems, and data can be stored directly on diskette, disk or tape. When the digitizer is used off-line, normally under the control of a dedicated microcomputer, either the raw digitized data are transferred to the main processing machine on computer medium or, if the processing software is contained in the microcomputer, the time and datum corrections may be made, and the digitized values are converted to the required time-series format before transfer.

If chart abstraction is performed manually, the data must be transcribed to a data-entry form for input. The simplest way to do this is to use a standard single-variable time-series form. Since the data would probably be extracted as an irregular time series, both time and data values would need to be entered on the form for key punching.

23.2.3 ***Manual stations using telemetry***

At some stations, data are observed manually, but are relayed by telemetry. Such semi-automated data collection is used frequently in real-time processing systems and increasingly for routine hydrological-data collection.

At the simplest level is the use of telephone, telex, and radio links. This approach requires sufficient capability at the data-processing centre to receive the peak levels of incoming messages and the availability of on-line terminals through which the data may be manually entered into the computer. Similarly, data-entry software needs to be developed that will allow random sets of single observations from different sites to be input and will use these values to update the individual time-series files. The input and update procedures should include an elementary level of data validation, e.g., range checks (section 22.2).

If the telemetered data are used for inventory purposes, it is recommended that the observer forwards the usual data-entry form at the end of each reporting period. While the data need not be re-entered again, the form may be used to check the digital record.

The above procedures involve human intervention at both ends of the telemetry link. Techniques are now available that allow the observer to encode the data in a computer-compatible format that may be received and processed automatically at the centre. The method employs a small keyboard, similar in appearance to a hand-held calculator. The observer enters the station and parameter-identification codes and the observed values. The instrument, variously called data collection and transmission terminal (DCTT) or touchstone keypad, codes the data into the required transmission format. The transmission is done by telephone or radio, and may include the use of satellite relays. These units are relatively cheap (including the radio transmitter) and eliminate the need for centralized manual data operations. Where well trained hydrological observers are available, this technique provides an excellent balance in combining the advantages of on-site data observation with the advantages of automated data transmission and processing.

23.2.4 *Automatic station data*

This section is concerned with stations equipped with automatic sensors from which data are recorded on computer-compatible media and/or transmitted by telemetry to some central data collection centre. Whether data are recorded locally or transmitted from the station, there are many common features of the two types of automatic station. These common features are briefly discussed before considering the specific characteristics of each individual technique. It should be noted that not all hydrological variables can be monitored automatically. The status of automatic sensor development may be summarized as:

(*a*) Operational with stage, temperature (air, water, soil), rainfall, humidity, systematic reliability: solar radiation, wind speed, wind direction, pH, and salinity;
(*b*) Operational with open-channel water flow, pan evaporation, snowfall, variable reliability: snow depth, soil moisture, water turbidity, dissolved oxygen, sediment and bed load, some water quality variables, and ice thickness;
(*c*) Not yet developed: most water quality parameters.

It can be seen that the main hydrometeorological elements and surface-water level are very adequately covered, but that water quality data collection still relies extensively on manual data collection techniques. However, a considerable amount of research and field testing is being undertaken in this area.

Sensors fall into two groups, those that provide analogue signals, e.g., float actuated water level gauges and radiation thermopiles, and those that produce digital outputs, e.g., tipping bucket raingauges. Analogue signals must generally be converted into digital form for any subsequent operations. Water level recorders are usually equipped with mechanical/electronic converters, such as shaft encoders, while most climatological sensors are digitized by wholly electronic means. Many sensors produce signals that need conversion to provide data in standard units for analysis. The conversions may be general or may relate to calibration relationships derived for the individual sensor. Data recorded on-site are generally not converted, but this is done at the processing centre. However, transmitted data are normally converted prior to transmission.

There are two time bases for data collection, one is the frequency of sampling, and the other is the frequency of data recording. For some sensor/recording systems, e.g., float/chart at water level stations, these time bases are the same. However, for systems that rely more on electronic techniques — particularly if phenomena being observed have appreciable time variation, e.g., wind speed — the sampling interval could be as little as from five to 10 seconds, while the summed or averaged data might be recorded or transmitted every 10 minutes.

At such stations, data are recorded on computer-compatible media. Hydrological observers visit the stations at intervals of one to three months to collect the data and renew the recording media for the next period. The medium is then taken to the data-processing centre. Data may also be transmitted from the site to a computer centre by radio, telephone, or satellite.

23.2.4.1 *Paper-tape and cassette recorders*

A feature of these types of storage media was that while they were computer compatible they almost invariably needed some translation or change of medium before they could be read directly by the standard range of computer-input devices.

Older digital water-level recorders were fitted with 16-track paper-tape punches. This 16-track format was popular because the data were encoded in a decimal format that could be read directly from the tape by field observers. Such a tape required a specialized tape reader at the processing centre. Similarly, data loggers with tape cassettes were widely used at automatic climate and water quality stations, yet it is only microcomputers that usually support direct data input from cassette.

The reason for this apparent incompatibility between digital media recorded in the field and the range of input devices found on most computers was basically one of data-transfer speed. With the substitution of diskettes and magnetic tapes for punched cards and paper-tape, all computer input devices are now capable of higher input speeds, that permit much more efficient handling of large data volumes. Even though five- and eight-track paper-tape recorders are still being used on some hydrological instruments in the field, five- and eight-track paper-tape readers are fast disappearing as computer-input peripherals.

Most paper-tapes are vulnerable to the environmental conditions experienced at hydrological stations, being affected in particular by changes in humidity. This results in slight but significant changes in tape dimensions that may subsequently give rise to errors in processing. Even the introduction of more stable plastic-coated tapes has not eliminated these problems, although recent experience indicates that aluminium backing on paper-tape has overcome problems caused by humidity changes in New Zealand. However, the risk of processing errors can be minimized by the use of low-speed tape readers that have wider tolerances on variations in tape dimensions.

The system of handling paper-tapes and cassettes is generally to have an off-line preprocessor, i.e., a small machine (probably a microcomputer) dedicated to the task of transferring the data to a high-speed medium, that subsequently can be input to the mainframe computer. Additional details on paper tape and cassette recorders can be found in the WMO *Manual on Stream Gauging* [1] and in the *Guidelines for Computerized Data Processing in Operational Hydrology and Land and Water Management* [2].

Data derived from paper-tape or cassette should always be kept, preferably after transfer to diskette or standard magnetic tape. Thus, original, detailed information would not be lost, regardless of the level of aggregation at which the data were currently stored in the database.

23.2.4.2 *Solid-state memories*

Increasingly miniaturized solid-state memories associated with microprocessors are being utilized for all types of on-site data recording. It already has been seen that microprocessors are used to control the operation of sensors and for the conversion and aggregation of sensor data. It is now possible to store the resulting data in exchangeable memory modules. The typical capacity of such a RAM module is 8 000 data items, that corresponds to about 11 months of hourly recorded data or almost three months of 15-minute data, and this capability is increasing.

At the start of each recording period, a blank RAM module is inserted into the field recording device. Periodically, the modules are exchanged and the removed module is taken to the processing centre where it is plugged into a module-reading device. The reader, having its own microprocessor, can process and format the data contained in the module, and the output may be printed and/or transmitted over standard (RS-232) interfaces to the central computer. After the data have been transferred, they are erased from the module, and may then be re-used. Alternatively, EPROMS are used to download the data directly to a field computer without removing the storage medium.

The advantages of these systems are that no mechanical moving parts are required in the field recording system, the power requirements are low, and the recording unit is much more compact. The extremely high level of automation that this system offers results in the observer having no means of visibly checking instrument performance in the field.

This type of on-site recording device is playing an increasing role in data collection and processing systems.

23.3 **Processing procedures**

23.3.1 ***General primary processing procedures***

A somewhat artificial distinction has been made between validation procedures and primary processing procedures for presentation purposes in this chapter. Data-validation procedures essentially make comparisons of test values against the input data. Primary processing has been viewed as the procedures necessary to manipulate and transform the input data for output and storage.

From an operational point of view, both validation (section 22.2) and primary processing are part of the master database updating procedures executed on a monthly basis in most hydrological systems (Figure 24.1). However, it should be noted that both updating and some stages of primary processing, are conditional upon the successful validation of data.

The main components of primary processing are:

(*a*) Data adjustments for known errors — These are the errors reported by the field technician or those persons responsible for manual quality control of the incoming data sets. As shown in Figure 24.1, corrections for these errors must be made before the data are submitted for validation. Corrections are often necessary for data derived from computer-compatible recording media, e.g., paper-tapes and cassettes, because the data may not be edited until they have been read into the computer. Similarly, automatically digitized-chart data are frequently input with known errors.

The most common adjustments required are compensation for datum errors and differences between the time and date recorded and those logged by the field technician for control purposes, as discussed in Chapter 22. The errors may be associated with gradual drift of the clock, sensor device, or recording mechanism, but may also be caused by discrete events, e.g., clock stoppage or pen/punch jam. In the former case, the processing system may automatically perform the required adjustment using linear or more complex scaling of recorded values. In the latter case, it is normal for manual estimates of missing data to be provided if the affected period is not too long and if sufficient background information is available.

Adjustments may also be required to compensate for more complex phenomena, such as the presence of ice at river-gauging stations. In this case, it is almost certain that the corrected stage (or flow) values would be manually computed for the affected period.

The reporting of errors should entail the use of standard procedures and standard forms for reporting errors to data-processing personnel. The form may be used for noting corrections to stage or flow. An essential feature of the correction process, whether performed by manual or computer methods, is that all modified data should be suitably flagged to indicate all adjustments that have been made;

(*b*) Aggregation and interpolation of data — Many variables, because of their dynamic nature, must be sampled at relatively short periods, but are only utilized as averages or totals over longer periods. Thus, for many hydrological applications, climatological variables may be required only as daily values, but must be sampled with greater frequency to obtain reliable daily estimates. Temperature and wind speed are good examples, but, in many cases, the same is true for water level and river-flow data. While aggregation is straightforward for constant interval time-series, a two-stage interpolation/aggregation must be made for irregularly sampled variables.

It is important to note that the levels of data aggregation are usually different for data output and data storage purposes. Data at a high level of aggregation, e.g., monthly and annual averages, may then be kept permanently on-line for general reference purposes.

Interpolation and aggregation need to be performed in space as well as in time. Cross-correlation of station records to estimate missing data is a common spatial interpolation, and the estimation of areal values from point observations is a common form of aggregation;

(*c*) Assessment of derived variables — The most frequently derived variables are runoff and potential evapotranspiration. However, the full range of derived variables is very broad and includes many water quality indices.

One important database management decision is whether derived variables need to be stored after they have been estimated and reported. It is obviously not essential to occupy limited storage space with data that may be re-computed from the basic data held. The basis for making this decision is:

(i) How often will the derived variables need to be retrieved?

(ii) How complex are the computations required, both in terms of the algorithms used and the amount of background data required?

(iii) Are the objectives of the database to store basic data for users to process themselves, or to compile inventories of all important (basic and derived) variables?

It is not usual to store sediment and dissolved salt loads because these are used less frequently and may be very rapidly computed by the multiplication of two basic time-series, flow and concentration. In the United States, the Water Data Storage and Retrieval (WATSTORE) system [3] keeps on-line daily average flows, while in New Zealand, the Time Dependent Data (TIDEDA) system [3] stores only stages in the original time-series formats used for input. The only fixed rule is that whatever subsequent values are derived, the original data series should be preserved, preferably on an off-line magnetic medium or other stable long-term storage facilities. Derived variables, particularly those derived from two or more basic time-series, may themselves need validation. Thus, while both the river-stage and rating-curve data may satisfy any validation tests applied to them on an individual basis, their combination to produce flow estimates may reveal some inconsistencies. Section 22.2.3.5 describes some validation techniques specifically suited to flow data;

(*d*) Output of statistical summaries — These are the routine outputs, usually on a monthly and annual basis, of data processed during the database updating cycle. These outputs may also be considered as the basic data retrieval outputs and, with this in mind, many elements of the primary processing and data-retrieval software should be common. Attention to this point will greatly reduce software development effort;

(*e*) Conversion to database storage formats — The complexity of this operation depends upon the difference between the formats in which input data are provided and the formats of the master database files. Data are normally held in the input format on a temporary basis while awaiting validation and primary processing. After primary processing, the quality controlled, processed data are transferred to (update) the master database files.

It should be emphasized that there is no need, and it is generally inadvisable, to use common formats. Data-input formats should be designed to suit the characteristics of the data-collection and data-entry systems. Data-storage formats should be designed to suit the storage media and the data-access requirements.

Examples of the merging of data from several input forms into a single record and, conversely, splitting the input data for storage purposes are outlined in the WMO *Guidelines for Computerized Data Processing in Operational Hydrology and Land and Water Management* [2].

In addition to the re-grouping of data, additional levels of data coding may be performed and measurement units may be converted to the standards adopted in the database. The conversion of irregular to regular time series (item (*b*) above) is also one of the operations necessary in many cases. There are many options regarding the way in which data may be compressed for efficiency of storage. These techniques are discussed in section 24.2.4.

Not all data would be subject to each of the above processing steps. The degree of processing necessary depends upon the particular hydrological parameter, the way data were recorded and/or abstracted for data entry, the type of processing system, and the ultimate purposes of the collected data. In real-time systems, it is quite conceivable that incoming data in the raw state (validated or unvalidated) are all that is required to trigger some management or operational action.

The extent of processing also depends upon the severity of data-status flags and reports produced during the data validation phase. Unless the validation system detects an indisputable error, i.e., failure to satisfy an absolute-error check (section 22.2), it is preferable to allow processing to continue, maybe even to the updating stage. Such a policy eliminates the need for any further processing action should the queried data prove later to be correct. The status of the data is flagged in the working files while confirmation or editing of the data is awaited (Figure 24.1).

23.3.2 ***Specific primary processing procedures***

The above general procedures may be applied differently to various hydrological data types, and it is necessary to identify some of the specific procedures commonly practised. As noted at the beginning of this chapter, several WMO and FAO publications deal directly with many of the procedures to be described, and reference to the relevant publications will be made frequently. These texts should be consulted for background theory and the formulation of techniques, primarily for manual processing. This section presents some additional information required to computerize and extend such techniques.

23.3.2.1 *Climatological data* **[H25]**

For hydrological applications, the most significant climatological variables are temperature, evaporation, and evapotranspiration in the order of progressive levels of processing complexity.

Before reviewing the processing tasks, it is useful to consider the means by which most climatological data are observed and recorded, because this has a significant impact on subsequent operations. The wide range of climatological variables and their dynamic nature have resulted in the situation whereby the majority of the primary data are obtained from one of two sources — permanently occupied climate stations and packaged automatic climate (or weather) stations.

The implication of the first source is that the observers tend to be well trained and perform many of the basic data-processing tasks on site. Because the processing required for most parameters is quite simple, field processing may constitute all that is required. Even where more complex parameters need to be derived, observers are usually trained to evaluate them by using specially constructed monograms. Thus, computer-related primary processing, if performed at all, largely comprises the verification of the manual calculations.

The implication of the use of automatic climatological stations is that there exists a manufacturer-supplied hardware and software system capable of performing the complete range of data-processing tasks (section 23.2.4). Indeed, many climatological stations are designed specifically to provide evaporation and, normally Penman-based, evapotranspiration estimates. Most packaged systems include a central microcomputer to read the recording media — cassette or solid-state electronic memory — and to perform the data validation, consistency, aggregation, and processing tasks. In this case, the main central database computer simply receives the processed data in a format directly suitable for storage and application. Care must be exercised in the use of automatic climate-station data because the range of quality of sensors is highly variable. Further details on the processing of climatological data can be found in the WMO *Guide to Climatological Practices* [4].

There are several climatological variables that need to be transformed to standard conditions for storage and/or application. For example, wind speeds measured at non-standard heights may need to be transformed to a standard two metre height by using the wind speed power law. Similarly, pressure measurements may be corrected to correspond to a mean sea-level value, if the transformation was not performed prior to data entry.

23.3.2.2 *Evaporation and evapotranspiration observations* **[H39]**

Where direct measurement techniques are used, the computer may be used to verify evaporation estimates by checking the water levels (or lysimeter weights), and the water additions and subtractions.

To compute lake evaporation from pan data, the relevant pan coefficient needs to be applied. In some case, the coefficient is not a fixed value, but must be computed by an algorithm involving other climatological parameters, e.g., wind speed, water and air temperature, and vapour pressure. These parameters may be represented by some long-term average values or by values concurrent with the period for which pan data are being analysed. Pan coefficients, or their algorithms, must be provided in the station description file (section 21.2). If an algorithm, uses long-term average values, these, too, must be stored in the same file.

Details on the estimation of evaporation and evapotranspiration are discussed in Chapters 9, 37 and 38. Some existing computer programs for solving the Penman equation are available in subsection I50 of the *HOMS Reference Manual*.

23.3.2.3 *Precipitation data* **[H26]**

Data from recording precipitation gauges are frequently analysed to extract information relating to storm characteristics, while data from totalizing gauges serve primarily to quantify the availability and variation of water resources.

Before analysing any data from recording raingauges, it is necessary to produce regular interval time-series from the irregular series in which the data are usually recorded. If the data have been subjected to a previous stage of validation, this time-series format conversion may already have taken place. The computer program used for conversion should be sufficiently flexible to allow the evaluation of any constant interval time-series compatible with the resolution of the input data. The program will need both to interpolate and aggregate in order to produce the regular series. The selection of a suitable time interval will be discussed below.

Whether the data are derived from recording or totalizing gauges, first priorities are the apportionment of accumulated rainfall totals and, the interpolation of missing records. Accumulated rainfall totals are common in daily precipitation records when, for example, over a weekend, a gauge was not read. However, they are also common with tipping-bucket gauges that report by telemetry. If reports of bucket tips are not received during a rainfall period, the first report received after the gap will contain the accumulated number of bucket tips. The difference between this accumulation and that provided by the last report must be apportioned in an appropriate manner.

The techniques for apportioning accumulated totals and for estimating completely missing values are essentially the same. Section 22.2.3.2 describes the technique of cross-correlation with adjacent stations for providing estimates of daily and monthly precipitation totals. While the objective was to validate actual precipitation totals, it can also be used to apportion accumulated totals, or to estimate the precipitation values when data gaps exist. Apportioned or estimated precipitation values should be suitably flagged by the computer program that performs these tasks. Exactly the same techniques may be applied to shorter interval data from recording gauges, but estimates of lower quality will be obtained because there will usually be fewer adjacent stations and because of the dynamic nature of short-term rainfall events.

23.3.2.4 *Streamflow data* **[H70, H71, H73, H76, H79]**

There are several processing steps required to produce streamflow data. The first deals with flow-measurement data, the second incorporates the gauged flows into rating curves, the third describes the computation of flows from stage data, and the final step outlines some standard analyses performed that use the flow estimates. Comprehensive details of techniques for flow computation are presented in the WMO *Manual on Stream Gauging* [1].

Flow measurements

As described in section 22.2.3.5, the computation of flows from current-meter gauging data is primarily performed as verification of the values computed manually in the field office. Although encountered less frequently, there is scope for the complete processing of dilution-gauging data (section 11.4), as this may not be analysed until laboratory analyses have been performed. The analysis techniques for both methods are described in the WMO *Manual on Stream Gauging* [1]. Because the volumes of data involved are small and the analyses are straightforward, many systems do not provide for computer processing of either data set. Some agencies issue small programable hand calculators to assist technicians for field evaluation of current-meter gauging data. Alternatively, the data are logged directly into a portable computer.

Because of their influence on subsequent flow estimates, it is recommended that flow measurement data be submitted for computer verification. The computer evaluation may be extended to perform error analyses and to assign confidence limits to individual measurements, and computer flows may be checked for statistical conformity with the existing rating curve.

Any program developed for flow measurement data should be capable of handling the maximum number of verticals to be encountered. If warranted by experience, provision should also be made to perform corrections for excessive deflection of sounding lines for suspended meters, and for cases where velocities are not perpendicular to the gauged section. If the program computes velocities as part of the flow calculation (i.e., if only the basic field observations are used as input data), it must have access to a reference file containing the serial numbers and calibration coefficients of the current meter(s) used.

It must be decided whether the program should compute the area of sections on the basis of the mid-section or mean-section method (section 11.2.4).

Rating curves

Rating curves define the relationship between stage and flow. This relationship is determined by performing many river gaugings, over a wide range of flows and by using the stage and discharge values to define a continuous rating curve. While gauging structures have standard, theoretical ratings, it is a recommended practice to rate structures in the field.

Traditionally, rating curves have been manually fitted to the plotted measurements. In many cases the curve may be fitted more precisely by computer methods [1]. If necessary, weights may be assigned to each discharge measurement to reflect the subjective or statistical confidence associated with it. However, because some sections have several hydraulic control points, many hydrologists still prefer to keep the definition of rating curves as a manual procedure. Many factors impact on the quality of the rating curve.

It is obviously imperative that a flow-processing system be able to identify and locate the correct rating curve and be aware of its limits of applicability. Section 24.2.6 describes the organization of station description data, which includes allowance for rating data. Of particular note is the importance placed on preserving historic rating curves to allow flows to be recomputed.

There are two forms in which rating curves may be stored in the computer, functional form and tabular form. Tabular forms are still the most common and the table is prepared by manually extracting points lying on the rating curve. The extraction is performed so that intermediate points may be interpolated, on a linear or exponential basis, without significant error in flow estimation. The functional form of the rating curve has one of three origins:

(*a*) A theoretical (or modified) equation for a gauging structure;
(*b*) A function fitted by the computer to the gauged points, i.e., automation of the manual curve-fitting process;
(*c*) A function fitted to the points of the table prepared as described in the previous paragraph, i.e., a smoothing of the manually-fitted curve.

Where possible the functional forms are to be prepared because they do not need interpolation. They are simple for the computer to handle and do not require a large amount of storage space. If functions are adopted, the computer may be used to prepare rating tables for manual purposes.

Flow computation

In order to evaluate flows, the following data sets must be available to the computer:

(*a*) A quality controlled set of stages, i.e., those that have been corrected for datum, gauge height, and timing errors and have subsequently been validated (section 22.2.3.4). If slope methods of flow computation are used, two sets of water levels are required;
(*b*) Rating curve(s) corresponding to the time and range of levels of the stage series. Where rating curves are related to frequently changing artificial controls, e.g., gates and sluices, a time-series of control settings may be needed to guide computer selection of the relevant rating curve;
(*c*) Any shift corrections that need to be applied to the stage record(s). This requires that the amount and duration of the shifts be specified.

After having verified that all the necessary data sets are available, flow computation may proceed in the following steps:

(*a*) Apply shift correction to the stage record. At very low flows, it is possible for negative shifts to produce a modified water level below the zero datum. Such an eventuality should be detected and reported;
(*b*) Check that the rating curve being used is still applicable to the time value of the stage being processed. If the curve is invalid, identify and locate the proper curve. Failure to locate the appropriate curve should be reported;
(*c*) Check that the stage being processed lies within the valid range of the rating curve. If it lies outside the valid range, the processing system must know whether extrapolations of the rating curve are allowed, and if so, to what extent. If extrapolation is not allowed, or if the stage lies outside the allowed extrapolation range, an "out of range" error should be reported;
(*d*) Apply the rating curve to the water level and obtain the corresponding flow value;
(*e*) Return to step (*a*) until all water levels have been processed; then
(*f*) Aggregate the flow time series to obtain the required standard time-unit (normally one day) average flows.

A problem frequently encountered when using multiple rating curves is that they can produce abrupt changes in flow rates at the time of change-over. The processing system needs to be given some rules as to how this situation should be treated. Such problems normally require manual adjustment of flows during the transition period if discontinuities are unacceptably large.

It should be noted that, unlike rainfall-data processing, the aggregation to produce the standard interval time-series was the final step in the above procedures. The reason for this is the non-linear relationship between stage and discharge.

As has been noted several times, flow data are usually aggregated into daily average values. If areal rainfall estimates become available for the catchment area, these may be collated with the flow file.

Apart from determining instantaneous stage and flow extremes, it is not common to output routinely the elements of the instantaneous flow time-series. The stage time-series and possibly the corresponding flow series are preserved on off-line tape or diskette to support future requests for detailed data.

Routine post-computation tasks

Some attempt is normally made to fill data gaps by cross-correlation with nearby gauging stations, particularly those in the same river system. In the absence of reliable cross-correlation relationships, rainfall-runoff models, including the use of conceptual catchment models, may be used. All estimated data should be suitably flagged.

Many river systems are significantly affected by man's activities and these effects tend to change with time. For hydrological and water-resource studies, it is frequently necessary to try to isolate these artificial effects from the natural catchment response, i.e., to try and obtain a stationary time-series. This process requires extensive background information on all forms of direct and indirect diversions, discharges, and impoundments in the catchment. Water-use effects may be aggregated into a single time-series of net modifications to river flow. When these corrections are applied to the measured streamflows, a naturalized time-series is obtained. Any modified data should be appropriately flagged.

A significant task for all data processing that is particularly relevant for flow systems is that of performing the necessary housekeeping operations on data sets. These operations require decisions on which data sets should be retained. According to the principles set out in section 23.3.1, it is advisable to try and save only the essential basic data (and security copies) and principal derived data, i.e., daily river flows that are very time consuming to create. Further consideration of this topic of data management is discussed in Chapter 24. However, for guidance purposes the following flow-related data should usually be preserved:

(*a*) The stage and stage-correction data;
(*b*) The adjusted stage data, i.e., the time-series of water levels corrected for datum, gauge height and time errors. A working copy and at least one security copy should be held (off-line);
(*c*) The rating curves and their associated shift corrections;
(*d*) The daily average flows, some of which may be held on-line (most recent water years, monthly summaries, or whole period for important reference stations);
(*e*) Basin water-use data used to obtain naturalized flows.

All other data sets are transient, or may be readily derived from these basic data sets.

23.3.2.5 *Water quality data* **[H05]**

There are four main areas of activity in the primary processing of water quality data:

(*a*) Verification of laboratory values;
(*b*) Conversions of measurement units and adjustments of values to standard reference scales;
(*c*) Computation of water quality indices; and
(*d*) Mass-balance calculations.

Verification of laboratory results may comprise the re-evaluation of manually-computed values and/or consistency checks between different constituent values. These operations are essentially an extension of the data-validation techniques described in section 22.2.3.6.

The standardization of units is important in obtaining consistency of values stored in the database. The operations necessary comprise the conversion of measurement units used, such as normality to equivalence units, or correction of values to match a reference standard, e.g., dissolved oxygen and conductivity values transformed to corresponding values at a standard water temperature of 20°C.

Water quality indices are generally based on empirical relationships that attempt to classify pertinent characteristics of water quality for a specific purpose. Thus, indices exist for suitability, such as drinking, treatability, toxicity, hardness, etc. Since these indices are derived from the basic set of water uality data, it is not generally necessary to store them after they have been reported. They may be recomputed as required.

Some indices have direct significance for water management. For example, empirical relationships of key effluent variables may be used as the basis of a payment scheme for waste water treatment. The higher the index, the higher the charges.

Mass-balance calculations are performed to monitor pollution loadings and as a further check on the reliability of water quality data. Loadings are calculated as the product of concentration and flow (or volume for impounded water bodies). By computing loadings at several points in a river system, it is possible to detect significant pollution sources that may otherwise have been disguised by variations in flow. Obviously, mass-balance calculations must be performed after flows have been computed.

Mass-balance calculations may be performed easily for conservative water quality constituents, i.e., those that do not change or that change very slowly with time. Non-conservative constituents, e.g., dissolved oxygen and BOD, may change extremely rapidly and quite sophisticated modelling techniques are required to monitor their behaviour. Additional information and techniques can be found in the WMO *Manual on Water Quality Monitoring — Planning and Implementation of Sampling and Field Testing* [5] and the *Global Environment Monitoring System (GEMS) Water Operational Guide* [6].

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CHAPTER 24

DATA STORAGE AND RETRIEVAL

24.1 **Archiving of original data**

Raw data — whether field forms, charts or reports — must be available after processing. Some errors in reporting and processing may not come to light until scrutinized by users. It may also be necessary to check transcriptions from the original or to re-assess the collector's interpretation of a doubtful trace.

Records from a particular site may be re-sampled in response to some future development, or changes in technology may result in an upgrading of standards. In either event, the data may require re-processing. Thus, the original data must be securely archived. The storage should be kept away from the electronic database and should be physically secure.

Raw data should be readily available to any user. To this end, archived material may be microfilmed for convenient reference.

24.2 **Management and storage of processed data**

24.2.1 ***General*** **[G05, G06, G08, G10, G12]**

A full description of the recommended procedures for storage and cataloguing of climatological data is given in the WMO *Guide to Climatological Practices* [1]. Hydrological data require a somewhat different treatment for storage efficiency, but many of the same considerations apply. A brief summary of the salient points in the *Guide to Climatological Practices* are included here, as are some notes on those technological advances not included in the *Guide,* and items of particular importance for hydrological data.

The vast quantities of climatological and hydrological data being gathered by many countries may preclude storage of all original data. However, copies can be made in media that require a small fraction of the space required for the original documents, and the original materials may then be discarded. For instance, microfilms of page data or graphical data require only about 1/300th of the storage space needed for the original records.

Most digital data are archived on magnetic tape or disc for permanent storage. Since one 2 500 feet (762 metres) magnetic tape at a density of 800 characters per inch (25 millimetres) will hold the data of about one quarter of a million punch cards, the storage space now required is a very small fraction of the space required previously. Duplicate copies of magnetic tapes may be made in minutes at a very small cost. Likewise, punched paper tape, being used less and less for permanent storage in the last few years, can be discarded after the data have been transferred to magnetic tape if storage space becomes a problem. Microfilm is often used for the permanent storage of data after all corrections have been made. Some countries now store data on CD-ROM disks that can hold large volumes of easily accessed data.

Storage conditions for any of these media should minimize destruction of stored records by excessive heat, temperature fluctuations, high humidity, dust, insects or other pests, radiation, and fire. Magnetic tapes should be safeguarded from electromagnetic influences. Non-flammable film should be used in microfilming. Where possible, duplicate sets of records should be kept, one in the main collection centre and the other at regional centres or at the observers offices or homes.

Despite their prodigious processing power, microcomputers are in their infancy with regard to handling large data volumes. For this reason, it is suggested that central minicomputer or shared mainframe computers are more relevant to regional-level hydrological-inventory systems. However, there does appear to be some advantage in distributing data-entry and validation tasks to field-level microcomputer centres. This strategy is recommended because:

(*a*) It concentrates limited skills at the centre for the major data-processing activities; and

(*b*) It exposes field personnel to computers and computer-related technology. This should greatly assist in the broad-scale development of computer-related skills in the hydrological sector.

The output from the initial quality control and processing stages described in Chapter 23 comprises intermediate files that may be used to update more permanent database files. The updating procedures require some thought toward minimizing the number of updates being performed and protecting the integrity of the data held in the master files. Furthermore, the efficiency with which updates and retrievals may be performed depends upon the physical and logical organization of data files. This section will review these topics, but will first consider the general question of controlling the flow of data through all stages of data processing.

24.2.2 ***Controlling data flow***

The importance of proper control of incoming data sets has already been mentioned with regard to data-entry operations. The need to be aware of the status of all data sets in the various stages of validation and updating is equally vital. This is particularly true when suspect data have been queried and some response is awaited from hydrological staff in charge of quality control.

Initially, the entire monitoring process may be manual, but ultimately some functions may be automated as part of the general computerized data-handling activities. Automation allows routine monitoring of data-batch status, validation summaries, and the physical disposition of data on the system, e.g., the tape or disk volume numbers and the data set names. Such control is essential where large quantities of data are handled.

Data-control personnel should be appointed with the following responsibilities:

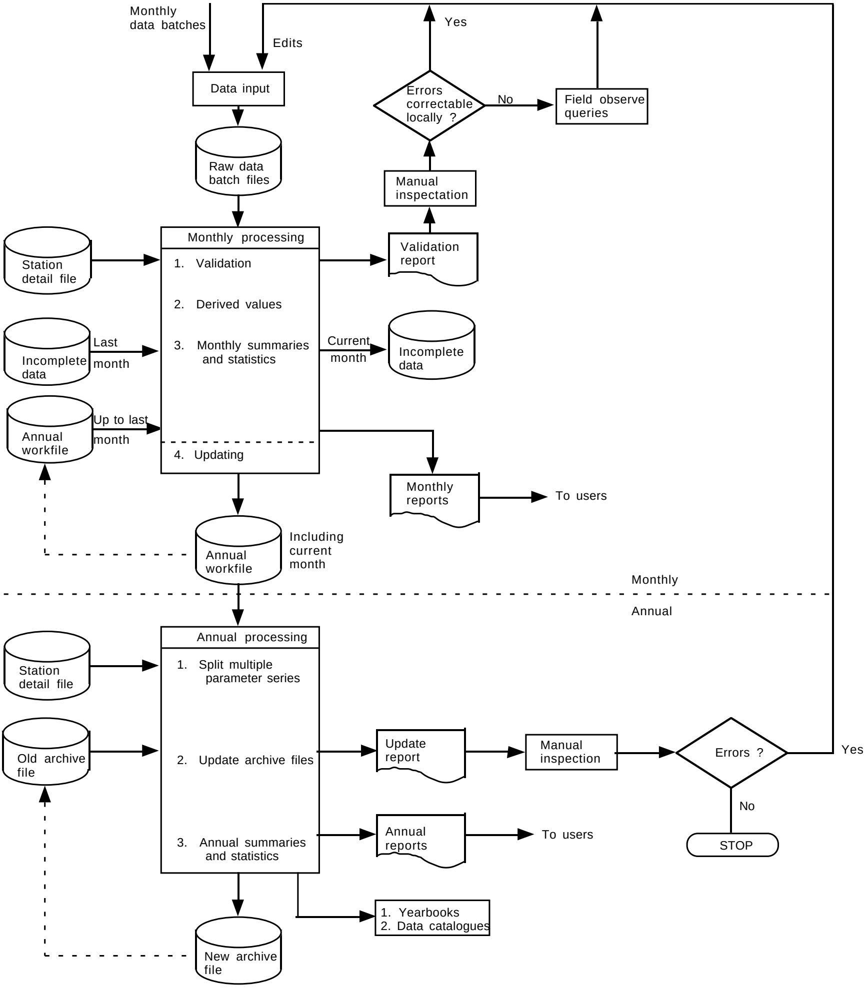
(*a*) Logging of incoming data batches and the routing of these batches to the appropriate data-entry system;
(*b*) Monitoring and logging data-entry status and the subsequent submission of data for initial validation and processing;
(*c*) Routing validation reports to appropriate hydrological personnel and receiving edited data;
(*d*) Repeating steps (*a*) to (*c*) until all data batches have been accepted for updating purposes; and
(*e*) Forwarding monthly and annual summary statistics to appropriate agencies and personnel.

The exact nature of the tasks depends upon the extent to which individual users have access to data for editing purposes. In on-line systems where users are responsible for their own quality control, central responsibilities are reduced. However, such users must have some means to indicate that quality control has been completed and that data sets are ready for further processing.

24.2.3 ***Updating procedures***

Most archival databases in hydrology are updated in at least two stages. These stages are shown in Figure 24.1. The first stage is the cycle of monthly updates corresponding to a standard reporting period. The extent to which the four first-stage activities are split into separate computer runs is dependent upon the user and the physical resources of the system. If most files are archived on tape, it probably would be impossible to perform the complete set of monthly processing with one program because too many tape drives would be required. There may also be a policy not to compute derived values, e.g., flows or potential evapotranspiration, until all the basic data have been checked manually.

For the end user, the main outputs from this first updating phase are the monthly summary reports. For database management purposes, the most important results are the updated annual workfiles. If this first phase system handles data only in monthly blocks, it may be necessary to maintain incomplete data files. This need arises from the use of computer-compatible recorders, where the recording medium is normally changed at irregular intervals. Thus, when processing month 1, there may be several days of month 2 on the recording medium. In this case, the month 2



NOTES: 1. Monthly processing typically starts 10-15 days after month ending.
2. Annual processing run typically starts 30 days after year ending.
3. Archive files may be held totally off-line (tape or diskette) or may be a mixture of on-line (say, last two years on-line) and off-line.
4. Small-scale data edits may be performed by on-line VDU terminals.
5. Validation and monthly reports shown separately may be the same document, particularly for parameters which do not need transformation, e.g., rainfall.

Figure 24.1 — Two-stage processing/updating procedure for hydrological data.

data are saved on a temporary file until the complementary data are available during month 3. The cycle is repeated, and a complete month 2 file and a new incomplete month 3 file are generated. This problem is rarely encountered with manual reporting or telemetry stations. If the computer-compatible medium requires pre-processing, there exists an option to perform the splitting and subsequent aggregation of months on the pre-processing (micro) computer before data are submitted to the main processing machine.

After passing the validation checks (section 22.2) and being subjected to any necessary primary processing (section 23.3), the monthly data batches are added to the current annual data file. Data not passing validation checks must be manually scrutinized, and, where errors are verified, relevant actions must be taken as indicated in Figure 24.1.

In order to provide an adequate turn-around of data, it is generally necessary to start processing each monthly data batch from the 10th to the 15th day of the following month. If processing is not started by this time, there is a danger that the total data handling, entry, and processing for the annual file updates may become backlogged.

The purpose of the annual updating cycle is to add the annual workfile to the historic database. This transfer carries with it a change in status of the data from a working data set to a quality controlled hydrological reference set. Thus, it must be ensured that as many data queries as possible are resolved before the annual updating takes place.

Output from the annual processing stage may be utilized for hydrological yearbooks.

24.2.4 *Compression and accuracy*

A significant operation in all database updating is the compression of data to make optimal use of storage space. The technique of packing is described in the WMO *Guidelines for Computerized Data Processing in Operational Hydrology and Land and Water Management* [2]. However, packing techniques tend to be machine specific, and several other data-compression techniques are used in various hydrological database systems. These are:

(*a*) Integer numbers are used in storage, which are suitably scaled for output purposes. For example, daily rainfalls, measured to a precision of 0.1 millimetre, could be stored in tenths of a millimetre (an integer) and subsequently divided by 10 for output. The storage requirement is halved. A normal integer uses two bytes of storage compared to the four bytes required to store a real (decimal) number;

(*b*) The use of unformatted (binary) data files instead of normal ASCII files. In addition to requiring less space, binary data are more rapidly stored and retrieved;

(*c*) The use of a counter for repeated constant values. Thus, a period of 10 days without rainfall need not be stored as a set of 10 zeros, but as a repeat factor of 10 followed by the zero value;

(*d*) A more sophisticated version of the above method is to totally remove redundant data. Redundant data are derived from the over-recording of hydrological phenomena by some types of field instruments, in particular, by fixed interval recorders. For example, in the sequence 40, 50, 60 it is apparent that the central value can be derived by interpolation from the adjacent values. Thus, software can be developed to scan data, eliminating all those values that may be linearly interpolated within a defined tolerance range. This technique greatly reduces the storage requirements but leads to no significant loss in the information content of the data. In New Zealand, the use of the Time Dependent Data (TIDEDA) system (HOMS component G06.2.01) has resulted in two to twelvefold savings in storage space; and

(*e*) The use of relative rather than absolute data values. For example, water level in a borehole may be quoted in absolute elevation terms or, more economically, in relation to some local datum or average water level. Only the difference from the previous data value need be stored. These various difference forms produce smaller numbers that may be stored in correspondingly smaller storage locations.

Some balance must be made in the levels of data compression employed. Increasing efficiency in the use of storage is gained at the expense of executing compression and expansion routines each time the data are stored or retrieved. The correct level of data compression should reflect the relative limitations of storage space and computation capabilities, and software development skills, at each installation.

With regard to the accuracy of the data stored, it is exceptional for any hydrological data to be observed to an accuracy of greater than one part in 1 000. For this reason, many hydrological databases store data only to an accuracy of three or four significant figures. Thus, a flow computed as 234.56 cubic metres per second may be stored as 235. Such a practice is also used to save data storage space.

24.2.5 ***Physical-file organization***

Sequential file organization is simple, may be used on all forms of storage medium, and is suited to time-series data that are input and most frequently accessed in a sequential manner.

Indexed sequential files are very attractive for the storage of most hydrological data as the inherent sequential nature of the data is preserved on the storage medium, but the ability exists to access directly individual, or groups of, records.

Random-access organization, like indexed-sequential, is only relevant to disk or diskette files, but requires higher system overheads in terms of storage volumes. Individual records may be accessed directly and more quickly if they are accessed in a random manner. By the use of cross-references (pointers), data in random-access files may be related in complex and effective ways.

If a hydrological database is being developed to support on-line (interactive) data manipulation, files must be available on disk, and the use of indexed-sequential or random-access files should be feasible. Indeed, their use is probably essential to obtain acceptable response times when handling large amounts of data.

Where on-line data access is not a priority, it may be worthwhile to keep single-variable time-series data, such as water levels or rainfall, on sequential files because they are usually searched to abstract a time sequence of data. For multivariate time-series files, there are some advantages in indexed-sequential or random-access organization. If a certain variable was measured at a few stations only, then all stations would need to be searched to locate the values in a sequential file. In some types of random-access file, it is possible to store a pointer with each variable value, and the pointer indicates the location of the next station record that contained a value for the same variable. This location could then be accessed directly. Such a technique is advantageous for water quality data where the variables observed vary widely both between stations and for the same station at different times.

Data held on magnetic tape, the most common format for large database archives, must be held in a sequential manner. However, when files are transferred from tape to disk, any of the range of access methods described above may be used. Whichever access method is used, it is recommended that all large database files be unformatted (binary).

Some database systems utilize a mixture of techniques to maximize storage and retrieval efficiency. This is done by storing large groups of sequential data in single records of random-access or indexed-sequential files. By using this method, each daily or even hourly station year data may be stored as one physical record in a random-access, or indexed sequential, file. To retrieve the data for a given month, the relevant station year record may be accessed directly on the disk. This record is then transferred to an in-memory buffer from which the data for the correct month may be rapidly read.

Some mention should be made of the use of database management systems (DBMS). These systems invariably rely on the use of random-access files [2]. Some caution is recommended in their use unless exact data input and retrieval formats are known (and relatively fixed), and there exists sufficient software support. An evolutionary approach to DBMS use is recommended.

Many agencies are now evaluating the use of relational database systems for the joint storage of data and other information. Advances in this field should be closely monitored.

24.2.6 *Logical-file organization*

There are two aspects of the logical organization of data — the major groupings, which determine the number of files, and the sets of variable values that are included in the records of each file.

A full hydrological base will contain the following groups of files:

(*a*) System reference files that include the code lists (dictionary file) used to check data input, encode data for storage, and decode data for output. If some form of spatial data coding is used then hydrological and/or geographical referencing files will also be needed;

(*b*) Station description files ranging from simple files relating station numbers to station name, type, location, and instrumentation, through to detailed files, such as the complete data for well or borehole logs;

(*c*) Calibration files containing the detailed background information necessary to compute derived variables, normally on a station-by-station basis. Examples include rating curves for river-flow stations and calibration coefficients for climatological and water quality sensors. Some data are independent of stations, e.g., current-meter calibration coefficients and reference tables for theoretical incoming radiation and sunlight hours; and

(*d*) Time-series files containing the series of observations made at hydrological stations. They may be single- or multiple-variable series and may be observed at regular or irregular intervals of time.

The relationship of these various groups of files is shown in Figure 24.2.

From an organizational point of view, it is possible to combine all information of types (*b*) and (*c*) into common files or to split each type into current and historic

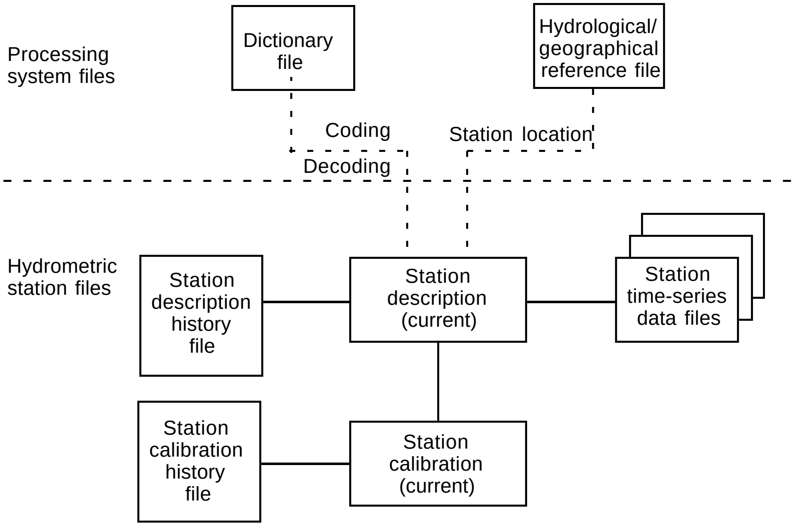


Figure 24.2 — Relationship of hydrometric station data files.

files. This has the advantage of enabling a standard format and size to be used for the current files. The decision is largely governed by the amount of descriptive data to be held in the computer files compared to that held in manual files.

It is useful to consider the various alternatives available for storing different types of time-series data in the same physical file.

At the simplest level, all stations are allocated their own files with data ordered sequentially in time. This technique is suitable for small data sets or for keeping archived data on tape. However, because hydrological networks may contain several thousand stations of various kinds, this simple system becomes extremely difficult to manage and support with large numbers of files.

At a higher level, that used for most hydrological database systems, is the use of files containing many stations, where each file contains data of a different type. This may be hydrological, e.g., daily discharge values, or may be mixed time-series, e.g., several variables at fixed intervals. In the first case, a daily discharge file, for example, would contain all daily discharge data for the entire hydrological network. The file, if sequentially organized, would be ordered by station and, within each station, by time. In the second case, all daily data would be included, regardless of the hydrological type, and the file would be ordered by both station type and station number. Both these cases are encountered in the Water Data Storage and Retrieval (WATSTORE) system [3], which comprises five large files. One file contains the station header (description) data. Of the remaining four, three are grouped by hydrological type (water quality, peak flow, groundwater-site inventory) and the fourth, grouped as time series, is the daily values file. This latter file contains data observed on either a daily or continuous basis and is numerically reduced to daily values. Instantaneous measurements at fixed time intervals, daily mean values, and statistics, such as daily maximum and minimum values, may also be stored. In 1981, this file contained 190 million daily values, including data for streamflows, stages, reservoir contents, water temperatures, specific conductances, sediment concentrations, sediment discharges, and groundwater levels.

At the highest level of integration (other than the utilization of a DBMS), are systems that handle all types of time-series data in one common storage format and that store all time-series data in one physical file. Such an approach, used in the New Zealand TIDEDA system [3], greatly simplifies software development for data management and retrieval tasks because the storage format is standard. Other similar data processing and storage systems that are also HOMS components are the U.K. HYDATA and the Australian HYDSYS systems. Details on how data are manipulated by these data processing and storage systems can be found in the WMO *Guidelines for Computerized Data Processing in Operational Hydrology and Land and Water Management* [2].

24.2.7 *Extraction of single variable data*

There are occasionally inefficiencies in storing data as multiple time-series. These inefficiencies relate to the wide range of variables that may be observed at each site and the way in which data may be retrieved.

Consider climatological data that, after its initial use in the computation of potential evapotranspiration, may be accessed only to retrieve individual variables. Such retrievals are commonly required for the spatial interpolation and/or mapping of data, e.g., temperature data for snow-melt computations or radiation data for assessing crop-production potential. The retrieval process would be inefficient because all stations must be searched even though the variable was observed at only a limited number.

It has been seen (section 24.2.5) that such problems can be overcome by using data pointers stored with each value, which give the location of the record containing the next value of that variable. However, if this technique is used for many variables, the overhead for pointer storage becomes very high.

A solution to this problem is to remove important variables — those frequently accessed individually — and to store them as single variable time-series. This practice is standard with rainfall data observed at climatological stations. This extraction of important variables is best performed during the annual update when validated data are transferred to the historic archive.

It should be stressed that the decision to perform single variable extraction is dependent upon the anticipated way that data will be retrieved. The frequent retrieval of values for a specific variable suggest the extraction of that variable from the multiple variable set. The fewer the stations at which such a variable is observed, the more inefficient is the multiple variable search, and the stronger is the case for a single variable format.

If, as is usually the case with water quality data, retrievals are made for several variables relating to the same observation time, then the original multiple variable format probably remains the most convenient.

24.2.8 *On-line versus off-line data storage*

On-line data storage and interactive access to data, supported by advances in the technologies of magnetic-disk storage and communications, are increasingly common. Data are always available for review, editing, retrieval and analysis, and the range of file organization alternatives allow the most rapid access methods to be used. However, hard disk storage is expensive, is frequently the largest cost component in a computer purchase, and must be justified in terms of the operational requirements of processing tasks and the purposes of the data being collected.

Real-time hydrological operations demand the use of on-line data and, because storage requirements are generally low, they may be satisfied easily and economically.

Research and analysis systems do not have the same operational needs, but because their storage requirements are usually modest, on-line storage of all important data sets is generally feasible and acceptable in terms of cost. An important exception to this general case is for systems handling remote sensing or digitized-map data, where the extremely large quantities of data require extensive use of off-line storage.

Hydrological inventory systems have total storage demands that are not excessive in a technical sense, but on-line storage cannot be justified economically given the non-real-time applications (planning and design) for which the data were collected. Data may be held off-line much more cheaply, but at the cost of extra time (minutes or hours) for the data to be brought on-line when needed. This time delay is usually not critical in inventory systems.

Off-line data storage is normally provided on magnetic tape, but exchangeable disks may also be used. Microcomputer off-line storage is provided by cassettes, diskettes, and high-density tape cartridges. There is increasing use of CD-ROM disk storage as an off-line data storage system.

A review of many existing hydrological systems indicates that provision is made for the permanent on-line storage of the following data sets:

(*a*) The current data batches still awaiting editing and/or primary processing — This includes both the monthly data batches and the annual workfile shown in Figure 24.1. On-line access to these data sets is particularly helpful in making limited data edits. If there is a central responsibility to perform validation and primary processing, these data sets may be protected from access by the data users until validation and updating are complete;

(*b*) A recent period of the master hydrological database — This may comprise the last one to three years of quality controlled data. As new batches are processed from (*a*) above, the oldest batches are transferred to the main master database that is held off-line on tape. Some systems include the current annual workfile — (*a*) above — in this data set, particularly if users are themselves responsible for data validation and editing;

(*c*) A catalogue or index of all available data held on-line and off-line — Where such catalogues exist, they have proved to be very valuable in helping users to define their data retrieval requirements. These catalogues may be published periodically for wider circulation. A simple form of catalogue can easily be made by abstracting relevant information from the station description files; and

(*d*) Temporary work files created by users for their specific applications — These data sets are usually extracted from the database, and they usually duplicate data held elsewhere. It should be noted that one of the main objectives of a DBMS is to eliminate such duplication.

The storage required for the above data sets does not constitute the total on-line storage requirement, which must allow for system and user programs and temporary work space. In some systems, these latter requirements may be very large.

The off-line storage of data sets includes:

(*a*) Copies of the primary data entered into the system, e.g., 15-minute water level values and *x*, *y* coordinates from an automatically digitized rainfall trace. Two decisions need to be taken with regard to these data:
   (i) Whether small-time interval data series should be aggregated to some fixed interval or compressed by using techniques, such as those described in section 24.2.4. In general, this aggregation or compression is performed despite the loss of information that occasionally results. This loss of information is not serious if the original field data recording media are maintained;
   (ii) Whether the corrected or uncorrected values should be saved, i.e., whether the policy is to preserve copies of the original field data or to preserve copies of the corrected data sets as used for database purposes. Normally this latter alternative is adopted and the original field data, charts (or microfiche), punched tapes, or cassettes, are kept separately for archive and reference purposes;

(*b*) The master database files, excluding the most recent period being held on-line. Small- and medium-sized files are stored on separate storage volumes or may be combined on one volume (multi-file volume). Very large files (such as the U.S. Geological Survey daily values file) may occupy several volumes (multi-volume files);

(*c*) Security copies of all data held (both on-line and off-line).

The disposition of these various on-line and off-line data sets is summarized diagrammatically in Figure 24.3.

24.3 **Data retrieval**

Data retrieval is discussed in detail in the WMO *Guidelines to Computerized Data Processing in Operational Hydrology and Land and Water Management* [2]. The ability to rapidly retrieve selected data sets is one of the fundamental advantages of electronic hydrological data processing. Efficient retrieval systems allow the hydrologist or water-resource planner to concentrate on data analysis by minimizing the previously time consuming tasks of locating, collating, and manually processing data.

A comprehensive retrieval system should contain the following features:

(*a*) A wide range of data-selection criteria — Typically these should be by variable, basin, station, time period, and variable value (or range). In particular, it should be possible to select data on the basis of any combination of these criteria;

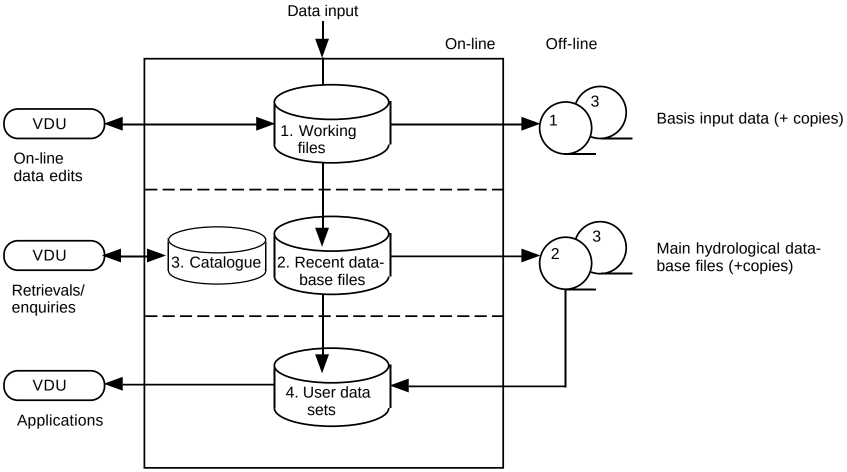


Figure 24.3 — Disposition of on-line and off-line data sets.

(*b*) Data interpolation/aggregation in time and space — Perhaps the most important of these options are the interpolation of irregular into regular time-series and the aggregation of short time-interval series into totals or averages of a longer time base (i.e., conversion of hourly into daily values or daily into ten-day values). If some form of geographical/hydrological referencing system is used, spatial data adjustments may also be made;

(*c*) Computation of simple statistics — Some facility should exist to enable the computation of simple statistics for the period(s) of record selected. This would include totals (if relevant), means, standard deviations, and ranges. More comprehensive statistics — cross-correlations, multiple regressions, probability analyses, etc. — may be offered as part of the standard retrieval system, or the selected data may be passed to a statistical package (or user program) as described below;

(*d*) Selection of output format — This feature should allow for the direct output of data in (specified) tabular or plotted format and for the creation of data files in formats suitable for further processing. In this latter case, the retrieved data set may be stored for input to statistical packages or user-specific application programs. A particular output format may be suitable for the interchange of hydrological data on a national or international basis; and

(*e*) Selection of output device — There should be broad flexibility in the choice of output device. As a minimum this should include line printer, VDU, and disk file. If available, a plotter should be selectable. Data to be transferred to tape or floppy disk is normally first stored on hard disk and transferred with a separate utility requiring several user-specified variables.

It is important that retrieved data, particularly that intended for printed tabular output, retain their codes and flags relating to status and reliability (section 22.3). Background information relating to the general reliability of data and/or unreliability during specific periods should be available to the user through the station description file (section 21.2) or the data catalogues.

Data retrievals may be generated in three ways:

(*a*) Routine data retrievals — These are station data summaries and statistics produced on a monthly and annual basis;

(*b*) User specified retrievals — After consulting hydrological yearbooks or data catalogues, users may request a data retrieval by using a pro forma, and the retrieval is submitted as a normal batch job. This relies on computer operators or other technicians to input the retrieval request using the data retrieval software. The retrieval request form should allow for a wide selection of output media; and

(*c*) On-line (interactive) retrieval of data — There are several modes of on-line specification of data retrievals which, because of their potentially wide use, are discussed below.

As discussed earlier in this chapter and as shown in Figure 24.3, the existence of an on-line master database allows the interactive retrieval of data. However, except for systems with small amounts of data or very large disk storage capacities, the major part of the database must be stored off-line. Thus, the direct interactive mode is usually suitable only for retrieving limited quantities of most recent data. In some systems, remote users can send messages to the computer operators to request the mounting of a particular off-line database volume. However, such requests are rarely satisfied immediately, and this can become very inefficient in terms of terminal usage and communications costs.

Probably the most efficient means of on-line specification of retrievals is the two-stage process. In the first stage, an interactive program allows the user to specify retrieval requirements, and in the second stage this request is automatically submitted as a batch job and the output is obtained later. The format of an interactive machine/user interface is called a menu system. Executing large data retrievals in batch mode is much more efficient in terms of the computer’s ability to allocate its resources, particularly for the extraction of data from off-line volumes.

The above discussion relates primarily to on-line retrievals of data from hydrological-inventory systems. However, the ability to review data being collected and stored for real-time systems is perhaps a more fundamental requirement. Retrieval options range from telemetry interrogation of individual or groups of field stations to the plotting and display of recently collected data, and recently made forecasts, at the processing centre.

References

1. World Meteorological Organization, 1983: *Guide to Climatological Practices.* Second edition, WMO–No. 100, Geneva.

2. World Meteorological Organization/Food and Agriculture Organization, 1985: *Guidelines for Computerized Data Processing in Operational Hydrology and Land and Water Management.* WMO–No. 634, Geneva.

3. World Meteorological Organization, 1981: *Case Studies of National Hydrological Data Banks (Planning, Development and Organization).* Operational Hydrology Report No. 17, WMO–No. 576, Geneva.

CHAPTER 25

DATA DISSEMINATION

25.1 General

Interrogations of a hydrological database may specify a variety of formats and media for the retrieval of the data (section 24.3). The majority of the requests should be handled by a suite of programmes. The formats chosen for these programmes should recognize user needs and conform to the requirements of most common applications.

A fundamental objective of the storage and retrieval system is that it encourages broad use. Special and continuing efforts should be made to ensure fast access and easy retrieval. To this end, direct user (read only) access to the database should be employed where possible, with particular care being paid to well-documented, user-friendly, interactive retrieval routines. The standard output formats should be well publicized to assist potential customers in making realistic assessments of their needs. This aspect has practical ramifications. Time and money can be wasted by over servicing clients.

One important aspect of data presentation is that it should accurately disclose the quality of the data (section 22.3). Data collectors pay great attention to tagging and documenting their product with the intention that this information be passed on to the eventual user. All output should be flagged with appropriate quality symbols and accompanied by explanatory comments. Users should be made aware that more detailed documentation may be available with the original data (section 21.2).

In addition to providing output in response to specific requests, periodic updates of the data should be published. This is normally done in standard output formats. The resulting publications may be in book form, on microfiche, or in a computer-compatible form, such as disk or CD-ROM.

The dissemination of processed information encourages feedback by the data users. Awareness of the users' needs allows collectors to review their methods and collecting frequencies, to reassess the quality of data, to check for any errors in processing, and broaden their knowledge base in relation to the stations they operate.

25.2 Catalogues of information

A catalogue is designed to assist users to identify the hydrologic records that are suitable for their particular needs. For this purpose, information is assembled for each hydrological station and, if it is on a stream, for its related catchment (referred to as a gauged catchment), as well.

For each gauged catchment, the information provided should include:

(*a*) Details of the catchment, e.g., its size, geomorphology, landforms, vegetation, and land use;
(*b*) Climate zone and average annual rainfall and evaporation for the catchment;
(*c*) Location, type, and quality of the gauging station;
(*d*) Details of any upstream regulation or factors that may complicate the use of the records;
(*e*) Period, completeness, and quality of the streamflow and water quality (including sediment transport) records; and
(*f*) Locations of meteorological stations in or near the catchment and their periods of record.

This information is grouped and discussed under three headings, namely descriptive information, catchment map, and data availability.

In order to assist the users in identifying the gauged catchments that are appropriate for their purposes, a description of the characteristics of each gauged catchment and the principal features of the gauging facilities and an indication of the quality and reliability of the flow record should be provided.

Suggested headings and pertinent information are illustrated in Table 25.1. In practice, all details may not be available or appropriate under each heading for each gauged catchment, but it is suggested that the same format be retained throughout. An example wich complements Table 25.1 is provided in Figure 25.1.

A map for each catchment or group of catchments has proven to be valuable. The map should be produced at a scale that is convenient for displaying the information. Catchments of different scales may warrant maps of different scales. In the near future any information for the production of catchment maps will be retained within computer-based geographic information systems (section 40.7) for ease of presentation at a variety of scales. The information to be included on the map is described in Table 25.2 and a basic example is provided in Figure 25.2.

The data-availability page should present a relatively concise and easily updated summary of streamflow, precipitation, and water quality data. It should be based on monthly data for flow and precipitation and on annual water quality data.

For catchments with many precipitation stations, it is impractical to include a summary for each station. All stations and their period of record are shown on the map described in the previous section, so it would be sufficient to restrict the data availability to pluviographs and a selected set of key daily precipitation stations. Stations with long periods could require several pages to ensure adequate scales for legibility.

It is suggested that the information in Table 25.3 be included on the data-availability page.

TABLE 25.1
Outline of a data-catalogue format

Identification	
Name:	River name, station name and station number.
River basin:	Basin name and number.
Location:	Gauging station location in latitude and longitude and local grid coordinates.
Catchment details	
Catchment area:	The catchment area expressed in square kilometres.
Climate zones:	The climate over the catchment expressed in bioclimatic zones that reflect the amount and occurrence of precipitation.
Average rainfall:	An assessment of the mean annual rainfall at the centroid of the catchment and, for large catchments, the range of mean annual rainfall across the catchment. The sources of the figures should be quoted.
Pan evaporation:	An assessment of the mean annual pan evaporation at the centroid of the catchment. The source of the figures should be quoted.
Geomorphology:	Descriptive comments on the relief, landscape and underlying geology of the gauged catchment.
Landforms:	Quantitative estimate of proportions of major landforms within the catchment.
Natural vegetation:	Descriptions of the natural vegetation derived from vegetation surveys.
Clearing:	Proportion of natural vegetation cleared, or substantially altered by man’s intrusive activity. Source and date of clearing estimates should be included.
Present vegetation:	Descriptions of the present vegetation cover across the catchment with a reference to the source.
Land use:	Comments on land use. Source of information should be quoted, be it field observation, map of rural land use, or more detailed evaluation.
Regulation:	Comments on upstream developments that could modify the runoff regime. Possible sources of detailed information should be listed.
General comment:	Where the station does not measure total catchment runoff, or the record cannot be corrected for upstream regulation, the catchment characteristics are omitted in favour of a comment on the station’s particular special purposes or functions.

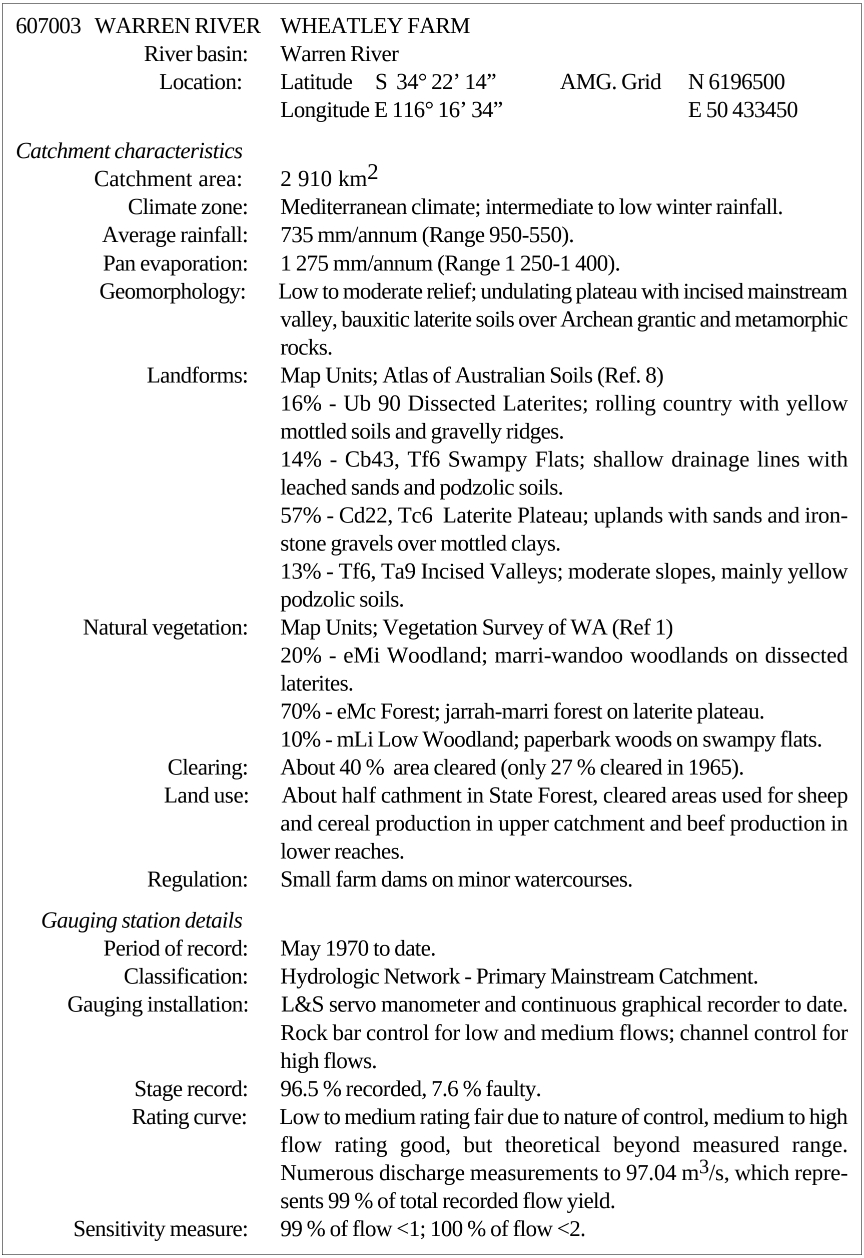
Table 25.1 (*continued*)

Gauging station details	
Period of record:	Month and year of opening and closing of the gauging station. When more than one station has operated near the same reach of river a suitable reference is included.
Classification:	The gauging station's present classification within the hydrologic network (e.g., project station or basic-network station).
Gauging installation:	Description of stage-recording instruments and the features controlling the river stage at the gauging station. Changes in either of these facilities during the period of operation should be noted.
Stage record:	Annual average percentage of data recorded and percentage of these data that required interpretation in processing (faulty record).
Rating curve:	Brief comments on the method and quality of the stage-discharge relationship, together with maximum measured discharge. Where possible, the proportion of measured flow that the maximum measured discharge represents should be shown.
Sensitivity measure:	Some measure of the rating-curve sensitivity should be provided. The preferred method to indicate sensitivity is the percentage of flow volume that could be measured to within one, two or five per cent with a one millimetre error in the stage record. Note that this measure is based on the slope of the rating curve and the cumulative flow duration curve. Alternatively, it may be defined for a 10 millimetre or 100 millimetre error in stage.

25.3 **Summary reports**

Many organizations publish summaries of data. Some examples include climate averages, rainfall statistics, streamflow statistics/records, and water quality records/ surveys.

Typically, such publications consist of station information including station number, latitude and longitude, type of data collected, other site specifications (name, river name, grid reference, catchment area, etc.), period of operation, period of data processed, and instantaneous, daily, monthly and annual data summaries (including minimum, maximum and mean values). Data may be presented as part of the text or attached as microfiche or provided on a computer-compatible form, such as a disk or CD-ROM.



607003 WARREN RIVER	WHEATLEY FARM
River basin:	Warren River
Location:	Latitude S 34° 22’ 14” AMG. Grid N 6196500 Longitude E 116° 16’ 34” E 50 433450

Catchment characteristics

Catchment area:	2 910 km^2
Climate zone:	Mediterranean climate; intermediate to low winter rainfall.
Average rainfall:	735 mm/annum (Range 950-550).
Pan evaporation:	1 275 mm/annum (Range 1 250-1 400).
Geomorphology:	Low to moderate relief; undulating plateau with incised mainstream valley, bauxitic laterite soils over Archean grantic and metamorphic rocks.
Landforms:	Map Units; Atlas of Australian Soils (Ref. 8) 16% - Ub 90 Dissected Laterites; rolling country with yellow mottled soils and gravelly ridges. 14% - Cb43, Tf6 Swampy Flats; shallow drainage lines with leached sands and podzolic soils. 57% - Cd22, Tc6 Laterite Plateau; uplands with sands and ironstone gravels over mottled clays. 13% - Tf6, Ta9 Incised Valleys; moderate slopes, mainly yellow podzolic soils.
Natural vegetation:	Map Units; Vegetation Survey of WA (Ref 1) 20% - eMi Woodland; marri-wandoo woodlands on dissected laterites. 70% - eMc Forest; jarrah-marri forest on laterite plateau. 10% - mLi Low Woodland; paperbark woods on swampy flats.
Clearing:	About 40 % area cleared (only 27 % cleared in 1965).
Land use:	About half cathment in State Forest, cleared areas used for sheep and cereal production in upper catchment and beef production in lower reaches.
Regulation:	Small farm dams on minor watercourses.

Gauging station details

Period of record:	May 1970 to date.
Classification:	Hydrologic Network - Primary Mainstream Catchment.
Gauging installation:	L&S servo manometer and continuous graphical recorder to date. Rock bar control for low and medium flows; channel control for high flows.
Stage record:	96.5 % recorded, 7.6 % faulty.
Rating curve:	Low to medium rating fair due to nature of control, medium to high flow rating good, but theoretical beyond measured range. Numerous discharge measurements to 97.04 m^3/s, which represents 99 % of total recorded flow yield.
Sensitivity measure:	99 % of flow <1; 100 % of flow <2.

Figure 25.1 — Sample data-catalogue page.

TABLE 25.2

Outline of map details

Catchment boundary:	Scale and source of map from which the catchment boundary was defined.
Streamlines:	The number of streamlines to be included should be a function of catchment area. Source of streamline data.
Catchment scale:	Variable — a function of catchment size.
Rainfall stations:	Location and station number, period of operation and type of raingauge, e.g., pluvio, daily read or storage.
Rainfall isohyets: (optional)	Average annual rainfall isohyets for the catchment with the referenced.
Land use: (optional)	Where applicable the boundaries of the main land uses should be shown. Forest, agricultural and urban boundaries would be one example.

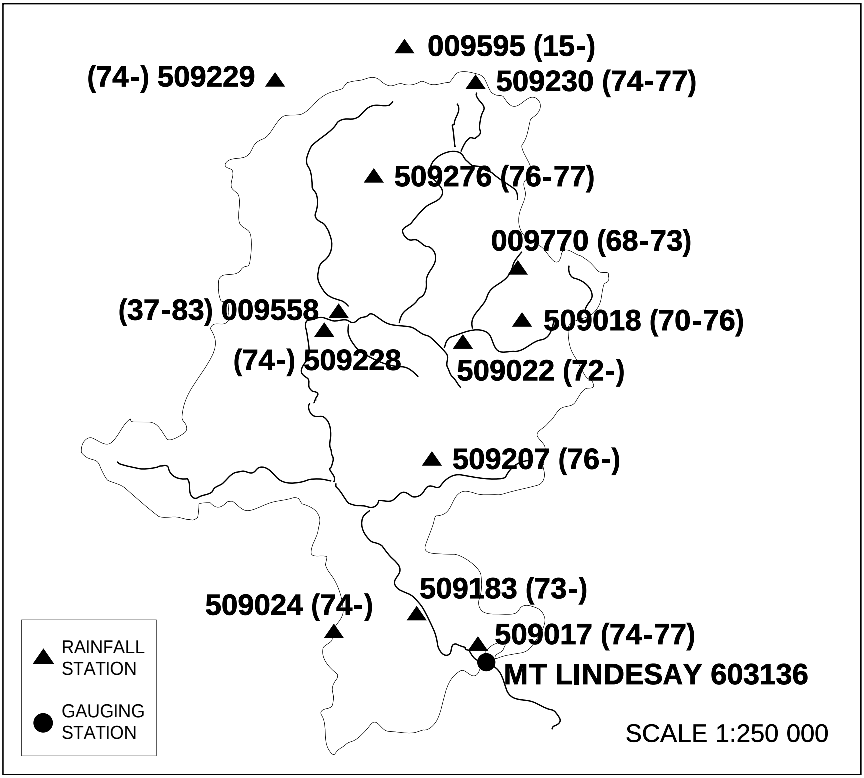


Figure 25.2 — Denmark river catchment.

TABLE 25.3
Outline of data-availability page(s)

Flow data:	Available record and record quality clearly presented in a month-by-month form.
Rainfall data:	Available record and record quality clearly presented on a month-by-month basis for the key pluviograph and manually read rainfall gauges. The period of record covered may be restricted to the period covered by the stream gauging station for practical reasons.
Water quality:	Number of samples analysed each year within a meaningful set of analyses groupings. The groupings suggested are: (*a*) Samples with basic analysis only (any or all of conductivity, pH, river temperature, colour, or turbidity parameters); (*b*) Samples analysed for major ions; (*c*) Samples analysed for nutrients; and (*d*) Samples analysed for heavy metals or other trace constituents.

25.4 Publication of data [G25]

25.4.1 *Purpose*

The primary purpose of a data-publication programme is to provide, in a form convenient to most users of the data, tabulations, maps, graphs and summaries of observations as well as the results of secondary processing of these observations. Regular publications that include processing data provide a safeguard against the loss or destruction of irreplaceable records and may reduce the number of special requests for data that must be answered by a central office. By publishing data, it becomes readily accessible and thus may encourage hydrological research. Since data publications may form one possible medium for international exchange of hydrological and climatological data, it is important that a high level of data reliability be maintained in these publications and that some degree of standardization of format, units, etc., be achieved.

25.4.2 *Frequency of publication*

If the main data requirements are related to monthly and annual water supply, an annual publication containing summaries of data for each month will probably suffice. Yearbooks of streamflow data containing monthly streamflow volumes and extremes of stage and discharge may be sufficient.

However, most hydrological studies (e.g., design storm and flood studies) require data at daily or shorter intervals. Thus, whenever possible, data publications should contain daily data on precipitation, temperature, and streamflow, and as much information on snow cover as is available, whether the regular publication interval is the month or the year.

If data are not published on a regular basis, they should be updated in the database and associated computer summaries should be made available on a regular basis.

In situations where publication of hourly data are warranted, a monthly publication is generally issued. Also, if there is broad interest in hydrological forecasts and their associated data, weekly publication of the forecasts may be justified.

In some cases, specialized requirements may be met by the infrequent publication of summaries of data, e.g., at five-year intervals. This interval is particularly relevant when considering the potential impacts of climate variability and change on water resources.

Special reports may be issued to document extreme events, such as heavy floods or droughts. Such reports should contain all relevant data, graphs, maps, as well as considerations on the magnitudes and recurrence intervals of the phenomena in view of the long-term frequency distribution.

25.4.3 ***Contents and format***

The contents and format of publications should be determined by the requirements of the majority of data users. In general, streamflow and water level data are published separately from meteorological observations, although a few countries publish all data pertinent to the hydrological balance in one volume. In the former case, it may be desirable to publish summaries of precipitation, snow cover and evapotranspiration for particular basins along with the streamflow record. Precipitation data for such summaries should be areal means derived from point precipitation data by one of the methods described in section 30.4.

Yearbooks should contain a comprehensive index of the observation stations, including elevation, latitude and longitude, instrumentation (with changes), years of record available, authority responsible for the observation programme and the address at which original records are kept. In larger countries, the index and the data in the yearbooks should be grouped by major drainage basins, rather than by political or administrative subdivisions, or purely alphabetically. Maps of drainage basins with the stations marked thereon are very valuable and should be included in yearbooks if possible. In countries in which data are published more frequently than once a year, only one issue per year need contain the index of stations. If yearbooks or other regular data publications are not issued, then periodic publication of a catalogue of stations should be undertaken (section 25.2).

Suggested publication formats for climatological data are given in the WMO *Guide to Climatological Practices* [1]. However, these formats do not include information on several important parameters that may be measured at hydrological stations, such as evaporation and rainfall intensity. Suggested formats for such data and for streamflow data are shown in Figures 25.3 and 25.4, respectively. In addition to the information indicated as required in the headings of these formats, it may be

Station
Latitude and longitude
Elevation
Drainage basin

Year
Type of recording raingauge
Type of evaporation instrument

Evaporation			*Total solar radiation (langleys) (3)*	*Precipitations*												*Snow cover water equivalent*	
Month	*Measured water loss (units) (1)*	*Estimated lake evaporation (2)*		*Total*	*Total rain*	*Total snowfall*	*Maximum intensities for durations indicated (minutes)*									
							5	*10*	*15*	*30*	*60*	*120*	*360*	*1 440*	*15th*	*End of month*

1. Loss of water from evaporation pan or other instrument.
2. Water loss adjusted to give free water evaporation estimate.
3. This could be replaced by hours of bright sunshine.

Figure 25.3 — Special table for annual climatological and hydrological summaries.

Section name .... Station number ....
....

Detailed location* ....

Type of gauge and method of discharge measurement ....

Gauge elevation datum ....

Drainage area ....

Period of record, maximum, minimum and mean flows of record ....

Remarks..

Summary-Water Year 19 -19

Month	Discharge (units)			Runoff Volume		Mean basin precipitation (units)	Mean basin water equivalent at end of months (units)
	Maximum**	Minimum**	Mean	Volume Units	Depth on drainage area (units)		
October November December January etc. September							
For the year							

Mean daily discharge (units) - Water Year 19 -19

Day	Oct.	Nov.	Dec.	Jan.	Feb.	Mar.	Apr.	May	June	July	Aug.	Sept.
1 2 3 etc. 30 31			***									

Peak discharge for year .... time .... date ....
Minimum discharge for year .... time .... date ....

* This can be designated by river distance from a fixed point, by bridge on which gauge is mounted, by distance from nearest village or town, or by other convenient means.

** These columns should be used to enter the best estimates of instantaneous peak and minimum discharges. If these have not been obtained by means of a continuously recording water level gauge but estimated by other means, they should be followed by the letter "E". The maximum and minimum mean daily discharges in each month may be indicated by underlining the daily values in the table.

*** A solid line to the right of the daily discharge values indicates an ice cover present. A dotted line denotes the presence of doting ice, and a solid triangle (Δ) can be used to indicate an ice jam visible from the observing station.

Figure 25.4 — Suggested format for streamflow data publication (18.5 x 17.5).

desirable to include some information concerning the nature of the drainage basin, the rating curve, the extremes of measured discharges, and the stability of the river bed. Local needs must be considered in selecting or revising a data-publication format.

It can be noted in Figure 25.4 that the hydrological year (water year) is not necessarily the same as the calendar year. In many countries in which there is a marked seasonal variation in flow regimes, it is often found desirable to select a water year which begins and ends at a time when large carry-over storage effects are unlikely, so that the hydrological year closely approximates a hydrologically meaningful time unit. For example, in northern hemisphere regions with severe winters and substantial snow accumulations, snow which falls in November and December and does not melt until April would cause difficulty in interpreting yearly precipitation versus runoff data if the water year were taken as the calendar year. In such regions, the water year is often taken as October to September. In other regions, different water years are used to minimize carry-over effects.

Of course, problems also arise from the adoption of other than the calendar year for the tabulation of streamflow data when the calendar year is selected as a base for climatological data. A decision as to which of these difficulties is most serious would depend mainly on the importance of the seasonal or monthly carry-over of components of the hydrological balance in the climatic regime of the region in question.

25.5 **Magnetic media** **[G30]**

Magnetic media used for the transfer of data include magnetic tapes and disks, with an increasing importance of the latter, due to the widespread use of micro and personal computers.

25.5.1 ***Tapes***

Standard magnetic tapes (12.7 millimetres [0.5 inches] wide 9-track) are available in different lengths, the most common being 732 metres (2 400 feet), but shorter lengths such as 90 metres (300 feet), 180 metres (600 feet), 365 metres (1 200 feet) are also available and are suitable for the transfer of small data sets. Tapes should be fitted with a write-protect ring to allow the data to be written initially and be protected from subsequent accidental overwrite.

It is possible to record data on a tape in a variety of densities and formats. Some of these formats relate to the organization of the data on the tape, and these are discussed in the next section. For those parameters relating to the recording characteristics of the tape drive, the following standards are recommended:

(*a*) A recording density of 800 bpi (see below);
(*b*) Non-return-to-zero-inverted (NRZI) recording mode;
(*c*) Odd parity;
(*d*) Extended binary coded decimal interchange code (EBCDIC) data coding;

(*e*) No tape labels;
(*f*) Data files separation by a single tape mark; and
(*g*) End of tape indicated by two tape marks.

While recording densities of 1 600 bpi and even 6 250 bpi are common, 800 bpi is the highest density for which the widely accepted NRZI recording mode is available. The technique called phase encoding, used for higher densities, is not yet standardized. The use of a lower recording density reduces errors associated with read/write head misalignment and allows for the use of lower quality and hence, cheaper tapes.

Parity checking, an internal system for validating the read/write operations, is almost universally available as specified above, as is the use of EBCDIC coding. Even where non-EBCDIC coding is the default option, practically every system allows EBCDIC to be used as an alternative.

Tape labels, that is information written by the host-operating system on a tape to help in identification and retrieval, are almost completely machine dependent. The alternative format of no tape labels should be used. All necessary identification must be written into a data file that will be written on the tape in the same format as all other data.

The logical-record length of 80 bytes is a standard because of the past importance of punched cards and the current width of most VDU screens. Since much software and many peripherals are designed to handle 80 byte records, it is recommended that this length (or shorter) be used. Furthermore, it is recommended that a fixed length of 80 bytes be used for all physical records regardless of the actual logical-record length.

The storage of data on magnetic tapes is considerably improved by blocking records [2]. A blocking factor of 20 produces data blocks of 1 600 bytes. The record and block lengths used for an exchange tape should remain constant throughout the volume. Thus, all the logical files of data transferred to the tape will appear as a sequence of blocks. Owing to buffer-size limitations on some machines, block sizes of less than 2 000 bytes are recommended.

An essential component of the organization of the data is the use of volume, e.g., tape, and file header records, which contain detailed descriptions of the contents and format of the tape and the characteristics of the specific hydrological stations from which the data are derived.

Where a more flexible format is required, it is necessary to utilize data fields that may be variably defined. Such a system relies upon the extensive use of codes to perform the field definition.

25.5.2 ***Magnetic disks***

Disks are being used increasingly for the transfer of small data sets for all types of computers. For microcomputers, disks represent the most commonly used storage medium on which data may be transferred between separate machines.

Currently, the most commonly used disk sizes are:

(*a*) 5.25” (13 centimetres) double sided, double density (2S/2D) with a capacity of 360 Kbytes;

(*b*) 5.25” (13 centimetres) double sided, high density (2S/HD) with a capacity of 1.2 Mbytes; and,

(*c*) 3.5” (9 centimetres) disks (both double and high density) with capacities ranging from 0.75 to 2.0 Mbytes.

Unlike tapes, the user has limited control over the recording format on the disk. The nature of recording data onto disks means that a directory of contents must be present to define the physical location of the files. Currently, most organizations use either the DOS operating environment on IBM-compatible machines or the Macintosh environment. The use of the American Standard Code for Information Interchange (ASCII) code for the transfer of data is recommended. Software to convert files from one machine to another is readily available.

25.5.3 ***Optical disks***

The optical disk is a shiny plastic disk, 12 centimetres in diameter. It is coated with a laser-sensitive film, protected by a thin layer of clear plastic. Any data that can be digitized (words, musical notes, etc.) can be transferred to the disk by using a high-energy laser beam, which burns pits in the laser-sensitive film in an appropriate pattern. To retrieve information, a user inserts the disk into a special disk drive. A low intensity laser beam inside the drive scans the surface of the spinning disk, passing through the plastic whenever it strikes a pit. Electronic chips translate the resultant flicker into intelligible data that can be transformed into sound or read by computer. Optical disks have tremendous storage capacity — several hundred times greater than that of conventional floppy disks and as much as five full magnetic tapes. A possible drawback is that the writing process onto optical disks is irreversible. Once entered, erroneous data cannot be corrected. However, a big advantage is that data access is very rapid.

25.6 **Real-time data-exchange formats** **[G40]**

The discussion so far has centred on transfer of archived data. There also exists an urgent need to utilize common formats for real-time data. WMO has responded to these needs as part of the overall data-processing and transmission standards adopted by the World Weather Watch. The standard formats, defined in the World Weather Watch Global Telecommunication System reference manuals, are grouped into several application areas serving the separate needs of meteorologists and hydrologists. The *Manual on Codes* [3] describes the HYDRA and HYFOR codes that should be utilized in any hydrological-data-transmission system and are essential if data are exchanged internationally (section 4.4).

The HYDRA code is designed for reporting observations on stage, discharge, precipitation, snow cover, air and water temperature, and ice conditions. The HYFOR code, used for the transmission of hydrological forecasts, specifies stage, discharge and ice data. Each forecast may carry with it an associated predicted time of occurrence and/or period of forecast validity. Both code forms require a system of station index numbers.

References

1. World Meteorological Organization, 1983: *Guide to Climatological Practices.* Second edition, WMO–No. 100, Geneva.
2. World Meteorological Organization/Food and Agriculture Organization, 1985: *Guidelines for Computerized Data Processing in Operational Hydrology and Land and Water Management.* WMO–No. 634, Geneva.
3. World Meteorological Organization, 1988: *Manual on Codes.* Volume I, International codes. WMO–No. 306, Geneva.

PART D
HYDROLOGICAL ANALYSIS

CHAPTER 26
INTRODUCTION TO HYDROLOGICAL ANALYSIS

26.1 Methods of analysis in hydrology

Hydrological analysis is generally based on well-established principles of hydrodynamics, thermodynamics, and statistics. However, the central problem in hydrological analysis is the application of these principles in a natural environment that is non-homogeneous, sparsely sampled, and only partially understood. The events sampled are usually unplanned and uncontrolled. Analyses are performed to obtain spatial and temporal information about certain variables, regional generalizations, and relationships among the variables. Often, the pertinent components are not measured directly. Analyses can be performed through different approaches, such as deterministic, parametric, probabilistic, and stochastic. An analysis based on the deterministic approach follows the laws that describe physical and chemical processes. In the parametric approach, an analysis is performed by intercomparison of hydrological data recorded at different locations and times. In the probabilistic approach, the frequency of occurrence of different magnitudes of hydrological variables is analysed. In the stochastic approach, both the sequential order and the frequency of occurrence of different magnitudes are analysed.

There are variables that are measured directly, such as stage and velocity, or that are computed directly from measurements, such as discharge. There are other variables that are computed from a sample of direct measurements, for example rainfall depth over a catchment. The evaluation of still other variables, such as lake evaporation, can only be performed indirectly.

In many cases, the measured variables are not the most relevant subject for an analysis. In the analysis of direct runoff, for example, the hydrograph is often separated into its components, so that the portion associated with a particular rainfall event is separated from the rest of the hydrograph. This separation is achieved by computation, based on analytical models, rather than by a physical measurement.

Analyses include case studies and statistical examination of large quantities of data. Statistical analyses include fitting of data to frequency distributions and to parametric models by regression or time-series analysis. The validity of derived relationships should be tested on independent data. Hydrograph reconstitution is a typical hydrological test.

The degree of both detail and precision of the analysis should be consistent with the quality and sampling adequacy of the available data and with the accuracy required by the application of the analysis. Consideration should be given to the relationship between the cost and time devoted to an analysis and to the benefits expected. In many instances, graphical and other relatively simple computational methods are more cost-effective than more sophisticated methods, and they may be sufficiently accurate for the data and purposes involved.

26.2 **Scope of Part D**

Part D of this *Guide* presents well-established methods of analysis which, in the aggregate, cover the procedures required for most hydrological purposes. Alternative methods are given to meet practical needs in situations where varying types and amounts of data are available.

Analyses may serve one or more of several purposes, such as network design, evaluation of control measures, forecasting of streamflow, and planning of programmes for managing water resources. Those methods of analysis that are oriented primarily to a single purpose appear in the parts of this *Guide* that refer to them. For example, methods used primarily for forecasting streamflow appear in Part E and methods for estimating required reservoir-storage capacity are described in Part F. Parts E and F present sequences of operations, often requiring several analytical steps, which are necessary for producing forecasts and design values.

The methods discussed in Part D are general. Where pertinent, these general methods are cited in other chapters. The chapters in this part are not exhaustive, either in their depth or breadth of coverage of a topic, nor should it be assumed that the methods described are necessarily the best for a particular situation. The reader is encouraged to look beyond this *Guide* for other technologies that may be applicable for the solution of a given problem. The selection of particular technologies for addressing real-world problems should be based on the representativeness of the actual hydrological conditions that is captured by the technology and on the availability of the data to meet the technologies requirements.

CHAPTER 27

FREQUENCY ANALYSIS

27.1 The use of frequency analysis in hydrology

The occurrence of many extreme events in hydrology cannot be forecasted on the basis of deterministic information with the sufficient skill and lead time as those decisions which are sensitive to their occurrence. In such cases, a probabilistical approach is required in order to incorporate the effects of such phenomena into decisions. If the occurrences can be assumed to be independent in time, i.e., the timing and magnitude of an event bears no relation to preceding events, then frequency analysis can be used to describe the likelihood of any one or a combination of events over the time horizon of a decision. Hydrological phenomena that are commonly described by frequency analysis are storm precipitation (Chapter 29) and annual flood maxima (Chapter 36).

Frequency analysis can be conducted either graphically or mathematically. In the graphical approach, the historical observations of the variable of interest are ordered in increasing or decreasing magnitude, and a graph of the magnitudes of the events versus an estimate of their frequency of exceedance, or recurrence interval, is plotted. A smooth curve is then fitted through the plotted points to describe the probability of any particular event's future occurrence. Special graph paper is available that can be used to attempt to depict the smooth curve as a straight line.

The mathematical approach to frequency analysis relies on the assumption of a specific mathematical description, known as a probability distribution, to define the equivalent of the smooth curve of the graphical approach. The parameters of the probability distribution are defined as functions of the statistics of the hydrological observations.

27.2 Statistical series and return periods

In probabilistical analysis, a series is a convenient sequence of data, such as hourly, daily, seasonal, or annual observations of a hydrological variable. If the record of these observations contains all the events that occurred within a given period, the series is called a complete-duration series [1]. For convenience, the record often contains only events of magnitude above a pre-selected base. Such a series is called a partial-duration series. A series that contains only the event with the largest magnitude that occurred in each year is called an annual-maximum series.

The use of the annual-maximum series is very common in probabilistical analysis for two reasons. The first is for convenience, as most data are processed in such a way that the annual series is readily available. The second is that there is a theoretical basis for extrapolating annual-series data beyond the range of observation, but with partial-series data, such theory is lacking. A reason for the absence of statistical theory for the partial-duration series is the lack of independence of events that might follow one another in close sequence.

A limitation of annual-series data is that each year is represented by only one event. The second highest event in a particular year may be higher than the highest in some other years, yet it would not be contained in the series. Accordingly, an event of a given magnitude would have a different frequency of occurrence for each of the two series.

The complete-duration series may be required for the stochastic approach in which independence is not required. It may also serve for a probabilistical analysis of data from arid regions where the events are rare and almost independent.

The return period, T_r, of a given event is the average number of years within which the event is expected to be equalled or exceeded only once. The event that, in expectation, will be equalled or exceeded every N years is the N-year event, X_{Tr}. Both terms refer to the expected average frequency of occurrence of an event over a long period of years. The return period is equal to the reciprocal of the probability of exceedance in a single year.

For return periods exceeding ten years, the differences in return periods between the annual and partial series is inconsequential. Table 27.1 presents factors for conversions between the two series.

TABLE 27.1

Corresponding return periods for annual and partial series

Partial series	*Annual series*
0.50	1.16
1.00	1.58
1.45	2.00
2.00	2.54
5.00	5.52
10.00	10.50

27.3 Mathematical approach to frequency analysis

27.3.1 *Probability distributions used in hydrology*

Probability distributions are used in a wide variety of hydrological studies, e.g., water-resources studies, studies of extreme high and low flows, droughts, reservoir volumes, rainfall quantities, and in time-series models. The principal distributions used in hydrology are listed in Table 27.2. Their mathematical definitions are given in the WMO *Statistical Distributions for Flood Frequency Analysis* [2].

Annual totals, such as flow volumes or rainfall depths, tend to be distributed normally or almost so because of the central limit theorem of statistics. Monthly and weekly totals are less symmetric, display a definite skewness (mostly positive) and cannot usually be modelled by the normal distribution.

Annual extremes (high or low) and peaks over a threshold have positively skewed distributions. The part of a sample that lies near the mean of the distribution can often be described well by a variety of distributions. However, the individual distributions can differ significantly and very noticeably from one another in the values estimated for large return periods. Since hydraulic design is often based on estimates of large recurrence-interval events, it is important to be able to determine them as accurately as possible. Hence, the choice of distribution is very important for such cases. The choice of distributions is discussed in the WMO *Statistical*

TABLE 27.2

Probability distributions used in hydrology

Name	*Acronym*	*Reference*
Normal	(N)	(Gauss)
Log-normal	(LN)	(Hazen, 1914)
Pearson type 3	(P3)	(Foster, 1924)
Extreme value type 1	(EV1)	(Gumbel, 1941)
Extreme value type 2	(EV2)	(Gumbel, 1941)
Extreme value type 3	(EV3)	(Jenkinson, 1969)
Three-parameter gamma distribution		(Kritsky, Menkel, 1946)
Gamma	(G)	(Moran, 1957)
Log-Pearson type 3	(LP3)	(U.S. Water Resources Council, 1967, 1981)
General extreme value	(GEV)	(Jenkinson, 1955)
Weibull		(Wu and Goodbridge, 1976)
Wakeby	(WAK)	(Houghton, 1978)
Boughton		(Boughton, 1980)
Two-component EV	(TCEV)	(Rossi, *et al.*, 1984)
Log-logistic	(LLG)	(Ahmad, *et al.*, 1988)
Generalized logistic	(GLG)	(Ahmad, 1988)

Distributions for Flood Frequency Analysis [2], which includes a discussion on the methods available for choosing between distributions and how these choices are dependent on a number of technical issues, such as the character of hydrological data and the method of parameter estimation.

27.3.2 *Parameter estimation*

In addition to the consideration of the choice of distribution, the method of parameter estimation used with it may have an effect on the outcome. Traditionally, the method of ordinary moments (MOM) has been popular in hydrology even though it has been recognized as statistically inefficient in comparison to the method of maximum likelihood (ML). The method of probability-weighted moments (PWMs), introduced by Greenwood, *et al.* [3] is, in many cases, convenient to apply, and it has been found by Hosking, *et al.* [4] to be comparable with ML in its statistical properties for sample sizes which are normally encountered in hydrology.

A more recent methodology employing L-moment statistics [5] shows considerable improvement over the more conventional maximum likelihood or method at moments techniques. Applications of this regionalized technique are beginning to be reported in the analysis of extreme value data.

27.3.3 *Homogeneity of data*

The homogeneity of hydrological data is the requirement for a valid statistical application. There are many reasons why data series may not be homogeneous, for example:

(*a*) A time-series of maximum discharges may contain both snow melt and rainfall discharges;
(*b*) A time-series may contain discharges formed both before construction of a hydraulic structure in undisturbed conditions and after construction when the runoff regime is controlled; or
(*c*) A time-series may contain discharges that include mixtures of systematic and random errors.

Data homogeneity may also be disturbed by the anthropogenic changes of climate as well.

A detailed analysis of the data is the most effective method of evaluating data homogeneity. The methods of analysis are usually based on plotting different types of runoff dependencies upon runoff-producing factors (physical and mathematical) to discover causes of a disturbance of homogeneity. The following types of time-series reconstructions are possible when non-homogeneity is established and when its causes are discovered:

(*a*) Non-homogeneous data are corrected to homogeneous conditions (recovery of natural runoff, computation of empirical frequencies, etc.);

(*b*) The record is subdivided into a number of homogeneous samples (water discharges produced by mud-flows, maximum rainfall discharges, runoff availability and absence, etc.); and

(*c*) Known systematic errors are corrected and spurious data are deleted from the record.

References

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2. World Meteorological Organization, 1989: *Statistical Distributions for Flood Frequency Analysis* (C. Cunnane). Operational Hydrology Report No. 33, WMO–No. 718, Geneva.

3. Greenwood, J. A., Landwehr, J. M., Matalas, N. C. and Wallis, J. R., 1979: Probability weighted moments: definition and relation to parameters of several distributions expressible in inverse form. *Water Resources Research,* Vol. 15, No. 5, pp. 1049-1054.

4. Hosking, J. R. M., Wallis, J. R. and Wood, E. F., 1985: Estimation of the generalized extreme value distribution by the method of probability-weighted moments. *Technometrics,* Vol. 27, No. 3, pp. 257-261.

5. Hosking, J. R. M., 1990: L-Moments: analysis and estimation of distributions using linear combinations of order statistics. *Journal of the Royal Statistical Society*, B, Vol. 51, No. 3.

CHAPTER 28

RAINFALL FREQUENCY AND INTENSITY

28.1 **Rainfall frequencies**

The frequency of occurrence of rainfall of various magnitudes is important in the application of mathematical models for synthesizing hydrological data, in determining the required capacity of small water control structures, and in other applications. Estimates of design runoff from small areas are often based on rainfall-runoff relations and rainfall-frequency data due to sparse streamflow measurements and limitations in transposing such data among small areas. Generalized estimates of rainfall frequencies for a duration of up to ten days and return periods to 100 years are available for the United States in the U.S. Weather Bureau Technical Paper and NOAA Atlas series, and for Australia in the *Australian Rainfall and Runoff: A Guide to Flow Estimation* [1], among others.

Chapter 27 presents basic considerations of frequency analysis, while this chapter discusses special applications for the analysis of rainfall. The selection of distribution types for extremes of precipitation are discussed in the WMO *Selection of Distribution Types for Extremes of Precipitation* [2].

28.1.1 ***Point rainfall***

For small drainage areas, point rainfall is an adequate estimate of catchment rainfall, while for larger areas, consideration must be given to the relation of rainfall depth to catchment area (section 28.1.2). The statistical methods described herein apply to storm or other short-duration rainfall. Similar methods are used for flood peaks, flood volumes, low flows, droughts, and other extreme events.

28.1.1.1 *Adjustment of data for fixed observational time intervals*

Rainfall data are usually published for fixed time intervals, e.g., 0800-0800 (daily), 0600-1200 (six-hourly), 0300-0400 (hourly). Such data rarely yield the true maximum amounts for the indicated durations. For example, the annual maximum observational-day amount is very likely to be appreciably less than the annual maximum amount determined from intervals of 1 440 consecutive minutes unrestricted by any particular time. Similarly, maxima from fixed six-hourly and hourly intervals tend to be less than maxima obtained from 360 and 60 consecutive one-minute intervals, respectively, unrestricted by fixed beginning or ending times.

Studies of thousands of station-years of rainfall data indicate that multiplying annual maximum hourly or daily rainfall amounts for a single fixed observational interval of one to 24 hours by 1.13 will yield values closely approximating those to be obtained from an analysis of true maxima. Lesser adjustments are required when maximum observed amounts are determined from two or more fixed observational intervals. Thus, for example, maximum six and 24-hour amounts determined from six and 24 consecutive fixed one-hour increments require adjustment by factors of only 1.02 and 1.01, respectively. Adjustment of fixed-interval rainfall amounts for the number of observational units within the interval may be made as follows:

Number of observational units:	1	2	3-4	5-8	9-24	> 24
Adjustment factor:	1.13	1.04	1.03	1.02	1.01	1.00

28.1.1.2 *Indirect estimation of point rainfall-frequency data*

In the absence of short-duration rainfall data either at a site or sufficiently nearby for interpolation, it may be possible to estimate the rainfall regime from any indirect data that may be available [3, 4]. Such data include mean annual precipitation and mean annual number of days with rain, which may be obtained from maps or, otherwise, estimated. For the United States, the average relationship of precipitation per precipitation day (mean annual precipitation divided by days of precipitation with a base of one millimetre) to two-year 24-hour rainfall is:

Precipitation per precipitation day, millimetres:	5	8	10	13
Two-year 24-hour rainfall, millimetres:	36	56	79	107

The relationship given in this table is merely for illustration. Due to the regional variation in such a relationship, its application should be based on climatic similarity between the regions of its derivation and use.

For durations of less than 24 hours, it is convenient to estimate the one-hour rainfall frequency amounts from the 24-hour values, to interpolate for intermediate durations, and to extrapolate for durations shorter than one-hour. The two-year one-hour rainfall is related to the two-year 24-hour rainfall according to the mean annual number of days with thunderstorms. Studies that have included a wide range of climate indicate the following relationship:

Ratio of two-year one-hour to two-year 24-hour rainfall:	0.2	0.3	0.4	0.5
Mean annual number of thunderstorm days:	1	8	16	24

Rainfall-frequency values for durations of less than one hour are often obtained by indirect estimation. Rainfall data for such short durations are seldom readily available in convenient form for the compilation of annual or partial-duration series for direct frequency analysis. Average ratios of rainfall amounts for five-, 10-, 15-, and 30-minutes to one-hour amounts, computed from hundreds of station-years of records, are often used for estimating rainfall-frequency data for these short durations. These ratios, which have an average error of less than 10 per cent, are:

Duration (minutes):	5	10	15	30
Ratio (n-minutes to 60-minutes):	0.29	0.45	0.57	0.79

Thus, for example, if the l0-year one-hour rainfall is 70 millimetres, the l0-year 15-minutes rainfall is 57 per cent of 70, or 40 millimetres.

It should be noted that these ratios could yield erroneous results in some regions. For example, in regions where most of the rainfall occurs in connection with thunderstorms, the above ratios would tend to yield values that are too low. On the other hand, in regions where most of the rainfall results from orographic influences with little severe convective activity, the ratios might tend to yield values that are too high. This variation has been handled on a continental basis for Australia [5, 6], with a relationship that was developed by using a geographical location and one-hour rainfall intensity as variables. The relationship is also dependant upon the average recurrence interval. When large quantities of rainfall data for a region are to be subjected to frequency analysis, as is usual in the preparation of generalized maps, the compilation of annual series data for all durations is a tedious and tremendous task. It is customary, therefore, to limit such compilations to data from a relatively small number of recording stations with good records for at least 10 years. The means of the annual series are then computed and used to prepare a diagram like that in Figure 28.1, which permits the estimation of rainfall values for durations of up to 24 hours when the one- and 24-hour amounts are known. The diagonal line in Figure 28.1 illustrates an example in which 24-hour rainfall is about 73 millimetres and one-hour rainfall is 22 millimetres. Values for other durations can be read off the intersections of the diagonal. Thus, the amount for 12 hours is 60 millimetres and for two hours is 30 millimetres.

Similar diagrams like Figure 28.2 may be constructed [1, 7] for interpolating between the two- and l00-year return periods. Such diagrams must be based on good long-record stations if they are to be reliable. Like the duration-interpolation diagrams, they vary from region to region, where climatic regimes differ appreciably. They are used in the same manner as the duration-interpolation diagrams, i.e., a diagonal is laid across the appropriate two- and l00-year rainfall depths on their respective verticals, and depths for other return periods are read at the intersections of the diagonal with the corresponding verticals.

With the use of the above two types of interpolation diagrams, only the one- and 24-hour rainfall amounts for the two- and l00-year return periods need to be computed for the majority of the stations in the region for which the diagrams were

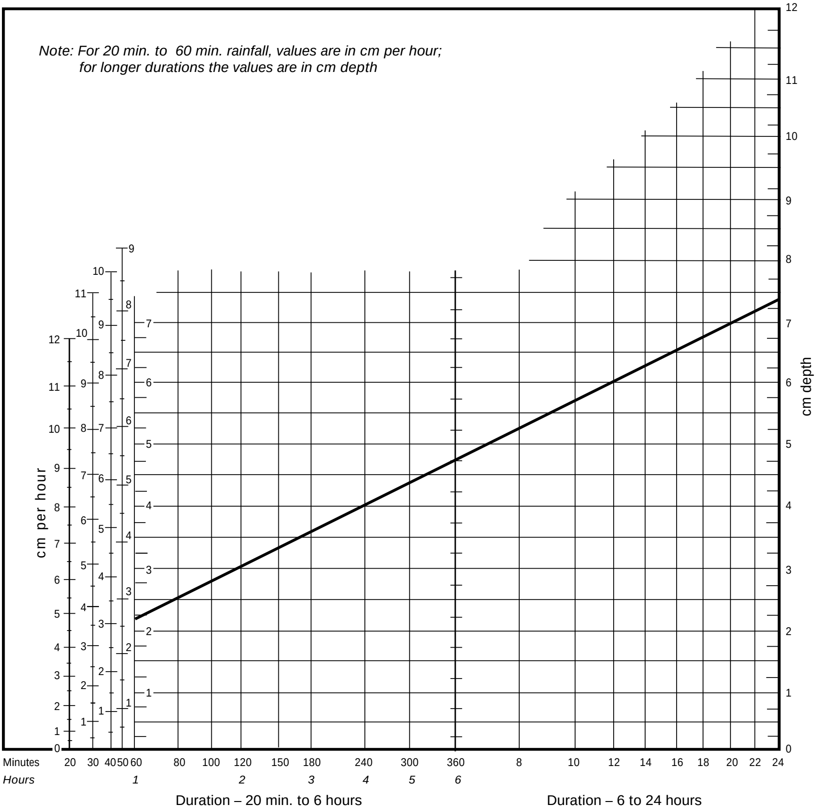

Figure 28.1 — Rainfall-intensity and depth-duration relationship.

developed. The diagrams are then used to estimate other required values. Both types are subject to regional variations, and caution should be exercised in trying to apply the diagrams in regions other than those for which they were developed.

28.1.1.3 *Maximum observed rainfalls*

Some of the largest point rainfalls for selected durations that have been observed are given in the Table below. These values, which approach probable maximum precipitation magnitude, are enveloped by the approximate equation [8]:

$$P = 422\,T^{0.475} \tag{28.1}$$

where P is rainfall in millimetres, and T is duration in hours.

World's greatest observed point rainfalls

Duration	*Depth (mm)*	*Location*	*Date*
1 min	38	Barot, Guadeloupe	26 November 1970
8 min	126	Fussen, Bavaria	25 May 1920
15 min	198	Plumb Point, Jamaica	12 May 1916
20 min	206	Curtea-de-Arges, Romania	7 July 1889
42 min	305	Holt, MO, U.S.A.	22 June 1947
1h00 min	401	Shangdi, Nei Monggol, China	3 July 1975
2h10 min	483	Rockport, WV, U.S.A.	18 July 1889
2h45 min	559	D'Hanis, TX, U.S.A. (17 mi NNW)	31 May 1935
4h30 min	782	Smethport, PA, U.S.A.	18 July 1942
6h	840	Muduocaidang, Nei Monggol, China	1 August 1977
9h	1087	Belouve, La Réunion	28 February 1964
10h	1400	Muduocaidang, Nei Monggol, China	1 August 1977
18h30 min	1689	Belouve, La Réunion	28-29 February 1964
24h	1825	Foc Foc, La Réunion	7-8 January 1966
2 days	2467	Aurere, La Réunion	7-9 April 1958
3 days	3130	Aurere, La Réunion	6-9 April 1958
4 days	3721	Cherrapunji, India	12-15 September 1974
5 days	4301	Commerson, La Réunion	23-27 January 1980
6 days	4653	Commerson, La Réunion	22-27 January 1980
7 days	5003	Commerson, La Réunion	21-27 January 1980
8 days	5286	Commerson, La Réunion	20-27 January 1980
9 days	5692	Commerson, La Réunion	19-27 January 1980
10 days	6028	Commerson, La Réunion	18-27 January 1980
11 days	6299	Commerson, La Réunion	17-27 January 1980
12 days	6401	Commerson, La Réunion	16-27 January 1980
13 days	6422	Commerson, La Réunion	15-27 January 1980
14 days	6432	Commerson, La Réunion	15-28 January 1980
15 days	6433	Commerson, La Réunion	14-28 January 1980
31 days	9300	Cherrapunji, India	1-31 July 1861
2 months	12767	Cherrapunji, India	June - July 1861
3 months	16369	Cherrapunji, India	May - July 1861
4 months	18738	Cherrapunji, India	April - July 1861
5 months	20412	Cherrapunji, India	April - August 1861
6 months	22454	Cherrapunji, India	April - September 1861
11 months	22990	Cherrapunji, India	January - November 1861
1 year	26461	Cherrapunji, India	August 1860-July 1861
2 years	40768	Cherrapunji, India	1860-1861

Revised: 29 November 1991, U.S.A. NWS; U.S.A. Bureau of Reclamation; Australian Bureau of Meteorology.

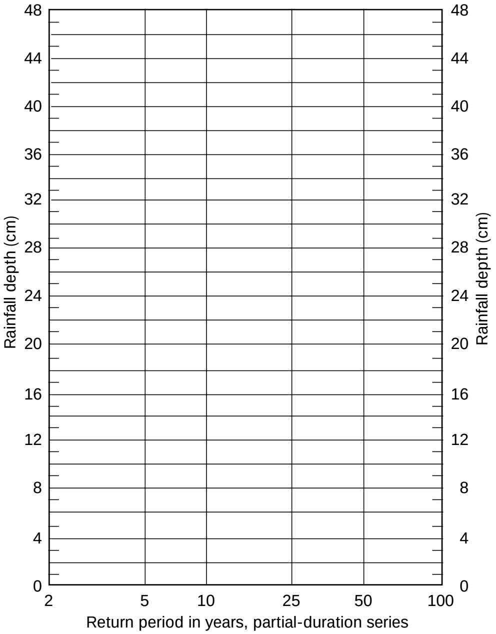

Figure 28.2 — Return-period interpolation diagram.

28.1.2 *Area rainfall*

When the area of a basin exceeds about 25 km^2, rainfall observations at a single station, even if it is at the centre of the catchment, will usually be inadequate for the design of drainage works. All rainfall records within the catchment and its immediate surroundings must be analysed to take proper account of the spatial and temporal variation of rainfall over the basin. For areas large enough for the average rainfall depth to depart appreciably from that at a point, a diagram such as that of Figure 28.3 may be prepared and used for reducing the point values. To illustrate the use of point rainfall values in Figure 28.3, assume that a T-year six-hour point rainfall of 63 millimetres is obtained for a particular place. To estimate the six-hour average depth over 250 km^2 for the same return period at the same place, the 63-millimetre value is multiplied by 89 per cent, which yields 56 millimetres. While the curves of Figure 28.3 indicate a reduction for all sizes of area, point rainfall values are often used without reduction for areas up to 25 km^2.

28.1.3 *Generalized maps*

Even a long record may be a relatively small sample of a climatic regime. A better measure of the regime at a station may be given by a smoothed map, which includes

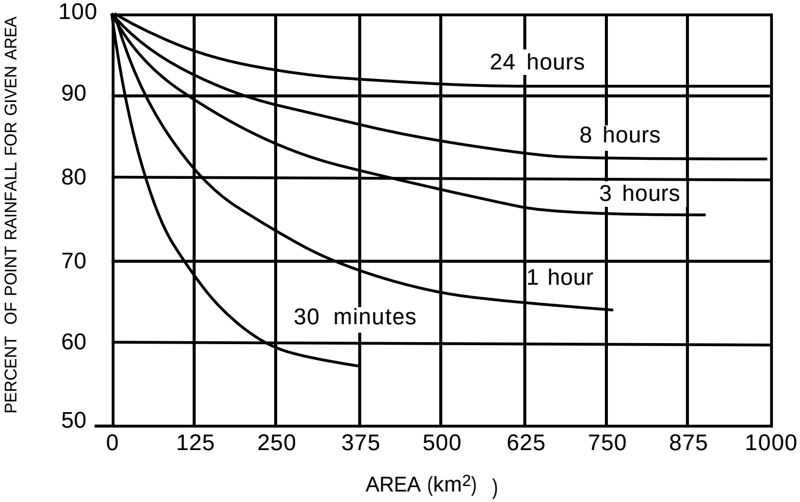

Figure 28.3 — Depth-area (area-reduction) curves.

the influence of data from nearby stations and, thus, broadens the sample. The degree of smoothing should be consistent with the spacing of observation stations and with the sampling error of the stations. Too little smoothing tends to confound sampling error with spurious regional variation.

28.1.4 *Drought*

Drought is the low hydrologic extreme resulting from perturbations in the hydrologic cycle over a sufficiently long time, which results in a significant water deficit. The local water resources become insufficient to support the established or normal activities of the area. Droughts are interpreted and categorized broadly as meteorological, hydrological, or agricultural. The meteorologist is concerned with drought in the context of a period of below normal precipitation. To a hydrologist, it means below average content in streams, reservoirs, lakes, tanks, aquifers, and soil moisture. To an agriculturist, drought means a prolonged shortage of soil moisture in the root zone.

For meteorological drought, a useful means of analysis is based on the magnitude-span frequency. A simple type of analysis would be that of comparing rainfall totals for calendar months or pertinent seasons with their corresponding normal values and assessing severity of drought based upon the negative departures from normal values. To take into account the effect of time distribution of rainfall, an antecedent-precipitation index (section 33.2.1) may be used instead of total rainfall. Another way to account for the month-to-month carry-over effects of rainfall for evaluating severity of meteorological drought is the Herbst technique [9].

The severity of agricultural drought may be judged by the drought index, a device for summarizing and periodically disseminating drought information and crop-moisture conditions on a regional basis. It can be used for evaluating the drought hazard over a sizeable area or for periodic assessment of the current extent and severity over a region.

Hydrological drought severity is related to the severity of departure from the norm of low flows (Chapter 35) and soil moisture (Chapter 38) in conjunction with excessive lowering of groundwater levels.

28.2 Rainfall intensities

28.2.1 *Point rainfall*

A large number of observations of significant rainfall intensities taken over a long period of years by a pluviograph of suitable design — to provide accurate evaluation of intensities for intervals from five minutes to 72 hours — is desirable for the construction of station rainfall intensity-duration curves. Intensities of one day or longer (say three days) can be recorded by daily read gauges. The measurements up to 72 hours for pluviographs allow an overlap with the daily network for statistical purposes.

The maximum mean-rainfall intensity, P_i, experienced during each storm may be determined for each of a number of durations, T. For urban-drainage design, the duration of interest generally range from five or 10 minutes to several hours. For each selected duration, the mean rainfall intensity, P_i , having return periods 1, 2, 5, . . . 100 years, may be determined by the methods described in section 28.1.1.

The analyses of rainfall-intensity data for a long series of storms may be summarized either by:

(*a*) Families of curves for given frequencies of occurrence or return periods, showing the maximum mean rainfall intensity for each of a number of durations; or

(*b*) Empirical formulae expressing the relationships portrayed by such curves. There are many such formulae appearing in the technical literature, of which the following forms are the most typical:

$$P_i = \left(\frac{a}{b + T} \right) \tag{28.2}$$

$$P_i = a(T - b)^{-n} \tag{28.3}$$

$$P_i = \frac{a + b \log T_r}{(1 + T)^n} \tag{28.4}$$

where P_i, generally expressed in mm h^{-1}, is the maximum mean rainfall intensity for time, T, T_r is the return period, and a, b, and n are parameters that vary from station to station and, for a particular station, vary with the selected frequency of occurrence (or return period). In some countries where an extensive analysis of rainfall-intensity data has been completed, maps showing isopleths of the parameters *a*, *b* and *n* are available. A set of isohyetal maps is generally more useful;

(*c*) A number of publications [1, 7, and others] provide mapped analysis of precipitation frequencies for various return periods and durations (10 year, 24 hour, for example). Rainfall intensities can be derived from these maps simply by dividing by the duration.

If a generalized empirical relationship is adopted for estimating rainfall intensity for a project catchment, the original derivation of the relationship should be examined, if possible. Relationships of this type are sometimes based on the analysis of limited data over rather restricted areas, and their application to other areas could lead to inaccurate conclusions.

The location of the period of maximum rainfall intensity in relation to the beginning of the storm is a further important factor in the design of drainage works intended to cope with the maximum, mean rainfall intensity. If the period of maximum rainfall intensity occurs at the beginning of the storm when the channels are dry or carrying only small discharges, peak discharge will be reduced because of the available storage capacity within the channels. Smaller drainage works would then be required for a given mean intensity than would be the case if the period of maximum intensity occurred at the middle or end of the storm.

When an analysis of rainfall records for a station shows that a majority of periods of maximum rainfall intensity occur near the beginning, middle, or end of a storm, this factor may be taken into account when determining the design flood. Where no such tendency is shown, the sequential order of recorded intensities need not be maintained for application in mathematical models.

28.2.2 ***Area rainfall***

When curves of cumulated storm rainfall are available for several pluviograph stations in a basin or within the area of a storm, a composite temporal pattern of rainfall for the total extent of the storm, or for its different parts can be deduced from the individual station records. The simplest method of deriving this rainfall temporal pattern (storm pluviograph) is by superposition of the individual station pluviograph records. The ordinate at any time, t, of the storm pluviograph is taken as the mean of the ordinates of the various curves at that time. This method can be refined by multiplying the ordinates of each station pluviograph record by a suitable coefficient, such as the Thiessen weight. When a sufficient number of storm pluviographs have been developed for a basin, intensity-duration curves for various return periods, T_r, can be derived for the entire basin or for any part of it.

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CHAPTER 29

STORM-RAINFALL ANALYSIS

29.1 General

A storm-rainfall analysis expresses the depth-area duration characteristics of the rainfall from a particular storm. The depth is defined for pertinent combinations of enveloping area and duration, and is usually portrayed by tables or curves. In the aggregate, such analyses provide useful records for the design of spillways and for research in quantitative precipitation forecasting.

Individual point-rainfall observations are analysed jointly and in combination with other information. The rainfall data usually consist of observations of daily totals, interspersed with a few recorder measurements that contain short-term rainfall intensity information. Sometimes, these data are augmented by observations obtained through special interviews, referred to as bucket surveys (section 21.8.2). Additional information may come from synoptic weather maps, radar, reports of rises of small streams, and other sources. The procedure, which is summarized in the following subsections, is described in detail in the WMO *Manual for Depth-area-duration Analysis of Storm Precipitation* [1].

29.2 Mass curves

The first step in a storm-rainfall study is to plot accumulated values of rainfall versus time of day (a mass curve or integrated curve) for each station or for selected representative stations, if there are many. The mass curves for non-recording stations are constructed by comparison with mass curves from recording stations by means of proportionality factors. In doing so, the movement of the storm and the reports of the times of beginning, ending, and heaviest rainfall should be taken into account. Figure 29.1 shows a typical set of mass curves from the storm of 31 March–2 April 1962 in south-eastern Canada.

The pertinent stations are then listed in a table and accumulated values of rainfall are tabulated for each station for a pre-selected time increment. A six-hour time increment is used in the present example, but other increments may serve equally well. For convenience, the stations should be listed in order of decreasing magnitude of total storm rainfall.

The next step is to examine the table and select the particular six-hour period that has the largest six-hour rainfall increments. The values for this time increment

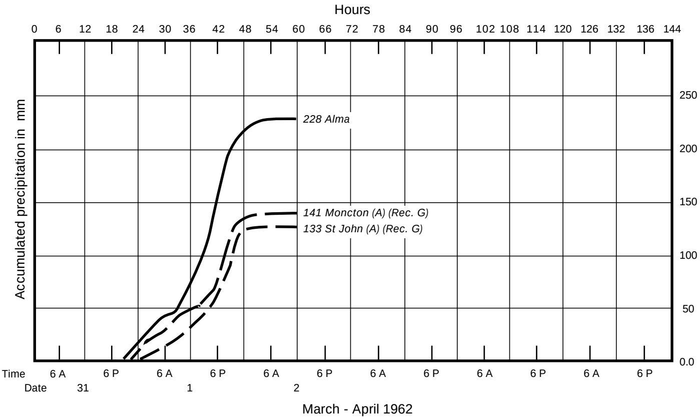


Figure 29.1 — Mass curves of rainfall.

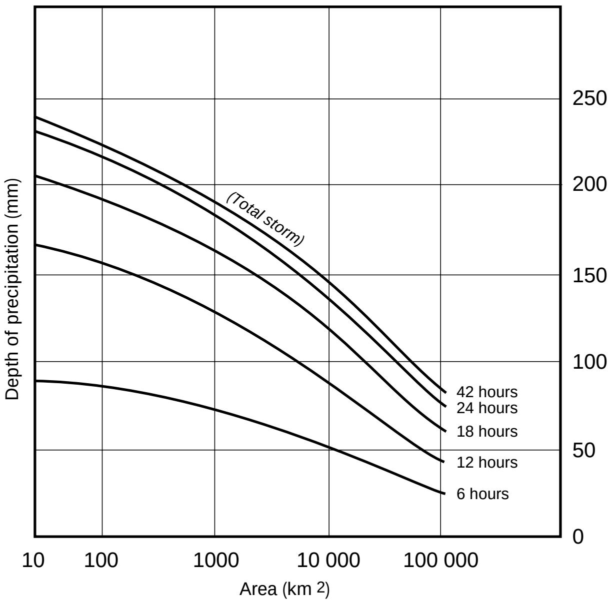
are then listed. The period of maximum 12-hour rainfall is found in a similar way and its rainfall is listed. The same operation is applied to define the maximum 18–, 24-, . . , *n*-hour increments. For periods embracing several six-hour increments, a considerable number of trials may be required to find the period that includes the maximum rainfall for a particular duration.

29.3 Depth-area duration analysis

From the tabulation of maximum rainfall increments, isohyetal maps are prepared for each duration (e.g., six hours, 12 hours). Areas enclosed by each isohyet are then evaluated by using a planimeter or by tallying grid points, and the resulting values are plotted on a graph of area versus depth, with a smooth curve drawn for each duration. A linear scale is commonly used for both depth and a logarithmic scale for area. The enveloping or maximum depth-area duration data for each increment of area and duration may be tabulated as in the Table below from curves such as those in Figure 29.2.

Maximum average depth of rainfall (millimetres)
Storm of 31 March–2 April 1962, south-eastern Canada

Area	*Duration, hours*				
km^2	*6*	*12*	*18*	*24*	*42*
25	90	165	205	230	240
100	85	155	190	215	225
1 000	70	130	165	185	190
10 000	50	90	115	140	145
100 000	25	45	65	75	85



Representative convective dew point......... 18° C ....

Distance of representative dew point from centre of heavy precipitation.................... 1400 KM, 0700 LST April 1st ......

Rain gauge density (km2/gauge) for stated isohyet in mm 200-61; 175-364; 150-1061; 125-621; 100-647; 75-796; 50-851 ....

Number of recording gauges... 4 ....

Scale of isohyet work chart .. 1: 2, 488,681 ....

Remarks...

Figure 29.2 — Enveloping depth-area duration curves.

29.4 Probable maximum precipitation (PMP)

The term, probable maximum precipitation, is well established and is widely used to refer to the quantity of precipitation that approximates the physical upper limit for a given duration over a particular basin. The terms, maximum possible precipitation and extreme rainfall, have been used with approximately the same meaning. To ask how approximate or how probable is at best a rhetorical question because the definition of probable maximum is an operational one that is specified by the operations performed on the data.

29.4.1 *Methods of estimating PMP*

Probable maximum precipitation for a river basin may be estimated [2, 3] by using storm models or storm transposition and maximization.

(*a*) Storm models — Precipitation rates are a function of the availability of atmospheric moisture and the rate at which this moisture can be converted into precipitation. Attempts have been made in the United States to develop storm models for the theoretical derivation of probable maximum precipitation. These are described in the WMO *Manual for Estimation of Probable Maximum Precipitation* [2]. A major difficulty in such studies has been to account for orographic effects on precipitation intensities. The difficulty arises because, within a particular storm, variations in precipitation are related both to changes in the storm mechanism and to orography. In order to determine probable maximum precipitation by means of a storm model, upper-limits of moisture and wind — for various levels throughout a layer of the atmosphere, the depth of which is a function of the model characteristics — are estimated and processed through the model. In many regions, the shortness of record and/or sparsity of upper-atmosphere wind and humidity observations complicates the estimation of upper-limit values;

(*b*) Storm maximization and transposition — A more commonly used approach to the estimation of probable maximum precipitation involves the maximization of observed storm-precipitation data [2]. Storm maximization is usually based on two assumptions:

   (i) Precipitation can be expressed as the product of the available moisture and the combined effect of the storm efficiency and the inflow of wind; and

   (ii) The most effective combination of storm efficiency and inflow wind can be estimated from outstanding storms on record. This second assumption often necessitates storm transposition, that is, the relocation of an outstanding storm from the area of its occurrence to a project basin within the same region of meteorological homogeneity.

The maximization of observed storm precipitation for determining probable maximum precipitation involves moisture adjustment with the basic assumption that a storm would have produced maximum precipitation had the maximum moisture supply been available. The method of moisture adjustment commonly used involves the estimation of air-mass moisture content, taken as the precipitable water, from surface level dewpoint observations and has been described in the WMO *Manual for Estimation of Probable Maximum Precipitation* [2]. In order to carry the maximum moisture supply into the project basin further adjustment of storm-precipitation data to the estimated maximum sustained wind is made by some investigators if very high design-safety factors are desired or if only a limited amount of storm-precipitation data are available.

29.4.2 *Preliminary estimates*

For major structures, the cost of the spillway may be an appreciable portion of the total cost of the project. Proper design of dimensions is important enough to warrant a very detailed study. However, in preliminary planning stages, it is sufficient to use generalized estimates of probable maximum precipitation if these are available for the area. Estimates of this type for the United States have been published as maps and diagrams in various issues of the U.S. Weather Bureau Hydrometeorological Report series. Similar reports have been prepared by several other countries for various parts of the world.

29.4.3 *Selection of design rainfall duration*

Unless depth-area duration analyses applied to a project basin have been constructed within the storm-transposition zone, a number of individual storm studies will be required to obtain estimates of probable maximum rainfall. Before these studies are undertaken, the likely critical rainfall duration(s) for the particular design problem should be determined. The selection of an appropriate tentative rainfall duration design can help avoid either the analysis of data which are not directly applicable to the project, or the subsequent need for analysis of additional data if too short a duration is adopted in the first instance.

The approximate time of rise of flood hydrographs for storms centering on different parts of the basin and the particular characteristics and proposed method of operation of the projected works should be considered in selecting tentative design rainfall duration(s).

29.4.4 *Selection of sub-basins*

For project sites with large drainage areas, it may be necessary to estimate the probable maximum rainfall for some sub-basins and in compound the resultant probable maximum flood hydrographs from these sub-basins. To avoid subsequent unnecessary or incomplete analysis of mean areal-rainfall depths during the storm studies, the sub-basins for which flood hydrographs are required should be selected before storm analyses are started. The selection of sub-basins is influenced by the physical characteristics of the basin and the availability and locations of stream-gauging stations from which the sub-area flood hydrographs could be routed to the project site.

29.4.5 *Storm transposition*

By considering large storms that have occurred within the surrounding meteorologically homogeneous region, the limitations imposed by shortness of rainfall records for a project basin can be minimized. Three major hurdles involved in storm transposition are:

(*a*) Definition of the meteorologically homogeneous region, of which the project basin is a part;
(*b*) Adjustment of meteorological factors affecting storm rainfall for climatic and topographic differences between the storm sites and the targeted basins; and
(*c*) Determination of the permissible change in orientation of a storm isohyetal pattern when it is transposed to another site.

The first step in a particular study is the collection of those storms considered to be transposable to the area in question. Factors to be considered in determining the areal limits of transposition for a particular storm include:

(*a*) Moisture source and barriers to moisture inflow for the storm *in situ*;
(*b*) Accessibility to the storm moisture source and relative height of barriers to moisture inflow of other locations within the tentative transposition zone; and
(*c*) Past occurrence elsewhere within the tentative transposition zone of similar synoptic patterns comparable with the subject storm in such features as atmospheric-moisture content, stability, direction and speed of the wind at the surface and at higher levels, duration of pattern intensity, and direction and speed of movement of low-pressure centres at the surface and at higher levels.

It should be recognized that a storm does not necessarily have the same probability of occurrence over all sections of its transposition zone. The relevant atmospheric processes may be deemed physically possible over the entire zone, but more likely to occur with a greater frequency over some sections of the zone than over others. Also, all storms occurring over a particular geographical area do not necessarily have a common transposition zone. The appropriate zone for each individual storm must be determined through a detailed study of its synoptic features.

Orographic influences have an important effect on rainfall distribution in mountainous areas. Transposition of storms in these areas must be limited to regions of similar orographic influences, unless a study of a storm's synoptic features and rainfall pattern suggests that the orographic effects were minor. Some advances have been made [4, 5] in the analysis and evaluation of orographic effects for use in storm transposition and synthesis.

29.4.6 ***Selection and analysis of major storms***

A convenient means of selecting storms for analysis is to determine first the meteorologically homogeneous region, of which the project basin is a part, and then to examine the records of rainfall stations within the region to select dates of occurrence of major rainfalls.

If there are few rainfall stations within the region, the records of each might be examined. In areas with relatively dense networks, stations should be selected at spacings such that high rainfalls of limited area (intense but short-lived thunderstorms) will be avoided, but all significant rainstorms with an areal extent close to or exceeding that of the project basin will be detected. It is usually possible to select, fairly quickly, those storms within the region that have produced the eight or 10 maximum rainfalls over areas similar in size to the project basin.

Synoptic features of each of the major storms are then examined to determine whether a storm may be transposed to the project basin. Depth-area duration analyses are then carried out for the transposable storms following the methods described in sections 29.2 and 29.3 or in the WMO *Manual for Estimation of Probable Maximum Precipitation* [2].

A complete depth-area duration analysis of rainfall for each storm is desirable for future reference and application. If necessary, however, analysis of a long-duration storm can be confined to that part having the greatest rainfall depth over an area equal in size to the project basin with a time interval equal to the design rainfall duration (section 29.3).

29.4.7 ***Maximization of selected storms***

The objective of storm maximization is to estimate the percentage by which the rainfall of a particular storm would have been increased had meteorological characteristics of the storm approached their estimated physical upper limits. Methods of maximization developed in the United States and adopted in a number of countries [5] have been described by Weisner in *Hydrometeorology* [3] and in a number of publications of the U.S. National Weather Service, formerly the U.S. Weather Bureau (see references in the WMO *Manual for Estimation of Probable Maximum Precipitation* [2]). The major storms selected for study are maximized in accordance with these procedures. The estimate for the project basin or selected sub-basins of highest rainfall depth for any selected duration can then be determined from the various maximized storm-rainfall depths.

29.4.8 ***Orientation of storm-rainfall patterns***

The orientation of a storm-rainfall patterns on the basin may have an important influence on the resultant flood. The permissibility of changes in orientation of isohyetal patterns for historical storms over the project basin and storms transposed to the basin becomes a question of estimating the probable maximum flood.

It is common practice to assume that large changes in orientation would suggest major modifications in the storm track, wind direction, and transformation of the particular set of atmospheric conditions that produced the storm. Slight changes in orientation are normally accepted, and a maximum change in orientation of 20 degrees has been adopted in some countries. Concern for the orientation of precipitation patterns, relative to basin orientations, has led to special studies [2, 6].

29.4.9 *Regional consistency of estimates*

The final estimates of probable maximum precipitation for a project basin should be compared with similar estimates available for other basins in the same meteorologically homogeneous zone. Estimates should be re-examined if any lack of consistency is detected which cannot be explained in terms of differences in topographic features, accessibility to moisture sources, etc. A check for regional consistency involving numerous comparisons has been described by Hansen, *et al.* in *Hydrometeorological Report* [7] and in the WMO *Manual for Estimation of Probable Maximum Precipitation* [2].

29.4.10 *Estimating in the absence of data*

In the absence of meteorological and streamflow data, generalized estimates must be prepared by analogy to the probable maximum precipitation in climatologically similar regions for which data are available. Such generalizations can be made with relative confidence over level terrain. However, most medium- and large-sized dams are located in regions where rainfall is affected by variations in elevation and other local topographic influences. The transposition of estimates from elsewhere into such regions is less certain and demonstrates the need for meteorological and streamflow measurements to be initiated as soon as possible in and near a basin where a project is contemplated.

If daily rainfall observations at individual stations are available, but if moisture and other data necessary for storm maximization are lacking, then the tentative estimates of probable maximum precipitation for small areas represented by single stations (e.g., up to about 1 000 km^2) may be obtained by the statistical method developed by Hershfield [8, 9]. The maximum rainfall amount in each year of record for the duration, or durations, of interest is used to compile the annual series (sections 27.2 and 28.1.1.1). The mean, $\overline{P}$ and the standard deviation, S_P, of the series are computed. The mean of the series is then used to obtain a value of K from Figure 29.3, and the probable maximum precipitation is then computed by:

$$PMP = \overline{P} + K\,S_P \qquad (29.1)$$

Care should be taken that the highest one or two values in the annual series are consistent with the other values comprising the series. If, for example, the maximum value in a 30-year period is twice the second highest value, it is obviously an outstanding value or outlier, as is often referred to. The easiest way to detect an outlier is to arrange the series in descending order and then to compute the return period (section 27.2) of each value. The values are then plotted against their corresponding return periods on probability paper as in Figure 29.4. If the maximum value of the series lies well above the line delineated by the other items in the series, it can be considered an outlier. An outlier should not be used in computing the mean or

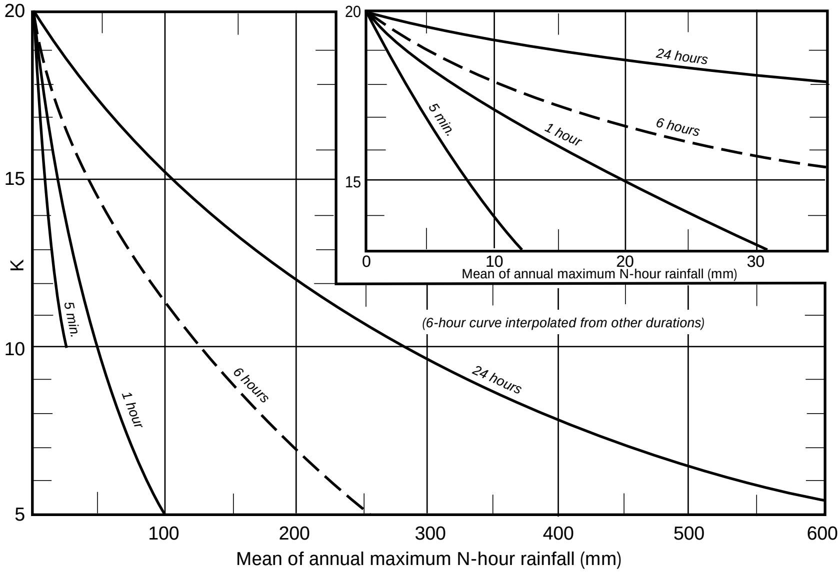


Figure 29.3 — *K* as a function of rainfall duration and mean of annual series.

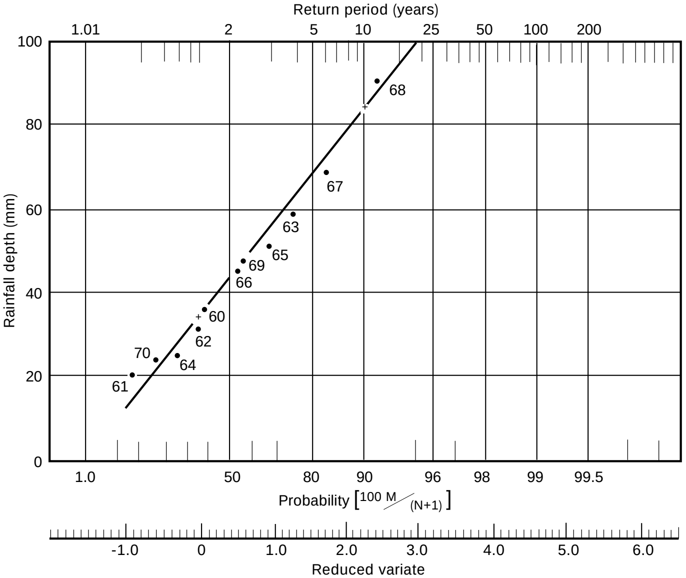


Figure 29.4 — Example of an extreme probability plot.

standard deviation of the series. If used, the mean and standard deviation should be adjusted as indicated by Hershfield [8], who also provided an adjustment for length of record. A complete, detailed description of the entire procedure, including diagrams for making the necessary adjustments, is given in Chapter 4 of the WMO *Manual for Estimation of Probable Maximum Precipitation* [2].

When the probable maximum precipitation is to be applied to an area larger than about 25 km^2, it should be reduced. No modification is considered necessary for smaller areas. For larger areas, the point value is generally reduced by means of depth area, or area reduction, curves similar to those of Figure 28.3.

The statistical method just described may overestimate the probable maximum precipitation in regions of heavy rainfall and in regions of frequent storms of similar types. In regions of low rainfall and in regions where heavy rain-producing storms, such as hurricanes, are rare but possible, the method may underestimate probable maximum precipitation. Values of K as high as 30 have been found necessary in order to exceed maximum observed point rainfall amounts in some regions. In the United States and in a few other countries, where storm studies are the preferred source of data for PMP determination, the statistical method has been used primarily as a means of checking for consistency.

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CHAPTER 30

INTERPRETATION OF PRECIPITATION DATA

30.1 General

Interpretation of precipitation has two major purposes. One purpose is to evaluate the observations that sample a precipitation event or series of events. The evaluation of the observed sample includes consideration of extraneous influences, such as deficient or changing gauge exposure, and interpretation of the effects of physical environment, such as physiography.

The other purpose is to describe the event in a form appropriate for display, subsequent analysis, or other application. Examples are the expression of a rainstorm in the dimensions of depth, time, and space, the presentation in tabular, graphical, or algebraic form, and the expression of the storm magnitude in terms of its frequency.

30.2 Adjustment of data

All measurements are samples of elements that vary in time and space. For example, stream measurements are made intermittently and at points in the stream cross-section. Even weather radar samples, which integrate areal, water droplets in a narrow rotating beam of intermittent pulses. For measurements to be useful in practical hydrology, they must represent, or be convertible to, significant areas and durations. To obtain homogeneity among measurements of various kinds, adjustments are necessary. These adjustments must be made without violating the integrity of the measurements.

Adjustments generally have three purposes. One purpose is to make the record homogeneous with respect to a given environment, such as a standard regime. An example is the conversion of measurements to a standard height of instrument. The second purpose is to eliminate or reduce the effects of extraneous influences. An example is an application of double-mass analysis, which can be used to correct for changes in gauge location or exposure. The third purpose is abstracting or summarizing data for presentation or examination. This process is inherently selective. An example is a smoothed isohyetal map. Another example is a regression line, which shows an average relationship instead of the complexities of a scatter diagram. Calibration curves result from a combination of the latter two purposes.

30.2.1 *Standard base period of record*

A frequent problem in regional generalization of hydrological data, such as mean annual precipitation, comes from the fact that gauging stations have varying periods of record. One station might have operated during a period of high precipitation, and another station's record might have covered a particularly dry period. Attempts to compare records from these two stations, e.g., in the preparation of mean annual isohyetal maps, would confound variation in space with variation in time.

A device to help solve this problem is a bar graph such as that shown in Figure 30.1, which shows the period of record of several stations on the same time scale. It is relatively easy, by inspection, to select an optimum period of record. For example, in Figure 30.1, one might consider the period between the years 1913 and 1950 as optimum, depending upon the spatial distribution of gauges. For stations with a missing record during this period, estimates may be made by the correlation of data for the portion of the period common to other stations and by applying the relationship to estimate values for the missing period.

The choice of optimum period requires consideration of a period long enough to represent a good sample of record through time. If the period is too long, there will be too much synthesis of the record. If the period is too short, it will be a poor sample of time variations and might be unduly influenced by an unusually dry or wet period.

30.2.2 *Double-mass curve analysis*

Double-mass curve analysis is a graphical method for identifying and adjusting inconsistencies in a station record by comparing its time trend with those of other stations. Accumulated annual or seasonal values at the station in question are

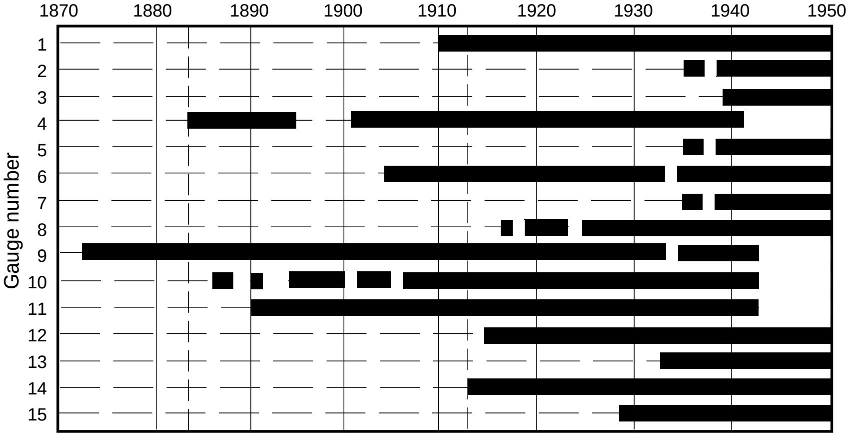

Figure 30.1 — Bar graph of period of record.

plotted against those of a nearby reliable station or group of stations. Changes in slope of a double-mass curve may be caused by changes in exposure or location of gauge, changes of procedure in collecting and processing data, etc. An example of double-mass analysis for detecting the change of exposure at a precipitation station is shown in Figure 30.2, where the record of this hypothetical station is compared with the relatively stable record of an average of several nearby surrounding stations. From examination of the curve in Figure 30.2, it may be seen that the relationship of annual precipitation at station A to the 12-station mean changed rather abruptly in 1955, with a slope change from 0.95 prior to 1955 to 0.75 after 1955. The older records can be adjusted by the ratio of 0.75 to 0.95 to compensate for a change that must have taken place at station A.

When double-mass analysis discloses a change in slope, some purposes are served by making the adjustment indicated by the ratio of the two slopes of the double-mass curve. For other purposes, this disclosure is the beginning of an investigation to determine the reason for the change in slope. Plotted points in double-mass analysis usually deviate about the straight lines drawn through the points. The points can be fitted more closely by changes in slope at intervals of only a few years. However, it must be recognized that such brief changes in slope could arise from

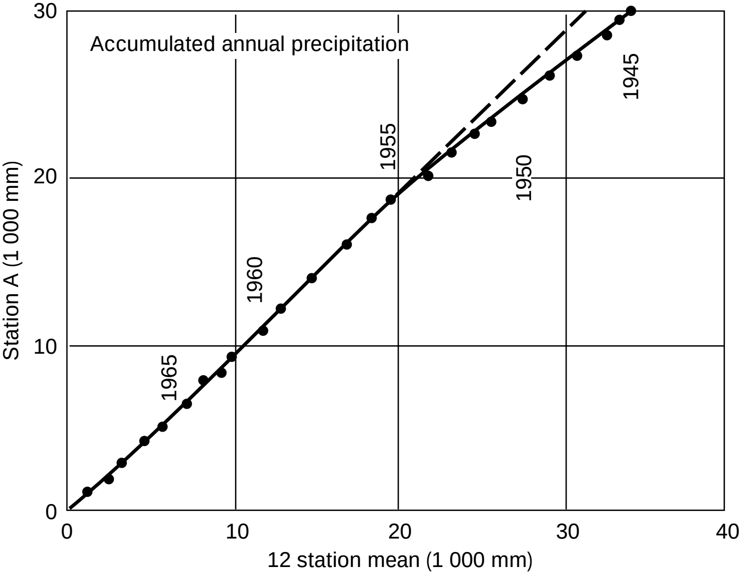

Figure 30.2 — Double-mass analysis.

chance, and no segment of less than about five points should be accepted as valid. In general, a change in slope is accepted as real only if it is substantiated by other evidence or is well defined for a long period.

The example of double-mass analysis given in Figure 30.2 is only one of many types of applications of this type of analysis. The plotting of accumulated annual or seasonal precipitation index versus corresponding accumulated annual or seasonal runoff may disclose time trends in the relationship. These may be identified later as coming from diversion of flow or changes in land use and can be evaluated after discovery by double-mass analysis (the plotting of accumulated runoff from a basin versus accumulated runoff from a nearby basin often discloses progressive or sudden changes in flow regime or channel characteristics [1]). Computerized methods have been developed for double-mass analysis [2].

30.2.3 *Estimation of missing data*

In preparing data for analysis, some records are often found incomplete. To fill gaps in a time series or blank spaces on a map, the missing portions of a record may be estimated by such methods as interpolating from simultaneous records at nearby stations. Methods for doing this are given in hydrology textbooks and WMO publications [3-5]. Judgement is required in deciding how much missing data should be estimated. If too few gaps are estimated, then large quantities of nearly complete records may be ignored. If too many data are estimated, then the aggregate information content may be diluted by interpretation. It is rarely justified to estimate more than five or 10 per cent of a record.

30.3 **Areal distribution**

30.3.1 *Illustration by isohyetal maps*

Station locations and precipitation amounts for appropriate durations are plotted on a suitable map, and contours of equal precipitation are drawn. Typical durations include hours, days, months, total storm, season, year, and mean monthly, mean annual, or mean seasonal.

In regions of little or no physiographic influence, the drawing of isohyetal contours is usually a relatively simple matter of interpolation in which the degree of smoothness of the contours and of the profiles that may be drawn or inferred from their spacing is consistent with the spacing of stations, and the quality and variability of the data. However, when precipitation is particularly erratic, the density of gauges plays an important part in the accuracy of the analysis [6].

In regions where precipitation is influenced by rugged topography or by large bodies of water, it is necessary to evaluate pertinent physiographic parameters (section 30.3.2). Factors to be evaluated include elevation, distance from coast, slope, and exposure to rain-bearing winds. The development and application of objective methods, in which explicitly defined physiographic parameters are related to precipitation amounts by regression analysis, are recommended for drawing isohyetal maps. A number of computer-based techniques are available [6].

30.3.2 *Evaluation of physiographic effects*

Mountains and other physiographic features greatly influence atmospheric circulation, storm occurrence, and precipitation. The evaluation of physiographic effects on individual storms is complicated by insufficient data on wind vectors, stability, and other storm characteristics and by great variability in storm characteristics. The areal pattern of individual storms in mountainous regions may be expressed effectively in terms of the ratio of storm precipitation to the seasonal or annual average, if the storms are of the type that dominate in determining the mean pattern.

The variation of mean annual precipitation with elevation and with lee and windward orientation has been recognized and studied for many years. Additional parameters include steepness of slope and degree of exposure. The degree of exposure can be defined objectively, for example, as the sum of the sectors of a 30-kilometre radius circle about the station not containing a barrier 0.3 kilometre or more above the station elevation. The steepness of the slope requires a convention as to the scale or length of the slope to be considered (section 40.5.1).

The effective definition of parameters and of their joint relation to mean annual or mean seasonal precipitation can be achieved by successive approximation through graphical correlation. An example of the product of such a process is shown in Figure 30.3. The technique for performing the correlation analysis is given by Linsley, *et al.* in *Applied Hydrology* [7] and in *Hydrology for Engineers* [8] and by Rainbird in *Methods of Estimating Areal Average Precipitation* [9].

30.4 **Computation of areal average precipitation**

Several methods [7] are commonly used for estimating average precipitation over a specific area. The choice of method requires judgement in consideration of the quality and nature of the data and the required precision of the result.

30.4.1 *Arithmetic mean*

The arithmetic mean of the precipitation values observed at the stations in a drainage basin is the simplest objective estimate of the average precipitation over a basin. This method is suitable for basins with a large number of precipitation stations that are spaced uniformly or otherwise adequately sample the precipitation distribution over the basin. Its adequacy may be tested by comparison with more sophisticated methods in given situations.

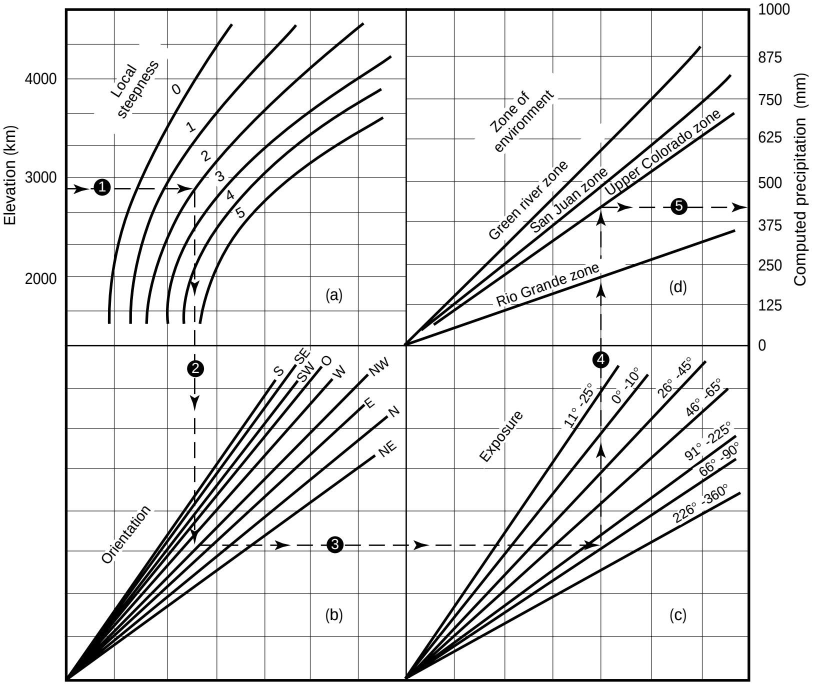

Figure 30.3 — Relation between average October-April precipitation and topographic parameters for western Colorado.

30.4.2 *Polygon method*

The polygon method, referred to in many texts as the Thiessen-polygon method [7, 10], and shown in Figure 30.4, is used with non-uniform station spacing. It gives weights to station data in proportion to the space between stations. In this procedure, lines are drawn between adjacent stations on a map. The perpendicular bisectors of these lines form a pattern of polygons with one station in each polygon. The area that each station represents is the area of its polygon, and this area is used as a factor for weighting station precipitation.

The sum of the products of each station area and precipitation is divided by the total basin area to get the average precipitation. Around the edge of the basin, where parts of polygons extend beyond the basin boundary, only the portion of polygon inside the drainage area is used. In this manner, stations near but outside the drainage basin may have polygon areas that extend into the drainage basin, and their data are included.

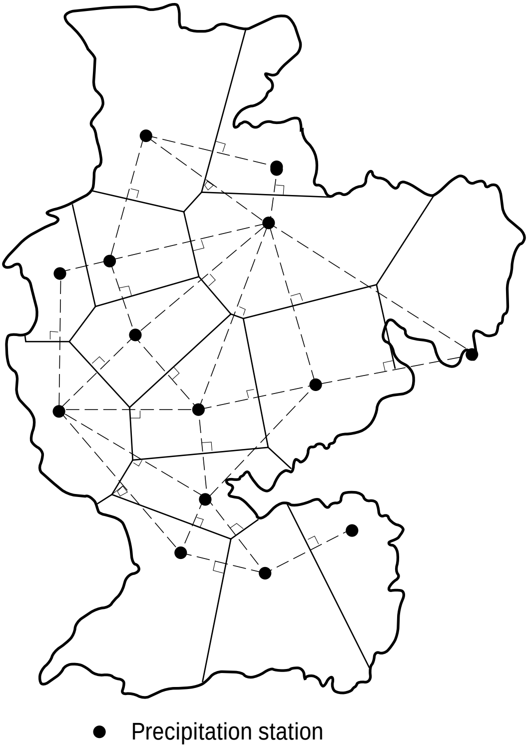

Figure 30.4 — Polygon method.

The procedure is mechanical and can be carried out readily by machine methods. A change in the network by the removal or addition of a station requires recomputation of the weighting coefficients. If data for one or more stations are missing for a particular day or storm period, these data are normally estimated in preference to recomputing the station weights. This may be done by interpolating between stations or by constructing isohyets (section 30.2.3).

While its objectivity is an advantage, the method rigidly excludes consideration of information other than station spacing and precipitation amounts.

30.4.3 *Isohyetal method*

The isohyetal method employs the areas encompassed between isohyetal contours (section 30.3.1). These areas may be determined by planimetering or by laying a transparent grid over the isohyetal map and by tallying the number of grid points within each contour interval. Manual analysis has been largely replaced by computer techniques [5].

The isohyetal method allows an analyst to apply all available information. Such information may include radar-echo patterns, physiographic relationships, storm tracks and types, and runoff data. Skilful use of this method will produce superior results. Again, a number of computer-based techniques are available to incorporate these and surface-fitting techniques into isohyetal analysis [5].

30.4.4 *Per cent normal method*

In mountainous regions of many parts of the world, mean annual and mean seasonal precipitation maps have been constructed that take into account the average effect of physiography on the precipitation. In using this method, storm precipitation is expressed as a percentage of mean annual or mean seasonal precipitation, and isopercental maps are used for preparing isohyetal maps. This method is most successful in regions of pronounced physiographic influence, where individual storms tend to have a similar isohyetal pattern.

30.4.5 *Hypsometric method*

The hypsometric method shown in Figure 30.5, is particularly useful in mountainous regions. The area-elevation curve in quadrant, (*a*) is constructed by plotting the area of the basin lying below the various elevation contours (*A*' on the *x*-axis) against the corresponding elevations (*z* on the *y*-axis).

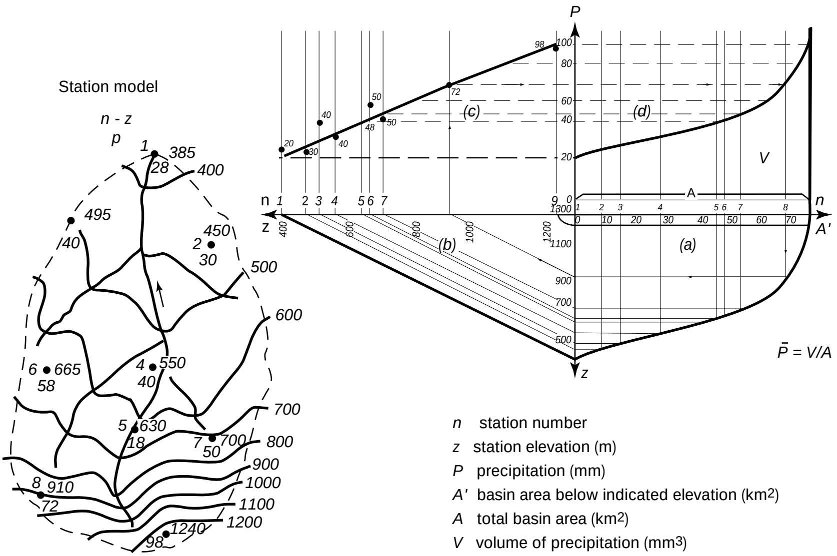

Figure 30.5 — Hypsometric method.

The locations of the station identifiers on the *x*-axis are then determined by back tracking from the station elevation on the *y*-axis to the area-elevation curve, then upward to the *x*-axis. The locations of the station identifiers on the *x*-axis are then determined as indicated in quadrants, (*a*) and (*b*) with the lines in quadrant (*b*) projected at an angle of 60° from the *y*-axis.

The curve of quadrant (*c*) is constructed by plotting station precipitation against the corresponding stations. From this quadrant, the values are projected to quadrant (*d*) and plotted against their respective station identifiers to derive the precipitation curve. The area in quadrant (*d*) lying below this curve represents the volume of precipitation. Dividing by the total area of the basin yields the average depth.

It should be noted that quadrants (*a*) and (*b*) are fixed for a particular basin and that only the curves of the two top quadrants have to be re-determined for each storm. The method may also be used for averaging monthly or annual precipitation.

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CHAPTER 31

SNOW-MELT RUNOFF ANALYSIS

31.1 General

Snow melt is exactly analogous to rainfall with respect to supply of water for infiltration and runoff, except for the relatively small storage and lag of the melted snow in the snow cover. During periods of no precipitation, successive differences in a series of daily measurements of water equivalent of a melting snow cover are practically analogous to daily increments of rainfall. Ordinary measurements of incremental changes in water equivalent of the snow cover are not satisfactory measurements of snow melt, largely because of the inherent observational and sampling errors. Taking cores from successive locations at a site confounds variation in time with variation in space. Two additional and compelling reasons exist for estimating, instead of observing, snow melt. One is in forecasting streamflow, where it is advantageous to forecast the causes of melt instead of merely waiting for the resulting melt. The other reason, particularly for design and planning, is the need to extrapolate extreme melting rates on the basis of physical processes.

31.2 Theory of snow melt at a point

A rational approach to estimating the rate of snow melt is based on an energy budget, which accounts for the significant modes of heat exchange. Heat is transmitted to snow by absorbing solar radiation, net long-wave radiation, convective heat transfer from the air, latent heat of vaporization by condensation from the air, relatively small amounts of heat from rain, and usually negligible amounts of heat from the underlying ground.

A melting snow cover typically contains from two to five per cent by weight of liquid water, but occasionally as much as 10 per cent is held for brief periods when melting rates exceed transmission capacity. Thus, for short periods of time, the total release of water from a snow cover may slightly exceed the amount of snow actually melted by the prevailing meteorological conditions. For practical purposes, this release of previously melted water is implicitly incorporated into the empirical constants, which are known only approximately and are burdened with other and greater uncertainties.

Absorbed solar radiation varies with latitude, season, time of day, atmospheric conditions, forest cover, slope, orientation of surface, and reflectivity of the snow. The effects of latitude, season, time of day, and atmospheric conditions are included in solar-radiation observations, which must usually be interpolated because of the sparse network of such stations. These effects may also be computed on a daily-total basis by means of formulae or diagrams that express solar radiation as a function of degree of cloudiness, time of year, and latitude.

The effect of forest cover on the transmission of solar radiation is important, and, in experimental areas, it has been expressed as an empirical factor that relates the transmission coefficient to canopy density. Usually direction and steepness of slope and forest cover are represented by constant factors, derived empirically for a given drainage area.

Reflectivity of a snow surface ranges from about 90 per cent for newly fallen snow to about 40 per cent for old snow that is coarse-grained and which is ordinarily covered late in the season by a thin layer of dark debris such as wind-blown organic or mineral dust. In middle latitudes during late spring, an unforested snow cover with low reflectivity commonly absorbs sufficient solar radiation to melt 50 millimetres of water equivalent per day.

Long-wave radiational exchange is the difference between outgoing radiation from the snow surface and downward radiation from clouds, trees, and the atmosphere. With dense low clouds or heavy forest cover warmer than 0°C, the exchange is a gain to the snow. Long-wave radiation from the atmosphere, in the absence of clouds or forest cover, is largely a function of air temperature and is nearly always less than the loss from the snow. Long-wave radiational exchange commonly ranges from a gain of heat equivalent to as much as 20 millimetres of melt water per day to a loss equivalent to 20 millimetres per day.

The major factors in the convectional exchange of sensible heat are the temperature gradient in the air immediately above the snow and the intensity of turbulent mixing as expressed by horizontal wind speed.

The major factors in heat from condensation are the vapour-pressure gradient and intensity of turbulent mixing, which may be indicated by wind speed.

The combined exchange of sensible and latent heat by turbulent exchange may range from a gain of heat that is equivalent to more than 100 millimetres of melt per day to a loss corresponding to two or three millimetres. The reason for the potential gain so greatly exceeding the potential loss is that the temperature and vapour-pressure gradients for heat gain can be very great with the snow temperature limited to 0°C, whereas with very low air temperatures and vapour pressures accompanying the loss of heat, the snow-surface temperature usually falls correspondingly. Thus, the gradients are reduced.

Heat gain from warm rain can be computed from the latent heat of fusion of the ice (80 cal g^{-1}) which comprises the snow, and the temperature of the rain, which can usually be taken as the wet-bulb temperature of the air. Computations show that an unusually hard rain (at least 120 millimetres of rain with a temperature of 16°C) is required to produce as much as 25 millimetres of snow melt in a day.

The rate of conduction of heat from the soil to a newly formed snow cover may be rapid for a short time, but the usual geological gradient of temperature, and the gradient of temperature after steady-state has been established, produce less than about one millimetre of snow melt per day.

The foregoing rates of snow melt from various modes of heat exchange are not additive. For example, the conditions for maximum turbulent exchange would occur during stormy weather and not with maximum solar radiation.

Numerous equations have been published that express the modes of heat exchange in terms of observed or observable elements. These equations usually take a form somewhat like those that follow.

Absorbed solar and diffuse sky radiation, R_{ab} in cal cm^{-2}, is given by:

$$R_{ab} = (1 - B)R_s C_s \tag{31.1}$$

where R_s is the total incoming short-wave radiation on a horizontal surface at the pertinent latitude and time of year and with a clear sky, B is the reflectivity of the snow, and C_s is a cloudiness function, which was defined in the former U.S.S.R. as:

$$C_s = 1 - (0.14N + 0.53N_1) \tag{31.2}$$

where N is total cloudiness and N_1 is cloudiness of the lower layer, both in fractions of sky cover. An additional expression is often given for areas that are significantly different from horizontal.

The effect of forest cover in depleting solar radiation may be taken into account by a coefficient such as:

$$K_f = 1 - f\sqrt{1 - (1 - C)^2} \tag{31.3}$$

where f is the portion of solar radiation that is withheld by a particular type of forest with 100 per cent canopy density (usually about 0.9) and C is the canopy density.

Net long-wave radiation loss from snow, R_1 in cal cm^{-2} min^{-1}, is given by:

$$R_1 = \sigma\left(d_n\,\theta_n^4 - d_a\,\theta_a^4\,U_e\,C_1\right) \tag{31.4}$$

where the Stefan-Boltzmann constant, σ, equals 8.13 X 10^{-11} cal cm^{-2} min^{-1} °K^{-4}, θ_n and θ_a are absolute temperatures of snow and air, that of air taken at a height of two metres, d_n and d_a are the black-body coefficients of snow and air, both near unity, U_e is a humidity function expressing the effect of atmospheric water vapour on long-wave radiation, and C_1 is a cloudiness function, which differs from C_s in that it applies to long-wave radiation while C_s applies to short-wave radiation. U_e has been expressed in several ways by different investigators, a common form being $U_e = a + b\sqrt{e}$. The parameter a may be taken as 0.62 and b as 0.05, with e, the vapour pressure in hPa at a height of two metres above the snow surface. With the usual range of vapour pressure over melting snow, U_e is between 0.7 and 0.8. C_1 may take the form:

$$C_1 = 1 + 0.12(N + N_1) \tag{31.5}$$

where N is total cloudiness and N_1 is cloudiness of the lower layer, both in fractions of total sky cover.

With forest cover, downward long-wave radiation, R_d, may be expressed as:

$$R_d = \left[F + (1 - F)\,U_e\right]\sigma\,\theta_a^4 \tag{31.6}$$

where F is a fraction of forest cover. Effective forest cover may be estimated from aerial photographs of canopy density or as a residual empirical constant.

Transfer of heat by turbulent exchange is given by the two following equations, for sensible heat and latent heat, respectively:

$$Q_h = ku\left(\theta_a - \theta_n\right) \tag{31.7}$$

$$Q_e = cu\left(e_a - e_n\right) \tag{31.8}$$

where u is horizontal wind speed at a given height, $(\theta_a - \theta_n)$ is the average temperature gradient in the layer of air above the snow, and $(e_a - e_n)$ is the corresponding vapour-pressure gradient. The empirical constants, k and c, include the mass-transfer coefficient, the aerodynamic roughness of the snow surface, stability (the tendency of the dense layer of air near the snow to resist overturning or mixing), the wind structure, the heights of the instruments above the snow surface, and the air density. The constant k includes the specific heat of air, and c includes the latent heat of vaporization of moisture in the air. The latter also may include the amount of condensate added to the snow melt from condensation unless the condensate is accounted for in some other way.

31.3 Estimates of catchment melt in the absence of rain

The integration of a rational snow-melt function over a heterogeneous drainage area of significant size is extremely difficult at best and practically futile without elaborate instrumentation. A measurement for the quantity or rate of melt introduces the complication of water accounting in addition to heat accounting. In the absence of rain, radiational exchange is relatively important, and consequently the effects of rarely measured snow reflectivity and forest canopy density are important. Daily solar radiation for a given latitude and time of year is influenced by local cloudiness, which in turn is observed subjectively, sparsely, and rarely with respect to its radiative transmissivity. Further, there is the problem of determining the active or contributing area of the snow.

The active or contributing area may be defined as the area over which snow is melting or over which snow melt reaches the soil. This area, however defined, varies diurnally. The equations given in section 31.2 may be expressed as daily totals, and a diurnal pattern may then be imposed. If the diurnal cycle includes nocturnal freezing, some account must be taken of the heat and moisture storage involved. Early in the melting period, some heat is necessary to raise the temperature of the snow to 0°C and to melt sufficient snow to meet the water-holding capacity of the snow cover. This heat is relatively small with respect to the total heat required to melt the snow cover.

The most widely applied method for estimating basin-wide snow melt is the use of degree-day factors. Temperature data are usually available, and the variation of temperature over a drainage area can usually be determined for deriving and applying degree-day functions. The rationale for the degree-day method is two fold. First, air temperature near the snow is largely a physical integration of the same modes of heat exchange that melt snow. Second, each mode of heat exchange can be related to air temperature except during abnormal winds. For example, minimum daily air temperature is highly correlated with dew-point temperature, which determines the vapour-pressure gradient for condensation melting. Maximum daily temperature or temperature range is an index to solar radiation. Within its usual range, long-wave radiation can be expressed as a linear function of air temperature.

Efforts have been made to give the maximum and minimum daily temperatures various weights and to use degree-day bases other than 0°C. Efforts have also been made to divide the day into smaller time units and to use degree-hour factors. However, the diurnal cycle of heat exchange and of snow melt makes the day a logical and convenient unit for snow melt, and the usual degree-day base is 0°C referred to the mean of the daily maximum and minimum temperatures.

Point snow melt degree-day factors for several mountainous regions in the middle latitudes of North America have been averaged in Table 31.1, expressed as millimetres of melt, and the mean of daily maximum and minimum temperature above a base of 0°C. Individual values may depart widely from these averages.

TABLE 31.1

Degree-day factors (mm °C^{-1}) for mountainous regions in North America

Month	*Moderately forested*	*Partly forested*	*Non-forested*
April	2	3	4
May	3	4	6
June	4	6	7

Similar degree-day factors are given in Table 31.2 for lowlands in moderate latitudes of the former U.S.S.R.

TABLE 31.2

Degree-day factors (mm °C^{-1}) for lowland regions in the former U.S.S.R

Non-forested areas	5
Sparse coniferous and average density of hardwoods	3 to 4
Average density of coniferous woods and dense mixed woods	1.7 to 1.8
Dense coniferous woods	1.4 to 1.5

With a shallow snow cover, the storage and delay of melt water passing through the cover are usually inconsequential compared with storage and delay in the soil mantle and uncertainties in the amount of snow melt itself. The time required for liquid water to drain from a snow cover is about one hour plus an hour for each 50 centimetres of depth.

Areal variations in melting rate and in the distribution and diminishing size of the area covered by snow during a melting period are related to somewhat permanent characteristics of the catchment area, such as its topography and distribution of vegetative cover. Consequently, the melting rate over a catchment reflects a fairly consistent trend in contributing area and snow condition during a melting period. This trend influences the shape of empirically defined S-shaped curves such as those in Figure 31.1. Because of the areal dispersion of the snow and of its local melting rates, some of the snow starts to melt before the rest. Thus, the average melt rate per unit area is small early in the melting period and increases as more of the area contributes. Toward the end of the melting period, the slopes of the curves of Figure 31.1 diminish because of the diminishing area of snow melt contribution. The steepest portions of the curves occur after melting conditions have become established over a large contributing area. The proportionality of melting rates to the initial quantities of snow comes largely from the fact that, with more snow, the contributing area is larger. The steepest portions of the curves of Figure 31.1 have a slope that corresponds to the values of Tables 31.1 and 31.2.

Evaporation loss from the snow cover is negligibly small during brief melting periods and may be more than balanced by condensation on the snow surface.

In mountainous regions, where great quantities of snow accumulate, where the melting season may cover several months, and where melting conditions vary greatly with a large range of elevation, curves such as those of Figure 31.1 have limited reliability. Evaporation during long warm periods may be significant. During the melting season, successive aerial or other surveys show the changing snow-covered area, and meteorological observations are interpreted to express the variation of

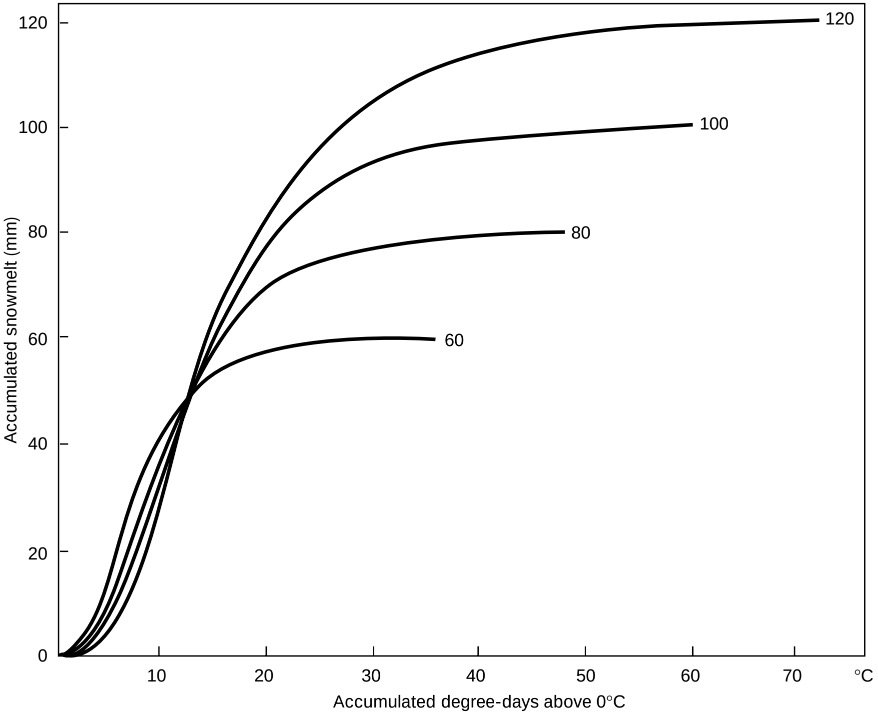

Figure 31.1 — Typical degree-day snow-melt relationship for a catchment.

melting rate with elevation. The contribution of snow melt should be determined by elevation zones. In addition, with deep mountain snow covers, more consideration must be given to the retention of melted snow in the cover.

Higher-than-average degree-day factors should be used when unusually high wind speeds or humidities occur.

31.4 Estimates of catchment melt with rain

During periods of heavy rain, the rate and amount of snow melt may be no greater than the error in estimating the amount and effects of the rain. During storms accompanied by considerable turbulent mixing and heavy, low clouds, short-wave solar radiation is relatively unimportant, and long-wave radiation, convection, and condensation are the major sources of heat. The difficulty of separating the contribution of rain from that of snow melt has left the question of snow melt during rain largely in the realm of theory with very little empirical evaluation.

Equations adapted from the U.S. Army Corps of Engineers [1] are for heavily forested areas:

$$M = (0.3 + 0.012P)\theta + 1.0 \tag{31.9}$$

and for open or partly forest-covered areas:

$$M = (0.1 + 0.12P + 0.8ku)\theta + 2.0 \tag{31.10}$$

where M is daily melt in millimetres, P is daily rain in millimetres, θ is mean daily temperature in °C, k is a basin constant ranging from 0.3 for moderately dense forest to 1.0 for open plains areas, and u is wind speed in m s^{-1} at 10 metre height. Saturated air is assumed, and the constants (1.0 and 2.0) include the effects of melting from the ground and the slight net solar radiation that penetrates the rain clouds.

31.5 Estimating snow-melt inflow rates

To determine the total snow-melt runoff in lowland basins, water-balance studies can be adopted as discussed in section 45.2. From these, the expected total snow-melt runoff can be estimated at the beginning of the snow-melt period. However, values of the daily snow-melt inflow are often required for hydrograph calculations. The following main factors should be taken into account for estimating these values:

(*a*) The heat inflow to the snow cover;
(*b*) The water-retention capacity of the snow cover;
(*c*) The area covered with snow; and
(*d*) The water-retention capacity of the basin.

In general, the daily snow-melt inflow, Q_n, can be described by the following equation:

$$Q_n = \frac{m}{1-\alpha_o} f_1(M, I_f)\, f_2(M, \alpha_o) \tag{31.11}$$

where m is the daily melt, α_o is the initial relative amount of melt water retained by snow, which is equal to the upper limit of water-retention capacity of the snow cover, $f_2(M, \alpha_o)$ is a function expressing the relative area of the snow-melt inflow related to the accumulated melt, M, and the initial water retention of snow, α_o, $f_1(M, I_f)$ is a runoff coefficient as a function of the accumulated melt and the index of the infiltration capacity of the basin I_f. The initial amount of melt water retained by snow depends on the structure and density of snow cover and can be determined experimentally. Limited data indicate that values of 0.15-0.20 can be used as a first approximation to α_o for lowland basins with the density of snow varying between 0.25 and 0.30. The relative area on which the snow-melt inflow takes place, $f_2 (M, \alpha_o)$ depends on the areal distribution of the snow. Thus, the relative area increases with accumulated melt because of the increase of the area on which snow becomes saturated. As the snow becomes patchy, the relative area decreases with the decrease of the snow-covered area. The simplest technique for estimating the snow-melt inflow area is based on the assumptions of uniform melt and constant initial water retention of snow over the whole basin. Under such conditions, the function $f_2 (M, \alpha_o)$ can be determined as the difference between two functions:

$$f_2\left(M, \alpha_o\right) = f_3(M) - f_4\left(M\right) \tag{31.12}$$

where $f_4 (M)$ is the area of the basin from which the snow has melted and $f_3 (M)$ is an integral function of the relative area on which snow becomes saturated,

$$f_3(M) = f_4\left(\frac{M}{\alpha_o}\right) \tag{31.13}$$

The method described above makes it possible to derive graphical relationships between accumulated degree-days and accumulated snow melt for different values of mean water equivalent of snow cover. Such relations, as shown in Figure 31.2, are convenient for operational use.

The runoff coefficient, $f_1 (M, I_f)$, is a function that increases with accumulated melt because of the decrease of the infiltration capacity of the river basin. Relationships between these variables can be determined empirically by using the index of antecedent-soil-moisture conditions and depth of soil freezing as parameters. Water-balance relations can be used for this purpose. After such a relationship has been established for a river basin, the function $f_1 (M, I_f)$ is determined by differentiation:

$$f_1\left(M,\ I_f\right) = \frac{dQ\left(W,\ I_f\right)}{dW} \tag{31.14}$$

where Q is the seasonal runoff and W is the mean water equivalent plus precipitation. By using this method, a series of curves for different values of infiltration capacity index I_f can be derived.

31.6 Evaporation from a snow cover

Equations for condensation on a snow cover may also be used for estimating evaporation from the snow. Evaporation occurs when vapour pressure decreases with height above the snow, and condensation occurs when vapour pressure decreases toward the snow. Snow-surface temperature is difficult to measure and is rarely available unless the snow is melting.

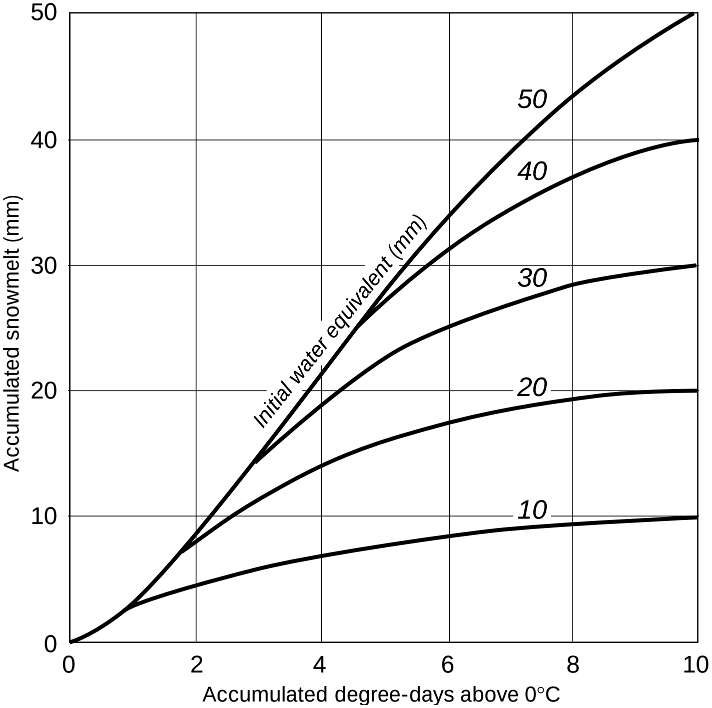

Figure 31.2 — Temperature-snow-melt relationship for different values of initial water equivalent for a lowland catchment.

Evaporation from snow is a self-limiting process, because it cools the snow and tends to maintain a relatively small vapour-pressure gradient in the layer of air above the snow. Conversely, the vapour-pressure gradient during condensation on snow is constrained at its lower end by the melting temperature of the snow, whereas the vapour pressure of the air can be much higher. Accordingly, condensation rates are ordinarily much greater than evaporation rates.

The measurement of evaporation from a snow or ice surface is difficult, and probably about as accurate as the computation of evaporation. In general, it is estimated that during winter periods, evaporation occurs from a typical snow surface at rates from zero to as much as 20 millimetres per month. During melting periods, condensation tends to prevail, and occurs at rates from zero to possibly as much as 10 millimetres of condensate per day.

It is possible, with cold dry air and clear skies, for snow to melt and evaporate at the same time, and rarely, with just the right heat and moisture balance, for the evaporation to equal the melt. At times, sublimation may occur, i.e., the snow is converted from the solid to the vapour form with no liquid water becoming apparent.

31.7 Probable maximum precipitation and snow melt

31.7.1 *Introduction*

In the case of very large basins at high latitudes, snow melt, instead of rainfall, may be the primary cause of the probable maximum flood. Flood-runoff volume and temporal distribution are then based on the estimation of snow melt resulting from the estimated maximum values of temperature, wind, dewpoint, and insolation in a manner analogous to maximization of storm rainfall (section 29.4.1).

A more common situation in lower latitudes is for rainfall to be the primary factor producing the probable maximum flood with snow melt adding an increment to the maximum hydrograph. Snow melt, compatible with estimated synoptic conditions accompanying the maximized storm, is then added to the maximized rainfall depth.

For some basins, only a detailed analysis will reveal whether the probable maximum flood will result from a cool-season rainstorm combined with snow melt or from a summer rainfall that may be more intense but, cannot be logically expected to occur in combination with snow melt.

31.7.2 *Probable maximum snow accumulation*

The snow-melt contribution to the probable maximum flood will depend upon the maximum rate of melting and the water equivalent of the snow cover available for melting. Water equivalent of a snow cover is the depth of water that would result from melting and depends upon the snow density as well as its depth. Various methods have been used to estimate the probable maximum snow accumulation, but three methods have been categorized [2] as follows:

(*a*) Partial-season method — The highest observed snow accumulations in each month or two-week period, according to the frequency of observations, are combined, regardless of the year of occurrence of each observation, to give a synthetic year of very high snowfall. The method can be applied to shorter time intervals, such as a week or four-day periods, if suitable records are available;

(*b*) Snowstorm maximization — The ratio of maximum atmospheric-moisture content in the project area at the time of year at which a storm occurs to the actual moisture content of the storm is determined. The observed snowfall produced by the storm is multiplied by this ratio to give maximized snowfall for the storm. Maximization of moisture content must be restricted to a value that will produce snow and not rain; and (*c*) Statistical methods — A frequency analysis of precipitation and snow-depth records is made to determine the values for various return periods. Analyses are made of three types of data — station precipitation depth, basin snowfall depth, and water equivalent of snow on the ground.

31.7.3 *Snow-melt estimation*

Owing to the complex spatial and temporal variability of snow melt over most catchments due to differences in slope, aspect, forest cover, and depth of snow cover, the degree-day method is often adopted as a practical solution to the problem of estimating snow melt over a catchment. Maximum degree-day conditions may be estimated from temperature records for the project basin or a neighbouring area and may be applied to the estimate of probable maximum snow accumulation to provide an estimate of probable maximum flood runoff.

A more rational method of estimating basin snow melt associated with rain is described in section 31.4. For probable maximum conditions, the air temperature and wind speed are made consistent with the assumed synoptic conditions accompanying the storm-producing probable maximum rainfall. It also is assumed that an optimum snow cover exists. Optimum in this situation means that:

(*a*) The snow cover has only sufficient water equivalent to melt completely during the storm;
(*b*) The snow cover has been melting and contains a maximum amount of liquid water; and
(*c*) The water equivalent of the snow cover is distributed so as to be at a maximum where the melting is maximum, which is different from the usual situation of increasing the snow-cover water equivalent with increasing elevation.

31.8 Runoff from short-period snow melt

31.8.1 *Plains regions*

In a plains region, where increments of runoff are relatively small and the melting period is brief, runoff may be estimated by incorporating estimated snow melt, obtained by methods such as described above, into a rainfall-runoff relationship (Chapter 33). It may be necessary to use the relationship in a way that reflects a high percentage of runoff because the snow cover or cold weather inhibits evapotranspiration losses antecedent to the melting period.

31.8.2 *Mountainous terrain*

In mountain catchment areas, where deep snow covers prevail and the melting season lasts several months, methods commonly used for estimating runoff from brief rainstorms do not necessarily apply. Runoff from the melt that occurs on a particular day is ordinarily spread over a long period, overlapping the melting increments of many other days. Also, evapotranspiration losses, which may be neglected during a period of rainfall, become important during a long melting season.

One way to estimate runoff from day-to-day snow melt is first to estimate the seasonal volume of runoff (Chapter 45) and then to distribute this volume in accordance with observed or estimated local daily-melting rate (sections 31.3 and 31.4), basin-storage characteristics, contributing area, and seasonal evapotranspiration. Basin storage and lag may be accommodated by routing though an analogous system of reservoirs with constants determined empirically from historical basin data.

Where the catchment is so small that the diurnal increments of snow melt are not damped out by storage, six-hour, rather than daily melting, increments should be used, or a characteristic diurnal distribution can be introduced into the routing method.

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CHAPTER 32

EVALUATION OF STREAMFLOW DATA

32.1 General

The analysis of streamflow data is usually performed for practical needs at certain locations. If there are streamflow records for these locations, they may be used directly in the analyses. If the accuracy or the representativeness of these records is not sufficient, it may be possible to adjust them to reach the required standard. When sufficient records are not available, there is a need to transfer information that is based either on streamflow data at other locations or on other types of hydrological and meteorological data.

32.2 Adjustment of data

A determined effort should be made to estimate discharges for periods of missing record or when the record is known to be unreliable.

Hydrographs of daily discharges plotted on semi-logarithmic paper are valuable aids in estimating discharges for periods of incomplete record because such hydrographs, when analysed over the period of record, indicate typical rates of recession between storms and typical responses to rainfall. A fairly reliable estimate of discharge can be made by using these hydrographs with other evidence such as precipitation records, range lines on the recorder chart, and concurrent hydrographs of other streams. The hydrographs are also useful in other hydrological interpretation, such as in separating base flow from storm runoff as described in section 33.3.1.

The need to adjust streamflow data may be detected by double-mass curve analysis similar to that described in section 30.2.2, but the adjustments should be based on re-analysis of the records rather than on the results of the double-mass curve analysis.

Cumulative runoff at one station is plotted against average cumulative runoff for a group of stations. If the resulting curve shows a break in slope, then the streamflow records are re-examined for a change in the method of record computation or data collection, and are recomputed, if necessary. If the objective is to obtain a record that reflects what the flow would have been if there had been no anthropogenic changes in the catchment, then the computed discharges should be adjusted for estimated diversions to or from the catchment and for changes in the amount of water used in the basin before being replotted against the pattern. If causes for a break in slope of the double-mass curve cannot be identified, then no adjustment of the record should be made.

If a reasonable amount of interpretation is used in computing a record of daily discharge, then the accuracy of that record will usually be better than the accuracy of any of the other items in the hydrological budget of a catchment. Streamflow is the only item of the budget with a single record that is integrated over the drainage area. All other items, such as precipitation, soil moisture, and groundwater, are only sampled with respect to the area. Therefore, adjustment of streamflow records on the basis of the other items is seldomly justified. Hydrological comparisons may indicate that the basic streamflow data should be re-examined but should not be used to determine a blanket adjustment.

A distinction should be made between the accuracy of a streamflow record and the accuracy with which the record represents the natural runoff of the drainage area. A record of streamflow can be accurate even though half the flow of the stream may have been diverted for use upstream. In those hydrological studies where it is necessary to estimate the natural flows of a stream, quantitative adjustments should be made from estimates of diversion and use. Such adjustments do not discredit the computed record of streamflow.

In some cases, the water-budget method (section 37.2) may be useful as a general assessment of streamflow records. If the runoff or loss is unreasonably high or low compared with that computed for other months or for other streams, then the basic stream-gauging data should be re-examined for possible misinterpretation.

32.3 **Areal distribution**

The average annual runoff differs considerably from stream to stream. At low flow, the yield per unit area from adjacent streams may vary by several-fold. For an accurate determination of the amount of water available, a stream-gauging station should be operated for several years at or near the site of any proposed development. For reconnaissance planning, however, less accurate information can be used. Examples of such information are maps of average annual runoff and correlations among gauging-station records.

32.3.1 ***Maps of average annual runoff***

Maps of average annual runoff may be based almost entirely on runoff records, on precipitation and evaporation records, or on a combination of these. If a good network of precipitation stations and streamflow stations has been operated concurrently for 10 or more years, both sets of data should be used. The isopleths of average annual runoff should be consistent with the isohyets of average annual precipitation and the geology of the region. They also should relate to records of other comparable hydrometric stations. In other words, the streamflow records are used to determine the average of the total runoff from the catchment, while the precipitation, evaporation, and geological data are used to help in estimating the distribution of runoff within the catchment. Average annual water loss, computed as the difference between the precipitation isohyets and the runoff isopleths, serves as a guide to consistent interpretation.

When only runoff records are available, a rough areal distribution can often be made on the basis of elevation and the character of the vegetation. In general, runoff should increase with elevation because of greater precipitation and cooler temperature. The character of vegetation serves to differentiate drier areas on the leeward side of a mountain from well-watered areas at the same elevation on the windward side.

32.3.2 ***Average runoff from precipitation and temperature data***

When only precipitation and temperature records are available, a method proposed by Langbein may be used [1, 2]. The method is applicable if there is no groundwater discharge from the basin and when groundwater storage does not change considerably from year to year. A modification of this method is given here. This method is based on a unique relation between P/F_θ and Q/F_θ, where P is the average annual precipitation, Q is the average annual runoff measured in the same units as P, and F_θ is a temperature factor. If P and Q are expressed in centimetres, $F_\theta = 10^{(0.027\theta+0.886)}$, in which θ is the average annual temperature in °C.
The relation between θ and F_θ is given by:

θ, in °C	F_θ
-20	2.22
-10	4.13
0	7.69
10	14.3
20	26.6
30	49.7

The relation between P/F_θ and Q/F_θ is given by:

P/F_θ	Q/F_θ
0	0.009
1	0.026
2	0.075
3	0.200
4	0.475
5	1.0
6	1.9
7	2.7
8	3.4
10	5.0
12	7.0
14	9.0

If, for example, the average annual temperature is 20°C and the average annual precipitation is 53 centimetres, then F_θ is 26.6 and $P/F_\theta = 2.0$. The Q/F_θ value, corresponding to P/F_θ of 2.0, is 0.075, and the average annual runoff is 0.075 × 26.6 or 2.0 centimetres. If the annual precipitation were 133 centimetres, however, P/F_θ would be 5.0, Q/F_θ would be 1.0, and Q would be 26.6 centimetres. In this instance, an increase of 150 per cent in precipitation increases the runoff by 1 230 per cent.

The relation between P/F_θ and Q/F_θ can be refined by making allowance for instances where the precipitation is concentrated in a hot season or in a cold season [1].

Although the relation between P/F_θ and Q/F_θ and the effect of seasonal distribution are based on data collected in the United States, the relationships probably have world-wide application. Their applicability to other countries can be verified or modified by plotting observed precipitation and runoff data in the manner indicated and by comparing the result with the tables given here.

A map of average annual runoff gives a general appraisal of the total amount of water theoretically available, but does not indicate the variation of flow among years or within a year. The flow for some years may be considerably less than the average annual runoff, and even in those years, much of the flow will occur during high water periods and will not be usable without storage. The variations among years can be appraised by frequency analysis. The variation of flow within years can be appraised by analysis of high and low flows, as discussed in Chapters 35 and 36.

The mean annual water loss, D, is defined by the relation:

$$D = P - Q \tag{32.1}$$

For many catchments in temperate climates, the value of D, calculated over a reasonably long period of years, varies relatively little. Values of this mean annual loss computed for neighbouring catchments can be used to estimate the mean annual discharge from a catchment precipitation record. In western Europe, D generally varies between 400 and 600 millimetres. Various empirical formulae have been developed for calculating D, one being credited to Turc [3]:

$$D = \frac{P}{\sqrt{0.9 + \frac{P^2}{L^2}}} \tag{32.2}$$

where $L = 300 + 25\theta + 0.50\theta^3$, P is mean catchment precipitation, and θ is the mean annual air temperature.

The first step in the correlation of streamflow with precipitation records is the selection of a suitable group of meteorological stations located in or adjacent to the drainage area concerned. The rainfall record at each of these stations must be concurrent with the available streamflow record and must extend either forward or backward in time over the period through which it is desired to project the streamflow records. The rainfall record at each station should be adjusted by the double-mass curve method (section 30.2.2) for deviations that may have resulted from local occurrences.

The simplest method of synthesizing annual flows consists of regressing observed annual mean discharges against the corresponding annual precipitation totals and applying the resulting regression equation to those precipitation observations that extend beyond the period of streamflow record.

Frequently, the correlation between annual discharge and annual precipitation is not sufficiently strong for practical applications, and relationships involving monthly values of discharge and precipitation must be developed. One form of relationship that makes allowances for the irregular temporal distribution of monthly precipitation is expressed as:

$$Q = k(1 + aC_P)(P - P_o) \tag{32.3}$$

where

$$C_p = \frac{1}{P_{12}}\left(\frac{1}{132}\sum^{12}\left(P_i - P_{12}\right)^2\right)^{1/2} \tag{32.4}$$

Q is annual runoff, P is annual precipitation, P_i is the rainfall in month i, P_{12} is the annual precipitation divided by 12, and P_o, a, and k are constants, with P_o being the maximum annual precipitation that can occur without producing runoff, i.e., unless P is greater than P_o, Q equals zero.

Another form of the relationship treats runoff during a given time period as a function of current and antecedent precipitation. This relationship may be expressed by an equation such as:

$$Q = aP_1 + bP_2 + \ldots + c \tag{32.5}$$

where P_1 is precipitation during the current period, P_2 is precipitation during the period preceding the current period, and a, b and c are constants. Values of the constants may be determined by multiple-regression analysis. Equations of this form can be applied to data for periods of various lengths. The number of precipitation terms and the values of the constants will vary with the length of period chosen. If the period is one year and substantial storage within the basin is carried over from one year to the next, it probably would be necessary to include the previous year's precipitation along with the current year's precipitation. If, on the other hand, the period is one month, it may be necessary to use more than one preceding month's precipitation to obtain an accurate relationship between precipitation and runoff. When the discharge interval of interest is less than one year, e.g., one month, the number of terms on the right side of the equation and the values of the constants may change seasonally within the year.

32.3.3 *Correlation between stations*

If records at some of the stream-gauging stations are considerably shorter than at other stations in the area, users should examine the records to see if the flows during the periods covered by the short records were above or below the average for the long period. The correlation between gauging stations is one method of performing such comparisons. In preparing maps of annual runoff, for example, a plot of concurrent annual discharge at pairs of stream gauging stations will indicate if the relationship between stations is sufficiently well defined to justify adjusting the mean given by the shorter record. Unless the coefficient of correlation is greater than 0.8, this adjustment may not be advisable.

If a short record is to be used in design, it can sometimes be extended to a longer period by correlating the monthly discharges with the concurrent monthly discharges at a long-term station. Plotting the concurrent monthly discharges of one station against those of the other will give a good idea of the degree of correlation. Logarithmic paper is recommended so as to accommodate the usually large range of values. The months should be indicated by distinctive symbols so that seasonal differences in the relationships can be identified.

Basic statistical parameters, $\bar{v}$ (mean value) and s_v (standard deviation), of discharges for a short-term station may be estimated on the basis of the data collected at the station, supplemented by observations from a related long-term station. If it is assumes that discharge, Q, follows a log-normal distribution, then the following equations apply:

$$\bar{Q}_y = exp\left[\bar{v} + 0.5 s_v^2\right] \tag{32.6}$$

$$s_{Qy} = \bar{Q}_y \sqrt{exp\left(s_v^2\right) - 1} \tag{32.7}$$

where

$$\bar{v} = \bar{v}_n + r_{uv} \frac{s_{v_n}}{s_{u_n}} \left(\bar{u}_N - \bar{u}_n\right) \tag{32.8}$$

$$s_v^2 = s_{v_n}^2 + r_{uv}^2 \frac{s_{v_n}^2}{s_{u_n}^2} \left(s_{u_N}^2 - s_{u_n}^2\right) \tag{32.9}$$

where Q_x denotes discharges for the long-term station, Q_y denotes discharges for the short-term station, $u = ln\ Q_x$, $v = ln\ Q_y$, and

$\bar{u}_n, \bar{u}_N$	are the means of the variable *u*, based on *n* and *N* observations, respectively,
$\bar{v}_n$	is the mean of variable *v*, based on *n* observations,
S_{u_n}, S_{u_N}	are the standard deviations of *u* based on *n* and *N* observations,
Sv_n	is the standard deviation of *v*, based on *n* observations,
r_{uv}	is the correlation coefficient between *u* and *v*,
n	is the number of years of observations at the short-term station, and,
N	is the number of years of observations at the long-term station.

Parameters $\bar{Q}_y$ and S_{Qy} are estimated by means of equations 32.6 and 32.7. Further details are provided by Kaczmarek in *The Estimation and Optimal Use of Surface Water Resources* [4].

Correlation is also useful in defining variations in low-flow characteristics. Here, the correlation is not between stream gauging stations but between low-flow measurements at ungauged sites and the daily discharge at a nearby gauging station [5]. When these data are plotted on logarithmic paper, they frequently define a straight line intersecting the line of equal yield per square kilometre at a discharge somewhat higher than the average annual flow. The low-flow measurements used in the correlation should be made during periods of base flow at least several days after any precipitation has occurred in the basin.

32.3.4 *Effective length of an extended record*

There is a minimum degree of correlation between streamflows of neighbouring streams or between streamflow and precipitation that is acceptable for extending a record. The longer the record of a stream, the smaller will be the sampling error in that record. For the correlation between two records to be useful, the error introduced by the correlation must be less than the sampling error in the shorter of the records.

A practical test of the validity of a correlation based on the effective length N_e of an extended record has been developed [6]. The effective length of record of a combined short-term and extended record is approximately:

$$N_e = \frac{N}{1 + \frac{N-n}{n-2}\left(1 - r^2\right)} \tag{32.10}$$

where *n* is the number of years in the short-term record, *N* is the number of years in the long-term record, and *r* is the coefficient of correlation. For example, if a five-year record is correlated with a 20-year record and $r = 0.8$, then the effective length of the extended record is 7.1 years, a gain of 2.1 years. Unless N_e is greater than *n*, the record extension is ineffective.

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CHAPTER 33

RAINFALL-RUNOFF RELATIONSHIPS

33.1 **General** **[K22]**

Rainfall-runoff relationships are used primarily for design, forecasting, and evaluation. If streamflow data are unavailable or are too limited for reliable interpretation or extrapolation, rainfall-runoff relationships can be very helpful because of their ability to extract streamflow information from the precipitation records. Because of the relative simplicity and inexpensive nature of the collection of rainfall data, they are generally more abundant than are streamflow data. If a strong relationship between rainfall and runoff can be established for a catchment of interest, the combination of the rainfall-runoff relationship and the rainfall data may give more reliable estimates of the frequency of high streamflows than either a regional flood relationship (section 36.2) or an extrapolation of meagre streamflow data from the catchment.

Rainfall-runoff relationships are usually developed in two distinct steps — the determination of the volume of runoff that results from a given volume of rainfall during a given time period, and the distribution of the volume of runoff in time. The first step is necessary because of the partitioning of rainfall among evapotranspiration (Chapter 38), infiltration, and runoff. The second step is required to account for the travel time and the attenuation of the wave of runoff that is generated by the rainfall. Discussion of these two steps constitutes the remainder of this chapter.

33.2 **Runoff volumes**

33.2.1 ***Antecedent-precipitation index***

The antecedent-precipitation index has been developed primarily for river forecasting and applies over a wide range of drainage areas and conditions [1, 2]. Its derivation for a particular drainage area requires observed rainfall and runoff data from many storms. The necessary variables are a graduated antecedent-precipitation index, I_t, time of year, storm duration, and storm rainfall in average depth over the drainage area. The antecedent-precipitation index is defined as:

$$I_t = I_o k^t + \sum P_i k^{t(i)} \qquad (33.1)$$

where I_o is the initial value of the index, k is a recession factor, t is the time interval for the computation, the P_i are the amounts of the daily rainfalls that have occurred during the time interval, and the *t(i)* are the number of days since each day with precipitation, respectively.

It is often convenient to use simplified forms of the antecedent-precipitation index. One or more of the variables may have a negligible influence in certain catchments,and it is then possible to reduce the number of these variables. But in all cases the general method is the same.

The effects of vegetative cover, soil type, and other more or less permanent characteristics of a catchment, as well as the time of year, are reflected in the choice of the value of the recession factor. Time of year is expressed as a family of curves representing the seasonal trend of solar energy, vegetative condition, and other factors that influence the evaporation and transpiration of moisture in the catchment. The antecedent-precipitation index is an expression of the moisture in the catchment and the moisture retention in the soil. A commonly used daily recession factor is 0.9, illustrated in Figure 33.1. The antecedent-precipitation index can be computed from average precipitation for several stations or individually for each station in a drainage area. The latter is preferable in most instances.

Figure 33.2 illustrates the method of estimating runoff volume from rainfall and the antecedent-precipitation index. The dashed lines and arrows demonstrate the use of this diagram. For example, the diagram is entered with a value of 22 millimetres

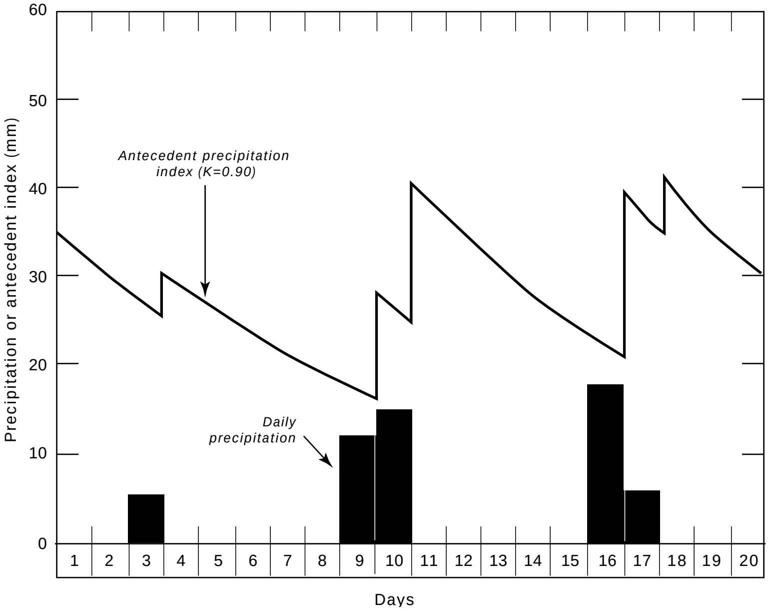


Figure 33.1— Antecedent-precipitation index.

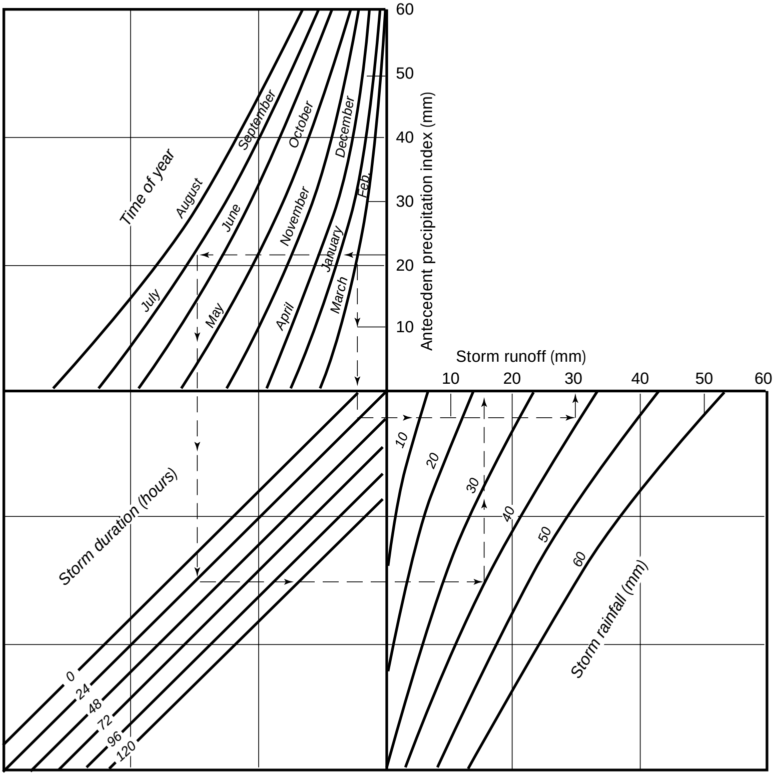


Figure 33.2 — Antecedent-moisture index of estimating runoff from rainfall.

for the antecedent-precipitation index. The long dashes and arrows lead to the month of July and then down to a storm duration of 24 hours. The example then proceeds to the right to the assumed storm rainfall of 40 millimetres and then up to a runoff of 16 millimetres average depth over the drainage area.

If the hypothetical storm in the foregoing example had occurred in February, with other conditions being the same, the effect of 22-millimetre antecedent precipitation would be different. Ordinarily, in February as contrasted with July, the same amount of antecedent precipitation would have left the soil more nearly saturated because of dormant vegetation and less evapotranspiration in winter. The short dashes and arrows in Figure 33.2 show that the runoff from the 40-millimetre rain in this second example would be 30 millimetres.

Frozen ground and accumulations of snow require special consideration in estimating antecedent-moisture conditions. With frozen ground, the time-of-year curve that gives the maximum runoff is commonly used. The influence of snow on the ground is properly expressed in terms of the amount and rate of melting, instead of the total accumulation. The subject of snow melt is discussed in Chapter 31.

33.2.2 *Initial base flow as an index to runoff volume*

In humid areas, where streams do not often go dry, base flow, i.e., groundwater discharge, at the beginning of a storm is often used as an index to the initial basin conditions. An example of such a relationship is shown in Figure 33.3. Base-flow discharge reflects conditions throughout the entire area. In some areas, it is found necessary to vary this relationship with season. A common method is to develop one relationship for summer and one for winter, which leads to the inevitable problem of storm events occurring between seasons. The usual solution is to make an estimate of runoff on the basis of each curve and then to interpolate.

The use of initial groundwater discharge as an index to runoff conditions is usually limited to small basins with short times of concentration. In larger areas during a rainy season, one rise of the hydrograph tends to be superimposed on the last, which makes a determination of initial groundwater discharge quite difficult. The usual approach is to determine initial groundwater discharge for small index basins and to apply them to other nearby areas having similar hydrological characteristics.

33.2.3 *Moisture-accounting techniques*

Soil-moisture deficiency is probably the most important factor involved in the relationship between rainfall and runoff. A practical means of estimating initial

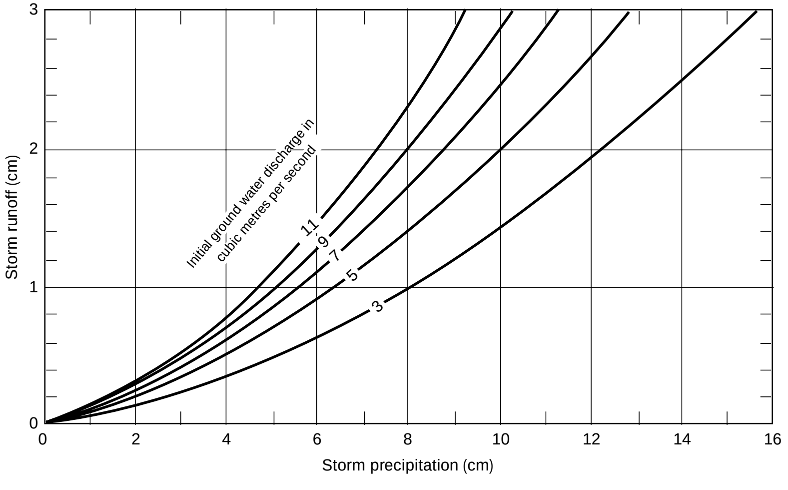


Figure 33.3 — Base-flow index to rainfall-runoff relationship.

soil-moisture deficiencies for an area would provide a very useful variable for inclusion in a procedure for correlating storm rainfall to resultant runoff. Instruments for measuring soil moisture for a specific soil profile have become reasonably practical (Chapter 15), but the wide variety of soil profiles and moisture conditions that exist in even a small basin makes point measurements of soil moisture of questionable value in a rainfall-runoff relationship.

A more promising approach is the use of an areal-accounting technique that results in soil-moisture values related to the entire area. In such an approach, precipitation is the inflow, and outflow consists of runoff leaving the area by the stream channels plus evapotranspiration into the atmosphere from soil and plant surfaces. The means of estimating the precipitation over the area is the usual problem of deriving spatial averages from point values. Runoff from the area can be determined from streamflow records. The problem becomes one of matching flow to the particular storm that caused it (section 33.3.1.1). The difference, rainfall less runoff, is the water that remains in the area and is referred to as recharge, R_c.

The third element, evapotranspiration, is the most difficult to evaluate because its direct measurement is extremely difficult (section 9.1). Most soil-moisture accounting techniques are based on the premise that actual evapotranspiration bears a simple relationship to potential evapotranspiration, E_{Tp}, and soil-moisture deficiency.

A simple form of soil-moisture accounting is one in which the soil profile is considered to have one capacity, S, over the entire area. Soil-moisture deficiency, DU_s, is then determined by the equation:

$$DU_s(t+1) = DU_s(t) - R_c + E_T \qquad (33.2)$$

where $DU_s(t)$ is the soil-moisture deficiency at time, t, $DU_s(t+1)$ is the value one time period later, and R_c is the recharge and E_T is the evapotranspiration that occurs between times, t and $t+1$. The deficiency varies between the limits of zero and S. This approach can be made more realistic by multiplying the evapotranspiration by the ratio $(S - DU_s(t))/S$, which acknowledges that actual evapotranspiration decreases as the supply of available moisture in the soil profile decreases.

Another possible modification would divide the soil profile into layers. In this approach, it is assumed that the upper-layer moisture must first be depleted before any depletion of the lower layer, and, conversely, recharge to the lower layer is limited to overflow from the upper layer.

The application of soil moisture accounting values to use in a rainfall-runoff relationship can be made by relating runoff, Q, to discharge computed in the accounting:

$$Q = cQ_U + (1- c)\, Q_L \qquad (33.3)$$

where c is a constant, Q_U is the computed runoff from the upper layer, and Q_L is the computed runoff from the lower layer.

33.3 Temporal distribution of runoff

To account for the travel time and the attenuation of a volume of water imposed on the catchment by a rainfall event, an accounting through time at the catchment outlet must be performed. This step is usually accomplished by the use of a unit hydrograph, which describes the temporal distribution of runoff leaving the catchment. The unit hydrograph is constrained by the principal of continuity of mass in the following manner:

$$V = \int Q(t)dt \tag{33.4}$$

where $Q(t)$ is the instantaneous discharge rate, t is time, and V is the runoff volume. The function $Q(t)$ defines a curve whose shape correctly represents the catchment characteristics. To compare hydrographs of different catchments and to assist in the preparation of synthetic hydrographs, deterministic models have been developed that relate the hydrograph characteristics to hydrological and meteorological data. These models are discussed below.

33.3.1 *Unit hydrograph*

The unit hydrograph for a catchment is defined as the discharge hydrograph resulting from a unit of direct runoff (or other component) generated uniformly (or in some specified pattern) over the catchment at a uniform rate during a specified period of time. In application, the unit hydrograph is assumed to be time invariant. It is further assumed that events with runoff volumes other than one unit produce hydrographs that are proportional to the unit hydrograph.

33.3.1.1 *Derivation from streamflow records*

In order to determine the volume of runoff from a particular rainstorm, it is necessary to separate the hydrograph into its pertinent components. One component is the direct (or storm) runoff associated with a particular storm. Another major component is the streamflow persisting from previous contributions to flow. The third major component is the flow from the immediate storm that is delayed by passing through the ground. A major portion of this third component is known as interflow, i.e., water passing through the soil with very little delay, and is often included as part of direct runoff. Some of the more recent conceptual models for the continuous simulation of streamflow have provisions for computing separately each of the above components.

With this type of analysis, it is not possible to identify each of the several components by inspection of the observed hydrograph. In less complex methods of analysis in which only two components are recognized, it is possible to separate the observed hydrograph and evaluate the magnitude of the two components. In the following illustration, direct runoff includes both surface runoff and interflow.

One of the simplest of many methods for separating a hydrograph into its major components is illustrated in Figure 33.4. The trace of base flow is extrapolated (line segment *AB*) to the time of peak flow by extending its trend prior to the stream rise. From point *B*, a straight line is drawn to intersect the hydrograph at point *C* a fixed time later. The time, in days, from *B* to *C* is determined largely by the size of the drainage area. It is generally about $(A/2)^{0.2}$, where A is drainage area in square kilometres.

Several methods of hydrograph separation are in common use. More important than the method is the requirement that the same technique be used in application as in development.

The total runoff associated with a particular storm or stormy period can be determined by the following method. In Figure 33.4, the area under the hydrograph between times *E* and *C* is the storm runoff because the beginning and ending points represent the same groundwater-recession conditions and, therefore, the same storage.

Figure 33.4 illustrates the essential steps for deriving a direct-runoff unit hydrograph from observed data. These steps may be performed either graphically or numerically. The hydrograph of direct runoff is the flow in excess of the trace *ABC*. The volume of direct runoff is obtained by integrating the area under the hydrograph. A convenient method, if a planimeter is not available, is the counting of squares. In this hypothetical example, the volume of direct runoff is found to be 4 320 000 m^3.

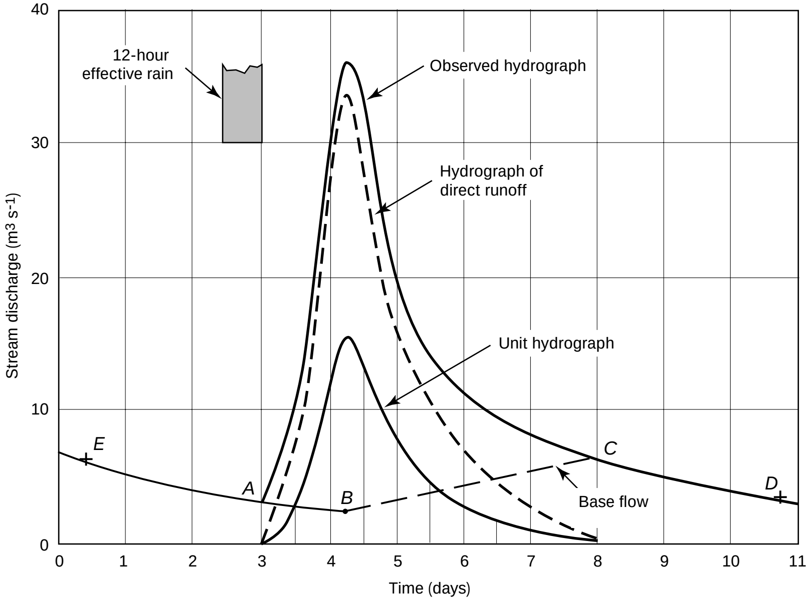


Figure 33.4 — Hydrograph analysis.

Over an assumed drainage area of 200 km^2, this volume represents an average depth of 2.16 centimetres. To obtain the unit hydrograph, it is necessary to divide each ordinate of the direct-runoff hydrograph by 2.16. The hydrograph thus determined shows the shape of the hydrograph that would result from 1.0 centimetres average depth of direct runoff over the drainage area, i.e., the unit hydrograph.

In the records of some catchments, it is difficult to find unit or single storms that produce stream rises uncomplicated by other events. In such cases, the derivation of a unit hydrograph becomes more complex. One method of deriving a unit hydrograph under these circumstances is to assume an initial unit hydrograph, and to reconstruct the hydrographs of direct runoff for several storms using estimated runoff increments, and to refine the unit hydrograph by successive approximations as indicated by the results. The method of reconstruction is shown in Figure 33.5 and by:

$$q_n = Q_n U_1 + Q_{n-1} U_2 + Q_{n-2} U_3 + \ldots + Q_{n-i+1} U_i + \ldots + Q_1 U_n \qquad (33.5)$$

where q_n is the rate of discharge from direct runoff at time, n, U_n is the n-unit hydrograph ordinate, and Q_{n-i+l} is the direct runoff for the ith interval. This equation can also be used as the regression model for unit-hydrograph derivation by least squares.

For drainage areas of 200 to 2 000 km^2, time increments of six hours are commonly used for unit-hydrograph development, but for higher accuracy, shorter time intervals may be employed. Smaller drainage areas may also require shorter time increments. The time increments should be small enough to give good definition of the hydrograph shape and to allow a forecast to be made before too large a time increment has elapsed. For drainage areas larger than about 2 000 km^2, unit hydrographs of larger time increments may be used, but generally unit hydrographs should be applied to tributary areas and may be combined by routing.

As might be expected from considerations of channel hydraulics, there is a tendency for the peakedness of unit hydrographs to increase with the magnitude of runoff. Accordingly, in practical applications, a family of unit graphs may be used for a particular catchment area, with higher peaked unit hydrographs for the cases with large amounts of runoff, and flatter peaks for the lesser amounts of runoff. Often only two categories comprise the family.

Skill in the use of unit hydrographs comes from study and practice. For other methods than those described in this section, and for refinements, reference may be made to textbooks and to handbooks of agencies that routinely use unit hydrographs in their regular operations.

33.3.1.2 *Derivation by synthetic methods*

It is frequently necessary to plan constructions or operations for ungauged streams. In such cases, it is helpful to develop synthetic unit hydrographs [3, 4]. A commonly

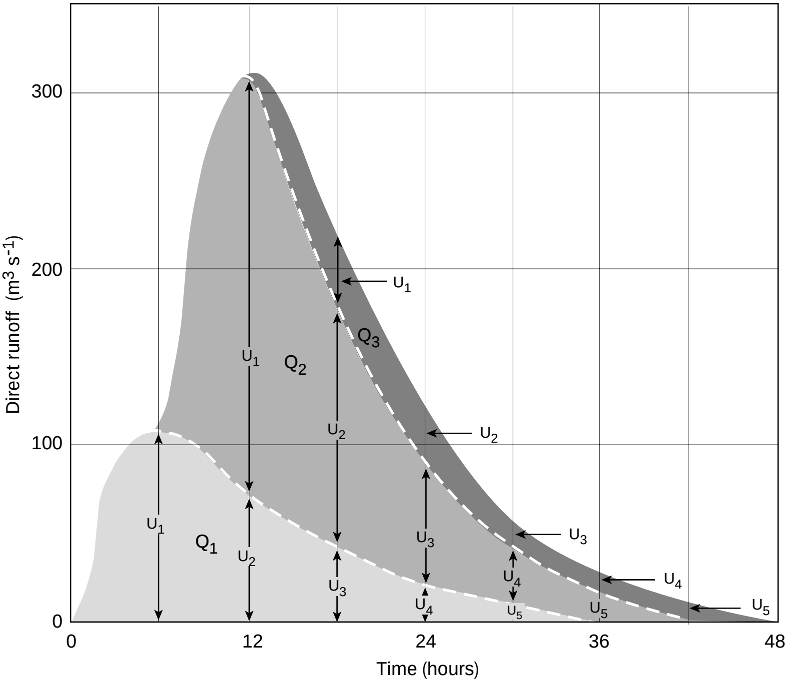


Figure 33.5 — Reconstruction of direct-runoff hydrograph.

used derivation of a unit hydrograph is the procedure derived by Snyder [5] in which a large number of basins and unit hydrographs were analysed to derive relationships between the shape of the unit hydrograph and the objective physical characteristics of the drainage basin.

The important parameters in the shape of a unit hydrograph are its peakedness, the length of its base, and the basin lag, which may be defined in various ways but, for this purpose, is the time from the centroid of rainfall to the peak of the hydrograph. In Snyder's method, the basin lag, t_p, is given in hours, as:

$$t_p = C_1 \, (l l_c)^n \tag{33.6}$$

where C_1 converts units and is an empirical coefficient, l is the length of the main stream in kilometres, l_c is the distance in kilometres from the centroid of the drainage area to the outlet, and n is an empirical exponent.

For peakedness of the unit hydrograph, this method uses a standard duration of rain, t_p/C_2, with C_2 being derived empirically. For rains of this duration:

$$Q_p = C_3 A/t_p \tag{33.7}$$

where Q_p is peak rate of runoff in $m^3\ s^{-1}$, C_3 is an empirical constant, A is drainage area in km^2, and lag t_p is in hours. The time base in days T_b is:

$$T_b = d + C_4 t_p \tag{33.8}$$

The constants d and C_4 are fixed by the procedure used to separate base flow from direct runoff.

For durations T_R other than the standard duration of rain, the corresponding lag, t_c, is:

$$t_c = t_p + f(T_R) \tag{33.9}$$

where $f(T_R)$ is a function of duration.

Snyder's coefficients were derived for streams in the Appalachian Mountains of the United States. The general method has been found applicable in other regions, but different coefficients are to be expected for different types of topography, geology, and climate.

33.3.1.3 *Conversion of unit-hydrograph durations*

A suitable rainfall of unit duration is rarely observed. Variations of rainfall in time and space produce different hydrographs, though the total amount and duration of the rain may be exactly the same. Thus, derivation of a general unit hydrograph requires an averaging of several unit graphs.

One technique for generalizing unit graphs is comparison of unit graphs of different duration. If a unit hydrograph of duration t hours is added to itself, lagged t hours, and the ordinates divided by two, the result is a unit hydrograph for $2t$ hours. Similar conversions are evident.

A broader application of this basic idea for manipulating unit hydrographs is known as the summation or S-curve method. The S-curve is the hydrograph that would result from an infinite series of runoff increments of one centimetre in t hours. The S-curve is constructed by adding a series of unit hydrographs, each lagged T hours with respect to the preceding one. With a time base of T hours for the unit hydrograph, a continuous rain producing one centimetre of direct runoff per t hours would develop a constant outflow at the end of T hours. Thus, T/t hours would be required to produce an S-curve of equilibrium flow.

Construction of an S-curve can be accomplished by a numerical, instead of a graphical, procedure. A unit hydrograph for any duration, t, can be obtained by lagging the S-curve t hours and obtaining ordinates of lagged and unlagged S-curves. To obtain unit volume, these ordinates must be multiplied by the ratio of the duration of the original unit hydrograph to t hours.

The instantaneous unit hydrograph is the unit hydrograph whose time unit, *t*, is infinitely small. Construction of a *t*-hour unit hydrograph from an instantaneous one is performed by means of an S-curve.

33.3.2 *Isochrone method*

The isochrone method is an expression of one of the first concepts of runoff from a basin. The runoff from different portions of a drainage basin arrives at a point in the stream at different times. The first water to leave the basin during a stream rise usually comes from the area nearest the catchment outlet. Later, water comes from larger areas in the central portion of the basin, and, finally, water comes from remote portions of the drainage area. Thus, the drainage basin may be divided into zones from which the water arrives sequentially at the measurement point. The lines dividing these zones in Figure 33.6(*a*) are called isochrones. The distribution of the isochronal areas (the time-area distribution) is considered to be constant for a given basin for all flood hydrographs.

In order to compute this distribution, it is necessary first to compute or assume an average travel time or average velocity of streamflow. The isochrones are drawn on a map of the basin according to the average velocity of flow in the channel or average travel time. The area of each zone is then determined by planimeter, and the values are plotted against the corresponding time lag (Figure 33.6(*b*)).

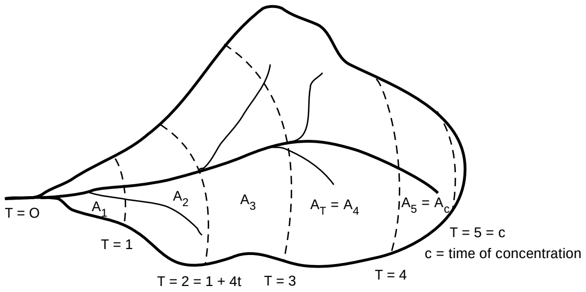
The time-area distribution is indicative of the hydrograph for uniform rainfall of unit duration, Δt, the time difference between isochrones. If there are several periods of rainfall, each resulting in varying quantities of runoff over the different zones:

$$Q_t \, \Delta t = A_1 V_t + A_2 V_{t-1} + A_3 V_{t-2} + \ldots + A_c V_{t-c+1} \qquad (33.10)$$

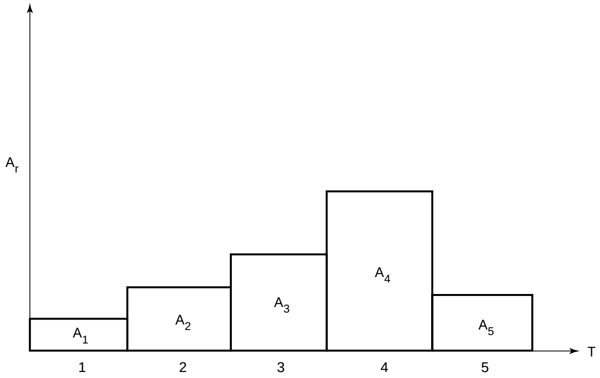
where Q_t is the average discharge during the period, Δt, ending at time, t, and V_t is the zonal runoff during the same period. Care must be taken to ensure consistent units. Figure 33.6(*c*) illustrates the computation of the resultant hydrograph with three periods of uniform runoff from the catchment.

The resultant hydrograph reflects the lag characteristics of the catchment. Since the actual hydrograph would be affected by channel storage, the hydrograph computed from equation 33.10 should be routed through storage. Any of the several routing techniques described in the literature can be used. Two such techniques are described in Chapter 34. It is usually found to be advantageous to adjust the isochrones and routing parameters by trial and error to obtain the best combination for simulation of observed hydrographs.

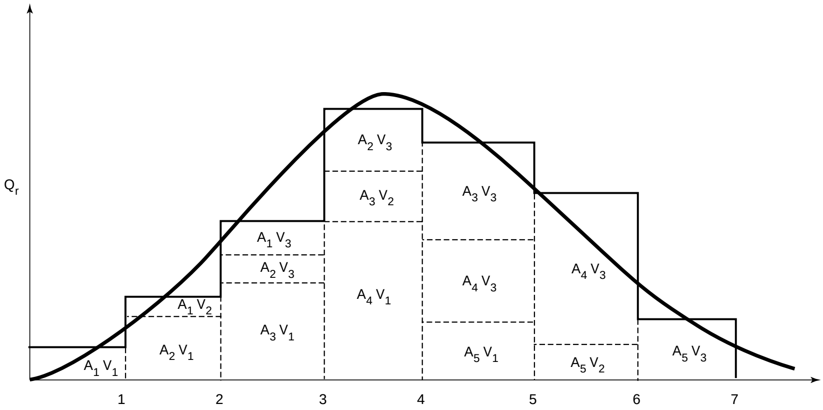
The isochrone method allows non-uniform distributions of rainfall to be taken into account when there are enough raingauges in the basin to delineate the rainfall pattern reliably. This is an advantage over the unit hydrograph described in section 33.3.1.



(*a*) Basin map with isochrones



(*b*) Time-area distribution



(*c*) Resultant hydrograph

Figure 33.6 — Isochrone method.

33.4 **Distributed models**

Several models that are more elaborate than those previously mentioned have been developed in recent years. Their formulation aims at following the hydrological processes more closely and, thus, may incorporate several meteorological variables and watershed parameters. Their product is a series of synthetic streamflow data and sometimes groundwater recharge. The basic input is a series of rainfall, but provisions may be made for snowfall, temperature, radiation, potential evapotranspiration, etc. Models for urban catchments may contain a description of their drainage network. Models for rural catchments may contain unit hydrographs, time-area curves, or routing sub-routines.

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CHAPTER 34

STREAMFLOW ROUTING

34.1 General [K35, K45]

A volume of runoff from a headwater area moves downstream as a wave whose changing configuration at various stations can be computed by a technique known as flood routing. Storage and other effects tend to attenuate the wave. Irregularities in channel conditions and tributary inflows are inherent complexities of the problem. The routing of flood waves through reservoirs and channels is accomplished by many methods that are based on the continuity and energy equations (St. Venant equations):

$$A \cdot \frac{\partial v}{\partial x} + v \cdot \frac{\partial A}{\partial x} + \frac{\partial A}{\partial t} = q \tag{34.1}$$

$$\frac{\partial v}{\partial t} + v \cdot \frac{\partial v}{\partial x} + g \cdot \frac{\partial h}{\partial x} + \frac{v \cdot q}{A} = g\left(s - s_f\right) \tag{34.2}$$

where t is time, x is the length in direction of flow, A is the cross-sectional area, v is the mean velocity over A in the direction of x, q is the lateral increment of discharge per unit length of x, g is the gravitational acceleration, h is the mean water depth, s is the longitudinal channel slope, and s_f is the frictional slope.

These equations are the basis for all flood-routing and reservoir-routing techniques. There are two basic methods for flood-routing computations in channels — hydrodynamic methods, and hydrological methods. More simplified models are used to compute the reduction of a flood through a reservoir.

34.2 Hydrodynamic methods

34.2.1 *Complete method*

Complete dynamic routing, which accounts for flow-acceleration effects and the water-surface slope, can determine flows and water-surface elevations accurately in the following unsteady flow situations:

(*a*) Upstream movement of waves, such as those produced by tidal action or sea-storm surges;

(*b*) Backwater effects produced by downstream reservoirs or tributary inflows;
(*c*) Typical flood waves occurring in rivers having flat bottom slopes, e.g., less than 0.05 per cent; and
(*d*) Abrupt waves caused by controlled reservoir releases or by the catastrophic failure of a dam.

Dynamic routing is generally based on the one-dimensional hydrodynamic equations of unsteady flow which are sometimes known as the St. Venant equations. These equations, given above, are generally expressed in their conservative form and appear as follows:

Continuity:

$$\frac{\partial Q}{\partial x} + \frac{\partial (A + Ao)}{\partial t} - q = O \tag{34.3}$$

Energy:

$$\frac{\partial Q}{\partial t} + \frac{\partial Q^2 / A}{\partial x} + gA\frac{\partial h_y}{\partial x} + S_f - qv_x + W_f B = 0 \tag{34.4}$$

in which:

$$S_f = \frac{n^2 Q}{A^2 R^{4/3}} \tag{34.5}$$

$$W_f = C_w V_w \cos \omega \tag{34.6}$$

where *Q* is discharge, *A* is the active cross-sectional area, A_o is the inactive or dead-storage cross-sectional area, h_y is the water-surface elevation, v_x is the velocity of lateral inflow in the *x*-direction of the river, *B* is the top width of the active cross-sectional area, *n* is the Manning roughness coefficient, *R* is the hydraulic radius, W_f is the wind effect, C_w is the wind coefficient, V_w is the wind velocity, ω is the angle between the wind direction and the *x*-axis of the river, and the other symbols are as previously defined.

The numerical techniques for solving the partial differential equations, equations 34.3 and 34.4 for natural rivers, may be classified into two broad categories, explicit and implicit. The most popular explicit method is the method of characteristics. However, nowadays it is not widely used. Both explicit and implicit finite-difference methods exist. There are advantages and disadvantages associated with the various solution techniques. Such factors as numerical stability and convergence, required computational time and computer storage, and degree of programming and mathematical complexity must be considered. Some solution techniques require modifications to the form of equations 34.3 and 34.4 before the techniques can be applied.

In general, implicit finite difference techniques [1, 2] are more complex but more efficient than explicit methods when calculating unsteady flows of several days duration. Much larger time steps can be used with the implicit techniques. Explicit techniques are simple but are troubled by numerical stability problems unless the time step is properly selected. These and other limitations should be thoroughly understood before selecting a particular solution technique for developing a dynamic-routing forecasting method or selecting an existing dynamic-routing technique for a particular application.

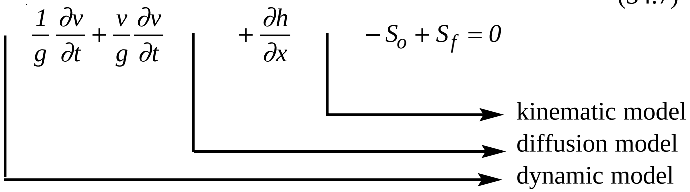
A critical task in applying dynamic routing to an actual forecast situation is the determination of the roughness parameter in the S_f, friction-slope, term of equation 34.5. The roughness-parameter often varies with flow or elevation, as well as with distance along the river. Formulations of this important problem are presented by the American Society of Civil Engineers in *Friction Factors in Open Channels* [3], by Rouse in *Critical Analysis of Open-channel Resistance* [4], and by Simons and Senturk in *Sediment Transport Technology* [5], while methods of estimating the roughness coefficient from field measurements are presented by Limerinos in *Determination of the Manning Coefficient from Measured Bed Roughness in Natural Channels* [6] and by Hey in *Flow Resistance in Gravel-bed Rivers* [7], and by pictorial comparisons presented by Ven Te Chow in *Open Channel Hydraulics* [8] and by Barnes in *Roughness Characteristics of Natural Channels* [9]. A prior determination of the roughness-parameter relationship with flow and distance by trial and error is very time consuming. Techniques for automatically determining the relationship greatly facilitate the operational utilization of dynamic routing in a forecasting environment. A proper evaluation of the boundary and the initial conditions for solution of the St. Venant equations in an operational mode is perhaps the most critical task in the implementation of dynamic-routing technique.

Another critical task is the establishment of an efficient data-acquisition and management programme linked integrally with the computational element. Cross-section geometry should be processed as efficiently and as effortlessly as possible for use by the dynamic-routing programme. Anticipated flow conditions should require as little data entry as possible for a dynamic-routing technique to be feasible for use as an operational forecasting tool.

34.2.2 *Diffusion and kinematic routing*

By rewriting slightly the momentum equation and by ignoring wind effects and momentum from lateral inflows, a very clear picture can be obtained that shows the fundamental differences between dynamic, diffusion, and kinematic routing.

Consider: (34.7)



$$\frac{1}{g}\frac{\partial v}{\partial t}+\frac{v}{g}\frac{\partial v}{\partial t}+\frac{\partial h}{\partial x}-S_o+S_f=0$$

where the new variables are v, the average cross-sectional velocity in the x-direction, h, depth, and S_o, the bed slope.

At the first level of approximation, the terms representing the accelerations related to the time variation of inflow and the spatial variation in velocity are neglected. The resulting model is referred to as the diffusion model. In some flow situations, it is also possible to neglect the pressure-force term and to treat the momentum equation as a balance between the forces of gravity and friction. This approximation is known as the kinematic model. It has been shown [10] that a finite-difference approximation of the kinematic wave model coincides with the Muskingum method (section 34.3).

Both the kinematic and diffusion approximations have been used successfully in recent years to describe overland flows and flows in streams where slopes are greater than approximately 0.1 per cent. The diffusion model can be used on rivers with smaller slopes, but with caution because the inertia terms may become important. In recent years, the kinematic model has become very popular in applications where the irregular geometry and topography of natural catchments can be replaced by a series of simple elements, such as flow planes and regular channel segments. The kinematic equations are also used in water quality models that predict the transport of soluble and insoluble pollutants. A kinematic model does not consider backwater effects from lateral inflows or downstream reservoir operations, nor can it be used to predict wave progressions in the upstream direction.

34.3 Hydrological methods

Besides the techniques incorporating both St. Venant equations, there are several methods that use the continuity equation only. These hydrological flood-routing methods are very popular. In these techniques, only the wave propagation is studied by considering the increases and decreases of storage in a reach lying between two measuring points. The hydrological model is much simpler, and it is easier to take account of additional inflows from a variety of sources. However, because the relationship between storage and flow is determined empirically by these methods, they cannot be used directly when flow data or levels are required for design purposes.

In using hydrological methods of routing, the flow at an upstream point is determined, and routing is used to compute the flow and stage at a downstream point. Routing consists of the solution to the following equation by using a relationship between storage and flow:

$$Idt - Qdt = dS \tag{34.8}$$

where I and Q are the discharges at upstream and downstream points, respectively, S is storage, and t is time. Solution of this equation involves approximations concerning the storage-flow relationship, which is the major difficulty in hydrological streamflow routing.

A number of practical routing methods are based on the equation:

$$\frac{I_1 + I_2}{2} \Delta t - \frac{Q_1 + Q_2}{2} \Delta t = S_2 - S_1 \tag{34.9}$$

where subscripts *1* and *2* represent the beginning and end of a time increment Δ*t*, respectively. This time increment or the routing period should never be greater than the time of travel through the reach. Generally, the routing period should not exceed one-half the time of travel. With sufficient hydrometric data, storage flow relations can be derived empirically.

The simplest routing methods are based on linear storage-flow relationships, which make it possible to obtain analytical solutions. Two such methods are applicable in short-range forecasting practice:

(*a*) The Muskingum method proposed by McCarthy [11]:

$$Q_2 = C_o I_2 + C_1 I_1 + C_2 Q_1 \tag{34.10}$$

is based on the following storage flow relation:

$$S = K\,[x\,Q_1 + (1 - x)\,Q_2] \tag{34.11}$$

The constants K and x are derived empirically for a given reach from discharge data. The constant K is the ratio of storage to discharge. It is approximately equal to the travel time through the reach. K and x are determined by plotting S versus $xI + (1 - x)Q$ for various values of x. The best value of x is that which results in the data plotting most closely to a single-value curve. The constants C_o, C_1, and C_2 are functions of K, x, and the routing period Δ*t*. The sum of the constants is equal to unity;

(*b*) The specific-reach method proposed by Kalinin and Miljukov [12]:

$$Q_i = aI_{i-1} + (1 - a)\,Q_{i-1} \tag{34.12}$$

where

$$a = I - e^{-\Delta t/K} \tag{34.13}$$

and

$$K = \frac{S}{Q} \tag{34.14}$$

is the storage constant equal to the travel time through the reach. The subscript *i* denotes the ordinal number of the time interval. Equation 34.12 is applicable to transit reaches of specific length, *L*, which is approximately equal to:

$$L = \frac{Q}{Z\dfrac{\delta Q}{\delta h}} \tag{34.15}$$

> where Z is the slope of the water surface, and $\delta Q/\delta h$ is the tangent of a stage-discharge relationship. If a river segment consists of several specific reaches, then routing is carried out in succession from one specific reach to the next downstream. The computed discharge for the downstream point of the first reach is taken as the inflow for the second reach and so on.

For long river reaches that lack the data needed to determine the number of specific reaches, a formula that expresses the transformation of flow by a system of identical linear reservoirs can be used:

$$Q(t) = I \, \frac{\Delta t}{K^n \, (N-1)!} \, t^{N-1} e^{-t/K} \tag{34.16}$$

where N is the number of reservoirs. The K and N parameters are determined by trial and error. Computers are very helpful for this purpose and for operational use.

There are other hydrologic methods, e.g., the kinematic wave method, the general linear model, and the diffusion analogy.

34.4 Reservoir routing

A reservoir will result in a considerable decrease in the peak discharge, as compared with the natural inflow. To calculate this effect, graphical methods have traditionally been used, although much less so since the advent of computers.

The passage of a flood through a reservoir is somewhat different than through a channel. The equations for the conservation of mass and for stage-outflow relationship are:

$$I - Q = \frac{ds}{dt} \tag{34.17}$$

and, for example:

$$Q = \underbrace{c_1 \cdot h^{1/2}}_{\text{outlet}} + \underbrace{c_2 \cdot h_1^{3/2}}_{\text{spillway}} \tag{34.18}$$

in which I is the net inflow discharge (inflow minus losses and minus beneficial use), s is the storage in the reservoir, h is the water depth in the reservoir, h_t is water depth above the spillway crest, and c_1 and c_2 are coefficients depending on local conditions. A relationship between h and s is required for the solution. The solution steps are similar to those described in section 34.3.

A comparison of the hydrograph of Q against the hydrograph of I shows almost always that the peak of Q is smaller and delayed with respect to that of I. This fact is the basis for the construction of reservoirs for flood protection.

Because the velocity of the flood wave in a reservoir is higher than it is in channels, the delay in the peak outflow with respect to the peak inflow does not necessarily also mean a delay with respect to the peak that would have occurred under the conditions prevailing prior to the construction of the reservoir. Furthermore, the construction of a reservoir may sometimes worsen downstream flood conditions, despite its effect in decreasing peak discharges. The attenuated peak may occur in phase with peaks of tributaries that are usually out of phase. Thus, reservoir construction should not be taken for granted as improving downstream flood conditions. The hydrology and the hydraulics that would prevail under the design conditions should be studied carefully.

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CHAPTER 35

LOW-FLOW AND DROUGHT ANALYSIS

35.1 General

Some analysis of low flow is necessary before a stream can be used as a reliable source of water supply. If the minimum flow of record far exceeds the proposed demand, further analysis may not be necessary, but if once or twice during the period of record the flow was less than the proposed demand, then further analysis should be made to see if the anticipated deficiencies in flow are too serious to be tolerated. Low-flow frequency analysis and flow-duration curves are the two most simple methods used in making such analyses. If the deficiency is likely to be too great too frequently, then storage must be provided to hold high flow for release during low-flow periods. Although detailed analysis of storage requirements is necessary for design, reconnaissance planning can often be facilitated by draft-storage curves based on low-flow frequency analysis.

In addition to analysis of low flows for planning water supplies on a duration or frequency basis, there are also situations in which the flow of a particular stream may be projected in time, as described in section 44.6. This extrapolation amounts to the extension of the hydrograph during periods of little or no rain.

The long-duration periods of low discharge insufficient to meet the demand of specific users are usually called droughts. In hydrological literature, no uniform definition of droughts has been established. This results from the fact that droughts may be defined differently depending upon the objectives of an investigation.

35.2 Flow-duration curves

Flow-duration curves of daily discharge show the percentage of days that the flow of a stream is greater than or equal to given amounts. However, they provide no information on the temporal sequences of the flows at a site. The flow-duration curve is usually constructed empirically by computing a series of ratios of the number of days in a streamflow record that have discharges greater than or equal to preselected values divided by the total number of days in the record. The ratios, which are estimates of the probabilities, are plotted against their respective discharge values to construct the curve. A duration curve of streamflow will generally plot approximately as a straight line if logarithmic probability paper, such as that shown in Figure 35.1, is used. This type of paper gives equal plotting accuracy at all discharges so that differences in low-flow characteristics can be discerned more precisely.

Flow-duration curves are sometimes based on weekly or monthly discharge to simplify the tallying process, in which case the resulting curve represents the percentage of weeks or months rather than the percentage of time. Such curves are usually less useful than a daily duration curve.

Regional relationships of flow-duration curves for gauged catchments in a hydrometeorologically-homogeneous area to their physiographic characteristics can be used to provide estimates of flow duration for ungauged sites within the region.

One of the most common uses of flow-duration curves is in computing hydroelectric-power potential both for prime power and secondary power.

35.3 Low-flow frequencies

Information on low-flow frequency is obtained from the analysis of the probability distributions of observed annual low flows. In computing the annual low flow for

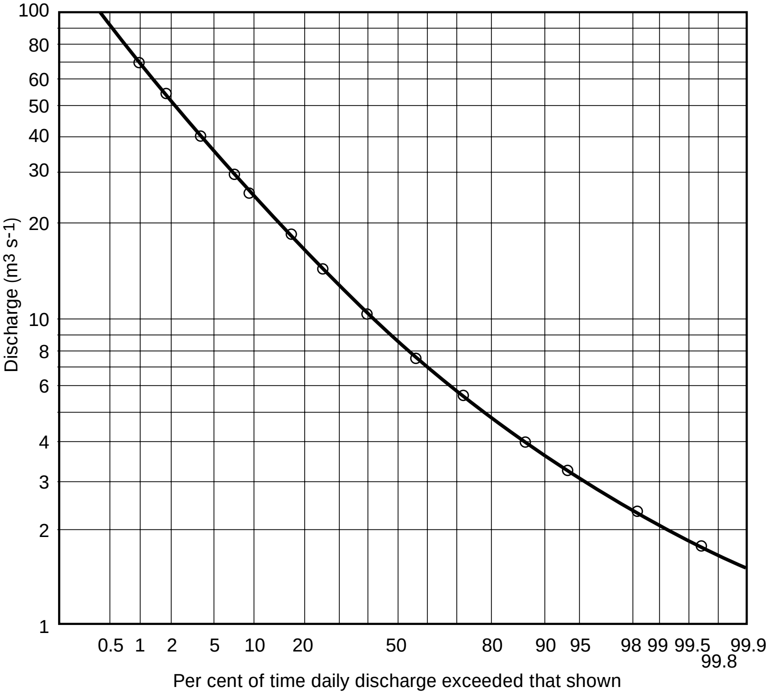

Figure 35.1 — Flow-duration curve of daily discharge.

periods of selected lengths, e.g., seven days or 30 days, the streamflow record should be divided into climatic years that start in a season when the flow is most likely to be high so that yearly low-flow periods are not likely to be partitioned.

Computation methods for low-flow frequencies, i.e., for determination of Q_{Tr} values for given return periods, are similar to the methods described in Chapter 27.

Examples of low-flow frequency curves are shown in Figure 35.2. The low-flow data are plotted with a logarithmic scale for the ordinate and an extreme-value probability scale as the abscissa. A straight line on this type of graph paper would indicate a Weibull distribution. Although few data plot as a straight line, the use of this type of paper tends to make the lower ends of the curves fairly straight.

Another way of defining low-flow frequency curves is to fit mathematically three-parameter log-normal distributions to the data. In one such approach, the skew coefficient of the logarithms of annual low flows is used to define the third parameter of a three-parameter log-normal distribution, and a table of frequency-curve coordinates is then used to plot a curve. In this method, a regional skew coefficient is sometimes used rather than the skew coefficient of the sample. In another approach, the transformation $y = \log (x - a)$ is made, where x symbolizes the series of annual low flows. The resulting frequency curve of y is assumed to have a normal distribution. The parameter, a, can be estimated graphically or computed from the statistics of the sample. The mean, standard deviation, and skew coefficient of the sample are used with the theoretical relationship between these statistics in a log-normal distribution to compute the constant a and the required logarithmic standard deviation.

The median annual seven-day low flow taken from low-flow frequency curves has been found to be a good index of draft storage requirements.

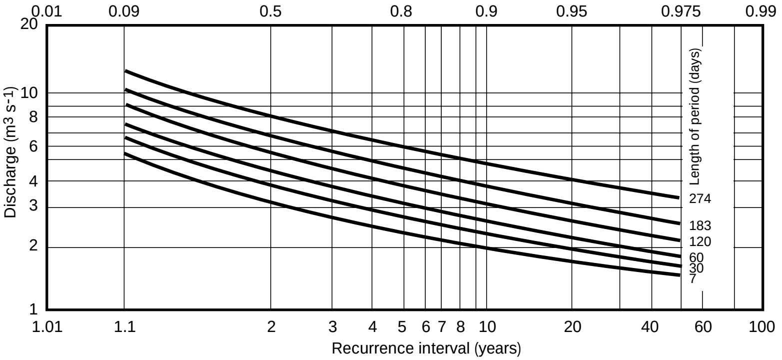

Figure 35.2 — Frequency curves of annual low flow.

Another distribution that may be useful for assessing annual flows for their adequacy of water supply is the gamma distribution. The relatively simple two-parameter form has been described by Thom [1] and applied by Alexander [2] to streamflow analysis. The distribution has a zero lower bound, which is a desirable property for the analysis of streamflow and precipitation data.

Low-flow frequency curves for ungauged catchments can be estimated based on the relationship between flow-frequency curves and catchment characteristics. An index low-flow method was suggested by Campbell [3] for estimating regional low-flow frequency curves.

35.4 Statistical analysis of droughts

The statistical analysis of droughts is an essential element in the evaluation of the water resources in a river basin for the purpose of water management. There are several methods of characterizing droughts for such analyses. One defines the drought period by means of the following variables:

Q_{min} — the minimum discharge in a drought period;
Q — the mean discharge during a drought;
V — the volume of water deficiency, i.e., the time integral during a drought of the differences between Q_{HLW}, the highest low-water discharge, and actual discharges; and
T — the duration of the drought.

For statistical analysis of these variables, a multivariate probability distribution must be used [4]. To simplify the computations, the variables Q_{min}, Q, V, and T are transformed to normal probability distributions.

Another method of characterizing a drought period is to investigate by multivariate statistical analysis, the variables $T_1, T_2, \ldots T_N$, which are defined as the maximum continuous time periods during a drought when discharge remains less than $Q_1, Q_2, \ldots Q_N$, respectively. In this case also, the variables should be transformed into normal distributions.

The Institute of Hydrology [5] has described frequency analysis of low-flow durations and volumes.

35.5 Recession-curve analysis

Low flow may consist of two components — drainage from the depletion of groundwater, and runoff from small rainfall events that occur during a recession period. If the contributing aquifer behaves like a linear reservoir, then the first component follows the relationship:

$$Q(t) = Q_o e^{-C(t-t(o))} \tag{35.1}$$

where $Q(t)$ is the discharge at time, t, Q_o is the discharge at time $t(o)$, and C is the recession coefficient. For streams with well defined rainy (or snow melt) seasons, Q_o and $t(o)$ should be specified after the end of the rainy season. After determining Q_o, it is easy to estimate the parameter of the recession curve with the observed values of the discharge plotted on logarithm coordinates. The residuals between the observed discharges and the recession curve may be correlated with monthly rainfalls of the dry season. On this basis, it is possible to compute low-flow discharges for months or other periods by projecting seasonal rainfall on the basis of historical record. Seasonal forecasting of runoff from antecedent river flow is discussed in section 44.6.

Experience has shown that under certain conditions the depletion of the seasonal water storage can be expressed by the exponential equation [6]:

$$Q(t) = (Q_o - Q_b)e^{-Ct} + Q_b \tag{35.2}$$

where Q_b is the base flow due to inflow of deep groundwaters. Equation 35.2 indicates that a linear relationship exists between the mean discharges for successive periods of equal duration, T:

$$Q_2 = aQ_1 + (1 - a)Q_b \tag{35.3}$$

where Q_1 and Q_2 are, respectively, the mean discharges for two successive T-day periods, and:

$$a = e^{-CT} \tag{35.4}$$

An example of such a relationship is given in Figure 35.3.

The minimum discharge for many basins varies widely from year to year, depending on the runoff during the previous high-water season. In these cases, the following empirical relationship can be plotted to determine the recession coefficient, C:

$$Q_2 - Q_{min} = f(Q_1 - Q_{min}) \tag{35.5}$$

where Q_1 and Q_2 are, respectively, the mean discharges for the successive periods and Q_{min} is the minimum discharge in the year in question.

Data for mean l0-day or mean monthly discharges for a number of years have been used to establish the empirical relationships of equations 35.3 and 35.5.

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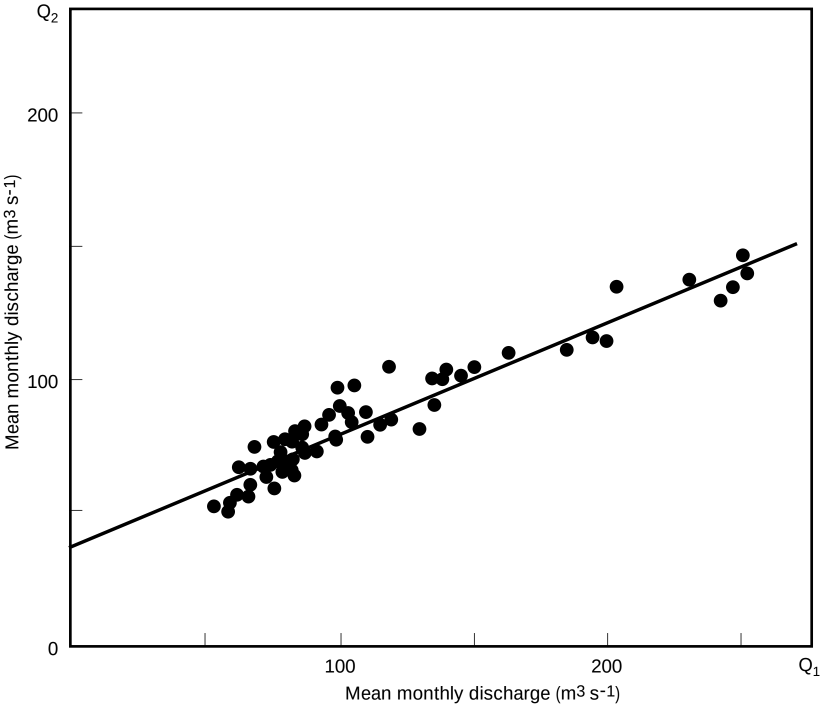

Figure 35.3 — Relationship between consecutive monthly mean discharges during a low-flow period.

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CHAPTER 36

FLOOD-FLOW FREQUENCY

36.1 Station analysis

36.1.1 *Peak flow* [I81]

The method for computing flood frequencies is generally analogous to that given in Chapter 27. The objective of the analysis is to relate the magnitude of a flood to its frequency or probability of future occurrence. The key assumptions that allow interpretation of the frequencies as probabilities are temporal independence of the elements of the analysed sample, and sample homogeneity. For flood studies, the use of partial-duration series is more questionable than for rainfall, as the different peak floods during the year may be less independent than the corresponding precipitation. However, if care is taken in the selection of the values exceeding a given threshold, a partial duration series analysis may be suitable. Since this is difficult to ensure, the application of frequency analysis to a series of the annual flood maxima (maximum annual series) is more popular [1, 2].

The maximum annual series may be comprised of either daily maxima or instantaneous flood peaks. It is important to distinguish which of the two is required for the analysis. The relation of the two series at a site is dependent on the physical characteristics of the watershed as well as the climatological factors causing the maxima of both events. For small drainage areas, it is common that the two maxima may not occur on the same date nor be a result of the same climatic processes acting on the watershed.

Another caution in computing frequencies of floods is the distinction between stages and discharges. Changes in the stage-discharge relationship may render many stage data non-homogeneous and unsuitable for frequency analysis. For certain studies, it may be preferable to work with discharges, and, if necessary, to convert the results to stage frequency by means of the most recent stage-discharge relationship. In certain cases, such as high stages caused by ice jams, it may be more suitable to work with only stages for defining flood plains.

Often, in addition to a relatively brief period of measurement, there may be additional historical information available that pertains to the magnitude of floods prior to the systematic collection of records. For example, a gauging station might have only 20 years of measurement record as of 1992, yet it might be known that in

1900 a flood peak, estimated to be 1 000 $m^3 s^{-1}$ occurred, which exceeded any flood measured, and which was also the greatest flood since the community was established in 1860. The magnitude of this flood and the knowledge that the other floods from 1860 to 1992 were less than the flood of 1900 should and can be used in the frequency analysis. In contrast, it may only be known that a certain number of floods since 1860 through 1972 exceeded a certain threshold. This also constitutes historical information and should be included in the frequency analysis. Two popular methods are used to incorporate certain forms of historical information into the estimation of the parameters of the mathematical distribution function. They are historically (adjusted) weighted moments [3] and maximum likelihood with censoring theory [4-7]. It has been shown that the maximum-likelihood procedure makes much more efficient use of the additional information than does historically-weighted moments [7]. The estimate of the return period of the historical flood, if its magnitude is known, can be estimated and plotted along with the systematically observed floods for the cumulative-frequency curve [1,3,4].

36.1.2 ***Statistical analysis of flood hydrographs***

In a number of cases, e.g., for storage-reservoir design, it is necessary to establish the frequency of flood volumes as well as peak flows. A multivariate-statistical analysis of flood hydrographs may be used in this case. A flood hydrograph may be defined by means of the following random variables:

Q_{max} — maximum discharge during the flood period;
V — volume (in m^3) of flood wave; and
T — duration of the flood period.

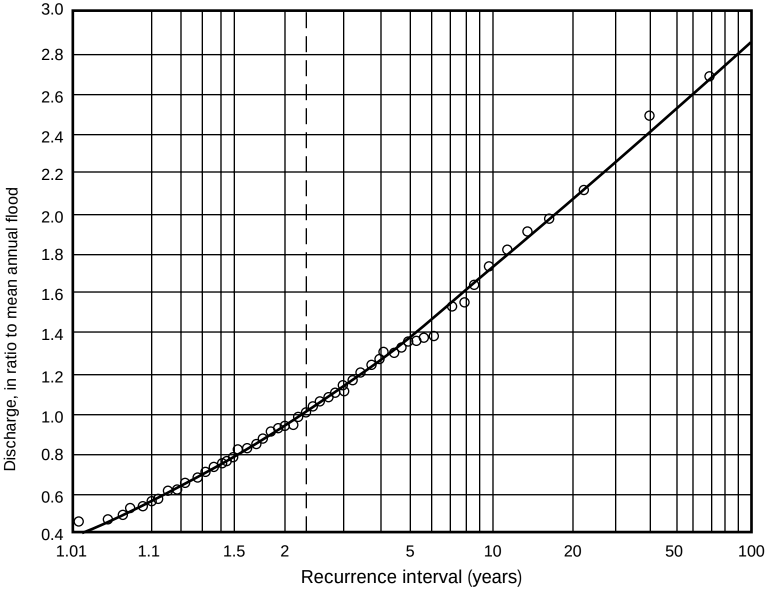
By using another system of variables, a flood hydrograph may be defined by means of the sequences of discharges $Q_1, Q_2, Q_3, ..., Q_n$ corresponding to successive equal intervals of time during the flood period. Statistical analysis of the random variables (Q_{max}, V, T) or $(Q_1, ..., Q_n)$ may be performed by means of a multivariate-probability distribution. Some definitions and computational techniques connected with such probabilistic models may be found in the papers given by Kaczmarek [8] and by Stammers [9]. In the case of flood characteristics, a power transformation or other methods may be used to normalize the data. Alternatively, the frequency or probability of occurrence or non-occurrence of a flood volume for an n-day period can be directly estimated from a frequency analysis of the site's flow data or by the use of the regionalization methods (section 36.2).

36.2 **Regionalization of flood flows** **[K10]**

For a site that does not have a large number of observations in its maximum annual series, regional flood-frequency analysis is recommended for the estimation of the flood quantiles. Two regionalization procedures have evolved and are popular. They are the index-flood and regression-based procedures.

36.2.1 *The index-flood procedure*

The index-flood procedure, as introduced by Dalrymple [10, 11], consists of two major steps. The first is the development of the dimensionless frequency curve for a homogeneous region. The curve results from individual frequency analyses of all sites. The curve for each site is made dimensionless by dividing the curve by an index, such as the flood corresponding to the two-year or 2.33-year return period. The median dimensionless values are selected for the sites for various return periods. They are in turn plotted on probability paper as shown in the Figure below. The second step consists of the development of a relationship between the index and the physical and climatological characteristics of the watershed. Regression-based procedures (section 36.2.2) can be used. The combination of the index with the dimensionless curve provides a frequency curve for any watershed within the region. The index procedure assumes that all floods within the region are from a Type I (double exponential or Gumbel) distribution and that the region is geographically defined. A homogeneity test was developed to determine whether the differences in



Regional dimensionless frequency curve.

slopes of frequency curves for all stations in a given region are greater than those attributable to chance. Similar tests have been devised for the three-parameter lognormal [12] and Weibull [13] distributions.

Much work has been done to extend these initial concepts and to assess the accuracy of index procedures to determine various flood quantiles [14-17]. Advances have been facilitated by the development of probability weighted moment [18] and L-moment [19] statistics. The need for analytical homogeneity tests can be circumvented by the Monte Carlo experiments. Homogeneity should and can be extended from the slope of the curve, which is the coefficient of variation of the sample in Dalrymple's approach, to include the skewness and kurtosis of the proposed region. This leads to a more flexible index procedure that allows higher moments of the region's data to indicate the potential underlying distribution. Heterogeneity of the lower moments can be assessed and potentially linked to characteristics of the watershed. Hosking and Wallis [16] show that "even when both heterogeneity and intersite dependence are present and the form of the [regional] flood-frequency distribution is misspecified, regional flood-frequency analysis is preferable to at-site analysis."

36.2.2 *Regression-based procedures*

Regression techniques can be used to estimate the magnitude of a flood event that will occur on average once in T_r years, denoted Q_{TR}, by using physical and climatological characteristics of the watershed [20-23]. The magnitudes of flood events for various return periods for each gauging station are estimated from an at-site frequency analysis by using a preselected distribution. In turn, characteristics for each watershed are derived from topographic maps or from generalized climatological data (Chapter 40). The parameters of the equations that relate Q_{TR} to the characteristics can be obtained by using ordinary least squares [20-23], weighted least squares [24], or generalized least squares [25]. The latter two approaches have been used to overcome the deficiencies in the assumptions of ordinary least squares. Ordinary least-squares regression procedures do not account for variable errors in flood characteristics that exist due to unequal record lengths at gauging stations. Tasker [24] proposed the use of weighted least-squares regression with the variance of the errors of the observed flood characteristics estimated as an inverse function of the record length. Generalized least squares has been proposed because it can account for both the unequal reliability and the correlation of flood characteristics that exist between sites. Using Monte Carlo simulation, Stedinger and Tasker [25] have demonstrated that the generalized least-squares procedure provides more accurate estimates of regression coefficients, better estimates of the accuracy of the regression coefficients, and better estimates of the model error.

The regional flood-frequency relationship developed by Benson [21] for the north-eastern United States is:

$$Q_{TR} = aA^b Z^c S^d P^e D^f M^g \tag{36.1}$$

where Q_{TR} is the T-year annual peak discharge, A is the drainage area, Z is the main-channel slope, S is the percent of surface-storage area plus 0.5 per cent, P is the T-year rainfall intensity for a particular duration, D is the average January degrees below freezing, M is an orographic factor, and a, b, c, d, e, f, and g are regression coefficients. In deriving equation 36.1 many independent variables were tested and many definitions were tested for each variable. The goal is to obtain independent variables that are physically related to the dependent variable. Independent variables that are related to a low return-period flood may not be a driving force behind a higher return-period flood. A logarithmic transformation of equation 36.1 may be taken to create a linear additive model for the regression procedures. Other types of transformations could be applied to the dependent and independent variables, but the logarithmic transformation remains the most popular. Both the signs and the magnitude of the coefficients of the model should make hydrologic sense. For example, the exponent d of the surface-storage term should be negative because of the effect of such storage (lake, reservoir, etc.) in flattening out flood peaks. Other exponents should be positive with their magnitudes varying with return period. Care should be taken to ensure that not too many independent variables are included in the model. The variables that are included in the regression model should be statistically significant at some preselected and generally accepted level of significance [26].

The resulting regression equation should be evaluated to determine if it is regionally homogeneous. Residual errors of the regression should be plotted on topographic maps to check visually if geographic biases are evident. If a bias in the estimation of the T-year annual peak discharge is geographically evident, then the Wilcoxon Signed Rank test can be applied to test its significance. The test provides an objective method for checking the hypothesis that the median of the residuals in a subregion is equal to the median residual of the parent region for which the regression equation was computed [27]. Different homogeneous regions may be found for different return periods. The homogeneous region for the relationship linking the index flood to the characteristics of the watershed need not coincide with the homogeneous region for the characteristics of the distribution of the index method, such as the slope of the dimensionless curve.

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CHAPTER 37

ESTIMATING LAKE AND RESERVOIR EVAPORATION

37.1 General

Reservoir or lake evaporation cannot be measured directly as streamflow and rainfall are [1]. It is necessary to determine evaporation from a lake or reservoir by one or more of several methods described in the following sections. These methods consist of water-budget, energy-budget, aerodynamic, and pan-evaporation techniques [2-4].

37.2 Water-budget method

The water-budget method is simple in theory. Evaporation is determined by the difference between measurements of inflow, outflow, and changes in storage. Unfortunately, the method is not generally practicable in the case of lake and reservoir evaporation because errors in measuring inflow, outflow, and storage are often large compared to evaporation. Seepage, ungauged local inflow, and bank storage are uncertain and often unmeasurable items. However, under certain conditions this volumetric method has given excellent results and has provided the basis for evaluating the accuracy of energy-budget and aerodynamic methods (sections 37.3 and 37.4) in studies of lake and reservoir evaporation.

The water budget for a lake or reservoir includes the following items: evaporation, E, inflow, I, precipitation, P, net seepage and bank storage, V_{SS}, outflow, O, and change in storage, ΔS. If all items can be measured or estimated, then:

$$E = I + P - V_{SS} - O \pm \Delta s \tag{37.1}$$

Volumetric units are used in the above equation. The volume of evaporation must be divided by the area of the open-water surface to convert to depth of evaporation. The period should be sufficiently long so that evaporation, E, is large compared to the errors contained in the other terms in the equation.

The application of this method is limited to those sites where seepage, inflow, and outflow are small compared to evaporation.

37.2.1 *Inflow and outflow*

The streamflow into and out of the reservoir must be in well-defined channels. The inflow and outflow should be continuously measured by the methods given in

Chapters 10 and 11. If feasible, control weirs should be installed at the gauging points to ensure a permanent and sensitive stage-discharge relationship, and thereby improve the accuracy of the observations.

37.2.2 *Precipitation*

The volume of precipitation on the lake surface must be accurately determined from precipitation gauges, which are generally located on the shore. However, if the lake is very large, some precipitation gauges should be located on the lake. Non-recording precipitation gauges (section 7.3) are adequate for this purpose because the items in the water budget are computed for time periods of a week or longer. The number of gauges required will depend on the variability of the precipitation and on the size of the lake.

37.2.3 *Net seepage and bank storage*

These items cannot be measured directly and must be evaluated by indirect methods. One such method of determining net seepage is described in section 37.4.1. Bank storage may be evaluated by a study of groundwater elevations as measured in wells around the lake. It should be determined that seepage and bank storage are relatively small before a lake or reservoir is selected for measurement of evaporation by this method.

37.2.4 *Change in reservoir storage*

Water-stage recorders, as described in Chapter 10, are sufficiently precise to determine the change in reservoir stage. The relationship between stage and storage should be accurately established by surveys.

37.3 **Energy-budget method**

The energy-budget method has been used to estimate evaporation from oceans, lakes, and reservoirs, and to estimate evapotranspiration from land surfaces (Chapter 38). The method is based on the assessment of all sources of incoming and outgoing thermal energy plus changes in energy storage, with the difference being the energy utilized in evaporation.

The estimation of evaporation from lakes and reservoirs by this method requires on-site observations of incoming solar and long-wave radiation, water-surface and air temperatures, vapour pressure of the air, thermal energy stored in the body of water, and net energy advected via liquid transport into or out of the body of water. The required instruments and observational procedures are discussed in section 9.5.

The energy-budget method is difficult to apply because of the complexity of the field measurements required. However, at the present time it will yield better results over a wider range of conditions than any other method.

The basic energy budget for a lake or reservoir may be expressed as follows:

$$Q_x = R_s - R_{sr} + R_a - R_{ar} - R_{bs} - Q_E - Q_h + Q_v - Q_w + Q_b \qquad (37.2)$$

where Q_x is the change in energy stored in the body of water, R_s is the solar radiation incident to the water surface, R_{sr} is the reflected solar radiation, R_a is the incoming long-wave radiation from the atmosphere, R_{ar} is the reflected long-wave radiation, R_{bs} is the long-wave radiation emitted by the body of water, Q_E is the energy utilized by evaporation, Q_h is the energy convected from the body of water as sensible heat, Q_v is the net advected energy (via liquid transport) into the body of water, Q_w is the energy advected by the evaporated water, and Q_b is the energy exchange between mass of water in the reservoir and its bottom. Energy from chemical and biological processes and transformation of kinetic energy into thermal energy are neglected because of their small magnitudes.

During periods of partial or complete ice cover, the energy budget is not considered reliable because of the difficulty in measuring reflected solar radiation, temperature of the ice surface, and the area of partial ice cover.

Determining an energy budget for a reservoir on a daily basis is not considered practical because of the difficulty in evaluating the change in energy-storage terms. For this reason, it is recommended that computations be made for periods of ten days or longer.

Each of the various terms in the energy-budget equation is either measured directly or computed from known relationships. The procedure used in evaluating each term is described in the following sections.

The terms of equation 37.2 that can be measured are R_s, R_{sr}, R_a, and the net-radiation balance is:

$$R_f = R_s - R_{sr} + R_a - R_{ar} - R_{bs} \qquad (37.3)$$

All the above values are expressed in W m^{-2}. Detailed descriptions of the instruments and measuring techniques concerning the above mentioned elements can be found in the WMO *Guide to Meteorological Instruments and Methods of Observation* [5].

The procedures used for the evaluation of other elements of Equation 37.2 are described in the next sections.

37.3.1 *Reflected long-wave radiation*

Reflected long-wave radiation may be taken as three per cent of the long-wave radiation received by the water surface.

37.3.2 *Radiation emitted by the reservoir*

Radiation emitted by the reservoir is computed according to the Stefan-Boltzmann law for black-body radiation, with an emissivity factor of 0.970 for water. The equation for computing radiation emitted by the water surface is:

$$R_{bs} = 0.97\sigma\theta^4 \qquad (37.4)$$

where R_{bs} is the radiation emitted by the water surface in W m^{-2}, s is the Stephan-Boltzmann constant (5.67 x 10^{-8} W m^{-2} °K$_{-4}$), and θ is the temperature of the water surface in °K. For computing purposes, the average temperature of the water surface, as recorded near the centre of the reservoir, is determined for each period of study. The temperature is converted to °K, and the average radiation emitted by the water surface is computed for the period of study in W m^{-2}.

37.3.3 *Change in energy storage*

The thermal energy of the volume of water in the reservoir for a given date is computed from a temperature survey made on that date. These temperature measurements, which should be accurate to within 0.1°C, are usually made at biweekly or monthly intervals. The reservoir may be divided into several layers from the surface to the bottom. The volume of water for each of the layers is determined from the stage-volume relationship. All temperature observations made in a particular layer are averaged to obtain a mean temperature for that volume of water. The summation of the products of volume times temperature (assuming a base temperature of 0°C) will give the total energy for that particular date. Density and specific heat are considered as unity for the range of temperatures that occur in the reservoir.

In order to determine the energy utilized in evaporation, Q_E changes in energy storage resulting from advection of energy in the volumes of water entering or leaving the reservoir must be evaluated. Again, a base temperature of 0°C is usually chosen in computing the amount of energy in these volumes. Their temperatures are determined by observation or recordings (section 9.5.5) depending on the variation of temperature with the rate of flow. If the temperature of the water changes with the rate of flow, the mean temperature of the volume should be weighted according to the rate of flow. The temperatures of bank storage and net seepage are considered as being equal to the mean annual air temperature. This assumption is admittedly subject to error, but is not considered serious if the surface inflow is a large item in the water budget.

If precipitation is a significant item in the water budget, then the energy of this volume of water must be taken into account. The temperature of rainfall is assumed to be that of the wet bulb at the time of rainfall.

In computing the energy for each of these volumes, centimetre-gram-second units are used, and density and specific heat are considered as unity for the range of temperatures that occur in these volumes. The product of temperature times volume will give the amount of energy for each volume in joules.

The difference between the computed energies of stored water for the thermal surveys made at the beginning and end of the period of study determines the change in energy storage.

37.3.4 *Energy utilized for evaporation*

Energy utilized for evaporation, Q_E, may be calculated by:

$$Q_E = \rho_w E L_v \tag{37.5}$$

where E is the rate of evaporation in m s^{-1}, P_w equals 1 000 kg m^{-3}, and L_v equals 2.47x10^{6} J kg^{-1}.

37.3.5 *Energy convected to or from the body of water as sensible heat*

Since the energy transferred to or from the body of water as sensible heat, Q_h, cannot be measured, it is evaluated indirectly by use of the Bowen ratio, B, which is defined as:

$$B = Q_h/Q_E \tag{37.6}$$

The Bowen ratio can also be expressed as:

$$B = \frac{0.61(\theta_o - \theta_a)}{(e_o - e_a)} \frac{p}{1000} \tag{37.7}$$

where θ_o is the water-surface temperature, in °C, θ_a is the air temperature, in °C; e_o is the saturation vapour pressure, in hPa, corresponding to the water-surface temperature, e_a is the vapour pressure of the air, in hPa, and p is the atmospheric pressure, in hPa.

To compute the Bowen ratio for the period of study, the terms, θ_o, θ_a, and e_a, are averaged for the period. The term e_o is determined from the average temperature of the water surface for the period. The term p is determined from the elevation of lake above sea-level and is usually considered constant. The ratio is dimensionless.

37.3.6 *Energy advected by the evaporated water*

Energy advected by the evaporated water can be calculated as:

$$Qw = \rho_w c_w E (\theta_e - \theta_o) \tag{37.8}$$

where c_w is the specific heat of water (4 200 J kg^{-1} °C^{-1}), θ_e is the temperature of the evaporated water assumed to be equal water-surface temperature in °C, and θ_b is the base temperature (0 °C).

37.3.7 *Energy exchange between the water in the reservoir and its bottom*

This term of energy budget can be important during periods with low values of other energy elements, which usually occurs in spring and autumn and particularly in shallow water bodies. Approximate values of Q_b may be found in Table 37.1.

TABLE 37.1

Approximate value of $Q_b[\mathrm{W\ m^{-2}}]$*

North latitude	*Average depth of water body [m]*				*North latitude*	*Average depth of water body [m]*			
	0-5	*10*	*15*	*20*		*0-5*	*10*	*15*	*20*
	January					July			
30	13	12	9	8	30	-11	- 9	- 8	- 7
40	11	9	8	8	40	-11	- 9	- 8	- 7
50	7	6	6	5	50	-12	-11	- 9	- 8
60	5	5	3	3	60	-12	-12	-11	- 8
70	3	3	2	2	70	-12	-12	-11	- 8
	February					August			
30	8	8	6	5	30	- 5	- 5	- 3	- 3
40	6	6	5	3	40	- 5	- 5	- 3	- 3
50	5	3	3	2	50	- 5	- 3	- 3	- 2
60	3	2	2	2	60	- 3	- 3	- 2	- 2
70	2	2	2	1	70	- 3	- 3	- 2	- 2
	March					September			
30	- 3	- 3	- 2	- 2	30	2	2	2	1
40	1	1	1	0	40	3	2	2	2
50	3	3	2	2	50	5	3	3	2
60	2	2	2	2	60	5	5	5	3
					70	6	6	5	5
	April					October			
30	-19	-17	-15	-13	30	14	13	12	9
40	-14	-13	-12	- 9	40	14	12	11	8
50	- 8	- 6	- 6	- 5	50	12	11	9	8
60	0	0	0	0	60	12	9	8	7
					70	11	9	8	7
	May					November			
30	-16	-14	-13	-11	30	16	14	13	11
40	-16	-14	-13	-11	40	15	13	13	11
50	-15	-14	-12	-11	50	13	12	11	8
60	-14	-13	-12	- 9	60	12	11	9	8
70	- 9	- 9	- 8	- 6	70	9	9	8	6
	June					December			
30	-15	-14	-12	-11	30	17	15	14	12
40	-16	-14	-13	-11	40	14	12	11	9
50	-16	-14	-13	-12	50	11	9	8	7
60	-16	-14	-13	-12	60	7	6	6	5
70	-17	-15	-13	-12	70	5	3	3	2

*If the average depth is more than 50 metres, $Q_b = 0$.

37.3.8 *Evaporation*

For computational purposes, use is made of the following relationships:

$$Q_E = \rho_w El_v \; ; \; Q_h = B \, Q_E \text{ and } Qw = \rho_w c_w E \, (\theta_e - \theta_b) \qquad (37.9)$$

where E is the rate of evaporation, in cm d^{-1}, ρ_w is the density of water, in g cm^{-1}, l_v is the latent heat of vaporization, in J g^{-1}, B is the Bowen ratio, C_w is the specific heat of water, in J g-1 °C^{-1}, θ_e is the temperature of evaporated water, in °C, and θ_b is the base temperature of 0°C.

Substituting the above described variables into the basic energy-budget equation and solving it for E results in:

$$E = \frac{R_s - R_{sr} + R_a - R_{bs} - Q_x + Q_v + Q_b}{\rho_w l_v \left(1 + B\right) + c_w \left(\theta_e - \theta_b\right)} \qquad (37.10)$$

where E is expressed in m s^{-1}.

The accuracy of the estimation of evaporation by the energy-budget equation will depend on the inherent accuracy of the measuring equipment and the completeness of record. If all terms are evaluated within the accuracy prescribed in section 9.5 and with a minimum loss of record, the accuracy of the results should be within an average error of 10 per cent in summer and 20 per cent in winter.

37.4 Aerodynamic approaches

Aerodynamic approaches are based on the theory that the transport of water vapour from a water surface is essentially a turbulent process. The turbulence in the process is related to certain meteorological phenomena. Many aerodynamic equations, both theoretical and empirical, have been derived to express this relationship. Some of the equations are complex mathematical expressions and require extensive meteorological instrumentation, while others are simple and require only measurements of wind and vapour pressure. There is also the eddy-correlation (eddy-transfer or eddy-flux) method, which employs the measurement of vertical flux in the atmosphere.

Many of the aerodynamic equations for computing evaporation were tested during the investigation in Lake Hefner (U.S.A.) and on the large reservoirs of Rybinsk, Kuibyshev, and Tsymlyansk (C.I.S.). Two simple equations, which gave good results, are introduced as examples. They require the measurements of only wind movement, water temperature, and the vapour pressure of the air. The instruments and methods of observation used for obtaining the required data are described in section 9.5.

The first equation, derived from the Lake Hefner investigation [6], is written as:

$$E = N \, u \, (e_o - e_a) \qquad (37.11)$$

where E is evaporation, in cm/day, N is a coefficient, u is wind speed, in m s^{-1}, above the water surface, e_o is the saturation-vapour pressure, in hPa, corresponding to the temperature of the water surface, and e_a is the vapour pressure of the air, in hPa.

The second equation [7], tested in the above-mentioned three large reservoirs of the Commonwealth of Independent States, is:

$$E_o = 0.14\,(1 + 0.72u_{200})\; n(e_o - e_{200}) \qquad (37.12)$$

where E_o is the evaporation from a water body, in mm month^{-1}, e_o is the average maximum water-vapour pressure computed according to the temperature of the water surface of the body, in hPa, e_{200} is the average water-vapour pressure above the water body at an elevation of 200 cm, in hPa, u_{200} is the average wind speed above the water body at an elevation of 200 cm, in m s^{-1}, n is the number of days in the time interval, which is usually taken as a month. The values e_o, e_{200} and u_{200} are monthly means and are averaged over all observation points above the water body. If these data are absent, their values can be computed from observations at meteorological stations nearest to the water body.

37.4.1 *Value of the coefficient N*

The value of coefficient N represents a combination of many variables included in more complex aerodynamic equations. Among these are the wind structure, size of the lake, roughness of the water surface, atmospheric stability, barometric pressure, and the density and kinematic viscosity of the air. However, experience has shown that, if u, e_o, and e_a are determined from measurements near the centre of the lake and if e_a is measured within the vapour blanket, then N is relatively constant for reservoirs greatly different in size. Studies at Lake Hefner (surface area 900 ha) [6] and at Boulder Basin of Lake Mead, U.S.A. (28 900 ha) [8] indicate that the value of N in the preceding equation is 0.0137 for both reservoirs if u, e_o, and e_a are determined from measurements near the centre of the lakes and u and e_a are measured at a height of two metres above the water surface.

If e_a is determined from observations at a shore site outside the lake's vapour blanket, then the value of N depends on the surface area of the lake. Harbeck [9] defined this relation as:

$$N = \frac{0.291}{A^{0.05}} \qquad (37.13)$$

where A is the area of the water surface in m^2. The standard error of estimate of this regression was 16 per cent, and thus, it should not be used to determine the value of N for an individual lake. However, the relationship should serve to prevent gross errors in determining the value of N by other methods.

The value of N can be determined if evaporation is evaluated by the water budgets or energy budgets on a monthly frequency for a year or longer. During this period, the value of N should be computed for each month from the average product of $u(e_o - e_a)$. Generally, N will be constant through all seasons of the year. Detailed descriptions of the methods used for determination of N are given in the WMO *Measurement and Estimation of Evaporation and Evapotranspiration* [10].

The value of N and the seepage loss can be evaluated for small lakes and reservoirs if other items in the water-budget equation can be determined for short time periods. The two basic assumptions of the method are:

(*a*) During periods of no surface inflow or outflow the fall in reservoir stage is composed of two parts, evaporation and seepage;

(*b*) When the product $u(e_o - e_a)$ is zero, evaporation is negligible. It is usually preferable to restrict the analysis to periods of no surface inflow or outflow, although it is not necessary to do so. If inflow and outflow are measured, the observed change in stage can be adjusted accordingly, but ordinarily even small errors in measuring inflow or outflow may make the adjusted stage change of questionable accuracy. Periods of rainfall should be excluded.

The beginning and end of each period should be chosen so that lake stages at these times are defined accurately. Times when the recorder chart indicates wind-induced surges should not be chosen as the beginning or ending of the periods, although they should not be avoided within the period. For each selected period, the change in stage, Δh, is computed in cm d^{-1}, and the average values of wind speed and vapour-pressure difference are computed for the same period. Values of the product $u(e_o - e_a)$ when plotted against Δh should define a linear relationship. The slope of the line is equal to the value of N, and the intercept defines the amount of seepage from the lake. Average daily values of u, e_o, and e_a are determined from the wind and temperature data, and the daily evaporation in cm d^{-1} is computed from equation 37.11.

37.4.2 *Wind*

A continuous measurement of wind speed should be made near the centre of the lake or reservoir at a height of two metres above the water surface. The anemometers commonly used are described in section 9.5.7.

37.4.3 *Water-surface temperature*

A continuous record of water-surface temperature should be obtained near the centre of the lake or reservoir. Suitable equipment for this purpose is discussed in section 9.5.5.

37.4.4 *Humidity or vapour pressure of the air*

Measurements of humidity should preferably be made near the centre of the reservoir at a height of two metres above the water surface. Instruments to measure humidity are described in section 9.5.6. Since it is difficult to maintain equipment of this type in the centre of the lake, humidity is usually measured at an upwind shore station near the lake. The difference in humidity over the lake and at the shore station may be accounted for empirically in the computation process described in section 37.4.1.

37.4.5 *Eddy-correlation method*

The vertical flux of sensible heat (convection) and water vapour (evaporation) may be measured directly by sensing the properties of eddies as they pass through a particular measurement level on an instantaneous basis. The mean vertical flux of (dry) air is zero, but the fluctuating vertical component of the wind carries with it other entities. Net vertical transport of heat (or moisture) requires that fluctuations in temperature (or humidity) are correlated with the vertical fluctuations in wind speed.

In the case of evaporation measurement, the eddy-correlation method is based on proportionality between the mean vertical flux density of water vapour and the time average of the instantaneous covariances of vertical wind speed and humidity. It requires specialized, delicate wind speed and humidity sensors and cannot be regarded as suitable for routine field measurements. However, eddy-correlation methods play an invaluable role in research and in validating other direct and indirect methods.

37.5 Combination of aerodynamic and energy-balance equations

Perhaps the most widely used method for computing lake evaporation from meteorological factors is based on a combination of aerodynamic and energy-balance equations [11-13]. In its general form, Penman's equation [12] is:

$$E_i = \frac{R_n \, \Delta + E_a \, \gamma}{\Delta + \gamma} \tag{37.14}$$

where E_i is the estimated evaporation from a free-water surface, Δ is the slope of the saturation vapour-pressure curve at any temperature θ_a, R_n is the net radiation, γ is the constant in the wet- and dry-bulb psychrometer equation, and E_a, a derived parameter, is a function of wind speed and $(e_s - e_a)$, where e_s is the saturation vapour-pressure at temperature θ_a, and e_a is the actual vapour pressure at the same temperature. The psychrometer constant γ for °C and l 000-mb pressure is 0.61. The net radiation R_n may be computed by:

$$R_n = R_t \,(1 - r)\left(0.18 + 0.55n/N\right) - \sigma\theta_a^4 \left(0.56 - 0.09\sqrt{e_a}\right)\left(0.1 + 0.9n/N\right) \tag{37.15}$$

where R_t is the mean extraterrestrial radiation expressed in equivalent evaporation, in mm d^{-1}, r is the reflection coefficient, n/N is the ratio of actual to possible hours of sunshine, σ is the Stefan-Boltzmann constant, also expressed in equivalent evaporation in mm d^{-1}, θ_a is mean air temperature (absolute), and e_a is the actual vapour pressure of the air in mm of mercury. Although it may be necessary to use the above equation, it would be preferable to use measured values of solar and long-wave radiation.

The parameter, E_a, in equation 37.14 is derived by:

$$E_a = (a + bu)(e_s - e_a) \qquad (37.16)$$

where u is the wind movement.

Mean daily temperature and relative humidity may be used in determining mean vapour pressure e_a and mean saturation deficit $(e_s - e_a)$. Wind observations may be adjusted to the proper level by applying the power law for variation of wind speed with height above the ground:

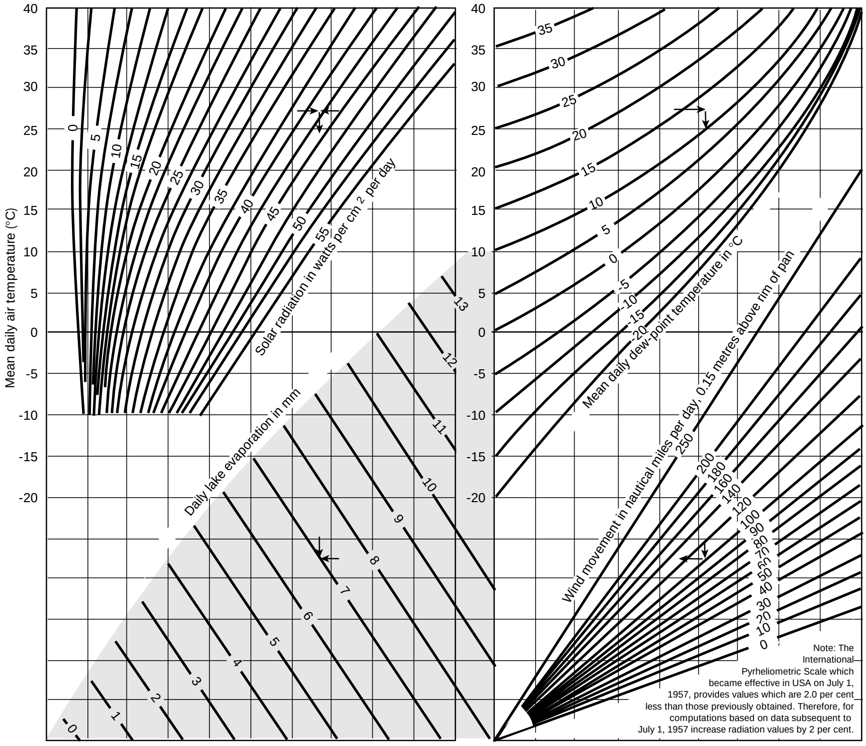
$$\left(\frac{u_1}{u_2}\right) = \left(\frac{z_1}{z_2}\right)^k \qquad (37.17)$$

where u_1 is the estimated wind velocity at required height above the ground, u_2 is the observed wind velocity at anemometer height, z_1 is the height above ground used in the evaporation equation, z_2 is the height of anemometer above ground, and k is a coefficient that varies with atmospheric stability and surface roughness. Numerical values of k can be calculated by an experimental formula of Timofeev:

$$k = \frac{1}{11.5}\left(1 - 0.42\,\frac{\theta_o - \theta_2}{u_1^2}\right) \qquad (37.18)$$

where u_1 is the wind speed at one metre height, and θ_0 and θ_2 are surface-water and air temperatures, respectively.

A similar approach was used by Kohler, *et al.* [2] and a graphical presentation of the relationship is shown in Figure 37.1. The meteorological observations of solar radiation, air temperature, dewpoint, and wind movement at the anemometer height of a Class A pan are required for application of this technique. In the absence of solar-radiation observations, radiation may be estimated from the percentage of possible sunshine or cloud-cover data. Lake evaporation computed for short periods by this method [2,11,12] would be applicable only to very shallow lakes with little or no advection of energy to the lake. For deep lakes and conditions of significant advection due to inflow and outflow, it is necessary to correct the computed lake evaporation for net advected energy and change in energy storage. These terms are described under the energy-budget method in section 37.3. However, all of the advected energy and change in energy storage is not utilized for evaporation. The portion of this energy used for evaporation can be obtained from a relationship such as shown in Figure 37.2. Observations of water-surface temperature and wind movement at four metres above the water surface are required for application of this



Note: The International Pyrheliometric Scale which became effective in USA on July 1, 1957, provides values which are 2.0 per cent less than those previously obtained. Therefore, for computations based on data subsequent to July 1, 1957 increase radiation values by 2 per cent.

Figure 37.1 — Lake-evaporation relationship.

relationship. Reliable estimates of weekly or monthly lake evaporation can be obtained by this approach only if an evaluation is made of the energy-advection and storage factors.

37.6 Extrapolation from pan measurements

The evaporation from pans exposed in or on the ground is influenced by the pan characteristics. Sunken pans are subject to undetected leaks, accumulation of debris on the water surface, and boundary conditions with the soil different from those of a large lake. Pans exposed above the ground are subject to heat exchange through the sides and to other effects that do not occur in lakes. Floating pans are subject to splash-in and splash-out, and are costly to install and operate.

Pans have much less heat storage than lakes and tend to experience a different annual cycle of evaporation, with pan-evaporation extremes occurring earlier in the

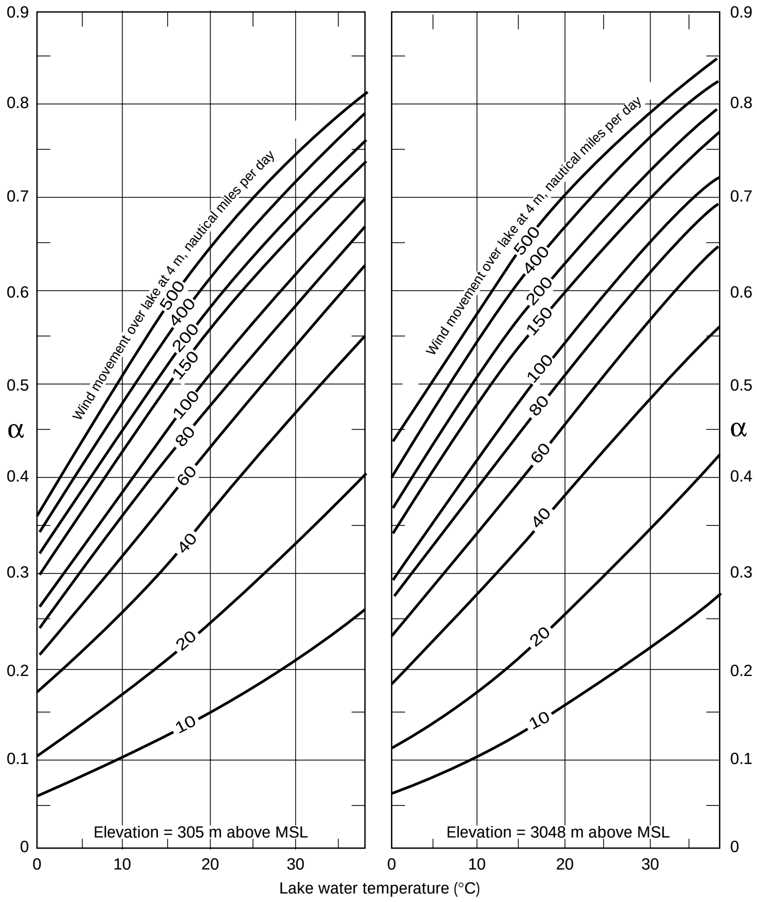


Figure 37.2 — Proportion of advected energy into a lake that is used for evaporation.

season. Reliable estimates of annual lake evaporation can be obtained by multiplying the annual pan evaporation by the appropriate pan-to-lake coefficient. These estimates will be reliable only if it can be assumed that, on an annual basis, any energy advected to the lake is balanced by a change in heat storage. The pan-to-lake coefficient for a particular pan is determined by comparison with actual lake evaporation, if available, or more commonly by comparison with a pan large enough to simulate a lake (sunken pans four metres or more in diameter). The coefficient for a specific pan is also dependent, to a degree, upon the climatic regime, that is different for arid or humid conditions. For an evaporation pan to serve as a valid index to take evaporation, the exposure of the pan should avoid the environmental effects of the lake. Such an exposure would be near the lake, but on the side toward the prevailing wind direction. An island exposure would not be satisfactory.

One method for determining the climatic variation of the pan coefficient is by field comparisons with large pans under the various conditions. This method is applied in the Commonwealth of Independent States with the GGI-3000 and 20 m^2 tanks. The pan-to-lake coefficients thus derived for the GGI-3000 range between 0.75 and 1.00. For estimates of monthly average evaporation, the coefficient for a floating GGI-3000 evaporation pan is estimated by the following equation:

$$\alpha = 0.8 \frac{e_o - e_{200}}{e_o' - e_{200}} \frac{\beta}{\gamma} \tag{37.19}$$

where e_o is the average monthly vapour pressure, in hPa, estimated from the surface temperature of water body, e_o' is the average monthly vapour pressure, in hPa, estimated from surface-water temperature in the floating GGI-3000 pan, e_{200} is the average monthly vapour pressure at 200 centimetres above the water surface, in hPa, β is a correction factor for the area of a water body, and γ is a factor that depends on the distance, l, along the average direction of wind from the shore to the pan (fetch).

The ratio, β/γ, needs to be determined only for water bodies located in tundra, forest and forest-steppe zones and when the pan is located at a distance of up to 500 metres from shore. In all other cases, this ratio is assumed to be equal to 1. For water bodies of approximately round or square shape, β is determined from the area of the water surface by using Table 37.2.

For water bodies of irregular shape (long with islands and gulfs), the area used is that of an assumed circle with a diameter equal to an average distance, l, weighted with the frequency of wind direction in per cent from the eight points of the compass. The weighted distance can be computed by the equation:

$$\bar{l} = \frac{1}{100} \sum_{i=1}^{i=8} l_i N_i \tag{37.20}$$

where N_i is a frequency of wind direction from the eight points, in per cent. γ can be determined from Figure 37.3.

TABLE 37.2

Determination of β

Area of water body (km^2)	0.01	0.05	0.1	0.5	1.0	2.0	5.0
Correction factor β	1.03	1.08	1.11	1.18	1.21	1.23	1.26

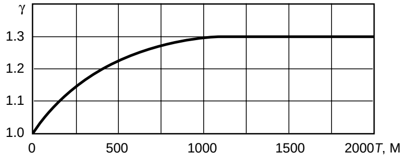


Figure 37.3 — Factor γ and l relationship.

In the Commonwealth of Independent States, the average seasonal value of the coefficient for a GGI-3000 pan from spring break-up to autumn freezing is calculated by the equation:

$$\overline{\alpha} = 0.98 - 0.0007E \qquad (37.21)$$

where E is the average monthly evaporation, in mm month^{-1}, from GGI-3000 pan measured during the whole observational season. For monthly average evaporation, the coefficient is estimated by the equation:

$$\overline{\alpha} = 1 - 0.063\,E^{0.6} \qquad (37.22)$$

where E is the average daily evaporation, in mm day^{-1}, for the month.

Another method is the adjustment of the pan evaporation for heat gain or loss through the sides and bottom. An example of this method is the technique in estimating evaporation by using data from the Class A evaporation pan. In humid seasons and climates, the pan water temperature is higher than the air temperature, and the pan coefficient may be 0.80 or higher. In dry seasons and arid areas, the pan water temperature is less than air temperature, and the coefficient may be 0.60 or less. A coefficient of 0.70 is assumed to be applicable when water and air temperatures are equal. The relationships for estimating lake evaporation by adjusting Class A pan evaporation for heat gain or loss are shown in Figures 37.4 and 37.5. Due to the important variation of wind with height, standard instrument heights are an essential requirement of the Class A station.

To obtain short-period estimates of lake evaporation with the pan method, it is also necessary to evaluate the net energy advection to the lake and change in energy storage as described in section 37.3. It is useful to have pan evaporation near a lake or reservoir as a source of alternative data in the absence of other meteorological data and to help verify estimates made by the energy-budget and aerodynamic methods.

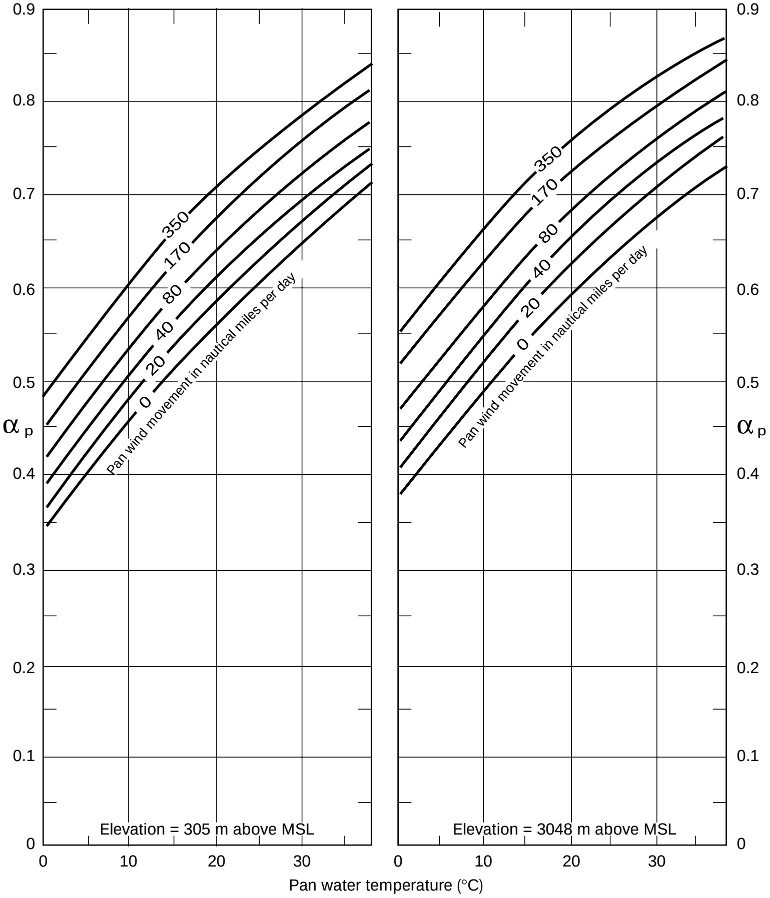


Figure 37.4 —Proportion of advected energy into a Class A pan that is used in evaporation.

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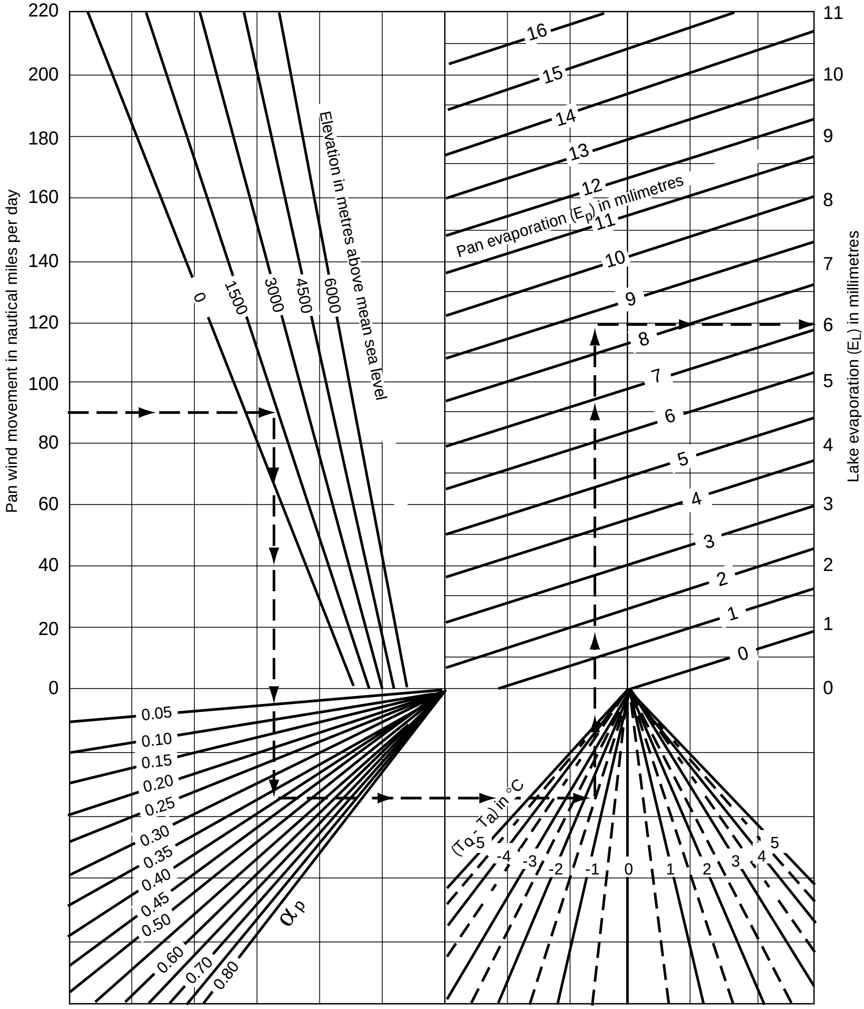

Figure 37.5 — Conversion of Class A pan into lake evaporation.

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CHAPTER 38

ESTIMATING BASIN EVAPOTRANSPIRATION

38.1 General

Evapotranspiration is commonly considered to be the evaporation from all water, soil, snow, ice, vegetation, and other surfaces plus transpiration. It is not possible to measure evapotranspiration directly from an appreciable area under natural conditions, but lysimeters (section 9.3) are used to measure it in limited-volume containers. Over a long period of time, a water-budget approach can be used to estimate evapotranspiration from a basin in which all items of inflow and outflow, except evapotranspiration, can be measured. When considering short-term values over sizeable areas, it is necessary to estimate evapotranspiration by using empirical relationships. Broader discussions of this topic are presented in the WMO *Casebook on Operational Assessment of Areal Evaporation* [1].

38.2 Potential evapotranspiration

Thornthwaite defined potential evapotranspiration as the “water loss which will occur if at no time there is a deficiency of water in the soil for the use of vegetation” [2]. Penman has suggested that this definition be modified to include the stipulation that the surface be fully covered by green vegetation. This modified definition is generally satisfactory but becomes meaningless during winter in northern latitudes.

Penman recommends that the annual free-water evaporation computed by his equations be multiplied by a factor of 0.75 (ranging from 0.8 in summer to 0.6 in winter) to obtain potential evapotranspiration. Under certain conditions, potential evapotranspiration may be equal to free-water evaporation. In some applications, free-water evaporation can be used as an index for potential evapotranspiration, e.g., in studies of soil-moisture conditions for purposes of water-supply forecasting.

38.3 Actual evapotranspiration

The effect of moisture deficiency in the soil profile is important to the relationship between actual and potential evapotranspiration. There seems little doubt that the rate of depletion from an initially saturated, heterogeneous area decreases with time approximately as a logarithmic recession because of variations in root-zone depth, root-zone capacity, slope, aspect of the surface, etc.

38.4 Water-budget method

The water-budget approach can be used to estimate evapotranspiration, E_T, when precipitation, P, stream runoff, Q, deep seepage, Q_{ss}, and changes in storage, ΔS, can be measured or estimated. The equation is:

$$E_T = P - Q - Q_{ss} \pm \Delta S \tag{38.1}$$

The annual evapotranspiration from a basin for a water year can be estimated as the difference between precipitation and runoff if it can be established by hydrogeological studies that deep seepage is relatively insignificant. The date chosen for the beginning and ending of the water year should coincide with the dry season, when the amount of water in storage is relatively small and the change in storage from year to year is negligible.

If evapotranspiration is to be estimated for a shorter period, such as a week or month, the amount of water storage in the ground and in the stream channel must be measured. This is feasible only on small basins, and application of the water-budget approach for such short periods is generally limited to experimental plots or catchments of a few acres.

For average annual evapotranspiration, the change in storage is usually negligible, and evapotranspiration can be estimated by the difference between average annual precipitation and average annual runoff.

38.4.1 *Precipitation*

The volume of precipitation falling on the catchment or plot should be accurately measured within a network of raingauges. Non-recording gauges (section 7.3) are adequate for this purpose. The required number of gauges will depend on the expected variability of precipitation over the catchment or plot.

38.4.2 *Streamflow*

Instruments and methods for continuously measuring streamflow are described in Chapters 10 and 11.

38.4.3 *Change in storage*

The change in water storage in the ground is measured as two separate components, the saturated and unsaturated zones. Measurements of the water table elevation in wells and measurements of soil moisture in the unsaturated zone are required.

The elevation of the water table can be determined by measuring the distance from reference points to the water surface in wells at the end of each time period for which evapotranspiration is to be computed. The change in volume of water storage is equal to the average change in water elevation times the specific yield of the formation times the area of the catchment or plot.

Soil-moisture profiles from the saturation level (or to a point of constant soil moisture in arid regions) to the ground surface should be measured at the end of each computation period at a number of points over the catchment (Chapter 15). The gain or loss of soil moisture during the period can then be computed.

38.4.4 *Deep seepage*

The amount of water that moves from or to the catchment as deep seepage cannot be measured directly. A hydrogeological study of the hydraulic characteristics of the underlying formations should indicate the relative magnitude of this flow, which must be considered when choosing the experimental area. This item should be small enough so that it can be neglected in water-budget studies.

38.5 Energy-budget method

This method [3] may be applied for the estimation of evapotranspiration when the difference between radiation balance and the heat flux into the soil is significant and exceeds the errors of measurement (section 37.3). This method is applied for estimation of evapotranspiration for periods of not less than 10 days. For shorter periods, the estimation of evapotranspiration by the energy-budget method is rather difficult.

38.6 Aerodynamic approach

The application of this method [4] for the estimation of evapotranspiration is difficult because of the lack of reliable methods to determine the turbulent-exchange coefficient (section 37.4). Thus, it is seldom used. It is used only for approximate estimation of evaporation.

In some countries, evapotranspiration is estimated by empirical methods — the Penman method and the Thornthwaite formula. Penman's method is used in conditions of sufficient moisture, and the Thornthwaite formula [2] is applied for regions with climatic conditions similar to those of the middle Atlantic coast of the United States for which this formula was based.

In the Commonwealth of Independent States, Konstantinov's method [5] is applied for the estimation of evaporation based on observations of temperature and humidity of the air in a psychrometer shelter at two metres above the ground. This method is mainly applicable for the computation of long-term mean monthly, seasonal, or annual evapotranspiration.

38.7 Penman-Monteith method

The combination equation (section 37.5, equation 37.14) represents the energy budget at the land surface and the transfer of water vapour and heat between the surface and the atmosphere. The Penman-Monteith method introduces aerodynamic and surface resistances. The former describes the effect of surface roughness on heat and mass transfer and the latter describes the resistance to the flow of water vapour between the evaporating surface and the air. Surface resistance for water surfaces is zero. In the case of vegetation, the surface resistance represents biological control of transpiration and is largely controlled by stomatal resistance. For drying soil, the surface resistance depends on soil moisture availability. This method may be used on an hourly or daily basis. However, its use is restricted because it requires sub-models for the surface resistance.

38.8 Priestley-Taylor (radiation) method

The method of Priestley and Taylor [6] is based on the argument that, for large, wet areas, radiation controls of evaporation must dominate rather than advective controls. If the atmosphere remains saturated when in contact with the wet surface, then the latent-heat transfer (evaporation) may be expressed by:

$$\lambda E = (\varepsilon / (\varepsilon + 1))(Q^* - G) \tag{38.2}$$

where Q^* is the available net radiation, G is the soil-heat flux, and ε equals $s\lambda/c_p$, with s equal to the slope of the saturation specific humidity curve, λ is the latent heat of vaporization, and c_p is the specific heat of water.

For equilibrium evaporation, it was proposed that:

$$\lambda E = \alpha (\varepsilon / (\varepsilon + 1))(Q^* - G) \tag{38.3}$$

with $\alpha = 1.26$, an empirical constant. This expression is used as an estimate of potential evaporation in the absence of local advection. It also gives good estimates for evaporation from well-watered but not wet vegetation in much smaller regions.

38.9 Complementary method

The complementary method, first suggested by Bouchet [7] is increasingly used in hydrological applications for large areas because it essentially only uses standard climatic data.

The method considers that potential evaporation is as much the effect of the actual evaporation as its cause. Heat and moisture released from the surface will modify the temperature and humidity of the air above it. Bouchet suggested that the increase in potential evaporation observed when an area dries out may be used as a measure of the actual evaporation rate.

If actual evaporation E is reduced below the potential rate E_{po} for an extensive wet region, then an amount of energy Q would be released, so that:

$$\lambda E_{po} - \lambda E = Q \tag{38.4}$$

This energy change will affect temperature, humidity, turbulence, and hence evaporation. If the area is big enough so that the change in energy does not result in changes in the transfer of energy between the modified air mass and that beyond, Q should just equal the increase in λE_p, the potential evaporation for the drying region. Hence:

$$\lambda E_p - \lambda E_{po} = Q \tag{38.5}$$

Therefore:

$$E + E_p = 2E_{po} \tag{38.6}$$

Most applications of the complementary relationship (see for example Morton, [8]) have been concerned with finding appropriate expressions for E_p and E_{po}. These may be estimated with the expressions of Penman (section 37.5) and Priestley-Taylor (section 38.8), respectively. The approach does not consider advection and assumes Q to remain constant. Also, the vertical exchange of energy, i.e., with air masses brought in by large-scale weather systems, is not considered.

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CHAPTER 39

MODELLING OF HYDROLOGICAL SYSTEMS

39.1 **General**

The term modelling of hydrological systems usually means the application of mathematical and logical expressions that define quantitative relationships between flow characteristics (output) and flow-forming factors (input). This is a very general definition that covers an entire spectrum of approaches. At one extreme are the purely empirical, black-box techniques, i.e., those that make no attempt to model the internal structure and response of the catchment but that only match the input and output of the catchment system. At the other extreme are techniques involving complex systems of equations based on physical laws and theoretical concepts that govern hydrological processes—the so-called hydrodynamical models [1, 2]. Between these two extremes, there are various conceptual models. These models represent a logical consideration of simple conceptual elements, e.g., linear or non-linear reservoirs and channels, that simulate processes occurring in the basin. Whether black-box, conceptual, or hydrodynamical, these models yield outputs without associated probabilities of occurrence. For this reason, they are often referred to as deterministic models.

However, the term modelling of hydrological systems is sometimes considered to include stochastic modelling, where the emphasis is on reproducing the statistical characteristics of hydrological time-series. No attempt is made to model input-output relationships.

Purely empirical and black-box relationships have proven and will continue to prove very beneficial under certain circumstances, but they are subject to serious error when it becomes necessary to rely upon them under conditions not previously experienced. Models that, through theoretical concepts, treat the varied and interacting hydrological processes are expected to be more trustworthy under such extreme conditions, and experimentation with them holds greater promise for advancing the science. Any attempt to classify deterministic models as hydrodynamical, conceptual, or black-box admittedly forces a decision as to the degree of empiricism. Nevertheless, it has been deemed appropriate to follow such a division in the treatment of deterministic models.

Developments in the modelling of hydrological systems are linked closely with the emergence of electronic computers and techniques for their application. The availability of electronic computers and the development of associated numerical methods have enabled hydrologists to carry out complex, repetitive calculations that use large quantities of data. Modelling of streamflow has become an important element in the planning and management of water-supply and control systems and in providing river-forecast and warning services.

The nature of modelling and the forced reliance on computer programing makes it impractical to include computational aids in the manner found elsewhere in this *Guide.* Many references are cited for further guidance on specific aspects of modelling, but no attempt is made to provide readily usable programs for the innumerable model-computer combinations that exist.

39.2 **Black-box models (system approach)** **[J04]**

A river basin can be regarded as a dynamic system in which lumped parameters, which are invariant over the basin, transform the input factors, precipitation and snow melt, into a hydrograph of outflow from the basin. The same is true for a river reach, except that the inflow at the upstream point(s) must be treated as an additional input factor. Diagrammatically, such systems can be represented as shown in Figure 39.1, where $P(t)$ is the input and $Q(t)$ is the output, both functions of time t. From the standpoint of dynamic systems theory, hydrological systems behave as linear systems if they satisfy the principle of superposition, namely that the reaction of the system to a combination of inputs is equal to the sum of its responses to the separate inputs and that the system parameters be independent of the system's response. The premise that the outflow hydrograph of a basin can be predicted from a sequence of precipitation and snow melt only involves the assumption that the variability of other natural inputs, such as evapotranspiration, is small or follows a known function of time [3].

The general expression for the relationship between input $P(t)$ and output $Q(t)$ of a lumped-parameter, linear dynamic system may be written as:

$$\begin{aligned} a_n(t)\frac{d^n Q}{dt^n} + a_{n-1}(t)\frac{d^{n-1} Q}{dt^{n-1}} + \ldots + a_1(t)\frac{dQ}{dt} + a_o(t)\,Q = \\ b_n(t)\frac{d^n P}{dt^n} + b_{n-1}(t)\frac{d^{n-1} P}{dt^{n-1}} + \ldots + b_1(t)\frac{dP}{dt} + b_o(t)\,P \end{aligned} \tag{39.1}$$

where the coefficients a_i and b_i are the parameters characterizing the properties of the system. The solution to equation 39.1 for zero initial conditions gives:

$$Q(t) = \int_o^t h(t-\tau)\,P(\tau)\,d\tau \tag{39.2}$$

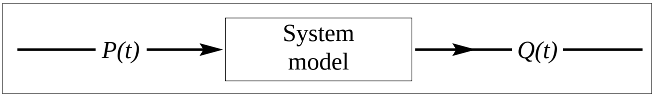


Figure 39.1 — Black-box system.

where the function *h(t,τ)* represents the response of the system at a time *t* to a single input impulse at time τ.

There are numerous approaches to the representation of hydrological systems by formulations involving the influence function *h(t,τ)*. These can be expressed in terms of the coefficients a_i and b_i. If the coefficients are constant, then the system is time-invariant and equation 39.2 becomes the Duhamel integral:

$$Q(t) = \int_o^t h(t - \tau)\, P(\tau)\, d\tau \tag{39.3}$$

It can be shown that the unit graph concept and the routing techniques discussed in section 33.3 are all examples of linear dynamic systems involving the principle of superposition.

Non-linear systems are those for which the superposition principle is not satisfied. In general, the response of a non-linear, lumped-parameter system to an input can be expressed either by an ordinary non-linear differential equation or by the equation:

$$\begin{aligned} Q(t) = {} & \int_o^t h(\tau)\, P(t-\tau)\, d\tau + \int_o^t \int_o^t h(\tau_1, \tau_2)\, P(t-\tau_1)\, P(t-\tau_2)\, d\tau_1\, d\tau_2 + \ldots \\ & + \int_o^t \ldots \int_o^t h(\tau_1, \tau_2, \ldots \tau_n)\, P(t-\tau_1)\, P(t-\tau_2) \ldots P(t-\tau_n) d\tau_1\, d\tau_2 \ldots d\tau_n + \ldots d \end{aligned} \tag{39.4}$$

where $h(\tau_1, \tau_2, \ldots \tau_n)$ is a function expressing the time-invariant characteristics of the physical system. It is analogous to the influence function in equation 39.2. The first term on the right-hand side of equation 39.4 defines the linear properties of the system, while the second defines the quadratic properties, the third defines the cubic properties, etc.

In quasi-linear systems and what may be called semi-lumped models, some account is taken of areal variability [4].

39.3 **Conceptual models** **[J04]**

The models discussed in the previous section make use of only very general concepts of the transformation of input data into the outflow hydrograph. For some purposes, such an approach is inadequate. Catchment modelling problems involving complex rainfall to runoff transformations usually do not respond well to this type of analysis, nor do many types of water-resource studies in which it is necessary to evaluate the effects of weather modification, changes in land use, and other of man's activities. As a result, an approach to modelling has been developed that involves equation structures based on various concepts of the physical processes of flow formation. These are commonly referred to as conceptual models.

One of the most difficult aspects of applying conceptual models is the calibration of a chosen model to a particular catchment. Most of the parameters are determined by iterative processes that use historical input-output data. Due to data limitations, model imperfections, and the interrelationships among the parameters, a small increase in the number of parameters is likely to have a major effect on the difficulty experienced in attempting calibration. It is necessary, therefore, that the number of parameters be compatible with the reliability of the input data and the required accuracy. In other words, modern concepts of theoretical merit must usually be simplified in favour of utility.

A wide variety of conceptual models are described in the literature [5]. Under the circumstances, it seems appropriate to limit the discussion to a brief description of three models, representing a reasonable cross-section of those suitable for treatment in this *Guide.*

39.3.1 *Model of the Hydrometeorological Centre of the former U.S.S.R.*

This model uses conceptual formulations to derive catchment losses, and then applies a systems approach to route the runoff volumes to the catchment outlet [6]. The rate of water yield, P_i, from the catchment in the form of surface runoff is computed from the equation:

$$P = h - E - I \qquad (39.5)$$

where h is the average intensity of precipitation during the selected time interval (six hours, 24 hours, etc.), E is the corresponding evapotranspiration, and I is the average intensity of infiltration (equation (39.8)). The mean evapotranspiration over the catchment is derived from the equation:

$$E\ (k_1 D + k_2 D_u)\ e^{-d/W} \qquad (39.6)$$

where D is the saturation deficit of the air, u is the wind speed, k_1, k_2, and W are empirical parameters, and the saturation deficit of the soil d is derived from the water-balance equation:

$$d = W - \int_{t_o}^{t} (E + Q + I - h)\, d\tau \qquad (39.7)$$

in which Q is outflow and t_o is the time when $d = 0$. The average intensity of infiltration is derived from the equation:

$$I = \frac{d}{k_3} + i_o \qquad (39.8)$$

where k_3 and i_o are empirical parameters.

The surface runoff is derived from water yield by the equation:

$$P_s = P_r \left[1 - e^{-m} \int_{tn}^{t} P dt \right] \qquad (39.9)$$

where t_n is the time runoff begins, and r and m are empirical parameters. The subsurface runoff is calculated from the equation:

$$P_i = i_o \, e^{-k_4 d} \qquad (39.10)$$

where k_4 is an empirical parameter.

The surface and subsurface runoff inputs are transformed separately, so that the outflow hydrograph is derived from the equation:

$$Q(t) = \int_o^t h_1 (t - \tau) \, P_s (\tau) \, d\tau + \int_o^t h_2 (t - \tau) \, P_i(\tau) \, d\tau \qquad (39.11)$$

in which $h_1(t)$ and $h_2(t)$ are influence functions (equation 39.3).

Examination of equations 39.5 to 39.11 will show that the model contains 12 empirical parameters, i.e., $k_1, k_2, k_3, k_4, i_o, m, r, W,$ and four parameters of the influence function.

39.3.2 *Sacramento model* [J04]

The Sacramento model was developed by the staff of the National Weather Service River Forecast Center in Sacramento, California, U.S.A. [7]. This model embodies a complex moisture-accounting algorithm to derive volumes of several runoff components, while a rather simple and highly empirical method is used to convert these inputs to the outflow hydrograph. The soil mantle is treated in two parts, an upper zone and a lower zone, with each part having a capacity for tension water and free water. Tension water is that which is closely bound to the soil particles and is depleted only by evapotranspiration. Provision is made for free water to drain downward and horizontally. The storage capacities for tension and free water in each zone are specified as model parameters. Water entering a zone is added to tension storage so long as its capacity is not exceeded, and any excess is added to free water storage.

A portion of any precipitation is diverted immediately to the channel system as direct runoff. This is the portion that falls on the channel system and on impervious areas adjacent thereto. The extent of this area is time variant in the model. All rainfall and snow melt, other than that diverted to direct runoff, enters the upper zone. Free water in the upper zone is depleted either as interflow or as percolation to the lower zone. If the rate of moisture supply to the upper zone is greater than the rate of depletion, then the excess becomes surface runoff. Free water in the lower zone is divided between primary (slow drainage) storage and secondary storage. Figure 39.2 illustrates the principal features of the model. Percolation from the upper to the lower zone is defined as:

$$\mathrm{PRATE} = \mathrm{PBASE}\left[1 + \mathrm{ZPERC} * \mathrm{RDC}^{\mathrm{REXP}}\right]\frac{\mathrm{UZFWC}}{\mathrm{UZFWM}} \qquad (39.12)$$

where PRATE is the percolation rate, and PBASE is the rate at which percolation would take place if the lower zone were full and if there were an unlimited supply of water available in the upper zone. It is numerically equal to the maximum lower-zone outflow rate and is computed as the sum of the lower-zone primary and secondary free-water capacities, each multiplied by its depletion coefficient. RDC is the ratio of lower-zone deficiency to capacity. That is, RDC is zero when the lower zone is full and it is in unity when it is empty. ZPERC is a model parameter that defines the range of percolation rates. Given an unlimited supply of upper-zone free water, the rate will

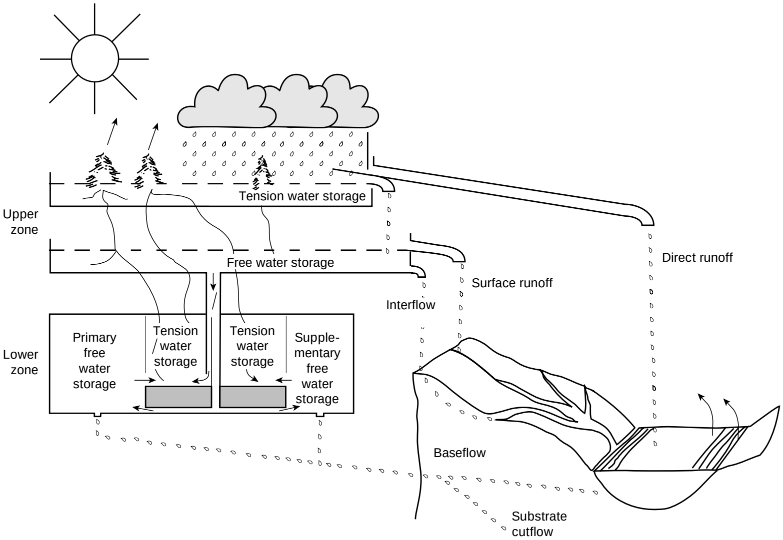


Figure 39.2 — Structure of the Sacramento model.

vary from PBASE (lower zone full) to PBASE(1+ ZPERC) when the lower zone is empty. REXP is a model parameter that defines the shape of the curve between the minimum and maximum values described above. UZFWC is the upper-zone free-water content. UZFWM is the upper-zone free capacity. The ratio, UZFWC/UZFWM represents the upper-zone driving force. With the upper zone empty, there will be no percolation. With it full, the rate will be governed by the deficiency in the lower zone.

This equation is the core of the model. It interacts with other model components in such a way that it controls the movement of water in all parts of the soil profile, both above and below the percolation interface, and, in turn, is controlled by the movement in all parts of the profile. Evapotranspiration rates are estimated from meteorological variables or from pan observations. Either day-by-day or long-term mean values can be used. The catchment potential is the product of the meteorological evapotranspiration and a multiplier that is a function of the calendar date, which reflects the state of the vegetation. The moisture accounting within the model extracts the evapotranspiration loss, directly or indirectly, from the contents in the various storage elements and/or from the channel system. The loss is distributed according to a hierarchy of priorities and is limited by the availability of moisture as well as by the computed demand.

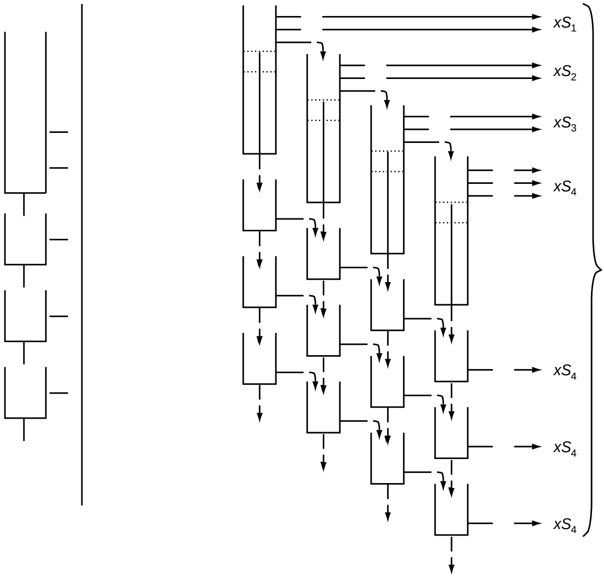
The movement of moisture through the soil mantle is a continuous process. The rate of flow at any point varies with the rate of moisture supply and with the contents of relevant storage elements. This process is simulated by a quasi-linear computation. A single time-step computation of the drainage and percolation process involves the implicit assumption that the movement of moisture during the time step is defined by the conditions existing at the beginning of the step. This approximation is acceptable only if the time step is relatively short. In the model, the length of the step is volume dependent. That is, the step is selected in such a way that no more than five millimetres of water may be involved in any single execution of the computational loop.

Five components of runoff are derived in the model. The three upper components (direct, surface, and interflow) are summed and transformed by a unit hydrograph (section 33.3). The two components from the lower zone, primary and secondary base flow, are added directly to the outflow hydrograph derived from the other three components. Provision is also made for routing the resultant hydrograph with variable routing coefficients.

39.3.3 ***Tank model*** **[J04]**

This model was developed at the National Research Center for Disaster Prevention in Tokyo, Japan [8]. As the name implies, the soil mantle is simulated by a series of tanks arranged one above the other, as shown in Figure 39.3 (*a*). All rainfall and snow melt is assumed to enter the uppermost tank. Each tank has one outlet in the bottom and one or two on a side at some distance above the bottom. Water that leaves any tank through the bottom enters the next lower tank, except for the lowermost tank in which case the downflow is a loss to the system. Water leaving any tank through a side outlet (sideflow) becomes input to the channel system. The number of tanks and the size and position of the outlets are the model parameters.

The configuration is a suitable representation of the rainfall-runoff process in humid regions, but a more complex arrangement is required for catchments in arid and semi-arid areas, as shown in Figure 39.3 (*b*). If extended dry periods are typical, two or more series of tanks, as described above, are placed in a parallel arrangement. The downflows in each series are the same as for the simple tank model. Each tank in each series contributes sideflow to the corresponding tank of the next series, except that all sideflow from the last series feeds directly into the channel system. Additionally, provision is made for sideflow from the uppermost tank in all other series to feed directly into the channel system. Each series is considered to represent a zone of the catchment, the lowest corresponding to the zone nearest the channels. As hydrological conditions make their seasonal progression from wet to dry, the zone nearest the channels can continue to be relatively wet after the one furthest removed has become rather dry. The originators of the model do not claim that the representation of storage elements is entirely realistic, but rather that the



(*a*) (*b*)

Figure 39.3 — Tank model.

configuration of tanks is an approximation somewhat resembling the finite-element method. Furthermore, the mathematical formulations defining the flow of water through the tanks resemble classical hydrological concepts.

Two types of water are recognized in the model, confined water (soil moisture), and free water that can drain both downward and horizontally. Provision is also made for free water to replenish soil moisture by capillary action. The model computes evapotranspiration loss from the catchment based on measured or estimated daily evaporation, on the availability of water in storage, and on a hierarchy of priorities from the different storage elements.

The basic numerical calculation within a tank involves a withdrawal function defined by:

$$\frac{dx}{dt} = \alpha x \tag{39.13}$$

where x is the contents of the tank and t is time. The outflow in a finite unit of time, Δt, is therefore $(1 - e^{-\alpha\Delta t})\, x$. The quantity $(1 - e^{-\alpha\Delta t})$ is computed for each outlet, based on the value of α and the specified time interval.

The computation for each time interval proceeds in the following order:

(*a*) For the uppermost tank:
  (i) Extraction of evapotranspiration;
  (ii) Transfer of free water to soil moisture;
  (iii) Addition of rainfall and snow melt; and
  (iv) Calculation and extraction of channel system input (sideflow) and percolation (downflow) from free water contents.

(*b*) For a lower tank:
  (i) Extraction of evapotranspiration, depending on hierarchy of priorities;
  (ii) Transfer of free water to soil moisture;
  (iii) Addition of percolation water from tank immediately above; and
  (iv) Calculation and extraction of channel system input (sideflow) and percolation (downflow) from free water contents.

The input to the channel system is the output from the moisture-accounting phase of the model. The outflow hydrograph is derived from the channel system input by routing, assuming that:

$$Q = KS^2 \tag{39.14}$$

where Q is outflow, S is channel storage, and the constant K is an additional parameter of the model. A limit of unity is imposed on dQ/dS to prevent the outflow from exceeding channel storage.

One interesting feature of the tank model is that changes in the values of model parameters can actually change the structure of the model.

39.3.4 *Selection of models*

The choice of models is not restricted to the models described above. It is often difficult to ascertain the relative advantages and disadvantages of models proposed for operational use. The selection of a model for a specific hydrological situation has implications in water-resources planning, development, and management. Some of the factors and criteria involved in the selection of a model include the following:

(*a*) The purposes and benefits of the model-output, e.g., continuous hydrograph of discharges, forecast of floods, water quality, water-resource management;
(*b*) The climatic and physiographic characteristics of the basin;
(*c*) The lengths of the records of the various types of data;
(*d*) The quality of the data both in time and space;
(*e*) The availability and size of computers for both development and operation of the model;
(*f*) The possible need for transferring model parameters from smaller catchments to larger catchments; and
(*g*) The ability of the model to be updated on the basis of current hydrometeorological conditions.

A WMO international project on the intercomparison of conceptual models used in operational hydrological forecasting, which was completed in 1974, produced useful information and guidance on the selection and application of conceptual models in various hydrological conditions. Ten operational conceptual hydrological models were tested on data sets obtained from six catchments with varied climatological and geographical conditions. The results of the project are summarized in the WMO *Intercomparison of Conceptual Models Used in Operational Hydrological Forecasting* [5]. They should be considered only as examples.

39.4 Hydrodynamic models

Recently, hydrological research has knowledge of the physical processes that comprise the hydrological cycle. Similarly, the high technology employed in continuous data acquisition and integration in time and space, combined with modern computers, permit rapid processing of hydrological and meteorological data of all types. All this has contributed to improvement of the third type of modelling, hydrodynamic.

Hydrodynamic models are based on a refined space discretization of the catchment and on numerical integration of equations of momentum and mass conservation that describe the physical processes in the basin.

Such models provide a basis for full use of distributed information relevant to the physical processes in the catchment.

Since hydrodynamic models are based on the physical laws governing the processes, extrapolation beyond the range of calibration may be performed more confidently than with conceptual models.

The European Hydrologic System (SHE) [9] is an example of a hydrological model. It is illustrated in Figure 39.4. SHE is a model with distributed parameters that has been developed from partial differential equations describing the physical processes in the basin: interception, evapotranspiration, overland and channel flow, movement of water through unsaturated and saturated zones, and snow melt.

The interception process is represented by a variant of the Rutter model [10] that gives the rate of change in the amount of water stored on the canopy:

$$\frac{\partial c}{\partial t} = Q - Ke^{b}\left(C - S\right) \tag{39.15}$$

where: $Q = \begin{cases} P_1 P_2 \,(P - E_p\, C/S) & \text{when } C < S \\ P_1 P_2 \,(P - E_p) & \text{when } C \geq S \end{cases}$

C is the actual depth of water on the canopy, S is the canopy storage capacity, P is the rainfall rate, P_1 is the proportion of ground in planview hidden by vegetation, P_2 is the ratio of total leaf area to area of ground covered by vegetation,

$P_1\, P_2 = P_1\;\; P_2$ when $P_2 < 1$

$P_1\, P_2 = P_1$ when $P_2 \geq 1$

E_p is the potential evaporation rate, K and b are drainage parameters, and t is time.

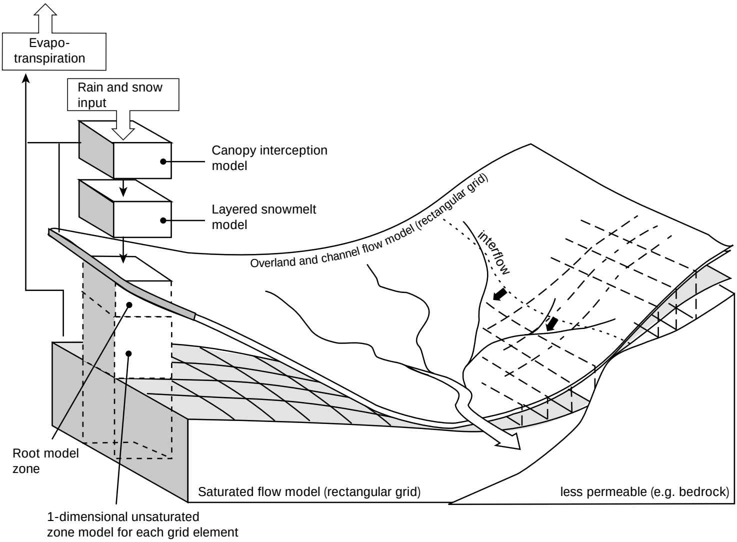


Figure 39.4 — Structure of the European Hydrologic System.

For the prediction of actual evapotranspiration rates, the Penman-Monteith equation [11] is used:

$$E_a = \frac{\Delta R_n + \dfrac{\varphi\, C_p\, v_e}{r_a}}{\lambda\left[\Delta + \gamma\left(17\, v_s/r_a\right)\right]} \tag{39.16}$$

where φ is the density of air, λ is the latent heat of vaporization of water, E_a is the actual evapotranspiration rate, R_n is the net radiation minus the energy flux into the ground, Δ is the slope of the specific humidity/temperature curve, C_p is the specific heat of air at constant air pressure, v_e is vapour pressure deficit of the air, r_a is the aerodynamic resistance to water vapour transport, v_s is the canopy resitance to water transport, and γ is the psychometric constant.

The total actual evapotranspiration depends on the wetness of the canopy and on the degree of ground coverage by the canopy:

$$E_t = P_1 P_2\, E_p\, c/s + E_a\,(1 - c/s)\, P_1 P_2 + E_{as}\,(1 - P_1 P_2) \tag{39.17}$$

where E_t is the total evapotranspiration rate, E_a is the acutal evapotranspiration rate, E_p is the potential evapotranspiration, and E_{as} is the soil evaporation.

Water accumulated on the soil surface responds to gravity by flowing downgradient over the land surface to the channel system, where it subsequently discharges through the stream channels to the outlet of the catchment. Both phenomena are described by equations of unsteady free-surface flow, based on physical principles of conservative of mass and momentum [9].

In the most comprehensive mode, the flow in the unsaturated zone can be computed by using Richards' equation:

$$C = \frac{\partial \Psi}{\partial t} = \frac{\partial}{\partial Z}\left(K\,\frac{\partial \Psi}{\partial Z}\right) + \frac{\partial K}{\partial Z} + S \tag{39.18}$$

where ψ is the pressure head, t is the time variable, Z is the vertical coordinate (positive upwards), $C = \partial \Theta/\partial \Psi$ is the soil-water capacity, θ is the volumetric moisture content, K is hydraulic conductivity, and S is a source/sink term.

The infiltration rate into the soil is determined by the upper-boundary condition, which may shift from flux-controlled conditions to soil-controlled (saturated) conditions and vice versa. The lower boundary is usually the phreatic-surface level.

The governing equation describing the flow in the saturated zone is the nonlinear Boussinesq equation:

$$S\,\frac{\partial h}{\partial t} = \frac{\partial}{\partial x}\left(K_x\, H\,\frac{\partial h}{\partial x}\right) + \frac{\partial}{\partial y}\left(K_y\, H\,\frac{\partial h}{\partial y}\right) + R \tag{39.19}$$

where S is the specific yield, h is the phreatic surface level, K_x, K_y are the saturated hydraulic conductivities in the x and y directions, respectively, H is the saturated thickness, t is the time variable, x, y are the horizontal space coordinates, and R is an instantaneous recharge/discharge term.

Equation 39.19 combines Darcy's law and the mass conservation of two-dimensional laminar flow in an anisotropic, heterogeneous aquifer. The recharge/discharge term R in equation 39.19 can be expressed by:

$$R = \Sigma q - \frac{\partial}{\partial t} \int_h^{qs} \theta\,(Z,t)\,dz \tag{39.20}$$

where Σq includes the transpiration q_R, the soil evaporation q_s, the infiltration q_I, the stream/aquifer exchange q_O, the external boundary flows q_e, and the soil-moisture content in the unsaturated zone θ.

The snow melt component of SHE represents an attempt to model both energy and mass flux within a snowpack by taking into account changes in the structure of the pack [12].

Two semi-empirical equations are used to complete the set of relationships required to define temperature and water-content distributions. Empirical equations are also used to define the hydraulic and thermal properties of the snow in terms of the structure, water content, and temperature.

39.5 **Parameter evaluation**

General methods of parameter evaluation or identification, sometimes referred to as model calibration, have been developed for a wide range of dynamic systems. Experience has shown that the success of such methods depends on the availability of adequate information concerning the system characteristics and the form of the influence function. There are two basic approaches to calibration. In the first approach, the mathematical model is combined with the data to solve for the unknown coefficients, the system parameters. Such systems of equations are usually difficult to solve because the solutions tend to be unstable and may have multiple solutions. The second approach involves experimentation with various combinations of parameter values in an effort to minimize (or maximize) some adopted criterion of optimization. A number of strategies have been developed by applied mathematicians with a view to minimizing the number of calculations required in the optimization of parameter values. Some of the strategies used in hydrology are the gradient method, the coordinate slope method, and the pattern search method [6, 13]. The adequacy of the solution can be highly dependent on the criterion used in the analysis. A number of criteria have been developed and introduced through WMO projects [5, 14]. These can be recommended for general use.

In order to determine the parameters of complex, conceptual hydrological models having several components, the following principles are recommended:

(*a*) Separate testing of the model components using all experimental and scientific information — It is a well known fact that the global determination of all parameters of a model through optimization may result in non-realistic values of the parameters, occasionally even outside their physical range. This is the case when certain model components contain systematic errors that are subsequently compensated within the model. In order to avoid such situations, it is recommended that the parameters of complex conceptual models be determined separately for each of the basic components and not globally;

(*b*) Data from a minimum three-year time interval should be used for the calibration of models, and for verification, another time interval of similar length should be used — The calibration and verification intervals should be performed so that they represent all possible conditions favouring runoff formation, e.g., floods generated by rainfalls, floods resulting from snow melting processes, and low waters;

(*c*) In the case of basins with a hydrological regime under anthropogenic influences, it is recommended that the model be calibrated for the natural runoff regime — Afterwards, the values of certain parameters may be modified to account for human influences. The validation of the model parameters should be done for a representative period that is not influenced by human activities.

The parameters of hydrodynamic models represent characteristics of the basin, e.g., the roughness of the slopes and the river bed, the soil hydraulic conductivity, and the soil porosity. In principle, all of these parameters are determined by field measurements and not through optimization.

39.6 Stochastic simulation of hydrological time-series

Stochastic models are black-box models, the parameters of which are estimated from the statistical properties of the observed time-series. Stochastic methods were first introduced into hydrology in connection with the design of storage reservoirs. Annual or monthly flow volumes provide adequate detail for such purposes, but the capacity of the reservoir must reflect the probability of occurrence of critical sequences of flow that can best be evaluated from a set of flow traces (sequences). Each trace must span a period of many years and should be indistinguishable from the historic record in so far as its relevant statistical characteristics are concerned. The statistical properties of the historical record that are to be preserved are of primary concern in the selection of an appropriate stochastic model. Modelling is much more difficult when it becomes necessary to generate simultaneous flow sequences for two or more reservoir sites in a basin because of the requirement that intercorrelations be preserved [15, 16].

Stochastic modelling has also been used in the establishment of confidence limits (probabilities) of real-time flow forecasts, and for the generation of precipitation input data for deterministic models [17, 18]. Since such applications have been extremely limited or even experimental in nature, they are not given further treatment here.

39.6.1 ***Markovian lag-1 models***

Many models for simulating monthly, seasonal, or annual flow volumes assume a first-order Markov structure, i.e., that the flow in any period is determined by that in the preceding period and a random impulse [19-23]. One such model for monthly flow can be expressed as [22]:

$$Q_i = \overline{Q}_j + \rho_j \frac{\sigma_j}{\sigma_{j-1}} \left(Q_{i-1} - \overline{Q}_{j-1} \right) + \varepsilon_i \ \sigma_j \sqrt{1-\rho_j^2} \qquad (39.21)$$

in which Q_i is the flow of the *i*th member of the series numbering consecutively from 1 regardless of month or year, *j* is the month in which the *i*th member of series falls, Q_j is the mean flow for the *j*th month, σ_j is the standard deviation for the *j*th month, ρ_j is the serial correlation coefficient between Q_j and Q_{j-1}, ε_i is a random variate from an appropriate distribution, with a mean zero, unit variance, and serial independence. Equation 39.21 is also suitable for seasonal flows (j = 1, 2, 3, or 4) and annual flows (j = 1). In the latter case, equation 39.21 becomes:

$$Q_i = \overline{Q} + \rho \left(Q_{i-1} - \overline{Q} \right) + \varepsilon_i \ \sigma \sqrt{1-\rho^2} \qquad (39.22)$$

Values of $\overline{Q}$, σ and ρ, derived from the historical record, are assumed to be applicable for the purposes to be served, and one need only select an initial value of Q_{i-1} to simulate a series of any length. Monte Carlo techniques are normally used with sequential values of the random variate derived by computer.

In principle, the development and application of the models depicted in equation 39.21 are relatively straightforward and simple. Nevertheless, there are several matters requiring careful consideration and decisions that may be critical to the particular problem under study:

(*a*) What is the distribution of the random variate [24]?
(*b*) Should the variance be corrected for serial correlation, if present [25]? and
(*c*) How accurate is the calculated value of the serial correlation [26]?

39.6.2 ***Autoregressive moving average (ARMA) models***

An important extension of the univariate stochastic models is represented by the ARMA group developed by Box and Jenkins [27-30]. There are three types — the autoregressive (AR), the moving average (MA), and the mixed (ARMA). The first two types (of order *p* and *q*) are, respectively:

$$x_t = \varepsilon_t + \Phi_1 x_{t-1} + \Phi_2 x_{t-2} + \ldots + \Phi_p x_{t-p} \tag{39.23}$$

$$x_t = \varepsilon_t - \theta_1 x_{t-1} - \ldots - \Phi_q \varepsilon_{t-q} \tag{39.24}$$

where x_t is the deviation of the *t*th observation from the series mean, Φ_i and θ_i are parameters to be estimated, and ε_t is a random variate as defined above. The third type (ARMA) is a combination of the first two, containing all non-repetitive terms of equations 39.23 and 39.24.

A systematic approach has been developed for fitting ARMA models [27]:

(*a*) Identification — The correlogram of the series under study is compared with the autocorrelation functions of various ARMA models for selecting the appropriate type and order;
(*b*) Estimation — The parameters of the model are estimated by using iterative least squares with the condition that the residuals are independently distributed and their sum of squares is a minimum;
(*c*) Diagnostic checking — The randomness of the residuals is checked to verify the adequacy of the selected model.

ARMA models are used to generate synthetic flow sequences by Monte Carlo techniques in the manner previously described. It must be noted again, however, that methods of stochastic generation should be used with caution and with critical consideration of the characteristics of the record that are important for the water-resources project under study.

39.6.3 *Fractional gaussian noise and broken-line process models*

The discovery by Hurst [31-33] that very long geophysical records display characteristics that are not in accord with stationary Markovian processes led to the development of two stochastic models that can accommodate long-term persistence (low frequency) elements. The first of these, the fractional gaussian-noise (FGN) model [34-37] is a self-similar, random process characterized by a spectral density function that emphasizes very low frequencies typifying the Hurst phenomenon. It also has been shown that a long-memory model of the broken-line process will preserve the Hurst phenomenon [38, 39].

The findings of Hurst do not necessarily indicate very long-term persistence [40, 41] and, moreover, some versions of ARMA models are capable of simulating substantial low frequency effects [42]. The non-stationarity of the process mean value could also result in the characteristics that Hurst found in analysing long records, whether these be the result of climatic change, man's activities, or simply non-homogeneity of the data series.

39.7 **Water quality modelling**

39.7.1 ***General***

The management of water quality in natural and artificial water bodies is a complex task that requires monitoring of the water quality characteristics, interpretation of the monitored data in relation to causative factors, and prediction of future changes in these characteristics in terms of various management alternatives being considered. The solution to these problems can be greatly aided by the use of water quality models. These represent techniques that enable prediction on the basis of:

(*a*) A series of input data on pollution inflow;
(*b*) Meteorological-environmental initial conditions;
(*c*) Hydraulic-hydrological and land-use characteristics of the water body and its watershed; and
(*d*) The evolution in time and/or space of certain water quality characteristics of the water body considered for various water management alternatives. Water quality models are frequently linked to hydraulic and hydrological models.

Water quality models can be used in water quality management for several purposes, including:

(*a*) The design of water quality monitoring networks in space and time;
(*b*) The interpretation of data obtained in relation to factors determining water quality;
(*c*) The interpolation of data in time and space and data assessment;
(*d*) The interfacing with other environmental (air, soil) pollution models and with ecological models;
(*e*) The assessment of trends in water quality without or with various alternative pollution-correction measures; and
(*f*) The forecast of the arrival time of a pollutant and of a concentration profile along the river.

39.7.2 ***Types of models***

Water quality models can be divided basically into the following three categories:

(*a*) Physical models — Intended to reproduce (usually at a reduced scale) the investigated phenomena. Water quality models of this type are usually limited to the study of well-defined processes representing links in a chain of such processes in a natural water body or in a treatment plant, e.g., variation of oxygen content due to a reaeration device and effect of chlorination on certain types of bacteria;
(*b*) Analogue models — Characterized by the use of a convenient transformation of one set of water quality properties into another that is easier to study. For example, certain chemical-biological changes in a river may be represented by certain electrical equivalent properties; and
(*c*) Mathematical models — In which the phenomena are investigated by means of an algorithm that represents, in an analytical form, the relationships between

various inputs in the water body, its hydraulic-hydrologic characteristics, and the time-space variation of the water quality characteristics.

In recent years the development of mathematical water quality models has exceeded by far that of the other two types, mainly as a result of the computational capabilities offered by digital computers. Currently water quality management uses primarily mathematical models. For this reason, only mathematical models are considered in the following discussion.

Mathematical models may also be classified according to:

(*a*) The water quality constituents: into single- or multi-constituent models;
(*b*) The type of constituent modelled: into conservative (e.g., salt), non-conservative physical (e.g., temperature), non-conservative chemical (e.g., dissolved oxygen), or non-conservative biological (e.g., coliform bacteria);
(*c*) The space dimensions considered: into one-dimensional, two-dimensional, or three-dimensional;
(*d*) Time variation: into steady state or dynamic;
(*e*) Method of analysis: into deterministic, stochastic, or mixed.

Further discussion of the classification of water quality mathematical models can be found in [43].

39.7.3 *Models of the pollutant transport in rivers*

For the description of pollutant transport in rivers, the most commonly used model in practical applications is the one-dimensional model based on the advection-dispersion equation:

$$\frac{\partial c}{\partial t} + u\,\frac{\partial c}{\partial x} = D_L\,\frac{\partial^2 c}{a x^2} \qquad (39.25)$$

where c is the pollutant concentration, u is the mean water velocity, D is the longitudinal dispersion coefficient, t is the time, and x is distance.

The longitudinal dispersion coefficient is calculated on the basis of the Fisher equation:

$$D_L = \frac{\sigma^2 U^3}{2L} \qquad (39.26)$$

where U is the mean velocity of the reach, and L and σ^2 are the variance of the concentration curve.

To apply this model to pollutant transport in a river, the river is divided into reaches, of several kilometres each within which the water velocity is considered to be constant. The water velocity within each sector is calculated by means of a hydraulic or hydrological model (section 34.3).

39.7.4 *Applications and examples*

Mathematical models can be used for a variety of purposes as outlined in section 39.7.2. The usefulness of a mathematical model for any of the purposes listed in that section depends on the ability of the user to obtain the required data for calibrating and validating the model, on the availability of a model for the given purposes and conditions, and on the ability to adapt the model to the specific problem and to correctly interpret the results.

Water quality models have been applied with various degrees of success to the solution of water quality management problems in many countries [44]. For example, a relatively simple model was used for investigating the effect on water quality of large-scale water transfers from the Severn river into the Thames river [45]. The model was used to assess the effect of such transfers on the concentration of a number of conservative and nearly conservative substances contained in the water. The model was based on river-flow separation according to source (surface, interface, and base flow) and on developing relationships between the concentrations of the determinants considered and the water inflow and inflow variation for each source. The simulation results approximate reasonably well the recorded data.

Another example of practical application of a water quality model for water management purposes is the study of the effect of removal of BOD loads by waste-treatment plants on the dissolved oxygen concentration in the water of the Thames river in Ontario, Canada [46]. The results indicate that obtaining dissolved oxygen concentrations above the criterion accepted for good water quality by removing BOD load is feasible at one point, while at another point this would be very difficult.

Other examples of water quality models developed and used in the United States are given by Cembrovicz, *et al.* in *Qualitative Modele, Arbeitskreis "Matematische Flussgebietsmodele"* [47] and by Thoman in *Systems Analysis and Water Quality Management* [48]. The WMO *Hydrological Aspects of Accidental Pollution of Water Bodies* [49] provides a detailed review of a number of water quality models applied in Germany, France, England, Poland, Canada, and the United States to a variety of rivers having significant pollution problems.

Water quality models are also used for computing the propagation of accidental pollution events. Such models have been operational on the Rhine river since 1989 [50].

While most of the models mentioned above primarily consider pollutants originating from industrial and municipal wastes, some also consider pollution originating from diffuse sources, e.g., related to forestry and agriculture activities or to non-sewered residences. An example of a model that was used to investigate diffuse sources of BOD from agriculture and unsewered residences, which simultaneously models surface runoff, sediment, and BOD in all points of the river basin, is presented by Solomon, *et al.* in *Application of WATMAP-WATFILE Data Systems in the Development of a Distributed Water Quantity — Water Quality Model for South Nation River Basin* [51].

39.8 Selection of models

The choice of models is not restricted to the models described above. It is often difficult to ascertain the relative advantages and disadvantages of models proposed for operational use. The selection of a model suitable for a specific hydrological situation has implications in water-resources planning, development, and management, in operational hydrological activities, and in setting directions of further research in modelling. Some of the factors and criteria involved in the selection of a model include the following [2]:

(*a*) The general modelling objective: hydrological forecasting-data extrapolation (deterministic simulation) or human influences on the natural hydrological regime;
(*b*) The type of system to be modelled: small watershed, aquifer, river reach, reservoir, or large catchment;
(*c*) The hydrological element to be modelled: floods, daily average discharges, monthly average discharges, groundwater levels, water quality, etc.;
(*d*) The type of model and the description of the most relevant hydrological processes, for instance:
    (i) If minimum streamflow is being investigated in a catchment then the model should cover structures best fit for modelling groundwater;
    (ii) It is very important that a forecasting model should cover an updating component;
(*e*) The climatic and physiographical characteristics of the watershed;
(*f*) Data required for calibration and operation: their type, length, and quality;
(*g*) Model simplicity, as far as both its hydrological complexity is concerned, its ease of application;
(*h*) The possible need for transposing model parameters from smaller catchments to larger catchments; and
(*i*) The ability of the model to be updated conveniently on the basis of current hydrometeorological conditions.

Useful information and guidance on the selection and application of conceptual models in various hydrological situations can be found in several WMO international projects:

(*a*) Intercomparison of conceptual models used in operational hydrological forecasting [5];
(*b*) Intercomparison of models of snow-melt runoff [14]; and
(*c*) Simulated real-time intercomparison of hydrological models [52].

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CHAPTER 40

MEASUREMENT OF PHYSIOGRAPHIC CHARACTERISTICS

40.1 General

The concepts discussed in this chapter cover two quite different physiographic characteristics — the location of feature(s) under study, and their physical response to atmospheric events. By locating these features, it is possible not only to catalogue them, but also to determine their spatial distribution and the climate zone to which they belong.

The features themselves can be examined in terms of points, lines, areas, or volumes depending on the relationship between a particular characteristic and the hydrological regime. For example, streamflow results from the transformation of climatic events (rainfall, snow melt) by the physical complex that comprises a drainage basin. The basin location partially determines the climatic characteristics, which are responsible for meteorological events that drive the hydrology. However, the basins physical characteristics not only control the hydrological response to the meteorological events, but some characteristics, e.g., orography and aspect, can also be causal factors in the determination of the basin’s climate.

40.2 Reference systems

The features of interest may be located surficially by using the international system of meridians and parallels divided into 360 degrees, with the zero meridian passing through Greenwich. This system is the most widely used. Its only disadvantage is that a degree in longitude varies from 111.111 kilometres at the equator to 0 at the pole and represents 78.567 kilometres at a latitude of 45° (a degree in latitude always measures 111.111 kilometres). Local systems and other modes of projection are also in use, e.g., the Lambert system, which is still widely used in France. However, these cannot be recommended in an international guide.

The third dimension, altitude, is located in relation to a given level or reference plane. While local reference datums are sometimes used, mean sea level is the most commonly used datum.

The basic elements used in estimating physiographic parameters are rarely measured directly by the hydrologist, who essentially works with maps, aerial photographs, and, more recently, satellite imagery. Therefore, the accuracy of the evaluation depends upon the accuracy of each type of basic document [1].

40.3 Point measurements

The geometric point is defined here as a unique location on a line or within an area or volume. A point may be a physical element, such as the location of a measuring instrument or the outlet of a basin. It can also be an element of an area (plot of land) on which a given characteristic or set of characteristics is to be defined or measured. The physiographic characteristics attributed to a point may be simple or complex. An example of a simple characteristic of a point on a map is its elevation, which is one of its unique identifiers in three-dimensional space. A more complex characteristic might be a description of the soil profile that underlies the point.

Applications of remote-sensing techniques, starting with aerial photography, has had the effect of expanding the notion of a point to an area (pixel), which may measure up to several km^2. Within their limits of accuracy, available techniques may not be able to distinguish between two points (e.g., an instruments' lack of resolution), and a pixel might be taken to be a point.

The horizontal location of a point, i.e., its position on the globe, is determined by a selected system of coordinates (section 40.2), which fall within the scope of geodesy and topography. A universal system has been invented to make the coding of a point in a catalogue explicit by indicating its geographical position. This is the GEOREP squaring system [2]. Other systems may locate points by their linear distances along a stream from a given origin (e.g., mouth, confluence).

The physiographic description of a point covers its geometric properties (form, relief, slope, etc.) and its permanent physical properties (permeability, nature of rocks, soil structure, land-use type, etc.). The former are limited to the local slope, while the latter comprise a whole range of possible physical properties, expressed in scalar form for a point on a horizontal surface or in vectorial form for a profile (e.g., geological core).

40.4 Linear problems

Any physiographic element is linear if it can be represented by a line on a map or in space. In hydrology, three types of linear elements are common:

(*a*) Boundaries;
(*b*) Isopleths of a permanent feature (e.g., contours); and
(*c*) Thalwegs.

The first two types are linked to areal aspects, which will be examined later.

The thalweg is itself to be considered not only as represented in horizontal projection and longitudinal profile, but also by the way in which it combines with other thalwegs to form a drainage network, which has its own physiographic characteristics. Some drainage network characteristics are linear, e.g., the bifurcation ratio, while others are areal in nature, e.g., the drainage density.

40.4.1 *The stream*

A stream in horizontal projection may be represented, if the scale of the diagram is suitable, by two lines representing its banks. From these two lines, an axis can be drawn equidistant to the two banks. The axis may also be defined as the line joining the lowest points on successive cross-sections. In fact, these elements, the visible banks and the lowest points, are not always very clear, and the map scale does not always permit the banks to be featured properly. Mapping, then, is reduced to representing a stream by a line.

Lengths along a river are measured by following this line and by using a curvometer. The accuracy of the determination depends on the map's scale and quality, as well as on the curvometer's error, which should not exceed six per cent for a distance on the map of 10 centimetres or four per cent for 100 centimetres and two per cent beyond.

The axis of a stream is rarely straight. When it comprises quasi-periodic bends, each half-period is called a meander. The properties and dimensions of meanders have been thoroughly studied by geographers and specialists in river hydraulics [3].

40.4.2 *The drainage network*

Within a basin, streams are organized to form drainage network. In a network, all streams are not the same size, and several systems have been proposed for classifying them. The best known is Horton's, in which any elementary stream is said to be of order 1, any stream with a tributary of order 1 is said to be of order 2, and any stream with a tributary of order x is said to be of order $x + 1$. At a confluence, any doubt is removed by giving the higher order to the longest of the tributaries forming it (Figure 40.1) [1]. This introduces some inaccuracy that was avoided by Schumm by systematically giving order x to the reaches formed by two tributaries of order $x – 1$ (Figure 40.2). The main source of error in such evaluations is to be found in the mapping of the streams, where the definition of the smallest streams is often rather subjective.

Of the linear characteristics of the drainage network that are measurable on a map, the confluence ratio R_c and the length ratio R_l are based on Horton's laws and have been verified for Horton's classification. Given that N_x is the number of streams of order x, and $lm_x=\sum l_x/N_x$ is the mean length of the streams of order x, these laws are expressed by the following relationships:

$$N_x = R_c * N_{x+1} \tag{40.1}$$

and

$$lm_x = R_1 * lm_{x-1} \tag{40.2}$$

which form geometric progressions and may be written as follows:

$$N_x = N_1 * R_{c1-x} \tag{40.3}$$

and

$$lm_x = lm_1 * R_{1x-1} \tag{40.4}$$

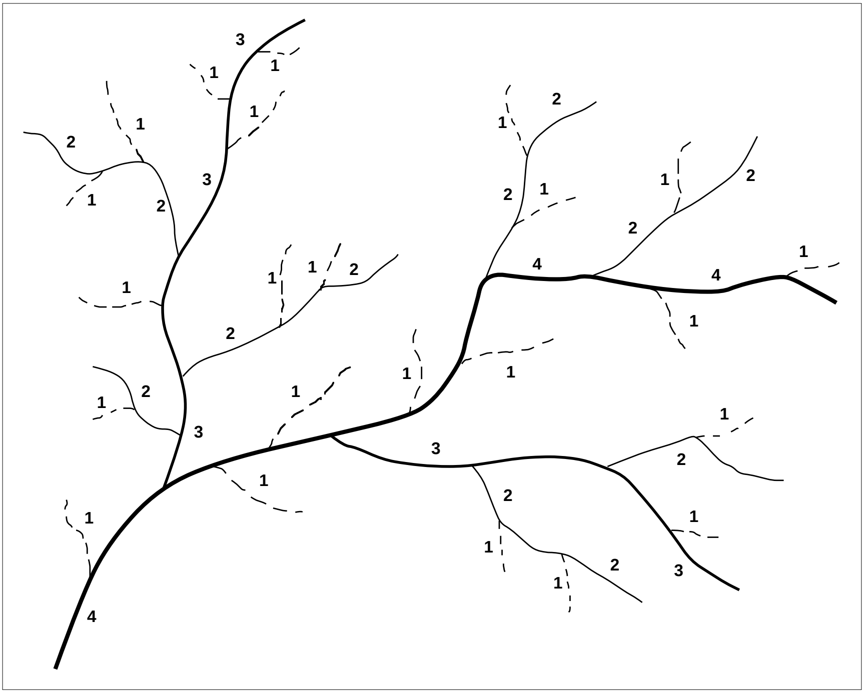


Figure 40.1 — Horton's classification.

where R_c and R_l are calculated as the slopes of the straight lines adjusted to the graph points ($\log N_x$, x) and ($\log lm_x$, x).

40.4.3 ***Stream profile***

The stream profile is the variation in elevation of the points of the stream thalweg as a function of their distance from the origin, which is generally taken as the confluence of the stream with a larger stream or as its mouth. On such a profile, a certain number of topographical features are to be found, such as high points (thresholds), hollows between two thresholds (pools), rapids, waterfalls, and changes of slope that frequently mark the boundary between two reaches with different geologic controls (Figure 40.3).

The average slope of a whole stream is the difference in elevation between its highest point and its confluence or mouth divided by its total length. This notion is simple, but not very useful. On the other hand, knowledge of the slopes of the successive stream reaches is essential for most runoff and hydraulic models.

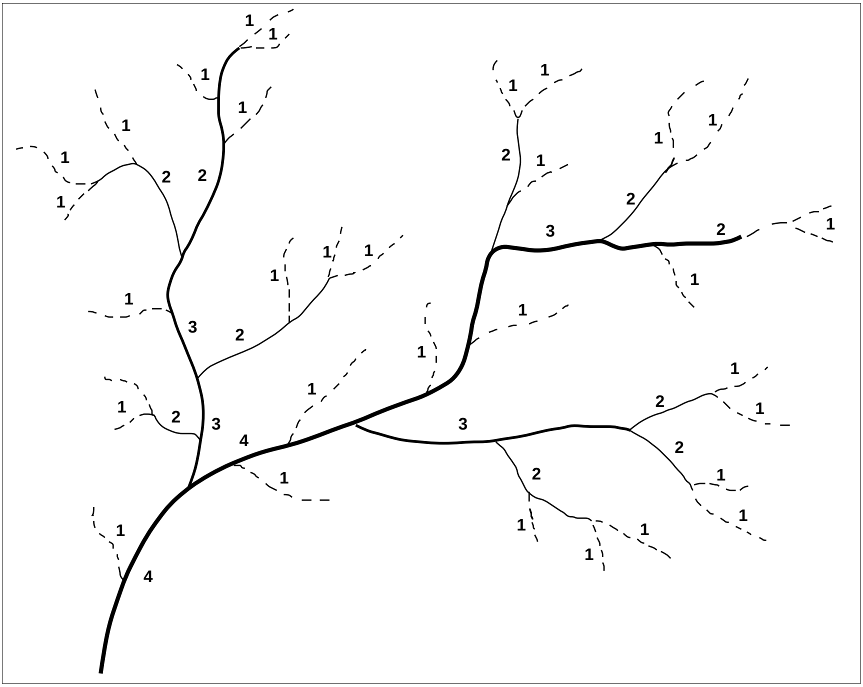


Figure 40.2 — Schumm's classification.

40.4.4 *The drainage network*

The profiles of the main stream and of various tributaries in the same basin can be represented on the same diagram. Figure 40.4 shows examples of stream profiles of the Niger river at Koulikoro and of its main tributaries and sub-tributaries. Such a diagram gives a synthesized view of the variation in slope of the drainage network's elements.

40.4.5 *Cross-section*

The profile of the valley taken perpendicular to a stream's axis is called a cross-section, and a series of these is valuable information for the development of streamflow models. Cross-sections are used in several types of calculations, and the way in which they are established may depend on the use to which they will be put.

An important particular case is the calculation of flow for a discharge measurement, in which elevation is expressed as a depth and is obtained by sounding (section 11.2.2). Cross-sections are usually obtained by making normal topographical measurements during the lowest flows.

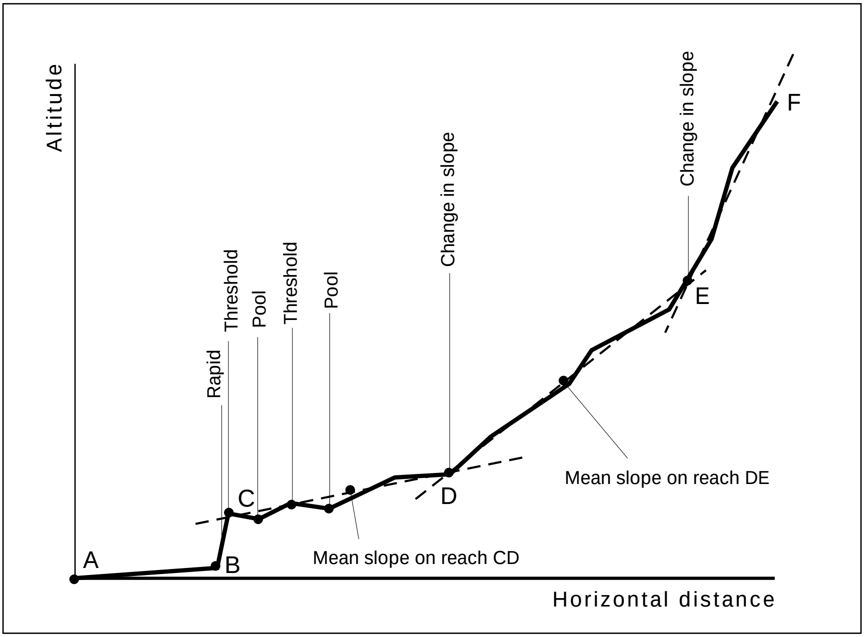


Figure 40.3 — Stream profile.

40.4.6 *Physical characteristics*

The type of material in the stream bed (particularly its cohesiveness), the type and amount of vegetation in and along the stream, and the roughness of the bed, which depends on the longitudinal and transverse distributions of the former, comprise the primary physical characteristics of a stream. Roughness is incorporated in the flow calculations by the indirect method (section 11.6) and in runoff models (Chapter 34).

40.5 Area measurements

40.5.1 *The basin*

The basin is defined as the area that receives precipitation and, after hydrologic processes resulting in losses and delays, leads it to an outflow point. The watershed boundary, the basin's perimeter, is such that any precipitation falling within it is directed towards the outflow, whereas any precipitation falling outside drains to a different basin and outflow. In some cases, the basin boundary may not be easy to determine, e.g., when the head of the main stream is formed in a very flat-bottomed valley or a marshland. The watershed is usually defined by using contour maps or aerial photographs.

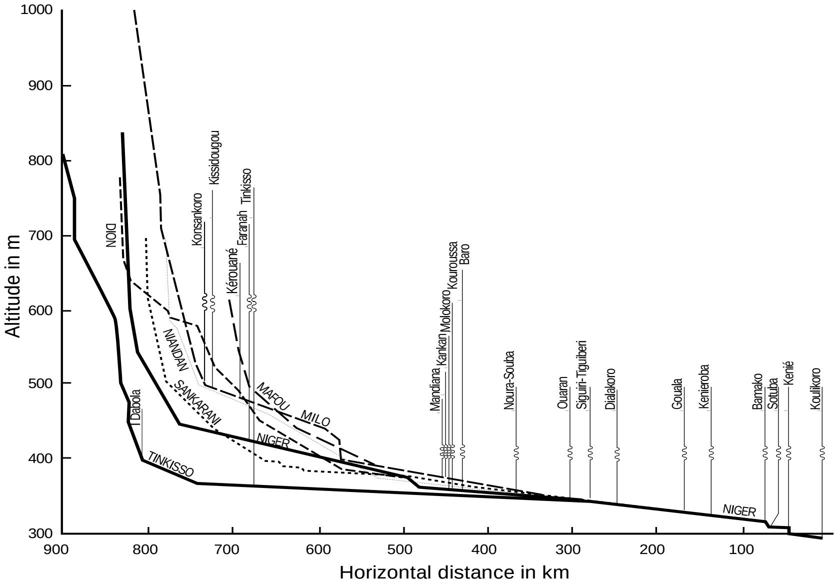


Figure 40.4 — Profile of the Niger river and its tributaries.

The basin perimeter is measured with a curvometer. The measured perimeter is a function of the scale and accuracy of the maps or photographs, of the quality of the curvometer, and the care taken in its use. The ultimate use that will be made of the measurement should determine the accuracy to which it is measured. For certain uses, the contour lines should be smoothed before measuring the perimeter (Figure 40.5).

The basin area is measured by planimetry by following the boundaries established as described above.

The basin's shape is characterized by comparing its perimeter with that of a circle having the same area. If A is the basin area and P its perimeter both measured according to the above rules and expressed in compatible units, then the ratio of the two perimeters is called the Gravelius coefficient of compactness, which is given by:

$$C = 0.282\, P\, A^{1/2} \tag{40.5}$$

The notion of an equivalent rectangle [1] is also linked to the basin's shape, and permits the definition of a particular slope index. The equivalent rectangle has the same area and the same Gravelius coefficient as the basin. The length of this rectangle is:

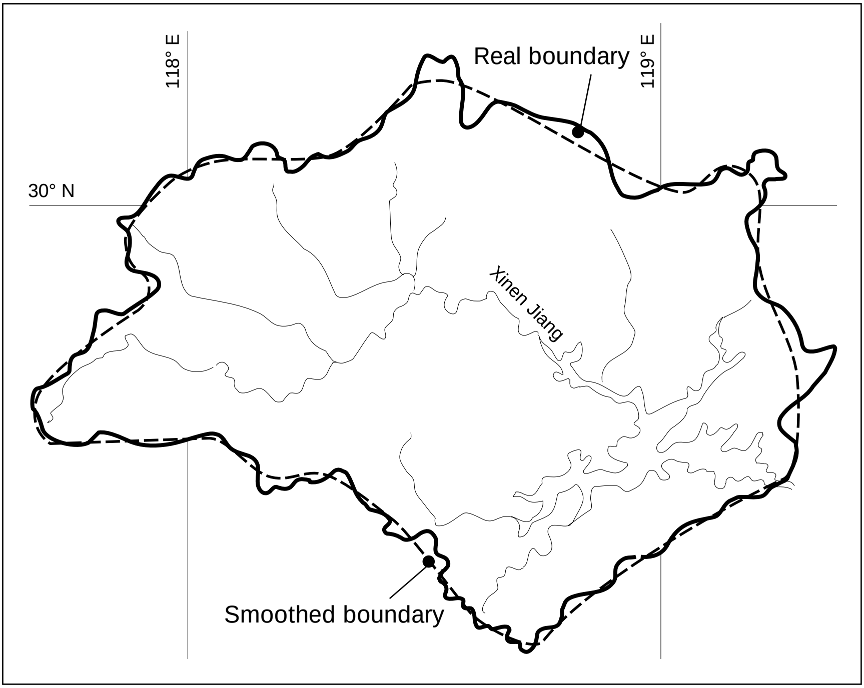


Figure 40.5 — Smoothing of a boundary.

$$L = A^{1/2} \frac{C}{1.128} \left[1 + \sqrt{1 - 1.272 / C^2} \right] \tag{40.6}$$

The drainage density is defined as the total length of streams of all orders contained in the basin's unit area:

$$D_d = (\Sigma L_x) / A \tag{40.7}$$

where L_x is the total length of the streams of order x. In common practice, the lengths are expressed in kilometres and the areas in square kilometres.

The basin relief, shown on maps by contours, can be described by the hypsometric distribution or the hypsometric curve. Figure 40.6 shows a representation of relief in two contiguous basins. The elevation ranges are shown by different marking.

The hypsometric distribution gives the percentage (or fraction) of the basin's total area that is included in each of a number of elevation intervals. The hypsometric curve shows, on the ordinate, the percentage of the drainage area that is higher than or equal to the elevation that is indicated by the corresponding abscissa

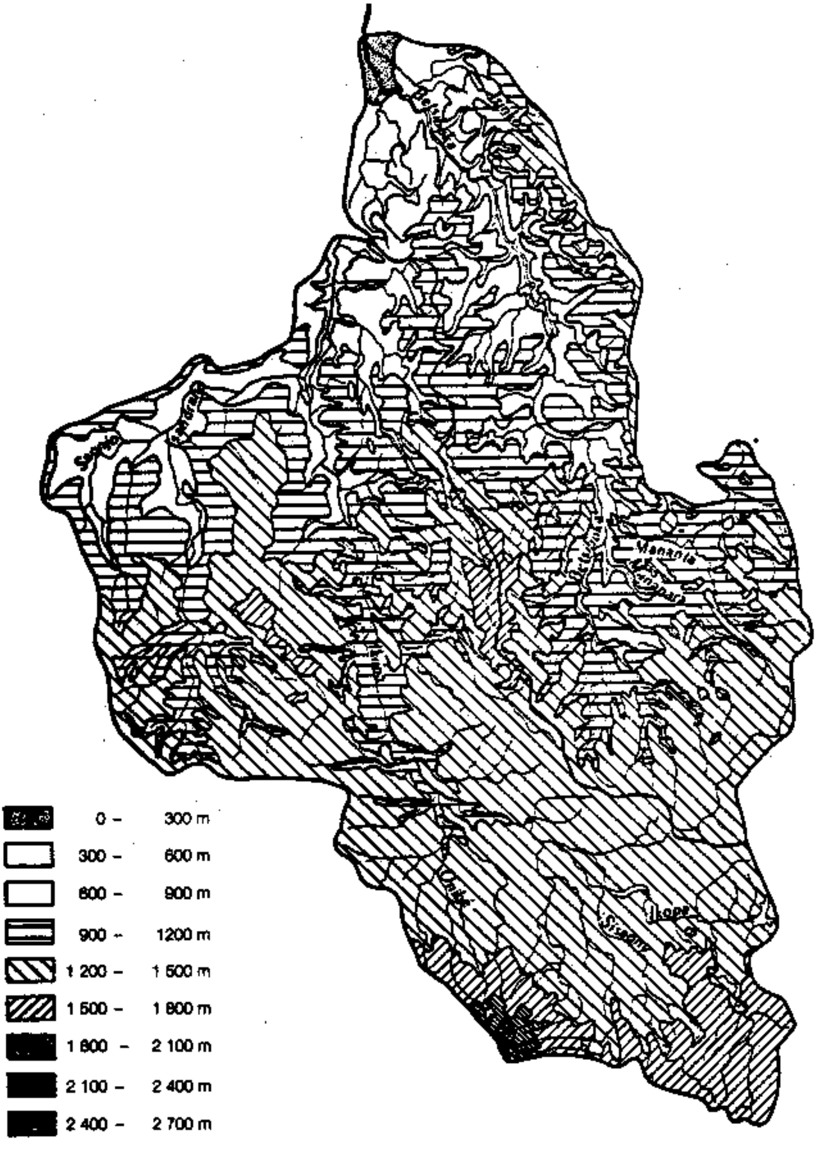
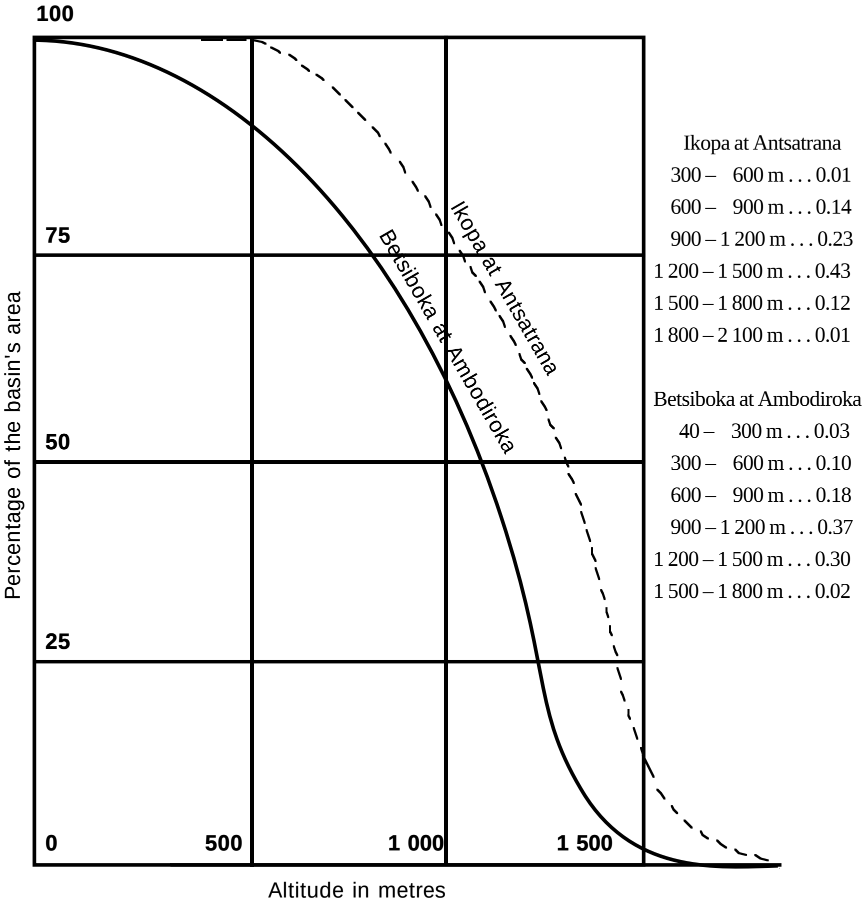


Figure 40.6 — Relief and drainage network.



Ikopa at Antsatrana
300 – 600 m . . . 0.01
600 – 900 m . . . 0.14
900 – 1 200 m . . . 0.23
1 200 – 1 500 m . . . 0.43
1 500 – 1 800 m . . . 0.12
1 800 – 2 100 m . . . 0.01

Betsiboka at Ambodiroka
40 – 300 m . . . 0.03
300 – 600 m . . . 0.10
600 – 900 m . . . 0.18
900 – 1 200 m . . . 0.37
1 200 – 1 500 m . . . 0.30
1 500 – 1 800 m . . . 0.02

Figure 40.7 — Hypsometric curves.

(Figure 40.7). In practice, the cumulative distribution of area is obtained by planimetric calculation of successive areas between contours of elevation beginning with the basin's lowest point.

It is possible to calculate the basin's mean elevation by dividing the area under the hypsometric curve by the length of the ordinate corresponding to the whole basin.

The basin slope can be represented by several indices. The oldest, and perhaps still the most widely used, is the basin's mean slope S_m. It is determined from the basin contours by the formula:

$$S_m = z * \sum 1/A \qquad (40.8)$$

where z is the contour interval, $\sum l$ is the total length of all contours within the basin, and A is the basin's area. The difficulty and main source of error in estimating this characteristic lie in the measurement of $\sum l$. The contours are almost always very tortuous and their real length is not really characteristic of the role they play in calculating the index. It is therefore necessary to smooth the irregularities, but this is much more hazardous than for the basin's perimeter. Therefore, the final results may be somewhat inconsistent and variable.

A mean slope can also be estimated by taking the basin's total difference in elevation and by dividing it by one of its characteristic dimensions. However, the distribution of slopes in the basin is neglected by this approach. One way of avoiding this is to derive the slope index from the hypsometric curve, which is a synthesis of the relief delineated by the contours, and to weigh the areal elements corresponding to the various elevation intervals by a non-linear function of the mean slope in each interval. Roche's slope index, also called the index of runoff susceptibility, meets these conditions. The notion of the equivalent rectangle (equation 40.6) is applied to each contour to transform geometrically the contours into parallel straight lines on the rectangle representing the entire basin (Figure 40.8). If a_i and a_{i-1} are the elevations of two successive contours and x_i is the distance separating them on the equivalent rectangle, the mean slope between these two contours is taken to be equal to $(a_i - a_{i-1}) / x_i$, and the slope index is written by designating as $\tilde{n}_i$ the fraction of the basin's total area included between a_i and a_{i-1}:

$$I_\pi = \sum (\tilde{n}_i(a_i - a_{i-1}) / L)^{1/2} \qquad (40.9)$$

The Table below gives the Roche's slope index.

Roche's slope index

Basin	*Length of equivalent rectangle*	*Slope index*
Betsiboka at Ambodiroka	238 km	0.078
Ikopa at Bevomanga	278 km	0.069

A basin's physical characteristics are essentially the soil types, the natural plant cover or artificial cover (crops), and the type of land use (e.g., rural or urbanized areas, lakes, or swamps). They may also be expressed in terms of the basin's reaction to precipitation (i.e., classes of permeability).

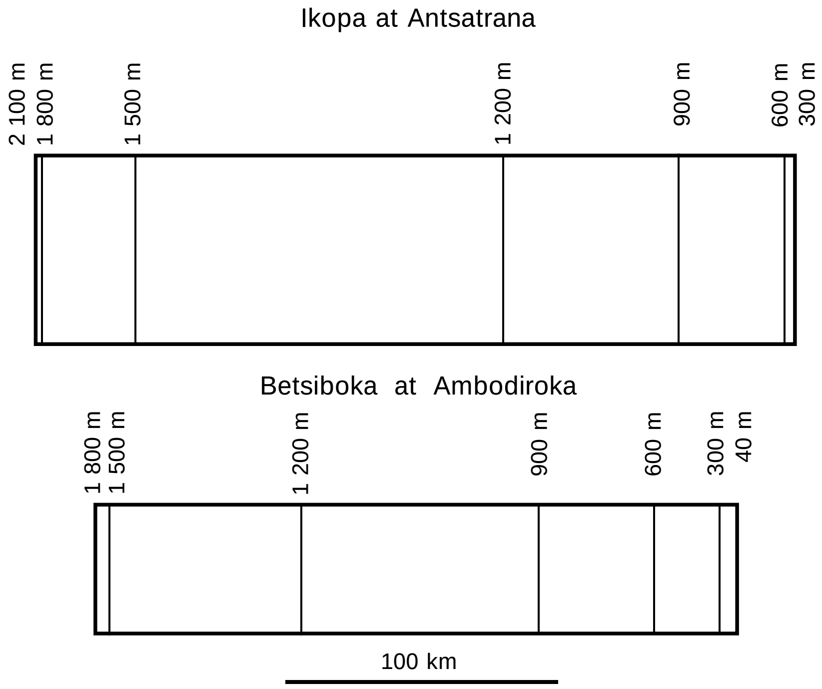


Figure 40.8 — Equivalent rectangles.

The quantification of these characteristics requires definition of criteria and procedures for delineating the areas meeting these criteria. It then only remains to measure each of these areas and to express each as a percentage (or fraction). The tools for determining such distributions are normal and/or specialized cartography, aerial photography, and remote sensing with relatively fine resolution (pixels not to exceed some hundreds of square metres).

40.5.2 *The grid*

The formation of physiographical data banks, especially for the development of rainfall-runoff models with spatial discretization, leads to the division of the basin area based on systematic squaring or griding. Depending on the objective, the grid size may be larger or smaller, and may be measured in kilometres (one or five square kilometres) or based on the international geographical system (1’ or 1° grid). Geographical information systems (section 40.7) have made interchanging between gridded and ungridded data a simple task once the initial databases are assembled.

40.6 Volumetric measurements

Volumetric measurements pertain primarily to the definition of water and sediment storage. Evaluation of groundwater storage is covered by hydrogeology. It therefore will not be discussed here, nor will the estimation of sediment deposited on the soil surface. Surface storages are generally either the volumes of existing lakes or reservoirs, for which bathymetric methods are used, or the volumes of reservoirs that are being designed, for which topographical methods are used.

40.6.1 *Bathymetric methods*

Ordinary maps rarely give bathymetric data on lakes and reservoirs. The volume of an existing reservoir, therefore, has to be measured by making special bathymetric readings. Usually, this is done from a boat by using normal methods for sounding and for positioning the boat. The depths should be referenced to a fixed datum, a stage gauge, or a limnigraph so that variations in stage can be monitored.

Depth measurements can be used to plot isobaths, and the reservoir's volume above a reference plane can be calculated through double integration (generally graphical) of the isobath network. One application of this method is sedimentation monitoring in a reservoir.

40.6.2 *Topographical methods*

Once the site of a dam has been fixed, the calculation of the reservoir's efficiency and management requires knowledge of the curve of volume impounded as a function of the reservoir's stage (stage-volume curve). To determine this relationship, ground-surface-elevation contours are needed throughout the area to be occupied by the future impoundment. This requires maps or topographical plans of the area on scales of between 1/1 000 and 1/5 000. If these are not available, maps on a scale of 1/50 000 can be used for preliminary design, but a topographical survey on an appropriate scale will be needed subsequently.

By using the contour map, planimetric measurements are made of the areas contained within the contours with the hypothetical reservoir in place. A plot of these areas versus their related elevations is known as a stage-area curve. The stage-volume curve is computed from the stage-area curve by graphical integration.

40.7 Geographical information systems

Geographical information systems (GIS) are finding wide application in the fields of operational hydrology and water-resources assessment. Many aspects of data collection and interpretation can be facilitated by means of microcomputer GIS's.

In network planning and design, the ability to map quickly and display surface-water and related stations enables a more effective integration to take place. Network maps, showing basins or stations selected according to record quality, watershed, or operational characteristics can be used for both short-term and long-term planning. The essential features of complex networks can be made very clear.

GIS techniques are being incorporated in hydrologic models for the purpose of extracting and formatting distributed watershed data. In future, such techniques may effectively link atmospheric models (global circulation models) to land-based hydrologic models. Used in conjunction with digital terrain-databases, complete physiographic and hydrologic depiction of basins can be readily accomplished.

Runoff mapping and interpolation is being carried out by GIS routines in several countries. The efficiency of handling large volumes of data means that more comprehensive and detailed maps, isolines, and themes can be prepared. This represents a significant improvement to water-resources-assessment technology, since map preparation is often time-consuming and expensive.

The interpretation of real-time data can also be facilitated through GIS systems. The thematic mapping of stations reporting over threshold amounts or digital indications of rainfall would obviously be very useful to both operational hydrology and forecasting agencies.

GIS systems are now available for common microcomputers in practical, low-cost formats. The main cost factor now resides in the areas of database compilation, and training and updating of technical staff.

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PART E
HYDROLOGICAL FORECASTING

CHAPTER 41
INTRODUCTION TO HYDROLOGICAL FORECASTING

41.1 General

A hydrological forecast is the estimation of the future states of hydrological phenomena. The necessity for such forecasts increases with a country's expanding economy and utilization of its water resources, which implies the best possible management of these resources. However, hydrological forecasts are essential for the mitigation of natural disasters, such as floods or droughts, at all levels of national development. The purpose of this part of the *Guide* is to provide information on the types of forecasts and warnings that are issued (section 41.2), the forecasting services that provide such services (section 41.4), the data requirements for hydrological forecasting (Chapter 42), the techniques that are used in forecasting (Chapter 43), and information on the value and use of hydrological forecasts (Chapters 44, 45, and 46).

41.2 Characteristics of forecasts

Hydrological forecasts and warnings are issued for many purposes, varying from those for short-term events like flash floods to seasonal outlooks of the potential water supply for irrigation, power production, or inland navigation. Techniques for forecasting range from the use of simple empirical formulae and correlations to the use of complex mathematical models representing all phases of the water balance of a river basin.

The calculation of the magnitudes of specific elements of the hydrological regime for a specified time in the future is the main distinction of hydrological forecasts from statistical calculations in which the hydrologist evaluates only the expected probability of the elements.

The dynamics of hydrological processes are driven by meteorological factors, but the changes these factors bring about in the regime do not occur instantaneously. For example, the duration of the runoff caused by precipitation is often many times longer than that of the rainfall itself, and a time lag intervenes between a causative temperature rise, the melting of snow, and a consequential rise in river level. The relatively slow rate at which hydrological processes develop and the fact that they lag behind the more rapid meteorological processes make it possible to forecast some elements of the hydrological cycle.

The basic factors that govern runoff and other hydrological processes can be divided into the following groups:

(*a*) Initial factors, which govern conditions existing at the time the forecast is made, and which can be calculated or estimated on the basis of current hydrological and meteorological observations or measurements;
(*b*) Future factors, which influence hydrological processes after the issue of the forecast. The most important of the natural future factors, namely the future weather conditions, can be taken into account explicitly only if a weather forecast is available.

However, no reliable methods of quantitative forecasting of long-range weather conditions have yet been developed. For this reason, the practical possibilities of extending the lead time of hydrological forecasts depend on the range of pertinent meteorological forecasts (i.e., short, medium, and long term) and on the impact of the evolution of the weather conditions on the forecasted event.

Subject to this limitation, the primary factors that influence the accuracy and timeliness of hydrological forecasts are the accuracy and reliability of the hydrological and meteorological initial conditions, the speed with which they can be assembled at the forecasting centre, the adequacy of the forecasting model, and the size of river basin.

Nevertheless, hydrological forecasts can be issued beyond the period of reliable weather forecasts if they are made contingent on possible weather conditions or if a probabilistic approach for the evolution of these conditions is used. Either contingent or probabilistic forecasts are quite common in seasonal water-supply forecasts.

The basic hydrological elements for which forecasting is of practical interest are:

(*a*) Volume of runoff in various periods of time (e.g., periods of high and low flows, month, season, year);
(*b*) Discharge or stage hydrograph;
(*c*) Peak flood stage or discharge, and the time of its occurrence;
(*d*) Maximum water level in lakes and the date this level will be reached;
(*e*) Average and minimum water levels in navigable rivers and lakes during various calendar periods;
(*f*) Height of waves created by wind on lakes and large reservoirs;
(*g*) Wind set-up in lakes, coastal waters and estuaries; and
(*h*) Water quality elements, such as temperature and turbidity.

Forecasting of the following elements of the ice regime of rivers, lakes, and reservoirs is of practical interest (Chapters 45 and 46):

(*a*) Date on which the formation of floating ice begins in autumn;
(*b*) Freeze-up date;
(*c*) Thickness of ice cover;
(*d*) Date on which ice begins to break up in spring; and
(*e*) Date on which ice disappears completely from lakes and reservoirs.

Forecasts of the following elements of the groundwater and soil-moisture regime may be required:

(*a*) Minimum aquifer level and month of occurrence;
(*b*) Maximum or future aquifer level;
(*c*) Date of ceasing of spring flow; and
(*d*) Date of return to field capacity.

The following are definitions of standard terms used to identify the range of hydrological forecasts:

(*a*) Short-term hydrological forecast — Forecast of the future value of a hydrological element for a period no greater than two days from the issue of the forecast;
(*b*) Medium-term (extended) hydrological forecast — Forecast of the future value of a hydrological element for a period ending between two and 10 days from the issue of the forecast;
(*c*) Long-term hydrological forecast — Forecast of the future value of a hydrological element for a period extending beyond 10 days from the issue of the forecast;
(*d*) Seasonal hydrological forecast — Forecast of the future value of a hydrological element for a season (usually covering a period of several months or more);
(*e*) Hydrological warning — Emergency information on an expected hydrological phenomenon that is considered to be dangerous.

Hydrological forecasts have six main characteristics:

(*a*) The forecast variable, the hydrological element being forecasted;
(*b*) Lead time, also known as forecast period or forewarning period;
(*c*) The computational methods;
(*d*) The purpose of the forecast;
(*e*) The form of presentation, e.g., single expected value, total hydrograph, probability distribution; and
(*f*) The means of dissemination.

41.3 **Effectiveness of hydrological forecasts**

Hydrological forecasts are valuable for the rational regulation of runoff, the utilization of river energy, inland navigation, irrigation (especially in arid regions), water supplies, and water quality management. Forecasts are also of great importance in coping with dangerous phenomena on rivers. As a result of advanced flood warnings, steps can be taken to prevent loss of life and damage to property, so that the disruption of activities and the destruction wrought by these natural calamities can be kept to a minimum.

Hydrological forecasts are also important in designing and during the construction and operation of hydraulic structures. For instance, reliable methods of forecasting seasonal runoff and peak river discharge can be incorporated into the design of dams and spillways and result in construction economies and operation efficiencies.

41.3.1 *Accuracy and timeliness*

The value of a hydrological forecast depends, to a large extent, upon the accuracy of the forecast. Accuracy requirements should be appropriate to the use of the forecast. However, accuracy has to be considered along with the timeliness of the forecast. Criteria to evaluate a forecast should ideally consider both accuracy and timeliness. The accuracy and timeliness depend on the reliability and amount of hydrological and meteorological information, the speed with which that information is provided to the forecasting centre, the lag time of the river basin, the type of forecasting method or model that can be used, and the time taken to disseminate the forecasts to the users.

Measurement errors, model limits, and natural variability of meteorological inputs to hydrological systems are causes of uncertainty in hydrological forecasts. Methods exist:

(*a*) To evaluate the accuracy of hydrological instrumentation;
(*b*) To quantify the natural hydrological variability of meteorological inputs to hydrological systems, either with probability distributions or with stochastic processes; and
(*c*) To assess empirically the accuracy of hydrological models by comparing computed results with observed data.

Based on these methods, the forecaster should estimate the total error and provide this information to the user. However, the major benefit of such an evaluation is to the forecaster himself in suggesting possible improvements in the forecasting procedures. Probability forecasts are also useful to certain users for assessing the risks associated with the decisions that they may take in response to a forecast. Quantitative precipitation forecasts (QPFs) are amenable to probability forecasting.

The uncertainty in future conditions, especially the occurrence of precipitation, is the primary source of uncertainty in hydrological forecasting. New techniques are being developed to make maximum use of data from all sources, e.g., radar, satellite, meteorological observations and forecasts, and surface measurements.

41.3.2 *Costs and benefits of hydrological forecasts*

The determination of benefits and costs for forecasting applications is similar to that for planning or design purposes. Factors to be considered in benefit assessment are:

(*a*) The extent to which damage can be avoided in typical domestic, commercial, industrial, and agricultural situations in the case of flood forecasting;

(*b*) The extent to which savings can be effected in operational aspects of agriculture, industry, or commerce in the case of other types of hydrological forecasts; and
(*c*) The determination of the total benefits accruing to the region. These should include both tangible and intangible benefits.

Additionally, one must consider, for forecasting, the effect of inaccuracies in the forecasts on the reaction and confidence of the user over a long period of time. When comparing alternative forecasting strategies the effect of relative time advantages of different forecasting schemes should be considered.

Such evaluation is an extensive project in itself, and because hydrological forecasting is relatively inexpensive, it is seldom the case that costs exceed benefits. Skilled hydrologists and economists in a project team have to consider the possible benefits for different sectors of activity, such as industry and agriculture. This is particularly the case with regard to power projects with a mixture of thermal and hydropower plants where hydrological forecasts are to be used in determining the relative proportion of the type of generating capacity to be utilized at any particular time. In view of its complexity, any decision to undertake a cost-benefit investigation for a hydrological forecasting system must itself be the subject of careful study before commencement. If the decision is taken to undertake such an investigation, then the assessment of the monetary benefits of a flood-forecasting service can be derived by using the following graphical relationships:

(*a*) Stage-damage relationships (Figure 41.1);
(*b*) Stage-probability relationships (Figure 41.2); and
(*c*) Gross-benefit-probability relationships (Figure 41.3).

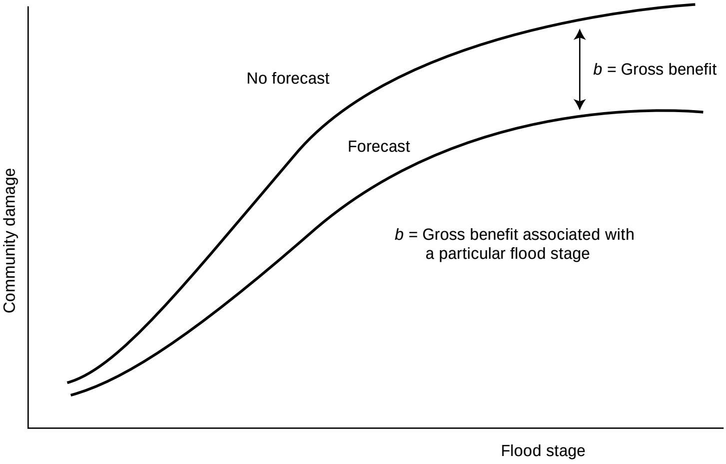

Figure 41.1 — Stage-damage relationships.

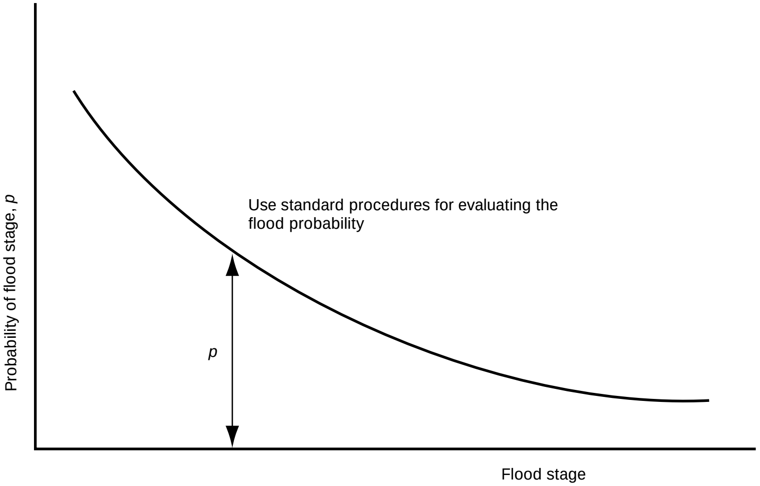

Figure 41.2 — Stage-probability relationships.

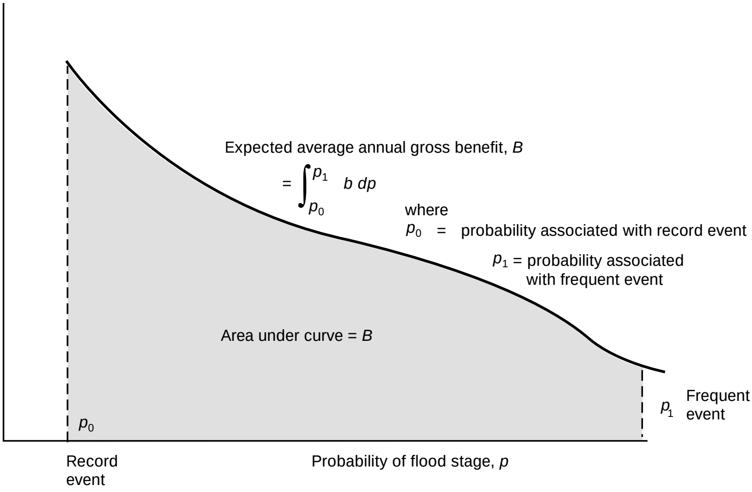

Figure 41.3 — Gross-benefit-probability relationships.

Analogous diagrams can be prepared for other types of hydrological forecasts. The approach can be used for a single community, a given reach of the river, or an entire regional forecasting service.

Stage-damage relationships for single residences, commercial properties, or any other land uses on the flood plain are combined with information on the number, type, and elevation of such properties on the flood plain, to prepare the curves in Figure 41.1. Note that the benefit is calculated from the difference between the social and economic impacts of the current flood-plain usage with no forecast or a rudimentary generalized warning, and the impacts, if a forecast is made. Forecasting benefits will generally be less than those of structural flood-protection measures. However, the costs associated with a flood-forecasting service are significantly less as well.

It may be possible to generalize the results of stage-damage curves based upon typical mixes of development types. Similarly, average factors representing lead-time and forecast-response factors can be employed. One technique that has been employed in the United Kingdom is to express the savings as a percentage of the total value of the property per hour of lead time. Experiments have shown that, up to a point, savings increase linearly with forecast lead time.

The second stage is the derivation of the stage-probability relation (Figure 41.2). This is normally approached through the flood-frequency relationships (section 36.1.1). An additional point is the concern with more frequent flooding events than customarily treated in design work — possibly down to floods that occur two or more times per year. Care must be taken with statistical definitions in these circumstances. The median flood for the annual-maximum series is exceeded, on average, in 50 years out of 100, but, on the basis of the partial-duration series, the flood event may be experienced more frequently with a return period of less than two years (about 1.6 to 1.8 years).

Difficulties in evaluating intangible benefits, especially those associated with the potential for the saving of life, usually prevent their inclusion, although this is an important element in the justification of a forecasting scheme.

The benefits, which should be compared with the costs of operating and maintaining the flood-warning service, can be converted to expected annual monetary values. If hydrological forecasts are issued on the basis of data and facilities established for the provision of other services, then relevant costs must be apportioned. Three main cost factors need to be considered:

(*a*) The personnel costs of operating a hydrological-forecasting service, which can be estimated by comparison with existing similar systems;

(*b*) The cost of support for a meteorological service, which probably can only be assessed subjectively as a realistic percentage of the cost of the total Meteorological Service; and

(*c*) The cost of the real-time-data network, which, despite its probable use as part of the standard network, should be fully costed to the forecasting system and its alternative use listed as an intangible benefit.

An important aspect of the justification of a hydrological-forecasting system is the fact that setting economic values on the saving of human lives and avoidance of suffering are not usually credible. Established techniques for doing so, based upon insurance data or the value of a working life, have been criticized, but should be sometimes considered to reinforce the need for hydrological forecasts.

The computation of changes in the cost-benefit relationship may become necessary when considering improvements to an existing flood-forecasting system. If the cost-benefit relationship for the existing system is satisfactory, one need only consider the incremental costs and benefits involved.

However, it must be emphasized that the existence of an effective warning service may encourage additional people to settle in dangerous areas, which could negate much of the value of the service.

41.4 The hydrological forecasting service

41.4.1 *Organization*

The organization of a hydrological forecasting service is an internal matter of each country. The organizational pattern with respect to such a service varies widely from country to country. Hence, this *Guide* can do no more than discuss the advantages of certain organizational structures which, as experience has shown, make for greater efficiency, and also consider certain general problems.

The main requirements for an efficient operation are:

(*a*) An adequate network of hydrological and meteorological stations;
(*b*) Facilities for rapid and reliable communications for collecting and distributing hydrological and meteorological information;
(*c*) Well-documented hydrological and meteorological records with facilities for data processing, storage, and rapid retrieval;
(*d*) A number of well trained personnel in the different fields of hydrological forecasting; and
(*e*) Information on the operation of water management and flood-protection works, e.g., reservoirs, hydropower, irrigation, and drainage systems.

There should be an emphasis on ensuring the reliability of the forecasting service under extreme conditions like floods, storms and hurricanes, which allow for the possibility that lines of communication, data transmission, and power supply may be broken. The staff of the forecast centre must be able to perform their duties smoothly under such extreme conditions. To ensure system reliability during such times, some reserve or backup should be established, such as radio transmission links, battery power supply, and provisions for the mobility of the forecast centre personnel.

The operation of water-resource management systems like reservoirs, irrigation and drainage works, and water supply and water-power facilities affects the natural river-flow regime. For this reason, information on actual reservoir operation, off-takes and diversions, state of the flood-protection dikes, man-made changes of the river channel and so on, should be available to hydrological forecast centres. This means that a hydrological forecast centre should cooperate closely with the water management operators to exchange all relevant operational information.

It is also desirable for the hydrological forecasters to work in close contact with meteorologists to have immediate access to their observation data, forecasts, and advice. This may be achieved either by combining services or, where the services are separate, by establishing appropriate administrative and operational links.

In countries of large extent or variable terrain or climate, a hydrological forecasting service cannot be carried out efficiently by a single centre. In addition to the main centre, in which scientific research and methodological work would be concentrated, it is useful to have regional forecasting centres. The watersheds of major river basins are the most suitable boundaries for these regions. In selecting a site for a forecasting centre, the main consideration should be the capability for collecting, processing, and distributing hydrological information.

41.4.2 ***Activities***

There are five main fields of activity of the forecasting centre:

(*a*) Collection and processing of incoming hydrological information on the state of water bodies, operational factors, and meteorological observations and forecasts;
(*b*) Issuing a periodical bulletin that relates the current situation and any current forecasts or warnings;
(*c*) Distribution of current information, analyses, forecasts, and warnings to interested users;
(*d*) Evaluation of forecast accuracy and effectiveness; and
(*e*) Analysis of user needs and consequential improvements to existing forecast systems.

Item (*e*) means that a hydrological forecasting system is likely to be in a permanent state of development and expansion. Developments in the use of water resources and land-use changes, especially urban expansion, create new needs for hydrological information and for improvements in forecast reliability and lead time, which the forecasting service should endeavour to meet.

41.5 **Dissemination of forecasts and warnings**

The method for distributing information about the state of rivers, lakes, reservoirs, and hydrological analyses, forecasts, and warnings, depends on the requirements of the users, the degree of urgency, the channels of communication, and the facilities that the hydrological forecasting service has at its disposal.

A daily hydrological bulletin, comprising the following, would be useful as a source of general information for the majority of users interested in conditions over large areas:

(*a*) A hydro-synoptic chart of the basin showing, in figures, the stages, discharges, and water temperatures for rivers, lakes, and reservoirs, including the actual volume of water stored in the reservoirs. These data would refer to a given time period and would use various symbols for ice conditions, the rise and fall of river stages by designated zones, and other pertinent hydrological characteristics. Alternatively, a table containing all the above data related to the observation stations could be used;
(*b*) A short survey of the state of water bodies and of tendencies toward changes in their regime in the near future; and
(*c*) Medium- and long-term hydrological forecasts.

Besides the daily bulletins, it may be useful to issue weekly, ten-day, or monthly bulletins that would contain a short survey of the hydrological regime during the respective periods. It would provide the necessary figures and data, including medium- and long-term forecasts with a lead time of a week, ten days, or a month. Part of the information contained in the bulletins may be distributed to the general public by means of radio, television, and the press.

In addition to bulletins, some users will require more specific information and forecasts. The content, format, time of delivery, and channel of communications of specialized information should be agreed upon by the hydrological forecasting service and by interested users. With an increase in the temporal resolution of data, for rivers that crest in less than 24 hours, more frequent forecasts may be warranted.

All of the above methods of information dissemination may be related to normal hydrological conditions based on routine operations. Another group of methods is applied under extreme conditions, e.g., floods, droughts, or other disasters in a state of emergency. In every country, a single responsible organization is normally designated to coordinate actions in a state of emergency. This organization becomes the most important user of hydrological information during the disaster, and it is especially important that all details concerning the information transmission to this user should be agreed upon in advance.

Generally, information under emergency conditions is transmitted to users more often, e.g., every one to two hours instead of the routine 24-hour transmission. Also, the information is more specific in the disaster-affected area. Flash-flood warnings are an extreme case where the most important requirement is the dissemination directly to users in the shortest possible time (section 41.3.2). Processed information in the form of bulletins, analyses, forecasts, and warnings is distributed by central and regional hydrological forecasting centres. In addition, some data may be transmitted to interested users directly by station observers. However, it is imperative that emergency services are provided with a single and unequivocal set of figures with their origin and bona fide clearly displayed in the bulletin.

Although there are various ways to formulate hydrological forecasts, it is impossible to provide an error-free forecast, although this may be expected by some users. This expectation sometimes creates a misunderstanding between forecaster and user. To avoid this, a user should be informed about the reliability of the forecast in question, using such criteria as described in section 41.3.2. These figures can be computed prior to the implementation of the forecast system and verified after each system operation, which should give an indication of the forecast improvement. Experience has shown that the comprehension of an error and a confidence interval is difficult to convey to non-technical forecast users.

CHAPTER 42

DATA REQUIREMENTS OF HYDROLOGICAL FORECASTING

42.1 **General**

The data used in hydrological forecasts can be divided into two groups — the first includes all material required for developing the forecasting method (section 42.2), and the second group includes the information needed to produce the forecast (section 42.3). The first group encompasses conventional hydrological and meteorological time-series that are necessary for testing and evaluating the trial forecast models. It also includes physiographic information, e.g., sub-catchment areas, land use, soil characteristics, channel dimensions, and slopes, that is needed to describe the catchments where forecasts are desired. The second group includes the hydrometeorological data specified by the forecasting scheme that will be used to characterize the state of the catchments just prior to the issue of the forecast as accurately as possible. It may also include measurements of the forecast variables that may be used to monitor the performance of the forecast or to update the forecast model by using a feedback method of optimization (section 43.10). The reliability of a forecast procedure can be directly related to the amount and spatial distribution of the data available for the development of the procedure and to their consistency. Care must be taken to ensure that there is not a bias between the data used to develop the forecast procedure and the data used for operational forecasting. For this reason, the consistency of the records is as important as the quantity of data.

Data requirements ideally depend upon the forecast method that is to be used, the time period of the forecast, and the hydrological characteristics of the basin. In practice, data availability may place restrictions on the choice of the forecasting methods. However, steps should always be taken to upgrade the network to meet the ideal data requirements.

42.2 **Data for developing forecast procedures**

Adequate data network and facilities for river surveying and basin mapping are prerequisites for the development of hydrological forecasts. At the developmental stage, alternative forecast methods may be under investigation, and analyses of hydrological events will be retrospective. Thus, in general, more observations will be required during the development stage than will be necessary subsequently. Nevertheless, it is necessary to have in mind the eventual purposes of the forecasts so gauge sitings and measurement frequencies can be investigated during the development stage.

The following sections describe the data elements which are integral parts of the development process.

42.2.1 *Hydrological variables*

At the development stage, the type of hydrological analyses that are undertaken is typified by many of the examples of Part D of the *Guide*, in which relationships between input and output variables are determined, e.g., snow melt as a function of degree days (Chapter 31) or unit-hydrograph derivation (section 33.3.1) from areal rainfall and catchment runoff. The network and the instrumentation requirements are those quoted in the relevant sections.

Note the differing data requirements of different approaches, e.g., between the degree-days and energy-budget approaches to snow-melt forecast and between the unit-hydrograph and conceptual-modelling approaches to runoff forecasting. The potential improvement in accuracy should be balanced against the costs of obtaining the input data in the subsequent operational phase.

42.2.2 *Catchment characteristics*

Existing surveys of the catchments may have to be collated or, if not available, to be undertaken to delineate the major hydrological features. Examples are soil or geological types that describe runoff relationships, and topographic surveys that serve as baselines for snow courses to identify the major contributing subcatchments, to assist with gauge siting, and to aid in distributed modelling. It is probable that, at the development stage, simple relationships will have to be created between existing measurements, e.g., snow depths and rainfall at the limited number of sites related to the total areal precipitation inputs. Areal and satellite photography can be a valuable aid for these purposes (sections 7.7 and 8.6).

42.2.3 *River characteristics*

Many hydrological models include a channel- or storage-routing phase (Chapter 34). Where these are based on hydraulic principles, physical characteristics of the river channels must be known. Cross- and longitudinal sections and storage data are needed for specified points within the major water bodies.

42.3 **Data required for forecast operation**

Once the forecast procedure has been determined, the data network used in the development stage can probably be reduced to those elements required to implement the forecasting procedure. There are numerous alternative networks for data, each depending on the interrelationship between the particular forecast method and the basin type.

The following variables may be measured for short-term forecasts of river stage or ice:

(*a*) Upstream river stage and storage conditions;
(*b*) Temporal and spatial distribution of rainfall and snow;
(*c*) Ground conditions, including soil moisture and frost;
(*d*) Ice character and coverage; and
(*e*) Meteorological data to compute energy balances.

For short-term forecasts, it is of paramount importance that all observations are promptly available at the forecast centre.

Long-term forecasting will require measurements from more remote parts of larger catchments as well as large-scale characteristics of the atmospheric circulation. Quantitative-precipitation or temperature forecasts may also be required. Some of the measurements related to short-term change may be omitted. The following subsections describe the more commonly required input variables.

42.3.1 ***Rainfall***

The minimum recommended densities for rainfall networks are defined in section 20.2.1.1 While these densities, and possibly greater ones for catchments less than 2 500 km^2, are appropriate for forecast development, logistic problems may dictate that a much lower density be accepted for operations of short- and medium-term forecasts. Radar and satellites can be very advantageous in such circumstances (section 42.6.2). Telemetering raingauges are essential at some of the sites for flood forecasting on all but the largest catchments.

42.3.2 ***Snow***

The snow-measuring network should be dense enough to provide a reliable estimate of the water equivalent of the snow cover. For short-term forecasting, frequent reports are necessary, whereas for long-term forecasting, weekly or monthly reports may be adequate. In mountainous terrain, snow observations are made by snow surveys and snow-storage gauges (section 7.5).

The areal extent of snow cover can be evaluated with some success from point observations, although, increasingly, remote sensing techniques (section 42.6.2) are being applied to this problem.

Temperature values are also required for the operation of snow-melt forecasting models.

42.3.3 ***Water levels and streamflow***

Although the basic equipment and site-suitability criteria required for water-level and flow measurement for forecasting is similar to that for general-purpose hydrometry (Chapters 10 and 11), one also needs to consider site location, accessibility, and data transmission to the forecast centre.

In flood forecasting, a compromise is often needed between maximizing the warning time and reducing the accuracy of forecasts. This depends on how far upstream the gauge is located from the forecast point. The designer of the flood-warning procedure must be sensitive to the ultimate use of the forecast and tailor the design and location of gauges to provide the data appropriate to the forecasting model or relationship to obtain the type of alerts that are expected. For example, a crest-to-crest correlation (section 43.4) obviates the need for stage-discharge relationships at water-level recording stations.

Some recently developed forecasting procedures also require a measurement at the point for which the forecast is made to update the model parameters and adjust the forecast (section 43.10). However, regardless of the models used, continuous monitoring of forecast performance is desirable.

42.3.4 *Other data requirements*

The use of channel-routing models has increased the need for information on the physical characteristics of the river channels. While cross-sectional and profile data are required during calibration, changes occurring during operational forecasting must also be known and appropriate adjustments should be made. Important land use changes must also be noted and network adjustments should be made.

In order to forecast the consequences of a dam failure, information on the type of failure can be used to improve the forecast of the resulting flood wave down stream.

42.4 **Use of meteorological forecasts**

The forecast of certain meteorological developments is frequently used as a basis for short-term forecasts of snow-melt runoff, rainfall-produced floods, and ice-formation breakup. As a consequence, hydrological forecasters will be concerned with:

(*a*) The quantitative precipitation forecasts (QPF) for periods of up to 72 hours;
(*b*) The air temperature, humidity, dewpoint, wind, and sky conditions for up to five days;
(*c*) The elevation of the freezing level in mountainous regions; and
(*d*) The wind speed and direction for 24 hours or more.

The reliability of meteorological forecasts decreases rapidly with the period of the forecast. The temperature is usually more reliably forecasted than precipitation or wind. The amount of precipitation is forecasted less reliably than the chance of precipitation. These are important considerations at the development stage, when decisions are made on the level of meteorological forecast information that can be incorporated into the hydrological forecast [1].

42.5 Precision of observations and frequency of measurement

Recommended guidelines for the accuracy and frequency of measurement for hydrological forecasting are given in the Table below. Elements considered observable by automatic stations are so indicated in the Table. Rainfall, stage (or discharge), and water equivalent of the snow pack are the elements most commonly used by general-purpose forecasting centres.

42.6 Operational data acquisition

42.6.1 *Networks*

Many types of hydrological forecasts are compiled on the basis of data from networks. Information may include measurements, as well as details of the operation of water-management and flood-protection works. A forecast system should make use of data from the basic network (section 20.1.3) as far as possible. The scope of the forecast network is determined by:

(*a*) User demands for forecasts at specified locations and for current information on the status of water bodies;
(*b*) The network density needed to describe the hydrological characteristics and the dimensions of water bodies;
(*c*) The technology for data transmission to the forecast centre;
(*d*) The representativeness of the observations; and
(*e*) The media for issuing forecasts.

The information on water-management operations should be organized to fit in with the normal operational routines of the water-management agencies that supply the information.

A schedule of reports transmitted to the forecast centre by non-automatic monitoring stations should be drawn up, and the reports should be classified according to whether they are regularly or occasionally transmitted. The regular reports should include daily information on water levels, discharge, and temperature and, where appropriate, ice phenomena, as well as observations every five or 10 days on ice thickness, snow depth, and water equivalent. The occasional reports contain emergency information on significant changes in the regime of water bodies and operational-control strategies, as well as specially requested reports that are needed to define the development of particular hydrological phenomena.

The WMO *Casebook on Hydrological Network Design Practice* [2] gives examples of spatial densities for various hydrological variables and the general principles for determining them based upon the time and space variability.

42.6.2 *Remote sensing*

Remote sensing from the ground, from satellites, or from aeroplanes offers many distinct advantages for certain classes of forecasts. It offers the possibility of

Desirable precision of observation and frequency of data measurement for hydrological forecasting

Element	*Precision*[1]	*Reporting interval*	*Measure by automatic land station*
Precipitation-total amount and form[2]	± 2mm below 40 mm ± 5% above 40 mm	6 hours[3]	yes
River stage[4]	± 0.01 m	6 hours[5]	yes
Lake level	± 0.01 m	Daily	yes
Soil moisture	± 10% field capacity	Weekly	yes
Frost depth	± 2 cm below 10 cm ± 20% above 10 cm	Daily	yes
Water equivalent of snow on ground	± 2mm below 20 mm ±10% above 20 mm	Daily	yes
Depth of snow cover	±2cm below 20 cm ±10% above 20 cm	Daily	yes
Density of snow cover	± 10%	Daily	—
Water temperatures[6] (rivers and lakes)	±0.1°C in 0-4°C range otherwise ± 1°C	Daily	yes
Surface temperature snow	±1°C	Daily	yes
Temperature profiles (snow and lakes)	±1°C	Daily	yes
River and lake ice thickness	±0.02m below 0.2 m ±10% above 0.2 m	Daily	—
Water level (in wells)	±0.02 m	Weekly	yes

(continued)

Net radiation	±0.4 MJm^2/day below 8 MJm^2/day ±5% above 8 MJm^2/day	Daily	yes
Air temperature	±0.1°C	6 hours	yes
Wet bulb temperature	±0.1°C	6 hours	yes
Wind speed	±10%	6 hours	yes
Pan evaporation	±0.5 mm	Daily	yes

1. With respect to actual observations, the WMO *Technical Regulations* use the term “precision of observation or of reading”, which is defined as the smallest unit of division on a scale of measurement to which a reading, either directly or by estimation, is possible.
2. It may be necessary to distinguish solid and liquid forms of precipitation.
3. Varies from one hour to one day, depending on river response. Event reporting, for example after two millimetres of rain required for flash-flood forecasts.
4. Depends on sensitivity of stage discharge relationship to stage change and can be ± one millimetre accuracy. If possible, an accuracy characterized by a relative standard deviation of ± five per cent should be arrived at.
5. See note 3. Event reporting may be appropriate for flash flood forecasts.
6. Hourly reporting with ±0.3°C for ice forecasting.

directly observing areally extensive variables that are otherwise only amenable to point sampling, and can provide observations over inaccessible terrain and over the sea. Remote sensing can provide direct inputs to forecasting procedures in the following areas:

(*a*) Areal rainfall, both qualitative and quantitative indications;
(*b*) Areal extent of flood plain inundation;
(*c*) Cloud images indicating tropospheric wind as input to meteorological and hence hydrological forecast models. Doppler radar (including profilers) can be used in addition to cloud images to indicate tropospheric winds;
(*d*) Tropical cyclone or hurricane movements;
(*e*) Areal extent and water equivalent of snow pack; and
(*f*) Water quality, and turbidity, in particular.

The following paragraphs describe the techniques, giving brief outlines of the properties of different equipment for various purposes.

42.6.2.1 *Radar*

The main uses of radar in hydrological forecasting are:

(*a*) In the observation of location and movement of areas of precipitation;
(*b*) In assessing areal rainfall; and
(*c*) In forecasting heavy rainfall and hence the resulting flood discharge, particularly on small catchments.

A radar with a peak-power output of the order of 500 kW is useful for the estimation of precipitation intensity and distribution. The range in which hydrological computations can be attempted with such radars is limited to about 150 kilometres in ordinary circumstances, but only 100 kilometres at times of heavy rainfall. This problem is not a substantial one with S-band radars. A radar with a peak-power output of 750 kilowatts allows an operational range of 230 kilometres.

The three basic types of equipment and the principles underlying the use of radar are described in section 7.6. Intensity is measured most accurately by S-band radar. This band is more susceptible to the effects of screening and to the effect of beam intersection with the melting layer (bright band).

Improved accuracy of quantitative estimates of precipitation can be obtained if the electronic calibration of radar signals is based upon the regional relationships between radar and rainfall intensity for different seasons and storm types. With one or more automated raingauges, this calibration can be applied to radar images in real time.

Some hydrological forecasts require information on antecedent precipitation. This can be achieved with radar if archival capabilities exist for past data. This information, when combined with the drainage characteristics of the region, may help in locating the existence of potential flood-producing areas.

Simpler manual analysis techniques that use periodic tracing of echo positions and grid overlays are described in section 7.6.4.2.

More modern developments in radar technology include the following:

(*a*) Computer graphics linked to a radar to display storm activities on a one kilometre (or less) by one degree of arc (radial grid) or on a cartesian grid of one kilometre per one kilometre;
(*b*) Processing of digital data to provide subcatchment areal rainfall integration;
(*c*) Linking and assembling data from a number of radars by telephone line to a central computer to increase the scanned area;
(*d*) Automatic calibration of radar data with ground truth (raingauge data) with direct input into the forecasting model;
(*e*) Use of Doppler radar to forecast mesocyclones that precede thunderstorms and tornadoes. This requires a measure both of the echo reflection and the precipitation particle velocity; and
(*f*) Techniques to filter out spurious returns from non-meteorological targets, principally topographic features.

Despite technical difficulties referred to here and in section 7.6, radar methods of estimating rainfall can have distinct advantages over other methods, particularly for flash floods and for determining areal rainfall. Its greatest merit lies in being able to obtain a large amount of data on a small scale in a real-time operational basis. However, to be able to derive these advantages, proper technical maintenance of the radar and its ancillary equipment is essential. Well trained operators and forecasters are also essential.

42.6.2.2 *Satellite-based methods*

Satellite data for hydrological forecasting are available primarily from two types of satellites, geostationary and polar orbiting. Geostationary satellites have an orbital period of exactly one day, and, therefore, remain stationary at about 36 000 kilometres above a point over the Equator, whereas polar orbiting satellites have an orbital period of between one and two hours. The usefulness of orbiting satellites for forecasting is limited by the frequency of their passing over the area of interest, the resolution and nature of sensing equipment, and its sensitivity to any obscuring clouds. Due to these problems, the most established uses of satellite imagery are for long-term forecasts that rely on snow-line detection and for augmenting the synoptic interpretation given by meteorological forecasts [3]. Remote-sensing techniques also provide the means to monitor changing land-use and land-cover, which are data that should be taken into account in hydrological forecasting.

Snow distribution and snow-line movement in mountainous basins can often be obtained in greater detail from satellite photographs than from available ground stations. Limitations on the use of satellite pictures include an inadequate number of satellite observations, cloud interference, forest cover, and the resolution of the satellite data. Quantitative analysis of snow depth is only possible when satellite observations are used in conjunction with ground observations. It has been found present automatic picture transmission (APT) satellite data can be useful in determining ice break-up for lakes and reservoirs with surface areas greater than 500 km^2.

In satellite images, snow appears considerably brighter than the normal background of a snow-free surface. Therefore, snow-covered areas are easily identified in cloudless weather. Snow cover can be differentiated from cloud by the stability of its pattern as compared with that of cloud (for this purpose, it is necessary to have observations a day or more apart), and also because snow-covered areas and clouds appear to have different textures (snow has a smooth appearance with sharp edges while clouds appear rough or lumpy with less defined edges). In mountainous regions, the dendritic pattern of the river systems helps to identify snow cover.

The snow line encloses all areas that are identified as being snow covered. The snow line is defined as the boundary delineating the area with snow accumulation greater than about two centimetres. It is emphasized that the analysis should be based on all types of snow observations available. The comparison between satellite and conventional snow-course data shows that the snow line can be mapped from satellite photography with an accuracy of about 10 to 20 kilometres [4, 5]. The accuracy depends on the scale of the picture.

Other meteorological and hydrological elements that may be observed or inferred by satellite-mounted sensors are liquid water content of clouds, cloud patterns, areas and intensity of precipitation, flood plain inundation, biomass loads, and soil moisture.

Microwave sensors are used to measure the presence of moisture either in clouds or as falling rain and inundated-ground area. Passive systems, which measure naturally emitted energy, can provide order-of-magnitude estimates of precipitable water and can track the progress of large flood waves through complete cloud cover. Currently, available instruments include the electrically scanning microwave radiometer (ESMR) and microwave spectrometer (NEMS).

Meteorological forecasts are assisted by geostationary satellite data that, by allowing comparison between images taken as close as 30 minutes apart, provide inputs to numerical models and visual information about weather systems and hurricanes. Radiation temperature can be input into heat-balance calculations for snowmelt forecasting (Chapter 45) and actual-evapotranspiration calculations. Some of the enhancement curves are especially helpful in precipitation analysis.

The visual information provided by satellite imagery can provide invaluable information, especially in areas not covered by detailed surveys, for catchment subdivision when developing forecast systems. LANDSAT and SPOT imagery is useful here and also where a high frequency of observation is not required, such as in detecting water quality changes in lakes and reservoirs by using its multispectral facilities.

42.6.2.3 *Aircraft sensing*

Many of the instruments and techniques referred to in the previous subsection can be mounted on aircraft. The resolution becomes much finer due to the lower altitude. However, the logistical problems of making an aircraft ready on short notice and constraints imposed by cloud cover and reduced areal coverage limit the usefulness of aircraft-mounted sensors for flood forecasting.

Side-looking airborne radar (SLAR) has been used for terrain and flood-wave mapping and for monitoring lake-ice build-up and migration. Radar equipment is heavy. Thus light aircraft are usually not suitable carriers. Aircraft gamma-radiation surveys have been used to determine the water equivalent of a snow pack (section 8.6) and, potentially, for soil-moisture measurement. A limitation of the gamma technique is the low flying altitude (150 metres) that is necessary [6].

42.6.3 ***Communication systems***

Communication systems transmit data from the field monitoring station back to the forecast centre. They may be manual or automatic and may report back at regular intervals or may only warn when some specified event has occurred.

An important item in determining the means of communication for an operational hydrological forecasting service is the density and location of the network of observation stations. Most data transmission systems are constrained by cost, availability of equipment, personnel, time, and communication channels. The manual and man/machine-mix methods presently used to collect and communicate data are becoming inadequate for modern hydrological forecasting models and for the increasingly precise user demands. Automation is one way to achieve faster collection and to obtain more frequent observations. Modern day data-acquisition systems that use computers for automatic collection of data on a predetermined schedule or on the occurrence of prescribed changes in observed data, provide a relief from most constraints of manual methods. They also provide the ability for expansion and evolution to meet users' increasing requirements.

The elimination of manual data and transmission has some inherent disadvantages. Human observers have a great ability to integrate disparate information and to supplement, with other environmental factors, the purely factual and numerical report provided by the sensor. Hence, the information from sensors in an automatic system may not be identical to that provided by an observer, and the success of an automated system is therefore quite dependent upon the availability of suitable and accurate sensors.

Experience under extreme conditions shows that a communication network is the most vulnerable element of any forecasting system. For this reason, much attention should be devoted to ensure adequate reliability by installing less vulnerable equipment (e.g., self-supporting radio units) and redundant facilities. Telephone and radio have been the primary means of communication of hydrological data from the observation site to the forecast centre. Communication systems based on land lines, such as telephones, are exposed to damage during floods, severe storms, and similar extreme conditions resulting in a considerable loss of information. Buried cables are more secure but also much more expensive. The telephone has the advantage of not requiring a power source at the measurement site. Regular-subscriber telephone lines may be used in most cases, and are much less expensive than dedicated lines. However, in some cases, the quality and capacity of standard land lines is not adequate for direct reading into computers, and more expensive dedicated lines are required. Interrogable equipment is available so that personnel at forecast centres may telephone a raingauge or stage gauge and receive a coded message [7].

When distance or natural obstacles prevent the use of land lines, direct radio links are commonly used for data transmission. The need for a line-of-sight transmission path limits the range of higher-frequency radio communication unless repeater stations are used. This increases the expense. The installation and operation of radio-transmission links is governed by national and international regulations.

Detailed information on the automatic collection and transmission of hydrological observations is contained in the WMO *Automatic Collection and Transmission of Hydrological Observations* [8] and the *Hydrological Data Transmission* [9].

42.6.3.1 *Satellite*

Geostationary and polar-orbiting satellite communication systems for the collection and transmission of hydrological and other environmental data are operational. The following geostationary satellites are equipped (or planned to be equipped) to collect and relay data sensed by *in situ* platforms:

GOES-7 and GOES NEXT	Operated by the United States of America
GMS-4,5	Operated by Japan
METEOSAT-4,5,6	Operated by the European Space Agency (ESA)
GOMS	Operated by the Commonwealth of Independend States
INSAT	Operated by India

Each spacecraft can accommodate data from 10 000 or more individual observing stations within its communication range, which extends 70° east and west longitude of its subpoint and north and south into the Arctic and Antarctic. The Geostationary Operational Environmental Satellite (GOES) of the National Oceanic and Atmospheric Administration (NOAA) of the United States is an example of a system presently in operational use [10]. Details of each of the satellite systems are given in the WMO *Information on Meteorological and Other Environmental Satellites* [11].

42.6.3.2 *Meteor burst*

Meteor-burst telemetry is also used for the collection of hydrometeorological data. A meteor-burst-telemetry system consists of one or more master stations and a network of remote data-acquisition stations. Meteor-burst communication relies on the electrons in naturally occurring meteor trails to reflect or reradiate the VHF radio signal transmitted by both the master station and the remote units. First, because the meteor trail only exists for a short time, and is generally measured in milliseconds, a burst transmission mode must be used. Second, the availability of properly oriented, suitably ionized meteor trails varies with the time of day and the month of the year. These factors combine to yield an intermittent type of communication that is acceptable for low volume data transmission but not for continuous communications.

The meteor-burst system is designed for use with networks having a maximum separation between master and remote stations up to 1 600 kilometres. Topographic barriers between the master and remote stations are not as significant as they are with other types of VHF systems. However, a significant area of poor performance for data transmission between two units may exist in some cases, and intense geomagnetic storms and solar flares can cause significant system degradation. These limitations severely restrict the use of such a system for short-term forecast purposes.

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CHAPTER 43
FORECASTING TECHNIQUES

43.1 General

This section treats those basic mathematical and hydrological techniques that form the component parts of any forecasting system and criteria for selecting the methods and determining the parameters. Examples of the use of these components for particular applications are given in Chapters 44-46.

Many successful forecasts depend on very simple linkages that have been empirically established between an observed variable, e.g., upstream stage, and a forecast variable of interest, e.g., downstream stage at some later time. Increasingly, forecast procedures are based on a more complete and physical description of hydrological and hydraulic processes, e.g., conceptual models of rainfall-runoff or ice-melt processes and channel-routing models. These methods may not necessarily improve forecast accuracy. However, they are more flexible in providing more information and allowing new data and experience to be incorporated.

The techniques, which fall into four categories as listed below, must be judged in the light of their applicability to real-time forecasting situations and not on their potential in the retrospective form of analysis that is appropriate to design models. The four categories are:

(*a*) Empirical (sections 43.3 and 43.4) and physically-based conceptual (section 43.7) models of the hydrological processes in the land phase;
(*b*) Methods based upon heat-exchange processes within water bodies (Chapters 45 and 46);
(*c*) Empirical (section 43.4) and physical (section 43.8) models for calculating flood-wave movement and translation; and
(*d*) Methods based on the analysis of atmospheric-circulation processes.

General-purpose mathematical techniques that can apply to any of the above are described in sections 43.2, 43.9, 43.10, and 43.11.

43.2 Correlation and regression

The correlation coefficient measures the linear association between two variables and is a very widely used mathematical tool at the root of many hydrological analyses. Regression is an extension of the correlation concept that provides formulae for deriving a variable of interest, for example, seasonal low flow from one or more currently available observations, e.g., maximum winter groundwater level (section 44.5).

The formula for calculating the correlation coefficient r between n pairs of values of x and y is:

$$r = \frac{\sum_{i=1}^{n}(x_i - \bar{x})(y_i - \bar{y})}{\sqrt{\sum_{i=1}^{n}(x_i - \bar{x})^2 \sum_{i=1}^{n}(y_i - \bar{y})^2}} \tag{43.1}$$

where $$\bar{x} = \frac{1}{n}\sum_{i=1}^{n} x_i \quad \text{and} \quad \bar{y} = \frac{1}{n}\sum_{i=1}^{n} y_i$$

The lack of correlation does not imply lack of association. Because r measures only linear association, a strict curvilinear relationship would not necessarily be reflected in a high r value. Conversely, correlation between two variables does not guarantee that they are causatively connected. A simple scatter diagram between two variables of interest amounts to a graphical correlation and is the basis of the crest-stage forecast technique (section 43.4).

If either x or y has a time-series structure, especially a trend, steps should be taken to remove this structure before correlating, and caution should be exercised in interpreting the significance test [1-3]. Time-series techniques should be applied (section 43.9) when previous values of a variable, e.g., river discharge, are used to forecast the value of the same variable at some future time.

Likewise, regression equations have many applications in hydrology. Their general form is:

$$Y = b_o + b_1X_1 + b_2X_2 + b_3X_3 + etc \tag{43.2}$$

where the X are currently observed variables and Y is a future value of the variable to be forecast. The b are regression coefficients estimated from observed Y and X values. The X variables may include upstream stage or discharge, rainfall, catchment conditions, temperature, or seasonal rainfall. The Y variable may be maximum or minimum stage. The multiple-correlation coefficient measures the degree of explanation in the relationship. Another measure of fit, the standard error of estimate, measures the standard deviation of departures from the regression line in the calibration set. The theory is explained in all general statistical texts [4].

Linear combinations of the variables are sometimes unsatisfactory, and it is necessary to normalize either the Y or X. A powerful transformation method due to Box and Cox [5] transforms Y to Y_T by:

$$\begin{aligned} Y_T &= (Y^T - 1)/T; \quad T \neq 0 \\ Y_T &= 1n\,(Y); \quad T = 0 \end{aligned} \tag{43.3}$$

which encompasses power, logarithmic, and harmonic transformations on a continuous T scale. A suitable T value can be found by trial and error as that which reduces skewness or graphically by using diagrams such as Figure 35.1.

Non-linearity can also be accommodated in a regression by using polynomials, e.g., by using X_i, X_i^2 or X_i^3. Alternatively, non-linear regression using function-minimization routines offers a simply applied route to fitting parameters of strongly non-linear equations.

The selection of a useful subset from a large potential set of explanatory variables calls for considerable judgement and, in particular, careful scrutiny of the residuals, which are the differences between observed and estimated values in the calibration data set. The circumstances giving rise to large residuals are often indicative of adjustments that need to be made. Advantage should be taken of computer facilities and graphical displays of residuals to explore a number of alternative combinations. The exclusive use of wholly automatic search and selection procedures, such as stepwise, stagewise, backward, and forward selection and optimal subsets should be avoided.

Examples of the application of regression to forecasting problems are given in sections 43.4 and 44.5.

43.3 **Moisture index**

The antecedent-precipitation index is described in section 33.2.1. This method has been a primary tool for operational forecasting in many countries. As a measure of the effect of precipitation occurring prior to the time of the forecast, it provides an index to the moisture in the upper level of the soil. The most frequently encountered indices are the antecedent precipitation index (API) and the antecedent moisture condition (AMC) (section 33.2.1).

The moisture index methods have two main features with respect to their application to hydrological forecasting. First, because the index is updated daily, it is suited to an event type of analysis rather than to continuous modelling. Thus, to apply this method to most forecasting, it is necessary to divide a precipitation period into events or to divide an event into separate precipitation periods. For example, during extended periods of precipitation interrupted by brief periods of little or no rainfall, the decision as to whether one or several storms are involved may be difficult.

The second feature is that the computed surface-runoff volume, when applied to a unit hydrograph, produces a hydrograph of surface runoff only. In order to synthesize the total runoff hydrograph, the base flow must be determined by some other method. The technique is of operational use if only event runoff is of importance and a simple approach is all that can be justified. Methods for operating an API-type hydrological model in a continuous simulation mode are described by Sittner, *et al.* [6] and Burakov [7]. The principles of using the United States Soil Conservation Service AMC index are given by the United States Bureau of Reclamation in *Design of Small Dams* [8].

43.4 **Crest stage forecasting**

A very common forecasting requirement is for a forecast of crest stage and, on moderate-sized rivers, a practical technique is to effect a simple graphical correlation with an upstream crest stage, thus providing a forecast with a lead time equal to the travel time of the flood wave. Figure 43.1 illustrates this procedure.

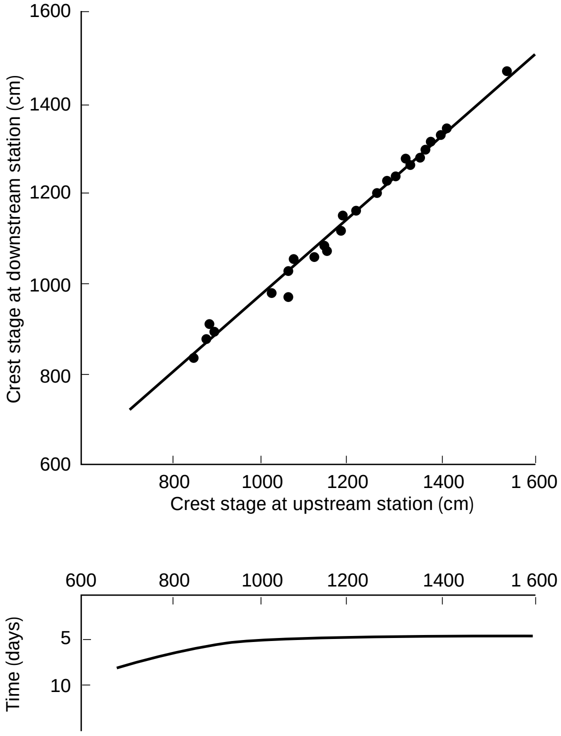

Figure 43.1 — Crest stage and travel time for the Volga river.

It is common to chain such crest-to-crest forecasts so that the output from an upstream forecast provides the input to a downstream one. Such graphs can, in many cases, be used to forecast the hydrographs if account is taken of the difference in lag time during the periods of rise and fall.

The following correlation relationship is useful when simple station-to-station relationships (Figure 43.1) are not successful:

$$(h_2)_{t+\Delta t} = f((h_1)_t, I_{loc}) \qquad (43.4)$$

where h_l and h_2 denote maximum stages at an upstream and downstream station, respectively, I_{loc} is the local inflow between the stations, and Δt is lag time. Figure 43.2 gives an example of the relationship of this type. Sums of discharges at two or more upstream stations at appropriate times, as a combined variable instead of individual tributary stage heights, may reduce the number of variables in the correlation.

Variations on these basic approaches can be devised to suit differing circumstances of travel time and tributary inflow. The graphical approach can be replaced by an entirely numerical one by making use of multiple regression (section 43.2). The regression equation may take the form:

$$h_{max} = b_o + b_1 Q_1 + b_2 Q_2 + etc. \qquad (43.5)$$

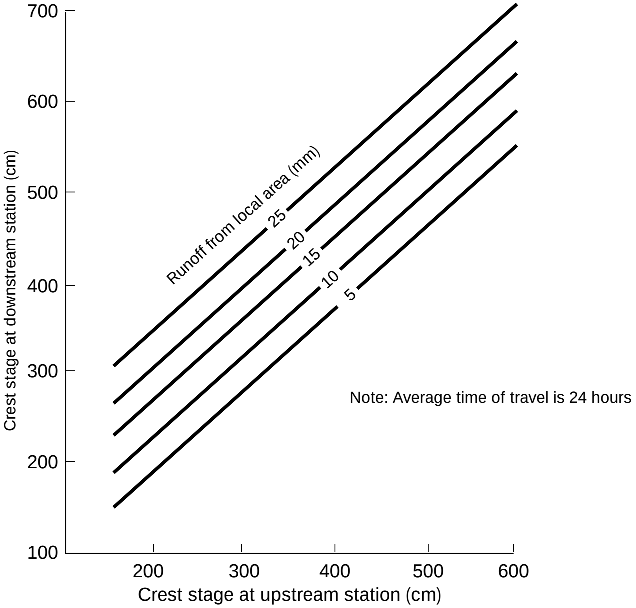

Figure 43.2 — Typical gauge relationship with variables for local inflow.

where Q_l, Q_2, etc., are discharges at upstream stations at a given time. Other explanatory variables, such as rainfall and antecedent catchment conditions (section 43.3), may supplement or be substituted for discharge.

43.5 Flow forecasts based upon storage volume

The total volume of water contained in all rivers, lakes and swamps represents a picture of the current state of the hydrological regime, and, through the inertia of the hydrological processes, it can be used to forecast flows several days in advance at the outlet.

Methods for determining total storage W_j vary from a detailed analysis of cross-sectional geometry of water bodies to relationships of the form:

$$W_j = 0.5l_j\ (c_jA_j + d_j) \tag{43.6}$$

$$A_j = f_jH_j + g_j \tag{43.7}$$

where l_j is the length of the ${}_j$th reach, A_j and H_j are cross-sectional area and stage, respectively, and c_j, d_j, f_j, and g_j are empirical parameters. Regression methods can be used to establish a forecast relationship between the total storage volume and the outlet flow t days. Alternatively, a distributed form of the storage can be retained, and the method of multiple regression can be employed to establish relationships between the forecast flows and the volumes of water storage in each of the major tributary areas.

43.6 Recession forecasting

The analysis of river recessions is an important component of flood and low-flow analysis, but in forecasting, its use is largely confined to low-flow forecasts (section 44.6) [9]. The principles underlying recession theory, and some practical procedures for defining constants and curves are given in Chapter 35.

Probably, the most direct method is to perform a graphical correlation (section 43.2) between the current flow or stage and flow or stage n (=1, 2, 4, etc.) days ago. The relationship so defined can be used to extrapolate forward in time if there are no disturbing influences, e.g., precipitation events. Departures from the most characteristic line can often be associated with natural or man-made phenomena, and this information can also be brought to bear on any particular forecast.

43.7 Conceptual streamflow models

A detailed discussion of conceptual streamflow models is given in section 39.3. It should be stressed that successful calibration and effective operation of a conceptual model is dependent on data sets that include the required observations and are reliable, accurate, consistent, continuous, and of sufficient length. Existing data satisfying all these criteria are rare and usually need to be augmented to apply conceptual models in forecasting. A long-range goal in using these models is to achieve a balance between the basin model and the quality, quantity, and timeliness of the required input data. Data collected during routine operations should be used to recalibrate the model and improve its performance. In recent years, several countries have utilized conceptual models for operational hydrological forecasting. Unless they develop a suitable model themselves, national services in charge of hydrological forecasting face the difficulty of ascertaining the relative advantages and disadvantages of the many models proposed for operational use. To provide information and guidance on the use of models in various forecasting situations, WMO has implemented a series of international projects on the intercomparison of conceptual models used in operational hydrological forecasting. The results and recommendations of these projects are given in the WMO *Intercomparison of Conceptual Models Used in Operational Hydrological Forecasting* [10], in *Intercomparison of Models of Snowmelt Runoff* [11] and in *Simulated Real-time Intercomparison of Hydrological Models* [12]. A comparison of the features of many such models is given in Fleming [13] and in Kutchment [14]. Practical applications of different models are described in the WMO *Hydrological Models for Water Resources System Design and Operation* [15].

It is important to ensure that the model parameters and state variables have a current set of values at the time that the forecast is made. Even so, because of data and model errors, simulated runoff will differ from observed runoff. Therefore, the output from the model should be updated to bring the observed and simulated runoff into closer agreement (section 43.10).

A major advantage of forecasting with conceptual models is that many different types of forecasts may be made with one model. For example, conditional probabilities of high and low flows can be extracted (section 43.11) and a hydrological model combined with a reservoir or water-management routine may provide specific tailored information for users, such as storage forecasts. Other applications might include forecasts of soil-moisture deficiencies for forest-fire alerts and snow-cover duration.

43.8 **Flow routing**

Techniques described in Chapter 34 are used extensively in forecasting techniques.

43.9 **Time-series analysis**

Since runoff is an indicator of the state of the drainage basin, univariate time-series analysis may be used to establish forecast relationships [16]. One such approach is to use autoregressive moving average models (ARMA) (section 39.6.2) that are well suited for use in basins with limited precipitation data, because only antecedent discharge is needed to make a forecast of the type:

$$Q_{t+1} = a_o Q_t + a_1 Q_{t-1} + a_i Q_{t-2} + \ldots + b \qquad (43.8)$$

where Q_{t+1} is the forecast with unit lead time, and Q_{t-i} are the measured values i time increments earlier. Coefficients a_i and b, are estimated in the time-series analysis. In addition to the forecast value Q_{t+1}, a time-series model can yield the distribution of possible deviations from the forecast value so that an estimate of forecast error is readily available. If a time-series forecast of monthly flows is to be reliable, then autocorrelation in the monthly time-series must be large. This is the case in large rivers and in streams draining large aquifers and lakes. However, forecasts will usually be feasible only one to four months ahead.

It is possible to include meteorological variables in a time-series model, but, if such data are available, it will often be preferable to make forecasts by using regression or a conceptual model.

Time-series models may also be fitted to the error series as discussed in the next section.

43.10 Forecast-adjustment techniques

Forecast adjustments should be based on model output and direct measurements of the state variables. There are many techniques for adjusting forecasts. If an observation is made of the forecast output Y_i the opportunity exists to adjust subsequent forecasts in light of the known forecast error $e_i = Y_i - \hat{Y}_i$, where $\hat{Y}_i$ is the forecast estimate. Most adjustments are the result of the subjective judgement of the forecaster, but various mathematical techniques have been developed that allow this process to be formalized. The underlying principles of the formal approach are described below.

At its simplest, adjustments may take the form of addition of the current error to the new forecast. In order to avoid discontinuities, the adjustment is usually blended into the computed hydrograph over several time periods. A more complicated procedure is to subject the error series $e_1, e_2, \ldots, e_i$, to a time-series analysis to extract possible trends or periodicities that can be extrapolated to estimate the potential new error $\hat{e}_{i+1}$ which can be used to modify the new forecast, $\hat{Y}_{i+1}$[17].

The observed values, $Y_1, Y_2, \ldots, Y_i$, can be used to redefine the state variables of the forecast model. This is termed recursive estimation and, if the forecast model can be cast in a sufficiently simple form, it provides a basis for a formal strategy for adjusting model output.

The Kalman filter and the extended Kalman filter are recursive-estimation techniques that have been applied to hydrological forecasting [18]. These techniques require considerable mathematical and hydrological skill to ensure that the forecast model is in a suitable form for analysis. However, a more conceptual technique for adjusting the output of a hydrological model may also be used. The method does not require any changes in the model structure nor in the algorithms used in the model. Rather, this approach adjusts the input data and, consequently, the state variables in such a way as to reproduce more closely the current and previous flows. These adjusted values are used to forecast the hydrograph [19].

Forecast adjustment need not be based only on the output of the model. It may also be accomplished by using measurements of state variables for comparison with the values generated by the model. For example, one such technique uses observed measurements of the water equivalent of the snow cover as a means of improving the seasonal water supply forecasts derived from a conceptual model [20]. Direct substitution of field measurements for numerically-generated values of the state variables of the model would be incorrect because, in practice, model simplifications could result in non-physical values.

The proper choice of an adjustment procedure depends on:

(*a*) The user requirements;
(*b*) The amount and quality of the available data;
(*c*) The equipment used for data collection, transmission, and processing of the data; and
(*d*) The qualifications and experience of the personnel.

43.11 **Probability forecasting**

Long-term forecasts, especially of seasonal runoff, are often expressed in probabilistic terms, i.e., a statistical distribution of possible runoff volumes contingent on rainfall subsequent to the date when the forecast is made. One source of uncertainty is the future weather between the date of preparing the forecast and the operative date of the forecast. For example, if a regression-based forecast gives:

$$Q_{summer} = b_o + b_1 R_{autumn} + b_2 R_{winter} + b_3 R_{spring} + b_4 R_{summer} \tag{43.9}$$

then a less informative, probabilistic forecast can be issued after only receiving the rainfall data for the previous autumn and winter. The probabilistic component must take into account the distribution of possible spring and summer rainfalls that might occur.

Unless the forecast model is very simple, it is almost certain that it will be necessary to simulate possible Q_{summer} values either by repeated sampling from the distribution of R_{spring} and R_{summer} values or by repetitively applying the model to the historical traces of R_{spring} and R_{summer}. If the sampling approach is adopted, it will be necessary to incorporate any correlation that might be present between the independent variables. If the historical approach is used, at least 30 years of record is desirable to obtain a representative range of combinations.

The application of this technique is not limited to regression models. Any hydrological-forecasting model can be perturbed retrospectively by real or synthetic data to construct a distribution of possible outcomes. A more realistic description of the distribution of actual values is obtained if a noise term is included in the model. This can be effected by adding to each forecast a random number whose standard deviation is equal to the standard error of the model estimate.

Probability forecasting should not be confused with forecast error. The latter is internal to the model and represents the error caused by model inadequacy and data error. Perhaps the best way of distinguishing between them is to view probability forecasting as an expression of the range of outcomes that are possible in light of the conditions that may arise before the forecast date, whereas forecast error is a totally undesirable feature of the shortcomings of the state of the forecasting science. Statistical approaches are being investigated that will allow all sources of uncertainty (data error, model error, future weather, etc.) to be considered in expressing the forecast in probabilistic terms [21].

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CHAPTER 44

FLOOD AND WATER-SUPPLY FORECASTS

44.1 **General**

The previous chapter described the hydrological and hydraulic techniques that may be used for a variety of purposes. In this section, these techniques are applied to the two most commonly occurring classes, flood and water supply forecasting. These are divided into several important subclasses, e.g., flash floods, urban floods, storm surges, and dam-break floods.

44.2 **Flood forecasting** **[J04, J10, J15]**

The need for flood forecasts and warnings is the most common reason for the establishment of a hydrological forecasting service. This is obvious because floods are probably the most dangerous hydrological phenomenon, causing a considerable loss of human life and great property damage every year throughout the world.

The choice of a proper method for flood forecasting depends on:

(*a*) The type of flood;
(*b*) The degree of development of the forecasting service, i.e., the observation network and the telecommunications and data-processing facilities;
(*c*) The length and quality of data records; and
(*d*) The availability of qualified personnel.

A forecast of the following flood parameters is commonly required:

(*a*) River stage and flow: Their maximum values and their changes in time (the hydrograph), including the time when the river first reaches flood level, the time of occurrence of the peak stage/flow and its duration, and whether and when a warning level will be surpassed;
(*b*) Total volume of the flood wave;
(*c*) Velocity of the wave-crest propagation along the river channel and impact and coincidence of tributary inflow;
(*d*) Extent of the flooded area and its variation in space and time;
(*e*) Influence of ice phenomena on flood-wave propagation and the possibility of ice jams forming; and
(*f*) Influence of storm surge, floating debris, reservoir or sluice operation on flood-wave propagation.

For the most common floods resulting from heavy rainfall, the following forecasting techniques may be applied: correlation (section 43.2), moisture index (section 43.3), crest-stage relationship (section 43.4), estimation of discharge as a function of channel storage (section 43.5), conceptual models (section 43.7), and river routing (Chapter 34). Dynamic-routing techniques, that provide solutions to the full dynamic equations, will require a high-speed computer with considerable memory to produce a timely forecast. Other techniques may require a less powerful computational machine. However, many of the hydrological forecasting methods described in Chapter 43, e.g., index, correlation, calculation of means, totals, and standard statistics, can be carried out without computers. Calculations can be expedited by using ancillary graphs, tables, and nomograms that have been previously prepared for commonly required forecast calculations.

44.3 **Flash floods**

44.3.1 ***General***

On rapidly responding small catchments, i.e., time of concentration less than six hours, intense rainfall can create a flash flood. Such floods develop so rapidly that there is a large element of surprise for flood plain occupants. Generally, in these situations, flood-forecasting procedures used in larger streams cannot be implemented rapidly enough to be effective in providing a forecast with sufficient lead time. Moreover, flood estimation is very difficult because of the high spatial and temporal variability of the intense rainfall events that cause flash floods.

Flash flooding has been the subject of several symposia including an international symposium held by the IAHS/UNESCO/WMO [1] and the American Meteorological Society [2].

The use of radar and satellites (sections 42.6.2.1 and 42.6.3.1), coupled with ground truth, offer the best chance of sufficiently accurate rainfall forecasts and areal assessments.

There is no single panacea for forecasting flash floods because the problems are specific to each site. Flash-flood warnings can be considered as one or as a combination of three different approaches:

(*a*) Self-help forecast programmes;
(*b*) Flash-flood alarm systems; and
(*c*) Generalized watches and warnings.

44.3.1.1 *Forecast programmes*

Self-help flash-flood warning systems are operated by the local community, which avoids delays in both the collection of data and dissemination of forecasts. A local flood warning coordinator is trained to prepare flash-flood warnings based on preplanned procedures or models prepared by qualified forecast authorities. The procedures are employed when real-time data and/or forecast rainfall indicate a potential for flooding. Multiple-regression equations (section 43.2) provide an operationally simple flash-flood forecasting technique. The procedure is suitable for a range of different flood-producing conditions of rainfall, soil moisture, and temperature. The former United Nations Disaster Relief Organization [3] gives an example of a simple flood-advisory table.

The increasing availability of microprocessors will lead to an increased tendency to automate much of the data collection and processing that are required to produce warnings of flash floods. Automatic rainfall and stage sensors can be telemetered directly to the computer that will monitor the data-collection system, compute flood potential or a flood forecast, and even raise an alarm. Such computers also permit simplified versions of conceptual streamflow models (section 43.7) to be used instead of simple techniques that are appropriate to manual computation. The most critical component in the self-help system is maintenance of active community participation in planning and educating the public to receive and act immediately on flash-flood warnings.

44.3.1.2 *Alarm systems*

A flash-flood alarm system is an automated version of the self-help type of warning programme. A stage sensor is installed upstream of a forecast area and is linked by land or radio telemetry to a reception point in the community, e.g., a fire or police station that is staffed around the clock. This reception point contains an audible and visual internal alarm and relay contacts for operating an external alarm. The alarm is activated when the stream at the sensor reaches a pre-set critical height. It is also possible to operate such a system by using several raingauges. However, it is much more difficult to determine the critical rainfall value than the river-level value because it presupposes some means of translating intense rainfall to flash-flood heights.

44.3.1.3 *Watches and warnings*

When neither of the first two approaches is feasible (usually where well-defined streams are non-existent), more generalized warnings are given. In several countries, if meteorological conditions conducive to heavy rainfall are observed or forecasted for an area, a watch is issued on radio and/or television. This alerts residents in the area to the potential occurrence of rainfall that could produce flooding.

When flood-producing rainfall is reported, the watch is followed by a warning. This advises the residents in the area to take necessary precautions against flooding.

44.3.1.4 *Flash floods and water quality*

Flash floods in particular can have a strong influence on water quality [4], and this is of particular importance in water supply catchments. A flash flood upstream from a weir drawing water for a water treatment works can induce high sediment loads and debris that, if forecasted, can be more readily handled at the treatment works.

At the same time, there is the potential for considerable devastation to other physical facilities of the sanitation systems, i.e., the excavation of pipes, back pressure in sewers, and also pollution of groundwater systems by oil or toxic substances.

44.3.2 *Flooding in urban areas*

Urban flooding can be of two distinct kinds. First, urban areas can be inundated by rivers overflowing their banks. Areas of inundation are forecasted from the specific river-stage forecasts. Second, urban flooding can occur as a special case of flash flooding. In this case, intense rainfall over the urban area may cause flooding of streets and property in low-lying areas or in built-up areas in old waterways, underpasses, depressions in highways, etc. Such floods arise primarily from inadequate storm-drainage facilities, and are invariably aggravated by debris that clogs inlets to pipes and channels or outlets of retention basins.

Flood-warning schemes similar to those outlined for flash floods can be employed. This usually consists of an automated flash-flood warning system or generalized warnings, as the areas concerned are often not large enough to make an assessment of runoff from rainfall within the time needed. On causeways subject to flooding, traffic can be alerted by using lights activated in the same way as the flash-flood alarm system. Urban flooding usually affects sewerage systems, even when waste water and storm sewerage are piped separately. Forecasts of urban runoff can assist in the treatment of sewage and the handling of polluted flood water in combined systems.

The opposite problem is the high level of pollution that accompanies urban runoff. Since this is ultimately discharged into natural watercourses, it leads to increased pollution with problems for downstream water users. The forecasting of such pollution loads depends on forecasting urban-flood runoff.

44.3.3 *Dam break*

Catastrophic flash flooding results when a dam (either man-made or artificial-ice walls, jammed debris, etc.) fails, and the outflow, through the breach in the dam, inundates the downstream valley. Often the dam-break outflow is several times greater than any previous flood. Little is known of failure modes of artificial or natural dams. Hence, real-time forecasting of dam-break floods is almost always limited to occasions when failure of the dam has actually been observed. Different failure modes may be assumed for planning calculations when the implications to downstream development are investigated with regard to zoning or evacuation contingency plans.

Earlier classical studies of this problem have assumed instantaneous dam failure and idealized downstream conditions. More recently, engineers have sought to approach the problem by assuming a triangular-shaped outflow hydrograph based on the Schocklitsch or similar maximum-flow equation:

$$Q_m = \frac{8}{27}\sqrt{gW_d Y_o{}^{3/2}} \tag{44.1}$$

where g is the acceleration due to gravity, W_d is the width of the breach, and Y_o is the height of the water behind the dam. By using equation 44.1 and an empirical recession coefficient, the synthesized hydrograph is routed through the downstream valley via a hydrological-routing technique, such as the modified Puls method [5]. Examples of this approach are given by the Water Resources Council in the *Proceedings of Dam-break Flood Routing Model Workshop* [6]. In the same publication, a more realistic approach uses dynamic-routing techniques (section 34.2) to route the rapidly changing and relatively large dam-break flood wave. Explicit account is taken of downstream dams, overbank storage, downstream highway embankments, and expansion and contraction losses.

Since time is of the essence in real-time forecasting of a dam-break flood, the operational techniques must be computationally efficient. However, an even more important consideration is the data requirement of the forecast technique. If dynamic routing is to be used, every effort should be made to minimize the amount of cross-sectional data needed in the routing phase of the forecast, and all data and program files must be immediately available for use.

44.4 **Storm surges in rivers**

Storm surges in the open seas are produced by wind and atmospheric pressure and can generate gravity waves that propagate upstream into rivers. Since the upstream movement of the gravity wave is opposed to the downstream flow, routing of the storm surge upstream may best be accomplished by dynamic-routing techniques (section 34.2). Hydrologic-routing or kinematic-hydraulic routing techniques are not suited to prediction of wave motions that propagate upstream. Also, the inertial components of the gravity wave that are ignored in the diffusion-hydraulic routing techniques are too important to be neglected in the case of storm surge.

Heavy rain falling inland is sometimes associated with a storm surge propagating into a river. Hence, storm surge forecasting can involve an upstream-directed gravity wave — the storm surge — and a downstream gravity wave — the flood wave. Suitable techniques to forecast the development and propagation of the storm surge in the open sea, e.g., the National Weather Service SPLASH model [7], and its propagation into bays — as presented by Overland in *Estimation of Hurricane Storm Surge in Apalachicola Bay, Florida* [8] — are required to define the surge at the river mouth, where it is then routed upstream via a suitable dynamic-routing technique. A number of papers on the subject of tidal rivers appear in the UNESCO

Proceedings of the International Workshop on Storm Surges, River Flows and Combined Effects [9].

44.5 Water supply forecasts [J22]

Water supply forecasts are an essential element of the operation of domestic, industrial, irrigation, and hydroelectric water supply systems. Forecasts commonly take the form of flow volumes over specific durations, e.g., as annual, seasonal, or monthly flows. The duration depends on the character of the demand and on the amount of storage in the system. Because water supply forecasts cover a wider time span than meteorological forecasts, errors will always be inherent due to climatic events during the forecasting period. Therefore, it is recommended that several forecast values with probabilities of exceedance are issued (section 43.11).

The choice of the forecasting technique is governed by the character of the drainage basin, the available data, and the requirements of the users of the forecasts.

Water supply forecasts may be made by using three basic techniques:

(*a*) Snow-melt forecasts;
(*b*) Conceptual models; and
(*c*) Time-series analysis.

The snow-melt methods are used in basins where snow-melt runoff dominates the flow regime. Snow-melt forecasting is described in Chapter 45. Normally, some measures of the snow-water equivalent and the basin losses are related empirically to total seasonal runoff by regression techniques (section 43.2). Satellite measurements of snow cover have been related to the discharge of the Indus river, for example. Reasonable results were obtained in this basin, where conventional ground data are very scarce [10].

The snow-melt methods are primarily suited to forecasts of total runoff volume and do not describe the time distribution of the runoff. Often, however, the time distribution and the peak flow are related to runoff volume, and a time distribution may be estimated, for example, by unit-hydrograph methods.

Conceptual models (section 43.7) can be used for water supply forecasting by running the model repeatedly and by using a number of historical climate time-series as input (section 43.9). The output becomes a range of forecasted values to which probabilities of exceedance can be assigned.

Models used for water supply forecasts should be calibrated so that deviations between observed and simulated runoff volumes are minimized. Since short-term variations are of minor importance, simple model structures may give satisfactory results.

Time-series methods (section 43.9) may be useful for water supply forecasts, where discharge is a valid measure of the state of the basin. The forecast relationships are usually very simple to apply. Regression models in which seasonal runoff is forecast from previous hydrological and climatic variables may be regarded as a special case of time-series methods equation 44.2.

44.6 **Low flow**

Short- and medium-term forecasts of low flows can be based on the recession characteristics of the basin (sections 35.5 and 43.6). An individual will have to recognize the particular circumstances that may cause the recession to differ from the average, e.g., human influences such as pumping for irrigation, local differences in catchment wetness leading to base-flow support arising from particular subcatchments, seasonal variation induced by phreatophytes, or effluent streams.

Long-term forecasts are usually based on the correlation or regression methods (section 43.2) by using soil moisture and climatic factors, such as rainfall and temperature, as explanatory variables. In many cases, the previous rainfall history is divided into separate seasonal variables and the relative weight of the term helps to identify the major causative time lags within the rainfall-runoff system [11, 12].

In streams where groundwater is a major flow component, discharge from springs may provide a useful explanatory variable representing the total storage below ground. Examples of low-flow forecasting from aquifer conditions are presented by the Bureau de recherches géologiques et minières in *Situation hydrologiques et prévision de basses eaux* [13]. Low flow in rivers, whose flows are derived from the melt of the previous season's snow, are forecasted by using snow variables, such as water equivalent or, where a stable relationship is found, the areal extent of snow cover.

It is common for long-term low-flow forecasts to be expressed in statistical terms. Thus, the forecast has the following appearance: given a current discharge of 100 $m^3 s^{-1}$, the discharge two weeks hence will be less than 80 $m^3 s^{-1}$ with a probability of 0.1, between 80 and 100 with a probability of 0.3, between 100 and 120 with probability 0.2, etc. Either a transition-matrix methods may be used for this purpose [14] or else a forecast equation [15] of the form:

$$Q_{t+1} = Q_{t+1} | Q_t + kP \tag{44.2}$$

where Q_{t+1} is the forecast discharge, $Q_{t+1}|Q_t$ is the discharge that would occur without rain, i.e., if the hydrograph followed the recession between t and $t + 1$, P is the rainfall contributing to the flow at $t + 1$, and k is a transition coefficient.

Statistical methods based upon transition matrices and Markov-chain theory could be used to calibrate this expression by using rainfall and runoff data. Alternatively, the simulation approach of section 43.11 can be applied to give a range of possible seasonal outcomes dependent upon the range of conditions found in the intervening season.

Another approach is to use continuous streamflow or water-balance models with historic climatological data to provide probabilistic streamflow forecasts.

Secondary considerations that apply to low-flow forecasting are the need to estimate bank losses and evaporation from water surfaces. These apply especially to forecasting the effects at a downstream point of reservoir releases or water management operations.

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CHAPTER 45

SNOW-MELT FORECASTS

45.1 General

Many countries use forecast methods based on conceptual models of snow-melt runoff (section 43.7). Such methods [1] make it possible to forecast snow melt from observational and forecast meteorological data. Short- and medium-term forecasts are possible for rivers and lowlands, and medium- and long-term forecasts for streams in mountainous areas. Seasonal volume forecasts may be prepared for lowland and mountain basins, where snow-melt runoff produces a significant portion of the total streamflow.

Snow-melt runoff is a characteristic feature of the regime of lowland rivers in temperate and cold climates and of some of the world's largest rivers, even in tropical zones. Snow-melt runoff of many rivers accounts for 50-70 per cent of the annual runoff, and in dry regions the corresponding figure may be 80-90 per cent. The most important forecast elements of snow melt are the resulting volume of runoff, the peak discharge, and the crest stage.

45.2 Snow-melt runoff processes in lowland and mountain rivers

During snow melt, many of the processes that govern runoff in lowland and mountain river basins are similar, e.g., snow melt, water retention of snow, snow melt inflow to a basin, snow-melt runoff losses, water yield of a basin, and time lag of snow-melt runoff to the outlet. On the other hand, some of the processes in these basins occur in different ways. For example, the year-to-year variation in the snow-melt runoff losses, from the snow and free water, are appreciably greater in the plain regions than in mountainous river basins.

The total snow-melt runoff from lowland basins depends on the water equivalent of the snow cover at the time the snow begins to melt, the volume of precipitation occurring after the snow has begun to melt, and the amount of water lost by infiltration and evaporation over the river basin. The first factor can be determined by measurement (Chapter 8). The second factor, the subsequent amount of precipitation and the water losses during the runoff period, must be handled by a forecast procedure, either probabilistically or by assuming climatological average values.

The third factor, snow-melt runoff loss from the basin, is controlled by the infiltration capacity of the soil and surface-depression storage, including large non-capillary pores in the upper soil layer. Evaporation losses are relatively small and vary little from year to year.

The size of the area covered by depression storage can be expressed mathematically as distribution functions of the depth of water required to fill these depressions. Such functions are relatively stable characteristics for each river basin.

Infiltration of water into the soil during the snow-melt period is a factor that varies greatly from year to year, depending on the soil conditions. The rate of infiltration into frozen soil and the total amount of water absorbed depend on the soil-moisture content, the temperature, the depth of freezing, and the soil properties.

45.3 **Forecast models**

In principle, a conceptual snow-melt runoff model is the coupling of a routine for snow accumulation and ablation with a rainfall-runoff model. The joint model can be used in all climatic conditions for year-round forecasting. Snow-melt runoff models have also been developed specifically for use for the spring snow-melt period. In contrast to conceptual models representing all phases of the runoff cycle, the spring snow-melt models have many more simplifications, especially pertaining to evaporation and soil moisture [2]. On the other hand, current spring snow-melt models can account more explicitly for the effects of frozen ground than the generalized conceptual model for the entire season.

45.3.1 ***Index methods***

Many forecasts of volume flow (either medium- or long-term forecasts) are based on index (statistical) methods. Available data on precipitation and snow cover in the mountains do not, as a rule, make it possible to determine the amount of snow and may serve only as an index of this value. For this reason, relationships between seasonal flow and a snow-accumulation index are of a statistical nature. Although suitable for forecasting purposes, they cannot be used for water-balance analysis in most cases.

The success of a long-term forecast depends very much on how faithfully the snow-accumulation index represents the actual conditions. There are at least two additional factors that may have some influence on runoff and consequently upon the correlation between the runoff and the snow-accumulation index:

(*a*) Antecedent groundwater storage; and
(*b*) Amount of precipitation during the snow-melt season.

In those river basins where base flow from aquifers represents a substantial proportion of the total runoff and where base flow varies considerably from year to year, the accuracy of the correlation can be increased by taking groundwater into account.

Precipitation can be taken into account in two ways:

(*a*) By combining a precipitation index with the snow-accumulation index and using the sum of these indices as a single variable; and

(*b*) By using a precipitation index as a supplementary variable.

Subsequent precipitation should be included in the runoff relationship during procedure development. This ensures that the precipitation effects are included in deriving the statistical snow-melt forecasting relationships.

The following formula can be used to calculate the weighted mean snow-accumulation index, I_n when sufficiently detailed measurements covering all altitudes of the basin are available:

$$I_n = \frac{A_1}{A} w_{n_1} + \frac{A_2}{A} w_{n_2} + \ldots + \frac{A_N}{A} w_{n_N} \tag{45.1}$$

where $w_{n_1}, w_{n_2}, \ldots, w_{n_N}$ are the mean precipitation or water-equivalent values of the snow cover at various altitudes, $A_1, A_2, \ldots, A_N$ are the areas at these altitudes, and A is the total area.

Snow surveys are conducted in the mountains several times during the winter so that snow-accumulation trends can be followed. The final snow survey is generally carried out at the end of the snow-accumulation period just before the beginning of the spring snow melt. Snow-survey data at the end of the snow-accumulation period are used for calculating the snow-accumulation index.

Snow courses located at various altitudes are used to obtain data to establish a relationship between the water equivalent of the snow cover and the altitude, $w = f(z)$. A different relationship is obtained for each year. When the observation data are insufficient for plotting graphs of $w = f(z)$, the multiple correlation between runoff and the water equivalent of the snow cover at each point of observation can be used. In this case, the weights of each snow course are assumed to be proportional to the regression coefficients, and their sum to be equal to unity:

$$I_n = a_1 w_{n_1} + a_2 w_{n_2} + \ldots + a_N w_{n_N} \tag{45.2}$$

where $a_1, a_2, \ldots, a_N$ are the weights and $w_{n_1}, w_{n_2}, \ldots, w_{n_N}$ are the water equivalents of snow cover.

In most cases, the best index of the water available for runoff from mountainous areas can be developed from a combination of precipitation and snow-survey data. This can be accomplished by graphical correlation or by a statistical approach.

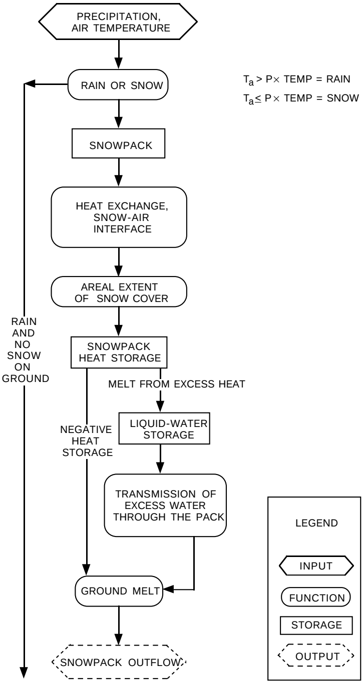
45.3.2 *Conceptual models*

The term conceptual model is used to describe any physically-based model in contrast to those models which are purely statistical.

Many models use some form of a temperature index (degree-day method) to determine both when snow melt occurs and how much snow melt may occur in a specific period of time. Snow-accumulation and ablation models use temperature and precipitation to accumulate the snow cover and air temperature as the sole index to the energy exchange across the snow-air interface. This is in contrast to the degree-day method, which uses air temperature as the index of snow-cover outflow. The degree-day method does not explicitly account for those processes that cause snow-cover outflow to differ from snow melt (i.e., refreezing snow melt caused by a heat deficit and retention and transmission of liquid water). A diagram of the model developed by Anderson [3] is shown in the Figure below. Actual measurements of snow cover from snow surveys or point measurements may be used as an additional source of information to improve the seasonal volume forecasts from conceptual models that use only temperature and precipitation as input [4].

45.3.3 *Extended streamflow prediction*

Conceptual models can only simulate snow-melt runoff for the period for which input data are available. Forecasts for the future can be made by using forecast values of precipitation and temperature.



Flow chart of snow accumulation and ablation model.

The pattern of the seasonal runoff cannot be forecast satisfactorily unless the effects of future weather conditions are taken into account.

For index and statistical forecast procedures, this can be accomplished by using indices for the rest of the season based on past records of precipitation and temperature. For conceptual models, climatological data for many years, generally twenty or more, should be used to develop hypothetical runoff sequences for each year's conditions (section 43.11). Probability distributions may be developed from these simulations for any specific period of time in the future and for a specific hydrological characteristic, e.g., peak flow, volume, and discharge per unit area [5]. This presupposes that the historic sequences are representative of what can be expected in future years.

45.3.4 *Input data*

Input data for use in physically-based or index types of conceptual models may be either precipitation measurements and/or measurements of the water equivalent of the snow cover.

With physically-based conceptual models, corrections should be made for systematic errors (section 7.3.6) in the precipitation measurements, so that the input data are as representative as possible of the average precipitation and/or snow cover. In mountainous regions, where the snow cover is highly dependent on altitude, the observations from meteorological stations are often affected by local exposure and must be adjusted to better represent the average meteorological conditions if they are used to simulate the snow cover conditions. In practice, snow cover and precipitation measurements complement each other.

45.4 Short- and medium-term snow-melt runoff forecasts

One technique [6] used for the development of short- and medium-term snow-melt runoff forecasts for large river basins can be summarized as follows:

(*a*) Lowland river basins are divided into partial (small) basins (assumed to be hydrometeorologically homogeneous) with an area of up to 15 000 km^2, and the river system is divided into sections beginning with the upper reaches;

(*b*) Mountainous basins are divided into altitude zones. The number of zones depends on the difference in altitude between the head and the mouth of the river system, as well as the variability of hydrometeorological conditions with altitude. In the experience of some hydrologists, the optimum altitude range for such zones is 200 to 400 metres with the number of zones around twenty;

(*c*) The models are calibrated with hydrometeorological data from preceding years;

(*d*) The forecast flows for the partial basins (or altitude zones for mountain areas) are routed to a downstream forecast point (Chapter 34).

45.5 Long-term snow-melt forecasts

The development of a method for long-term forecasting of snow-melt runoff consists of establishing water-balance relationships. The establishment of water-balance relationships should be preceded by:

(*a*) The determination of the relevant characteristics of the river basin, such as topography, the percentage of forested and swampy areas, and the nature of the soils;
(*b*) The determination of any factors governing the way in which water is absorbed by the soil and retained on the surface of the drainage area;
(*c*) The definition of the basic factors governing the loss of water in the river basin and the extent to which such factors vary from year to year;
(*d*) The determination both of the role of precipitation occurring after the snow melt has begun, in relationship to runoff, and of the variability of such precipitation; and
(*e*) The evaluation of the accuracy of data for runoff, water equivalent of the snow cover, and precipitation.

The procedures for forecasting long-term snow-melt runoff may be based on index methods (section 45.3.1) or on more physically-based conceptual models (section 45.3.2). The selection of techniques is dependent upon the basin characteristics and the data availability for operational use (section 45.2). Snow-melt runoff forecasts may be improved and extended by including probabilistically representative data and/or quantitative meteorological forecasts for the subsequent snow-melt period.

45.6 Seasonal snow-melt forecasts for the plains regions

The relationship between total snow-melt runoff Q_n and the water equivalent of snow cover for plains areas may be expressed theoretically [7] as:

$$Q_n = \left(w_n - f\right) \int_o^{w_{n-f}} f\left(y_d\right) dy_d - \int_o^{w_{n-f}} y_d \, f\left(y_d\right) dy_d \qquad (45.3)$$

where w_n is the water equivalent of the snow cover and f is the total infiltration during the snow-melt period, both expressed in millimetres. The function $f\,(y_d)$ is the area distribution function in relation to the depth of water, (y_d), necessary to fill depressions on the surface of the river basin.

In the absence of infiltration or when its intensity is potentially greater than the rate of snow melt, equation 45.3 can be simplified as follows:

$$Q_n = w_n \int_o^{w_n} f\left(y_d\right) dy_d - \int_o^{w_n} y_d \, f\left(y_d\right) dy_d \qquad (45.4)$$

In this case, the runoff becomes a function of the water equivalent of the snow cover and the infiltration capacity of the basin.

The amount of water contributing to the seasonal snow-melt runoff is calculated for each year as the sum:

$$W = \overline{w}_n + \overline{P} \tag{45.5}$$

where $\overline{w}_n$ is the mean water equivalent of the snow cover for the basin at the end of winter and $\overline{P}$ is the mean precipitation during the runoff period, both expressed in millimetres.

The mean water equivalent of the snow cover for the basin may be calculated as either an arithmetic mean or a weighted mean. The arithmetic-mean method is used when the number of snow-measuring stations in the basin is sufficiently large and when the spatial distribution of these stations is good. The weighted-mean method is used when observation points are unevenly distributed over the area and/or when the distribution of the snow cover is irregular. To calculate the weighted mean of the water equivalent of the snow cover, a map showing snow-cover average distribution in the area is drawn.

In regions where a thaw may take place in winter, an ice crust often forms on the ground. If measurements are available, the amount of water contained in such crusts should be added to the water equivalent of the snow cover.

Very often, direct determination of soil-moisture conditions throughout the river basin, particularly in winter, is not feasible because adequate data are not available. This is the main reason why indirect indices are used so commonly.

In dry steppe regions, the difference between precipitation and evapotranspiration characterizes the potential rate of infiltration. In the humid forest zone where every year the autumn soil-moisture content is equal to, or greater than, field capacity, this difference represents changes in the storage of the basin as a whole. The runoff caused by late autumn precipitation can also be used as an index of the retention capacity of river basins in these regions.

45.7 **Seasonal snow-melt forecasts for mountainous regions**

There are usually considerable differences in climate, soil, and botanical conditions because of the range of altitudes in mountainous areas. These features determine the nature of the snow-melt runoff and flow regime of the streams. This is the reason why the most important characteristic of a mountain basin is its area-elevation distribution. The main sources of runoff are seasonal snow, which accumulates in the mountains during the cold season, and precipitation occurring during the warm season of the year.

Due to the long period between the beginning and end of the snow-melt period, long-term forecasts of the seasonal flow of mountain rivers are feasible. The most favourable conditions for such forecasts exist where seasonal snow is the main source of runoff and the amount of summer precipitation is relatively small.

Steep slopes, rocks, and an extensive, highly permeable deposit of rough rubble in mountainous basins create conditions in which the water finds its way into channels mainly through layers of rubble and clefts in the rock. Under such conditions, water losses cannot vary greatly from year to year, and there should be a good relationship between seasonal runoff and the amount of snow in the basin. This relationship can be established empirically if measurements are available for a number of years. In practice, the problem of determining such relationships is often difficult.

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CHAPTER 46

FORECASTS OF ICE FORMATION AND BREAK-UP

46.1 General

Many rivers and lakes in middle latitudes freeze over in winter. The most important ice-regime phases for which forecasts are made are:

(*a*) The first appearance of ice;
(*b*) The formation of complete ice cover;
(*c*) The break-up of the ice cover; and
(*d*) The final disappearance of all ice.

The ice regime of rivers is closely related to weather conditions. Thus, the dates of the appearance of floating ice and those of the formation and breaking of the ice cover vary from year to year over a wide range. Ice forecasts are of great practical value for navigation, but many other users besides those in inland navigation are interested in these forecasts.

Exact relationships for calculating thermal and ice regimes are available, but their application to ice forecasting is severely limited by the stochastic nature of parameters governing the equations, which vary over the time span between the forecast and the event predicted. This chapter discusses the different ice-regime forecasts that exist.

46.2 Forecasts of ice formation

The formation of ice in a river begins when the surface layer of water cools to 0°C. Below the surface of the stream, the water temperature at that time generally remains above 0°C. Thus, forecasting the date of appearance of ice consists of computing the heat exchange at the surface of the water to determine the date on which the surface layer of the water will cool to O°C.

Forecasting water temperature should be performed by the stepwise solution of the heat-budget equation, while taking the variables affecting the heat loss into consideration. The heat loss from the water surface is a function of air temperature, wind speed, and turbulence of the water. In its most general form, the equation of the heat balance at the air-water interface for a certain interval of time is:

$$\alpha\left(\bar{\theta}_w - \theta_{sw}\right) + Q = 0 \tag{46.1}$$

where $\overline{\theta}_w$ is the mean temperature of the water mass of the stream, θ_{sw} is the water-surface temperature, α is the coefficient of heat transfer from the water mass to the air-water interface, and Q is the heat loss from the water surface.

A similar method [1] is based on the inequality between the two heat fluxes:

$$\alpha_n\, T_{wn} \leq - Q^*_m \quad \text{or} \quad T_{wn} \leq - \frac{Q^*_m}{\alpha_n} \tag{46.2}$$

where T_w is the mean temperature of water flow, α is the heat-yield coefficient of the water body, Q^* is the heat loss through the air-water interface, and n refers to the time when this inequality appears. The calculation of α, T_w, and Q^* requires several meteorological and hydrological variables. The method can be used if forecasts of air temperature are available several days ahead. Its accuracy is affected mostly by errors in the anticipated air temperatures. The original method could be improved in two aspects:

(*a*) The time increment can be increased according to the actual observation period (e.g., for 12 hours); and
(*b*) The variation of the time of travel and the average depth over the reach can be taken into account.

The necessary conditions for the beginning of freeze-up are the accumulation of sufficient amounts of floating ice with intensive heat loss, such that the merging of ice floes resists the force that is exerted by the flowing water. These conditions are expressed by the empirical formula:

$$\left(Q_a\right)_c = -6.5v^2 \left(\frac{b}{\Sigma Q_a}\right)^{0.8} \tag{46.3}$$

where $(Q_a)_c$ is the critical (highest possible) mean daily air temperature on the day of freezing, v is the mean velocity of flow in the reach, b is the river width, and ΣQ_a is the sum of mean daily temperatures from the day of ice appearance [2]. Calculations are made with forecasted mean daily temperatures for each day successively until the mean daily air temperature falls below the critical point $(Q_a)_c$, as calculated in equation 46.3. When the critical point is reached, the formation of a frozen section is forecast.

A generalized approach to long-term forecasts of freezing and ice break-up is used for northern European and Siberian rivers. The approach includes:

(*a*) Synoptic analysis of conditions leading to freeze-up, in which the northern hemisphere is divided into typical regions;
(*b*) Determination of quantitative variables for atmospheric processes, e.g., expanding meteorological fields by orthogonal functions; and
(*c*) Use of multiple correlations to determine the relationship between the time of ice occurrence and the variables representing the appropriate meteorological fields.

By using this method, it has been possible to forecast the dates when the ice cover increases from 10 to 15 centimetres and then to 20 centimetres.

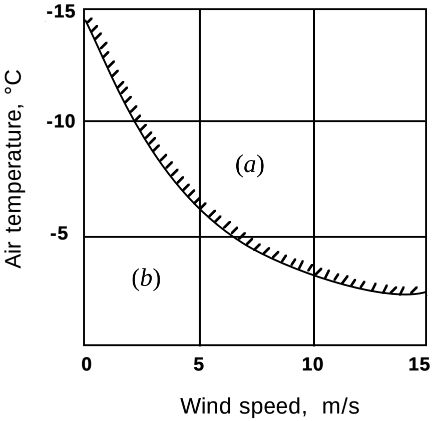
Empirical formulae that use available forecasts of air temperature and wind have been derived to predict frazil-ice formation for hydropower stations. An example of such a relationship is shown in the Figure below.

The operation of water-management schemes under winter conditions should be based on appropriate reports and forecasts. An ice-oriented hydrological network, which can operate according to the forecasting requirements, may be organized. Regular feedback from the water managers to the forecasting centre is also necessary.

A simplified form of the Shulyakovsky equation has been applied successfully to the Danube river:

$$\left(T_w\right)_n = \left(T_w\right)_o e^{-na_o} + \left[\overline{T}_a + \frac{d}{k} + \frac{\left(\alpha + h_o\right) q_b}{\alpha h_o}\right]\left(1 - e^{-na_o}\right) \qquad (46.4)$$

where $a_o = \dfrac{\alpha\, h_o\, t}{\left(\alpha + h_o\right) Hc\rho}$, $(T_w)_o$ is the initial water temperature selected within the interval corresponding to the time of travel through the upper portion of the reach, α is the heat-transfer coefficient between water mass and water surface, which is approximated by $\alpha_n = (1745\,\overline{u}_n + 106\,\overline{W}_n)\,4.1868$, $\overline{u}$ is the mean flow velocity in the reach during period n, $\overline{W}$ is the mean wind velocity during n, h_o is the heat-exchange coefficient between the water surface and the air, H is the average water depth of the reach, d is the specific-heat-exchange coefficient at a temperature equal to that of the water surface, $\overline{T}_a$ is the daily mean



Prediction of frazzle-ice formation (*a*) slush possible, and (*b*) no slush.

air temperature during the period in °C, q_b is the specific-heat flux from the river bed to the water, c is the specific heat of water, and t is the time unit used in the calculations (one day).

The resulting heat exchange between the water and the atmosphere, Q_m^*, can be expressed by the following empirical formula:

$$Q_m^* = h_o \, \overline{T}_a + d \tag{46.5}$$

Ice thickness can be predicted by:

$$\Delta h_i = 6.2 \frac{\sum D_{surf}}{h_i} \tag{46.6}$$

where Δh_i is the growth in ice thickness in centimetres, D_{surf} is the expected total negative temperature at the ice surface (degree-days) calculated from the date when ice thickness was first measured to the date when ice thickness is to be predicted and:

$$h_i = h_{ii} + \frac{k_{ti}}{k_{ts}} h_s \tag{46.7}$$

where h_{ii} is the initial thickness in centimetres, k_{ti} is the heat-conduction coefficient of ice, k_{ts} is the heat-conduction coefficient of snow, and h_s is the thickness of snow cover on ice in centimetres.

46.3 Forecasts of ice break-up

One of the methods for forecasting the break-up date is based on estimating the critical sum of degree-days of positive air temperature required for ice break-up on the river reach in question. In order to determine this sum, the relationship between break-up and the negative degree-day sum for the winter period is used. To forecast the date of break-up of ice by this method, it is necessary to have an air-temperature forecasts for a few days in advance. The date of break-up is obtained by the critical degree-days sum, $(+ \Sigma^N D_j)$ and the air temperatures expected for a few days in advance. For rivers where the break-up process is affected by the intensity of the inflow of snow-melt water, empirical relationships of the following type can provide results suitable for forecasts:

$$+ \Sigma^N D_j = f(-\Sigma^N D_j \Delta h) \tag{46.8}$$

where Δh is the rise in stage needed for the breaking-up process to begin.

46.3.1 *Forecasts of ice break-up on reservoirs*

Break-up of an ice cover on a reservoir results from melt and a gradual decrease in compactness. Under the action of wind, the ice may break into separate ice flows of various sizes, which then start to move as a general drift of ice. The condition for the commencement of a drift of ice is expressed by an inequality of the following form:

$$\Psi d_g^{1/2} \leq CU^2 \tag{46.9}$$

where Ψ is the compactness of the melting ice (relative bending stress), d_g is the thickness of the ice in centimetres, U is the maximum wind speed over a 24-hour period in m s^{-1}, and C is an empirical coefficient that depends on wind speed and is a constant for a given reservoir. For a number of reservoirs in the Commonwealth of Independent States, the value of C was found to be 0.018. The compactness of the ice Ψ and the thickness d_g when the ice starts to drift, are calculated from meteorological elements using the equations of the heat balance. Specific information on applying this method have been provided by Bulatov in *The Possibility of Creating a Universal Method of Computing the Time of Break-up on Rivers* [3].

46.3.2 *Forecasts of ice break-up on rivers*

The method for forecasting the break-up of ice on rivers can be based on models in which the condition for the break-up of the ice cover is determined from the thickness and compactness of the ice and the tractive force of the current. When the forces of resistance become equal to or less than the tractive force, the ice cover is broken up and the ice run begins.

The condition for break-up is expressed by the relationship:

$$\Psi d_g \leq f(H, \Delta H) \tag{46.10}$$

where Ψd_g — the product of relative stress of the melting ice and the thickness — is a measure of the compactness of the ice cover at the time of break-up, and H and ΔH are parameters representing the tractive force of the current. H is the height of the water level at the time of break-up (reflects discharge and speed of flow), and ΔH is the rise, up to the time of break-up, in the water level above the minimum winter level H_3, numerically equal to $\Delta H = H - H_3$. Since H and ΔH are interrelated, in most cases, it is sufficient to consider just one of these quantities in the relationship described in equation 46.10. The quantities are based on forecast and actual data for a few days before break-up. An approximation of the relationship may be expressed:

$$\Psi d_g \leq a + b\,(\Delta H)^2 \tag{46.11}$$

where a and b are empirical coefficients.

46.4 Long-term ice forecasts

The development of methods for long-term forecasting of ice phenomena usually includes:

(*a*) Consideration of the dates of ice formation and break-up on rivers across the area under consideration, e.g., average dates, variability of the annual dates, and the delineation of regions with uniform ice phenomena;
(*b*) The analysis of atmospheric processes that cause the arrival of cold or warm air masses that lead to ice formation or break-up; and
(*c*) Developing or using known mechanisms in meteorology of the evolution of atmospheric processes in time, which make it possible to assess the intensity of cooling or warming for a long time ahead.

The implementation of the points in this section is illustrated by examples for particular rivers in the Commonwealth of Independent States [4].

46.4.1 ***Ice formation***

The arrival of cold weather and of the date for ice formation on the rivers of eastern Siberia is closely connected with the dates of the beginning of the formation of the east Siberian anti-cyclone and the degree of its development. For example, this relationship for the Lena river is expressed by a regression for the month of August on the date of the beginning of stable formation of the anticyclone and the difference in the anomalies of land-surface atmospheric pressure between the regions situated west and east of the Lena. The forecast is made at the beginning of September and covers a period of about one-and-a-half months.

On the rivers in the central part of the European area of the Commonwealth of Independent States, the dates for the appearance of ice are connected with the intensity of cooling in the second half of October and the first half of November, i.e., in the synoptic season just before winter. This intensity of cooling can be estimated according to the degree of cooling and meridional location of the atmospheric processes during the second ten-day period in September. This relationship is expressed by linear regression. The forecast for the middle Volga, made at the end of September, covers about one-and-a-half months.

46.4.2 ***Ice break-up***

The dates for ice break-up on the rivers in western Siberia and the Kama basin occur during the second half of April and the beginning of May, i.e., the synoptic spring season. The forecast season begins in March because it is possible to estimate the degree of warming over the whole season based on the warming characteristics of that month. The forecast is issued at the beginning of April and covers about one month.

46.4.3 ***Use of atmospheric circulation***

A method has been used over the last few years to forecast ice formation and break-up on the rivers in Siberia based on a consideration of atmospheric processes over the whole of the northern hemisphere for the three preceding months. The method of principle components is used to derive optimal indices of the atmospheric circulation and the ice regime of the rivers. Forecasts take the form of regression equations between eigen vectors characterizing the two systems [5].

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PART F
APPLICATIONS FOR WATER MANAGEMENT

CHAPTER 47
INTRODUCTION TO APPLICATIONS FOR WATER MANAGEMENT

47.1 General

The purpose of this part of the *Guide* is to provide guidance on the application of the hydrological analysis methods described in Parts D and E for the design and operation of water-management projects. A number of economic, social, engineering, and other aspects must be considered in the design of water-management projects [1, 2].

47.2 Purposes to be served by a water-management project

In the usual scheme of development for a river basin, all flow that can be suitably regulated is ultimately utilized. The available water is divided among requirements in accordance with a system of priorities. Requirements with highest priority are satisfied at all times if possible, while others are served only when sufficient water is available. Purposes to be served by a project usually include a number of the following:

(*a*) Navigation;
(*b*) Irrigation;
(*c*) Power generation;
(*d*) Flood control;
(*e*) Municipal water supply;
(*f*) Pollution abatement;
(*g*) Industrial use;
(*h*) Recreation, aesthetics and tradition;
(*i*) Fish and wildlife conservation and other environmental considerations;
(*j*) Salinity and sediment control; and
(*k*) Recharge of groundwater.

Criteria used in the design and operation of water-resources projects are usually based on obtaining the maximum net benefits from the resources invested in the project. A design to meet the full demand need not always be the most desirable alternative. Supplies can only be made available at a unit cost that usually increases as the supply grows and can, at some point, exceed the loss resulting from the reduced efficiency of an under-supplied facility. Conflicts can also occur among the various intangible aspects arising, on the one hand, by making supplies available and, on the other, by curtailing demands. It is the objective of water-resources management to seek an optimal balance between water supplies and demands by quantifying, to the extent possible, the consequences of tradeoffs between the conflicting tendencies on the basis of cost-benefit studies and other considerations.

47.3 **Multi-purpose projects**

With the increasing level of development of water resources throughout the world, it is becoming more important to plan projects that can serve a number of purposes simultaneously. For example, a planned storage reservoir may provide both water supply and flood control downstream. Hydrological data required for the design of a multi-purpose project are basically an aggregate of the data required for the various single purposes involved. The methods of analysis, although similar to those applied in design of single-purpose projects, are more complex. A series of plans involving combinations of project sizes and methods of operation must be made to determine the optimum plan.

There is a basic conflict between the management of water resources for flood control and conservation needs (water supply and low-flow regulation) in multi-purpose projects. During the flood season, it is usually essential to maintain empty space in reservoirs in anticipation of possible flood flows, whereas it is usually desired to keep the reservoir as full as possible for low-flow regulation. Toward the end of each flood season, this conflict is particularly critical, because subsequent conservation benefits will depend partly on storage at that time, and it is therefore of particular importance to examine the project operation-plans in relation to flood and low-flow expectations.

47.4 **Water-resources systems**

If more than one water-resources project exists within a river basin, or if water is diverted between basins where water-resources projects exist, their overall effectiveness can be increased by coordinating the operations of the projects. Such coordination requires all the various projects to be treated as one interrelated system by considering the availability of water and the specific purposes of each project as well as the possible interactions and tradeoffs among them. A review of system operation should be undertaken as soon as a new project or a new demand is initiated that could have significant impact on existing operations.

47.5 **Preliminary investigation of water-management projects**

Before appreciable expenditure of time and money can be justified for the planning of a water-management project, a preliminary investigation must be made of its feasibility, desirability, possible scope, and its possible effect on those hydrological factors that influence the environment and the efficiency of other projects. Although this investigation has to be based on whatever material may be available, e.g., fragmentary hydrological records, old maps and reports, it must be carried out with great care because it is at this stage that conceptual planning decisions are often made and that important aspects and consequences of the project may become apparent. If preliminary investigation indicates that the project potential is favourable, then more detailed studies would normally be initiated. The types of hydrological data required for water management are given in the Table below.

Data required for water management

Purpose	*Features*	*Concern*	*Required data*
Reconnaissance		Hydrography	- Drainage network - Watersheds - Springs - Distinction of perennial form intermittent and ephemeral streams
		Physiography	- Geology - Topography and morphology - Soil cover and types - Urbanization
		Meteorology	- Common data: 10, 11* - Temperature distribution - Wind distribution - Snowpack distribution
		Streamflow	- Common data: 1, 2, 3, 4, 7, 8, 9 at selected sites
		Floods	- Common data: 4, 5, 6
Navigation	Channels	Water depth	- Depth-discharge relationship for important points - Common data: 2, 3, 7, 8
		Flood flows	- Common data: 4, 6 - Rates of high water rise - Time lag between rises at different points along the streams - Time lag from heavy precipitation to high water - Snow-melt distribution
Irrigation	Demand	Precipitation	- Common data: 10
		Evapotranspiration	- Common data: 11 - Transpiration
		Soil moisture	- Soil type - Groundwater level

* These numbers refer to items in the list of common hydrological data found at the end of this Table.

(continued)

	Supply	Streamflow Reservoir	- Common data: 1, 2, 3, 4, 7, 8, 9 - Common data: 1, 2, 3, 4, 5, 6, 8, 9, 10, 11
Power generation	High head reservoirs	Streamflow	- Common data: 1, 2, 3, 4, 5, 6, 8, 10, 11 - Common data: 2, 3, 4, 6, 7, 8
	Low head dams	Streamflow	- Tailwater depth-discharge relationship
Flood control	Structures	Water level	- Depth-discharge relationship for important points - Hydraulic-topographic relations in the flood plain - Common data: 4, 5, 6, 8 - Flood plain occupancy
		Rainfall	- Statistics of heavy rainfall in the general area under consideration - Pairs of floods and their causing precipitations
	Flood warning	Forecast	- Travel times of floods - Time lag between precipitation and runoff - Flood synchronization at different tributaries - Rise time of floods
		Prediction	- Time-series of floods - Time-series of heavy precipitation
	Flood zoning and insurance	Flood extent	- Area-duration frequency of floods - Scour and sedimentation by floods
Municipal supply	Rivers	Streamflow and springflow	- Common data: 1, 2, 3, 4, 7, 9
	Reservoirs	Streamflow	- Common data: 1, 2, 3, 4, 5, 6, 8, 9, 10, 11
Pollution abatement	Dilution	Streamflow	- Common data: 1, 2, 3, 4, 7, 8, 9
	Cleaning	Floods Reservoirs	- Common data: 4, 6, 9 - Common data: 1, 2, 3, 4, 5, 6, 8, 9, 10, 11
Industrial use	Rivers	Streamflow	- Common data: 1, 2, 3, 4, 7, 8, 9
	Reservoirs	Streamflow	- Common data: 1, 2, 3, 4, 5, 6, 8, 9, 10, 11

(continued)

Recreation, aesthetics and tradition	Lakes and reservoirs	Physiography	- Storage-elevation relationship - Shoreline properties - Wave possibilities - Common data: 9
		Climate	- Common data: 7, 10, 11 - Air temperature distribution - Wind distribution
		Streamflow	- Common data: 1, 2, 3, 4, 5, 6, 7, 8, 9, 10, 11
		Physiography	- Channel geometry - Depth-discharge velocity relationships - Bank soil and its cover
		Streamflow	- Common data: 2, 3, 4, 6, 7, 8, 9 - Reservoir release variations
Fish and wildlife conservation	Rivers	Streamflow	- Common data: 2, 3, 4, 6, 7, 8, 9,
		Lakes and reservoirs	- Water level fluctuation distribution - Common data: 9
		Structures	- Resulting changes in water depth, velocity, temperature, sediment load and bank characteristics, both upstream and downstream
Salinity and sediment control	Dilution	Streamflow	- Common data: 2, 3, 4, 6, 7, 8, 9
	Cleaning	Floods	- Common data: 4, 6, 8, 9
		Reservoirs	- Common data: 1, 2, 3, 4, 5, 6, 8 9, 10, 11
Recharge of groundwater	Reservoirs and ponds	Streamflow	- Common data: 1, 2, 3, 4, 5, 6, 7, 8, 9, 10, 11
	Bank infiltration	Streamflow	- Common data: 3, 4, 6, 7, 8, 9
	Wells	Streamflow	- Common data: 1, 2, 3, 4, 5, 6, 8, 9, 10, 11

1. Series of monthly and annual volume of streamflow.
2. Mean daily discharge series.
3. Low-flow frequency distribution.
4. Frequency distribution of high discharges.
5. Frequency distribution of large-volume floods.
6. Shapes of typical flood hydrographs.
7. Ice cover information.
8. Sediment transportation.

9. Quality of water.
10. Precipitation distribution in space and time.
11. Evaporation distribution in space and time.

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CHAPTER 48

SUSTAINABLE WATER DEVELOPMENT

48.1 General

The last two decades have witnessed a growing realization that natural resources are limited and that future development must come to terms with this realization. The concept of sustainability has become generally accepted. The concept means different things to different people. However, the definition adopted by the International Union of Conservation of Nature and Natural Resources, the United Nations Environment Programme and the World Wildlife Fund [1] is used herein: “Sustainable development is improving the quality of human life while living within the carrying capacity of supporting ecosystems”.

An important question is whether there is any way of measuring the sustainability of development. It is arguable that, if account can be taken of natural variability and trends in water-resources availability, the effects of development will be reflected in changes in the resource base. Monitoring of the quantity and quality of water in natural systems — streams, lakes, underground, snow, and ice — thus becomes a prerequisite for tracking the extent to which development can be sustained.

The building of adequate databases through the monitoring of hydrological systems is a fundamental prerequisite of water-resources assessment and management. The purpose of this chapter is to review the adequacy of present monitoring networks and techniques in the light of a changing resource base and changing water-management philosophies related to sustainable development.

48.2 The changing nature of the resource

48.2.1 *Natural changes*

The hydrological system, driven by meteorological conditions, is constantly changing. Over long periods of time — decades to millennia — variations in the receipt of energy from the sun, acting through the atmospheric system, cause important changes in hydrological regimes. For example, changes in the distribution and extent of ice masses and vegetation cover usually reflect hydrological changes.

Recently, there has been a realization that air/sea interactions are extremely important in affecting climate. *El Niño* events, with teleconnections over wide areas, may have far reaching hydrological ramifications, particularly important when associated with droughts and floods.

Natural events of a completely different type, such as major volcanic eruptions with massive emission of dust and gases into the atmosphere, can also have major effects on the hydrological system.

48.2.2 *Man-induced changes*

Human activities are having an increasing effect on hydrological systems. Some of the more important are:

(*a*) The construction of dams and diversions produces major effects on flow regimes and sediment transport on many of the world's rivers;

(*b*) Changes in land use often have major impacts on hydrological regimes;

  (i) Deforestation often leading to more pronounced flood peaks and increased soil erosion;

  (ii) Draining of wetlands often leading to changes in runoff regime;

  (iii) Farming practices leading to changing infiltration rates and groundwater recharge; and

  (iv) Urbanization leading to characteristically flashy runoff;

(*c*) The quality of water in many places has been adversely affected by industrial and municipal wastes and by agricultural practices involving fertilizers, pesticides, etc.; and

(*d*) The emission of greenhouse gases is expected to cause climate change in the next century and may affect hydrological systems.

In order to understand the hydrological system better, to predict water availability in the future, and to manage effectively the resources, monitoring systems should take into account these many changes.

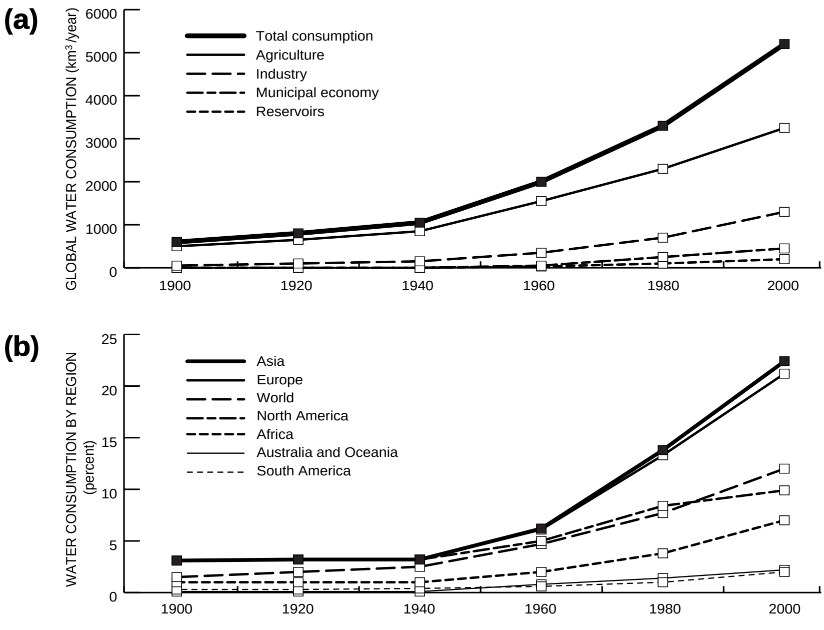
48.3 Changing attitudes to management

There have been significant socio-economic changes in many parts of the world. Fast population growth, particularly in many developing countries and especially in burgeoning urban centres, combined with industrialization and rising living standards, has increased the demand for water. Water pollution in many regions has reduced quantities fit for consumption. Rising demand outstripping the supply will become more common in the future. Thus, more efficient and effective water management is imperative.

The past two decades have witnessed dramatic changes in water management. There have been two very important underlying themes. First, there is a growing awareness that water is a fundamental element in the natural environment. The presence and movement of water through all biological systems is the basis of life. Water, land, and biological systems must be viewed as interlinked, and monitoring of the various components of the ecosystem should be harmonized. Second, water is absolutely essential in all forms of economic activity. Water is essential for agriculture and food production, for much of industrial production, and for the creation of energy. Water is also critical for human health. Too much water (in the form of floods) or too little (drought) can lead to human and environmental disaster.

Part (*a*) of the Figure below shows the evolution of world water consumption from 1900 to the year 2000. Globally, consumption has increased ten-fold and by the year 2000, almost half of the available water supplies will be in use. Agriculture, and particularly irrigation, remains the primary consumer despite a continuing decrease in the percentage that it uses — from 90.5 per cent of water consumed in 1900 to 62.6 per cent by the year 2000. During the same period, the portion used by industry will pass from 6.4 per cent to 24.7 per cent, with cities sharing the same rate of growth, climbing from 2.8 per cent in 1900 to 8.5 per cent by the year 2000.

How has water consumption compared with the available water resources in each of the world's major regions during the twentieth century? Part (*b*) of the Figure below answers this question in terms of percentages calculated on the basis of theoretical resources, i.e., the amount of water flow in rivers. According to these



Evolution of world water consumption according to (*a*) activity, and (*b*) region.

calculations, Europe and Asia clearly consume much greater percentages of their water resources than North America, Africa and, particularly, South America and Australia-Oceania. It is also clear that Europe and Asia have the highest growth in consumption, except for South America, where the increase is offset by plentiful reserves of water.

Growing awareness of the pervasive nature of water and of its importance in the natural environment, and in human activity, has brought to light the need to take a holistic approach to its management. Development of the resource for human use may have detrimental environmental impacts while, conversely, changes in the natural-resource base may limit or, otherwise, affect human activities. These changes have caused the emergence of the approach to integrated water-resources management.

48.3.1 *Watershed management*

There is general recognition that the natural management unit is the river basin. It makes sense to manage the water resources within a river basin and in a coordinated manner, as the water is often used several times as it moves from the headwaters to the river mouth. It makes sense, too, to manage all natural resources, vegetation, soils, etc., within the basin unit. Water demands for human activities should also be managed within the basin in an integrated fashion.

Unfortunately, political boundaries do not normally coincide with basin boundaries. Rivers often cross international frontiers, and they traverse from state to state within countries. Globally, about half of all the land surface falls within international basins and more than 200 basins are international in character.

48.3.2 *Management fragmentation*

It is common that several agencies or institutions within a state or country have authority over different aspects of water-resources management. Departments or ministries of agriculture, energy, industry, and health often have conflicting mandates. It is also commonplace to find relatively new environment departments trying to define and grapple with the problems of their mandate, jurisdiction, and authority relative to pollution concerns, conservation, and husbandry of the natural environment.

All too often, the monitoring networks within a country or state are also fragmented politically and institutionally. Even within single agencies, the responsibilities for water quantity and water quality monitoring are often not coordinated. Confused institutional responsibilities and mandates within countries and conflicting demands on water use between countries (within international basins) pose real problems for the establishment and maintenance of effective monitoring networks.

It is against this complex background of rapidly changing philosophies of water management, changing political and socio-economic realities, and changes in the resource base itself that monitoring systems have to be designed and operated.

48.4 Water-data programmes

48.4.1 *Assessing data needs for the future*

The Report of the International Conference on Water and the Environment (ICWE), held in Dublin on 26-31 January 1992, [2] provides a compelling assessment of the importance of water resources to the world's environment and to its economy. Its specific policy statements highlight very effectively the role that hydrological services should play in achieving goals related to sustainable development. ICWE addressed the issues of:

(*a*) Integrated water-resources development and management;
(*b*) Water-resources assessment and impacts of climate change on water resources;
(*c*) Protection of water resources, water quality, and aquatic ecosystems;
(*d*) Water and sustainable urban development and drinking water supply and sanitation in the urban context;
(*e*) Water for sustainable food production and rural development and drinking water supply and sanitation in the rural context; and
(*f*) Mechanisms for implementation and coordination at the global, national, regional, and local levels.

The kinds of information that will be required to meet the needs considered in these six areas in the long-term future is difficult to project. Perhaps, the best ideas can be gathered from considering recent trends in water management (section 48.3). Since data are gathered for the use of water managers, whether in Government or private agencies, changes in how water is managed will influence the data and information demands.

The impacts of these changes may include:

(*a*) Growing competition for water, resulting in a higher value being placed on available supplies and, ultimately, goods and services being redefined in terms of their water content — this could be exacerbated by declining water availability and quality in many areas;
(*b*) Economic pressures resulting in more user fees, cost sharing, and local financing of water programmes, with a concurrent shift in emphasis from water-development activities to environmental programmes and demand management;
(*c*) Increased focus on water conservation and re-use in all phases of project development — in some areas, reclaimed water now costs less than freshwater supply;
(*d*) Environmental legislation designed to hold polluters and users accountable for their impacts on available supplies;
(*e*) Legal trends towards forcing users and water managers to justify their uses, needs, and management practices more rigorously, and the likely increase in the priority accorded to environmental water uses (e.g., fish and wildlife habitat) versus the traditional economic uses (e.g., agriculture and industry) in legal proceedings; and
(*f*) Basin and regional water planning will be emphasized to resolve transboundary issues and disputes.

These trends indicate that greater coordination of data-collection efforts will be required to meet the needs of water managers in the future. Water management is becoming more integrated across disciplines and specialities, and therefore compatible data on quantity and quality, surface and groundwater, and in specific basins and regions will be required. Current problems related to data accessibility, compatibility, and reliability will have to be resolved to meet these needs.

Integrated planning of data networks are essential if comprehensive climate, and streamflow data are to be available for basins of concern. While the bulk of users will continue to need data for design and analysis purposes, increased attention must be paid to the need for comprehensive regional surface-water information that can be applied to many different kinds of water issues and problems. This means overview information, fact sheets and summaries, surface water and precipitation mapping, hydrological assessments of basins and regions, and water information relevant to the assessment of water quality and groundwater problems. The use of real-time water data will continue to grow to serve many needs.

48.4.2 *Network character and relevance*

An example of trends is the Canadian network, which is managed under a series of federal-provincial agreements and includes 2 700 active hydrometric and 200 active sediment stations (with 3 100 and 600 discontinued stations, respectively). This network and its data are largely driven by client needs for a range of resource-management applications, both economic and environmental. In this sense, the network has been and will continue to support sustainable water management through a wide range of water planning, design, and operational applications. However, the value of the database can be further enhanced by developing interpretative products that address the needs for information on the status of the water resources and their characters and trends.

However, the existing Canadian network is considered insufficient to meet the multiple needs of sustainable water management. Recent evaluations have highlighted several areas where data are inadequate. For example, more hydrometric stations are needed to define the variations in regional hydrology. Today, only about 500 stations exist with natural-flow conditions and sufficient record length and quality for regional-hydrology applications. These stations do not provide a good representation of natural conditions on either basin scales or across Canada. Most are in the southern latitudes, which leaves little opportunity to document and understand natural flows in mid-latitude and northern basins. The record length and the spatial coverage of these stations are basic inputs to hydrological appraisals of all types, which include the calibration of hydrological and environmental models.

Increasing urbanization is cited in the ICWE report as a significant problem for sustainable development. However, for studies of the impacts of urbanization on water resources, the existing coverage of urban basins is limited and unevenly distributed.

Sediment-transport monitoring provide similar opportunities and limitations. While most of the Canadian stations were established in association with engineering projects (e.g., reservoir sedimentation) or for the purpose of collecting long-term records at key sites, the data can be used to document the transport of sediment through river systems. This information is required for most environmental concerns, e.g., sediment-associated contaminant transport. However, better knowledge of system-scale sediment transport is required, and sediment-monitoring activities need to be coordinated along river systems. Sampling strategies, record length, and record quality must be compatible throughout the basin.

In summary, the existing national networks, while confirming the essential inputs to sustainable water management, will require continuous adjustment to provide sufficient information to address some of the more pressing environmental questions facing water-resources managers.

48.4.3 *Network-strategy options*

Besides seeking to improve representativeness of existing surface-water data networks, hydrological services should develop more comprehensive monitoring strategies. For selected basins, the hydrometric data-collection activities need to be integrated with sediment, water quality, meteorology, and aquatic-habitat programmes (section 20.1.4). For example, concerns for sediment-associated contaminant transport require knowledge of the source, pathways, and fate of fine particles. This requires an understanding of both the flow and sediment regimes. Whether for the interpretation of concentrations or for calculating contaminant loadings, such integrated monitoring requires close coordination at all stages from planning to reporting.

Integrated planning of related data networks should be developed to maximize the effectiveness of all water-data programmes. Recent studies [3] attempt to define network needs from many different perspectives, and, ultimately, to coordinate the data collected on a watershed basis so that adequate water data (i.e., precipitation, runoff, groundwater, and water quality) are available to meet future needs.

Present monitoring programmes can be enhanced by the use of supplementary studies. For example, river studies of sediment sources and morphologic change [4, 5] supplement regular programme data to determine the river behaviour. This knowledge, which is not possible from monitoring studies alone, is being used for fisheries management, river-engineering studies, and water quality studies.

On a different scale, water quality considerations are increasingly important to urban-drainage design. The design of appropriate monitoring programmes should consider short-interval sampling, integrated precipitation and runoff monitoring, and extremely rapid response times if the data are to be useful. These conditions are quite different from those covered by standard monitoring procedures.

The use of computer models is an additional strategy for enhancing the information derived from water-monitoring activities. In certain circumstances, monitoring-network designs can be improved by the use of models.

48.5 **Conclusions**

Hydrological services have a great deal of the data and information needed by the hydrological community. To be of maximum use and benefit, the data must be sufficient, reliable, and accessible to the users. A major problem is that data are often not available for a particular basin of interest. Meteorological data are often incompatible with available streamflow records in terms of timing and location. Integrated network-planning procedures could identify opportunities for coordinated network design and operation. In this way, compatible data sets could be produced, and more effective operational procedures could be developed. In addition, better techniques for data transposition and transfer could be identified and developed for hydrological applications. Incompatibilities of data sets between agencies, regions, and countries may not be resolved in the short term. However, summarized data sets, incorporating the most commonly applied parameters, such as precipitation and runoff, would be a useful step in increasing the usefulness of data for hydrological purposes.

This chapter has highlighted the need for holistic approaches and truly integrated management philosophies. It will be a major challenge for national agencies to adapt to these new ways of thinking, but it will be imperative that they do so if water-resources development is to become sustainable.

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CHAPTER 49

WATER QUALITY AND RESOURCE PROTECTION

49.1 General

Water-resources projects should be designed and operated to comply with water quality standards and to avoid detrimental effects on water quality downstream. There is a close relationship between the quantitative characteristics of a water body and water quality. Since water-resources projects usually alter quantitative characteristics of the affected water body, estimates of the changes in water quality are possible if this relationship is well understood and defined. Unfortunately, such relationships are very complex, and the data needed to define them are rarely available. For this reason, only rough estimates of water quality after completion of a project are generally possible. Water quality models may be helpful in reducing the magnitude of the problem. However, the proper calibration and validation of such models require a relatively long period of simultaneous observations of water quantity and quality, as well as other data on existing projects. Some recommended actions to protect water quality and associated aquatic ecosystems are provided by the United Nations in the *International Conference on Water and the Environment: Development Issues for the Twenty-first Century* [1].

49.2 Relationship between water quantity and water quality

49.2.1 *Streams and rivers*

A significant proportion of the variations of river water quality can be related to variations in river flow. The effects of changes in river flow on the concentrations and loads of substances are numerous, and they may act counter to each other. An increase of river flow usually leads to:

(*a*) The dilution of pollutants entering with waste water;
(*b*) The increase in suspended solids from surface runoff and from disturbance of bottom sediments;
(*c*) The release of materials adsorbed by or precipitated in the sediments (e.g., phosphates, heavy metals);
(*d*) The increase in biochemical oxygen demand caused by stirring up reducing substances from the river bed;
(*e*) The decrease in the ratio of groundwater to surface runoff in the river flow, leading usually to a lower pH;

(*f*) The washing out of benthic micro-organisms, reduced concentration of aquatic micro-organisms, and reduced residence time;
(*g*) The attenuation of effects of sudden inputs of pollutants;
(*h*) The reduced absorption of solar radiation and related decline in photosynthetic activity; and
(*i*) Higher turbulence and better aeration.

The sequence and the time of occurrence of high flows is critical for the extent of many of these effects. A second flood wave, following shortly after a first, may contribute little to the effects of the first flood. Thaw and rain after a long period of frost may lead to a sudden influx of road de-icing salts and may cause significant sodium and chloride peaks despite the rise in flow. The land-use, land-cover, and other characteristics of the portion of the basin in which the flood-generating runoff originates is another factor that affects the magnitudes of changes in water quality caused by high flows.

When the rise in river flow results in significant flood-plain inundation, a number of additional water quality effects may follow. Most significant among them are the following:

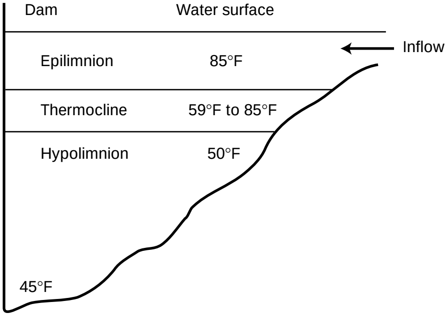
(*a*) Flood attenuation related to additional valley and bank storage, leading to a general reduction of the effects of the flow increase;
(*b*) Increase of the water surface-to-volume ratio and resulting in increased opportunities for solar-radiation absorption and photosynthetic activity;
(*c*) Reduced flow velocity in the flood plain, leading to decreased re-aeration and to deposit of suspended solids outside of the main river channel; and
(*d*) Intensive contact with previously deposited sediment, various types soil structures, dumps, etc., that can lead to river contamination.

Low-water periods usually lead to effects that are opposite those caused by flow increases. In addition, low-water periods are often accompanied by a relatively high diurnal variation in water quality characteristics, e.g., dissolved oxygen, carbon dioxide, pH and temperature. In arid climates, the effect of evaporation on the concentration of various substances in the water is significant. In cold climates, low-water periods in winter may also be periods of oxygen deficit whenever the ice cover interferes with the re-aeration process.

49.2.2 ***Large lakes and reservoirs***

Thermal stratification is a result of natural factors. However, thermal pollution may be a contributing element (section 49.5.4). The Figure below shows a representative profile of the summer stratification in a large storage reservoir. Thermal stratification corresponds, particularly in nutrient-rich lakes, to dissolved oxygen stratification and, frequently, to the stratification of other dissolved substances.

The epilimnion, i.e., the upper layer of water, which is warmer in summer, generally has better water quality. In the upper layer, one may expect reduced silicate



Representative profile showing summer stratification in a large storage reservoir with a high dam.

content following increases in diatoms, and decreased hardness from direct inputs of precipitation water.

The hypolimnion, i.e., the deeper layer of water, which is colder in summer, has a reduced dissolved oxygen concentration. Various substances frequently accumulate in this layer due to deposition on the bottom, adsorption on sediment, and ingestion by living organisms. Anaerobic decomposition of algae and other organisms may occur in the hypolimnion. One may expect the hypolimnion to show trends of increasing concentration of ammonia and hydrogen sulphide, reduction in nitrate and sulphate concentration, accumulation of sediment, and occasionally of heavy metals, and periodic increases in iron, manganese, and phosphate concentration. During the turnover caused by the seasonal cooling of the surface layer of the lake, a convective circulation takes place that results in mixing and a uniform temperature.

In addition to the effects listed above, one may expect that:

(*a*) In large lakes and reservoirs, organic matter is biodegraded to a large extent due to long residence time;
(*b*) Variations in water quality are dampened out for the same reason; and
(*c*) Algae trigger the formation of chelating substances and halocarbons.

49.3 Effects of water-resources projects on water quality in streams and rivers

49.3.1 *Dams and weirs*

By raising upstream water levels, a dam and, to a lesser extent a weir, usually has the following effects on water quality in the upstream reach of the river:

(*a*) Intensification of self-purification processes because of increased residence time in the reach and more deposition of suspended solids, which result in increased solar-radiation absorption and in changes in the sediment characteristics of the river bed; and (*b*) This, in turn, leads to a rise in phytoplankton production, greater oxygen consumption, and increased day-night fluctuations in oxygen, pH and carbon dioxide.

Fish migration may be disturbed both by the physical barrier and by changes in water quality. Changes in bank vegetation, which are governed by local topography, climate, and water-level variation, may also affect water quality. In cold climates, dams and weirs create favourable conditions for an extended duration of ice cover in upstream reaches. This leads to decreased re-aeration. Further effects in the case of large storage volumes may result from thermal stratification. Increased pollution retained in the upstream reach may lead to eutrophication or to anaerobic conditions (section 49.5.1).

The effects of a dam or weir on water quality in the downstream reach depend on the upstream storage volume, dam design and operation, and other factors. The most important effects are the following:

(*a*) Reductions in suspended solid load, pollution load, and turbidity;
(*b*) Changes in the chemical characteristics of the water (often a lower concentration of dissolved oxygen and nitrates, and increases in phosphate, carbon dioxide and hydrogen sulphide, the latter particularly when anaerobic conditions prevail upstream);
(*c*) Decreases in the summer water temperature, increase in the winter temperature; and
(*d*) Reductions of the day-night temperature fluctuation to which the river flora and fauna are adapted.

49.3.2 ***River-training works***

River training usually involves a deepening and straightening of the river channel for various purposes (e.g., navigation, flood control, land use improvement and erosion protection) and, thus, results in changes in the geometric and hydraulic characteristics of the river channel and in some cases of the flood plain as well.

When river training is done for navigational purposes, it usually involves the construction of navigation weirs and locks. In addition to the effects of weirs (section 49.3.1), the training works and the operation of navigation canals lead to increased turbidity and mixing of the water and aeration from the mechanical effects of the moving boats. On the other hand, the boats are a source of both routine and accidental pollution.

In other cases, river-training works lead to reduced self-purification processes because the straightening of the banks eliminate stagnant water zones both as areas of self-purification and as a favourable environment for animal and plant life development. The reduced surface-to-volume ratio leads to a reduction in the solar-radiation absorption and re-aeration. The re-aeration reduction may be partly compensated when river training leads to higher water velocities.

49.3.3 *Flow reduction and augmentation*

In addition to the flow-regulation effects of dams, many water-resources projects involve downstream flow reductions by diversions for various water-supply purposes or augmentation from inputs of water coming from sources outside of the basin.

When the extracted water undergoes treatment and the resulting sludge and residues are returned to the donor river, or when water is diverted from the less polluted portions of the river cross-section, the diversion effects are equivalent to a reduction in flow or to a pollution input (section 49.5). The disposal of sludge and residues is usually subject to control by legal requirements for the quality of effluents.

The effects of flow augmentation depend mainly on the quality of the additional water as compared to that of the river water. An addition of water of poorer quality is equivalent to a pollution input.

49.4 Effects of water-resources projects on water quality in large lakes and reservoirs

Water quality in large lakes and reservoirs may be either improved or degraded by water-resources projects. A water-resources project involving a withdrawal of water of a better than average quality (e.g., from the epilimnion) will generally worsen the water quality in the lake. The same is true when water of poorer than usual quality is introduced into the lake or reservoir.

Water quality in a large reservoir depends, to a large extent, upon the characteristics of the underlying terrain before flooding and upon the treatment applied to it. If the future reservoir bottom is covered by soil with rich organic (humus) content, the latter is leached after the reservoir is filled and accelerated eutrophication (section 49.5.1) may result. This may be avoided by the removal of vegetation and soil prior to flooding, which is a costly operation.

49.5 Water quality changes due to pollution

49.5.1 *Eutrophication*

One of the most common forms of pollution is excessive concentrations of nutrients originating either in urban waste waters or in rural runoff. This usually results in excessive development of algae populations, particularly in areas with low water velocity, and in significant reductions or even the disappearance of a number of plant and animal species. This process is known as eutrophication. Eutrophication is a natural process that marks the maturing and ageing of lakes. However, under conditions not involving man’s activity, this process may take hundreds or thousands of years depending upon lake size, hydrological conditions, and land cover in the basin. Civilization is responsible for accelerated eutrophication in a large number of lakes all over the world.

The problem of eutrophication and its causative factors is a major water quality problem. Although considerable research has been devoted to it, it is not yet possible to explain quantitatively the process of nutrient enrichment and the growth of algae or other eutrophication processes. The following elements have been reported as essential for algae growth: B, C, Ca, Cl, Co, Cu, Fe, H, K, Mg, Mn, Mo, N, Na, P, S, V and Zn. Although the deficiency of any of these elements can limit growth, nitrogen and phosphorus are the ones most likely to limit the growth of algae in natural waters.

In some countries, attempts to stop the advance of eutrophication are made by banning the use of phosphorus compounds in detergents and by introducing treatment processes for the removal of phosphorus and nitrogen.

The effects of eutrophication are reflected in striking changes of the corresponding aquatic ecosystem. Extremely polluted environments have few species. When pollution is due to toxic substances, the number of individuals surviving in each species is low, sometimes extremely low, and when pollution is due mainly to nutrients, although the number of species is small, the number of individuals in each species is very large.

49.5.2 *Organic matter and self-purification*

A large amount of polluting substances of municipal, industrial, and, particularly, of agricultural origin consists of organic matter. A number of phenomena occurring in natural waters tend to transform this organic matter into more or less innocuous inorganic matter. This phenomenon is known as the self-purification process. Some of this matter is recycled by micro-organisms and generates secondary organic pollution. Before the biological degradation leading to self-purification can take place, the organic substances dissolved in the water must be adsorbed and concentrated on the surface of solid particles. Adsorption can take place on the solid particles on the river bottom, banks, and macrophytes, and on suspended solids.

Most biological degradation is associated with oxygen consumption, which is the key factor in the self-purification process. When oxygen consumption in water proceeds so rapidly that it exceeds the rate by which it is replenished from the air or by the oxygen-producing biological activities, the aerobic self-purification capacity of the water body is exceeded. This occurs when one or several of the following conditions occur:

(*a*) A too large load of organic matter;
(*b*) Biological-degradation processes are accelerated by certain factors, e.g., temperature rise; and
(*c*) Oxygen replenishment is diminished by thermal stratification, ice cover, or other causes.

When the self-purification capacity is exceeded, the decomposition of the organic matter usually continues under anaerobic conditions. This interferes with many uses of the water body. The use of water for recreation and fisheries is impossible under such conditions, and it may be much less desirable for other uses, such as water supply.

49.5.3 *Adsorption and accumulation of pollutants*

Some harmful substances are adsorbed on organic and inorganic suspended solids and, when the latter settle on the bottom, the harmful substances are temporarily removed from water. Micro-organisms are also capable of concentrating, through biochemical processes, a number of organic and inorganic pollutants. For example, the concentration of some pesticides in micro-organisms reaches levels of up to 300 000 times higher than those found in the corresponding water environment. However, due to physical and biological processes, substances absorbed and accumulated by micro-organisms may be returned subsequently into the water body in solution or in particulate form.

The concentration of pollutants by micro-organisms is of particular significance because they are at the starting point of the food chain and are passed from one level of organism to another in increasingly higher concentrations. Such a process is responsible for mercury poisoning related to the well-known minemata disease.

49.5.4 *Thermal pollution*

Thermal pollution is defined as an increase of the temperature of a water body over the natural level caused by the release of industrial or municipal waste water — in particular, cooling water.

The effects of thermal pollution on water quality are complex and relate to the effects of higher temperatures on the viscosity of water, to its decreased solution capacity for oxygen, and to the increased chemical and biological activity. Thermal pollution may also be a contributing factor in thermal stratification. Due to thermal pollution, the period of biological productivity is lengthened, which leads to an increased load of organic pollution. In addition, certain species of green algae are replaced by blue-green algae, which transmit undesirable characteristics of smell, taste, and toxicity to the water.

As already mentioned, self-purification processes are accelerated by higher temperature, and thus by thermal pollution, to the extent that acute oxygen deficits may occasionally occur. In winter, ice formation is delayed by thermal pollution, and this extends the possibility of re-aeration.

49.6 **Measures to reduce effects of pollution on water quality**

Such measures can be essentially grouped into two broad classes, preventive and corrective. Whenever feasible, preventive measures should be applied.

49.6.1 *Preventive measures*

Preventive measures consist primarily in removal of pollutants from the waste waters, changing of industrial processes to reduce wastes, changes in the chemical composition of certain industrial products (e.g., elimination of phosphorus compounds from detergents), artificial cooling of industrial waste waters, etc. If pollution originates in the matter washed away by runoff from the surface of a river basin (e.g., pesticides and herbicides, fertilizers, the uncontrolled urban waste), then pollution abatement can be obtained by only changing the practices that lead to uncontrolled spreading of pollutants in the river catchment and to measures to reduce runoff and soil erosion.

Significant pollution is generated by soil erosion. Its prevention requires adequate forestry management and construction and farming practices. Finally, pollution from leachates resulting from garbage dumps may be locally very significant. This can be avoided by appropriately locating and designing such dumps.

49.6.2 *Corrective measures*

Reducing pollution in water bodies after pollutants have reached them is generally difficult and costly. In most cases, it is possible only to treat the water diverted from the water body for various purposes (e.g., domestic or industrial water supply). However, in special circumstances some remedial work can be done for the whole water body. Such remedial work consists, in the case of rivers, mainly in artificial re-aeration (oxygenation), or mixing and dredging of settled pollutants and, in the case of lakes and reservoirs, on the following measures:

(*a*) Emptying regularly the lake during the period between late fall and early spring in an attempt to expose organic matter directly to the air and permit aerobic decomposition of the organic matter;
(*b*) Dredging the bottom of the lake in the areas that contain most of the organic and polluting matter;
(*c*) Forced re-aeration by compressed air in the de-oxygenated layers; and
(*d*) Harvesting and disposing of organic matter produced in the form of algal bloom, undesirable fish, etc.

Reference

1. United Nations, 1992: *International Conference on Water and the Environment: Development Issues for the Twenty-first Century,* 26-31 January 1992, Dublin, Ireland.

CHAPTER 50

WATER-RESOURCES ASSESSMENT

50.1 General

Water is, like the air we breathe, a basic requirement for all life on Earth. It is vital for many aspects of economic and social development, e.g., for energy production, agriculture, domestic and industrial water supply, and it is a critical component of the global environment. There is growing awareness that development, including development of water resources, must be sustainable, which implies that the world's natural resources must be managed and conserved in such a way as to meet the needs for present and future generations (Chapter 48).

50.2 The need for water-resources assessment

Water-resources assessment (WRA) is the determination of the sources, extent, dependability, and quality of water resources, which is the basis for evaluating the possibilities of their utilization and control [1]. Water-resources assessment is of critical importance to wise and sustainable management of the world's water resources. Several reasons for this may be cited, including [2]:

(*a*) The world's expanding population is placing increasing demands on water for drinking, food production, sanitation, and other basic social and economic needs, but the world's water resources are finite. The rising demand has reached its limit in some areas. It is going to reach the limit in many other areas within the next two decades while, before the end of the next century, the world's water resources will be fully utilized should present trends continue;

(*b*) Human activities are becoming increasingly intensive and diverse, and are having an ever-growing and more evident impact on natural resources through depletion and pollution. This is particularly the case for water, whose quality for many purposes can be severely degraded by pollution from a wide range of chemicals, micro-organisms, radioactive materials, and sediments and by physical changes;

(*c*) Water-related natural hazards, e.g., floods, droughts, and tropical cyclones, are among the most destructive of human life and property and have been responsible for death and widespread misery of countless millions during the course of history. Deforestation and urbanization, in particular, have exacerbated flood hazards by increasing the magnitude and frequency of floods; and (*d*) There is a growing realization that the world's climate is not constant, and indeed may well be changing in response to human activity. While the postulated rise in global temperature due to greenhouse-gas induced warming has been widely publicized, the more important effects are likely to be on the distribution of rainfall, runoff, and groundwater recharge. It cannot be assumed that the future patterns of these hydrological phenomena will continue to be as they have been in the past.

Only with reliable data and information on the status and trends of the water resources, including quantity, quality, statistics on such events as floods, and use for human purposes, can wise decisions be made on how best to manage water.

To a large extent, water-resources assessment is a prerequisite for all aspects of water-resources development and management. This fact was recognized by the United Nations Water Conference, held in Mar del Plata in 1977, through the adoption of Resolution 1 and Recommendation A of the Mar del Plata Action Plan [3], which stressed the need for greater knowledge about the quantity and quality of surface-water and groundwater resources, and for comprehensive monitoring to guide the management of these resources. Furthermore, the International Conference on Water and the Environment, held in Dublin on 26-31 January, 1992 recommended a number of actions in support of national water-resources assessment [4].

50.3 **Uses of water-resources information**

Hydrological or Hydrometeorological Services or related agencies have been established in countries for systematic water-resources-data collection, archiving, and dissemination (Chapters 21-25). Their primary role is to provide information to decision makers on the status and trends of water resources. Such information may be required for the purposes of [2]:

(*a*) Assessing a country's water resources (quantity, quality, distribution in time and space), the potential for water-related development, and the ability of the supply to meet actual or foreseeable demand;
(*b*) Planning, designing, and operating water projects;
(*c*) Assessing the environmental, economic, and social impacts of water-resources management practices, existing and proposed, and planning sound management strategies; and
(*d*) Providing security for people and property against water-related hazards, particularly floods and droughts.

Most frequently, water-resources information has been collected for a specific purpose, such as the design of a hydroelectricity scheme. However, increasing, competition among users for scarce water requires that resources be managed in an integrated fashion, so that the interactions among several projects and users may be understood. This places a much greater burden on the suppliers of water-resources information, because a variety of different types of information is simultaneously needed, and has to be presented in different forms for different users. This makes it essential that assessment agencies understand the needs of all their users, and not just those with whom they have traditionally dealt. Even more demanding is the need to look ahead to the possible needs of future users of data and to commence collecting the information before an actual demand can be demonstrated with certainty. Therefore, it is necessary that the design and updating of data-collection networks, especially the principal stations, be coordinated to ensure that stations for monitoring the different elements of the water cycle are sufficiently related, both in number and location, to achieve an integrated network (sections 20.1.4 and 48.4). Such an approach would enhance the information content of the data sets for both present and unforeseen, future needs.

With the growing recognition of such issues as the possibility of global climatic change and the environmental impacts of human activities, such as urbanization, there is an increasing emphasis upon the information required as a foundation for sustainable development and management of water resources.

50.4 Types of water-resources information

The diversity of possible uses of water-resources information implies that there is a considerable range of types of data. Conventional water-resources information comprises the statistics of a variety of meteorological and hydrological elements. The elements include [2]:

(*a*) Precipitation, e.g., rainfall, snow, and fog-drip;
(*b*) River levels and flows, and lake and reservoir levels;
(*c*) Groundwater levels;
(*d*) Evapotranspiration;
(*e*) Sediment concentrations and loads in rivers; and
(*f*) Water quality (bacteriological, chemical, and physical) of surface water and groundwater.

The statistics include:

(*a*) Mean annual, monthly, or seasonal values;
(*b*) Maxima, minima, and selected percentiles;
(*c*) Measures of variability, such as the standard deviation; and
(*d*) Continuous records in the form, for example, of a river flow hydrograph.

There is a requirement for both historical and real-time data to cater for the full range of needs from water-resources planning to project design and flood warning. Flood or low flow forecasting (Chapter 44) may require data to be synthesized for the future by using numerical flow-routing models (Chapter 34).

The UNESCO/WMO *Water-resource Assessment Activities: Handbook for National Evaluation* [1] recognizes a number of types of water-resources projects for which hydrological information is required, as given in the Table below. In addition to the more conventional measurements, there is a growing recognition of the need to measure other aspects of the fresh water environment and of the wider environment in which freshwater is only a single component. These include:

(*a*) The volumes of water needed for industrial, domestic, and agricultural use, and for navigation. These are now significant modifiers of the hydrological cycle in many basins;
(*b*) Attributes of rivers related to instream uses, e.g., freshwater fishery habitats or recreation;
(*c*) Watershed characteristics that may be related to hydrology, e.g., vegetation patterns, soil moisture, topography, and aquifer characteristics; and
(*d*) Environmental concerns, e.g., eutrophication of lakes and damage to natural fresh water and estuarine ecosystems.

Together, these imply a vast range of water-related data and information that the Hydrological Services and other related agencies may be required to collect and archive. Different countries have different priorities that depend on their level of economic and social development, the sensitivity of their natural environments to disturbance by human activity, and the nature of the physical environment itself, e.g., climate, topography, and the abundance or otherwise of water.

There are several critical requirements for an effective WRA programme:

(*a*) Data of high quality must be collected to permit confident statistical analysis;
(*b*) The data and the information that they provide must be carefully targeted to the users' requirements;
(*c*) An integrated observation programme, in which measurements of several variables are made simultaneously, is required to provide the greatest total value;
(*d*) Other forms of information that are compatible with and can be analysed with water-resources information should be available;
(*e*) An effective system is needed for archiving and disseminating data to ensure that they are not lost or corrupted and that they are made available in a form that enables analysis (Chapters 24 and 25).

The above requirements can be met by the application of new technologies — e.g., telemetry, to make data available in near-real time — by archiving and processing data by personal computers, by remote sensing to collect areal information more effectively, and by geographical information systems (section 40.7) to provide a means of analysing spatial data. At the same time, new microcomputer storage devices (i.e., optical disks) make the data more readily available. Nevertheless, technology is not the only requirement, and a trained and well-managed staff is of even more fundamental importance. As financial resources become increasingly limited in many countries, it becomes ever more vital that effective organizational structures are in place to ensure that those resources are used most efficiently.

Hydrological information required for water-resources projects

	Water levels			*River flow*			*Sediment*			*Water quality**		
Water projects	*time-series*	*max*	*min*	*time-series*	*max*	*min*	*time-series*	*max*	*min*	*time-series*	*max*	*min*
Redistribution of water (diversions, intakes, canals)	M	M	M	H	H	H	H	M	M	H	M	M
Redistribution of water in time (reservoirs)	M	M	M	H	H	H	H	M	M	H	M	M
Energy production (hydropower, waste heat disposal)	H	M	M	H	M	H	H	M	M	M	M	M
Water confiners (dams, flood banks)	H	H	M	M	H	M	M	M	M	M	M	M
Water relievers (spillways)	M	H	M	H	H		M			M		
Quality improvements (water and sewage treatment)				H	M	H	M	M	M	H	H	H
Zoning (flood plain, scenic rivers)	H	H	M	M	H	M	M					
Insurance (flood damage, water quality damage)	H	H		H	H					H	H	
Flow and level forecasts (flood control, reservoir operation)	H	H	H	H	H	H						
Standards and legislation (water quality)	M	H	H	M	H	H				H	H	H

H = high level of priority; M = medium level of priority

* Water quality parameters are diverse depending on the type of project.

50.5 Components of a WRA programme

In order to permit a preliminary assessment of available water resources on which to found national or regional long-term plans for overall water-resources development, a basic WRA programme involves the collection and processing of existing hydrological and hydrogeological data, plus the auxiliary data required for their areal interpolation. These plans should be based on or keyed to present and future water needs.

The components of a WRA are shown in the Figure below, and consist mainly of the following [1]:

(*a*) The collection of hydrological data — The collection of historical data on water cycle components at a number of points distributed over the assessment area;

(*b*) The collection of physiographic data — Obtaining data on the natural characteristics of the terrain that determine the areal and time variations of the water cycle components, such as topography, soils, surface and bed rock geology, land-use and land-cover. These characteristics are designated for brevity as physiographic characteristics;

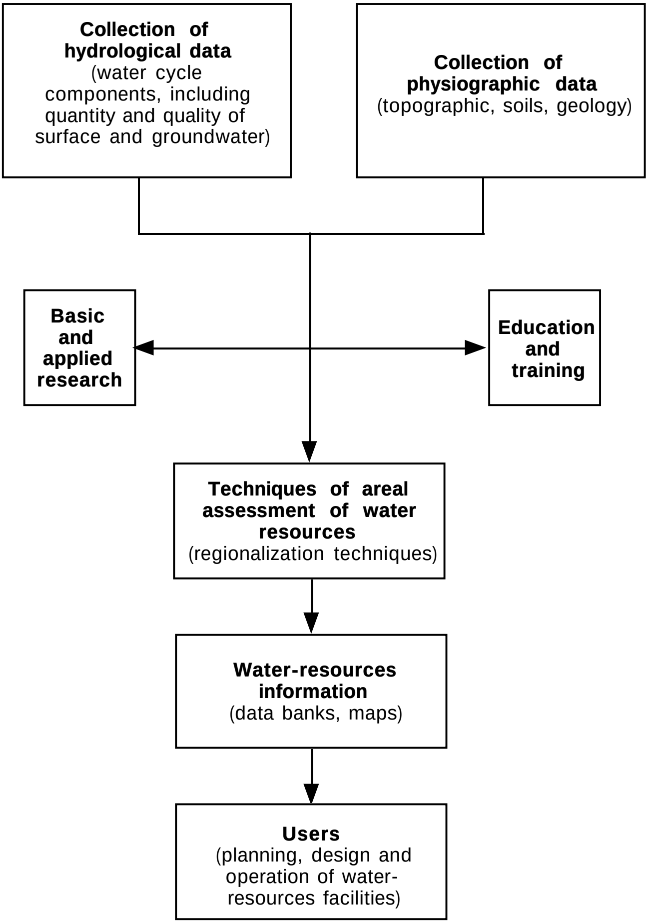
(*c*) The techniques used for the areal assessment of water resources — Techniques of transforming data into information and of relating the hydrological data to the physiographic data for the purpose of obtaining information on the water-resources characteristics at any point of the assessment area.

The basic WRA programme is considered adequate if the three components of the programme are available and if, by relating them, they are sufficiently accurate to supply the water-resources information required for planning purposes at any point of the assessment area. This will require definition for the given country of the type of information required for planning, the manner in which this information is produced and transmitted to users, and the effects of lack of information or inaccurate information on the decision-making process at the planning stage.

All basic WRA activities require skilled personnel, efficient equipment and techniques for field surveys, network design and operation, and development of reliable areal interpolation techniques. This, in turn, may require training and education of the required personnel, and basic and applied research for developing the required technology. An analysis of these activities can provide indications of their adequacy for the purpose of basic WRA or, when they are inadequate, on the additional means to be devoted to them to provide the required base for future development of an adequate WRA programme.

50.6 Evaluation of WRA activities

Water-resources assessment is a national responsibility, and any evaluation of the extent to which it is being undertaken adequately in a country is also the responsibility of the country concerned. The WMO/UNESCO *Water-resource Assessment Activities: Handbook for National Evaluation* [1] was prepared with the aim of increasing the



Components of a basic WRA programme.

capabilities of countries to evaluate their achievements in WRA and to provide a general framework for determining their needs and the actions necessary to achieve minimum requirements. The methodology proposed in the *Handbook* comprises the full range of topics and activities that are included in a WRA programme. The current levels of basic WRA are compared with minimum acceptable requirements in terms of installations, equipment, skilled personnel, education, training, and research. It contains detailed checklists for each component (see the Figure above) and offers advice as to how each activity might be evaluated, in most cases in quantifiable terms.

The results of the evaluation will be different for each country, depending on the characteristics of the corresponding basic WRA programme and the country's characteristics and needs. Nevertheless, there will be a minimum set of results that are expected in practically each case. This set includes:

(*a*) An analysis of the existing institutional framework for performing the basic WRA programme with its resulting advantages, disadvantages, and related constraints;
(*b*) A comparative evaluation of the measurement networks and indications of network elements that require improvement with respect to station density, equipment, operational and supervisory staff, and other factors;
(*c*) A review of the available surveys and programmes for collecting and processing of physiographic data pertinent to basic WRA;
(*d*) An evaluation of the application of various techniques for areal extension of basic WRA and related data and information-transfer techniques;
(*e*) An analysis of the hydrological information requirements for long-term planning, of the production and flow of this information to the user, and of the results of the use of such information in the planning process, which demonstrates the basic WRA programme adequacy or inadequacy;
(*f*) An estimation of the personnel and skills required for an adequate basic WRA programme and appraisal of existing education and training programmes compared to current and future requirements;
(*g*) A review of basic and applied research activities in the country (and region), their adequacies (or inadequacies) for water-resources assessment compared to current and future needs, including needs for scientific and technological regional and international cooperation;
(*h*) Definition of the major sources of inadequacies in the programme in terms of institutional framework, financial resources, instrumentation, techniques, and others; and
(*i*) Recommendations for eliminating any inadequacies of the basic WRA through national or regional cooperation and/or international aid.

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CHAPTER 51

ESTIMATING WATER DEMAND

51.1 General

Water managers have only recently begun to recognize that water use is actually a demand that can be influenced by pricing policies. This recognition has been propelled by the realization that water resources, even in so-called water-rich countries, are becoming increasingly scarce. More stringent limitations on public expenditures, concern about stretching available resources as far as possible, and re-awakened interest in maintaining and enhancing environmental quality are some of the manifestations of this realization. The demand-management approach differs from traditional supply-oriented approaches in that it emphasizes social and economic policies to influence the uses to which water is placed.

Water-demand management relies on a range of tools and techniques that can be divided into three categories — economic, structural and operational, and socio-political [1]. Realistic water pricing is one of the fundamental keys to water-demand management and is central to many of its options. Structural techniques are those that alter existing structures to achieve better control over water demand. Examples of structural measures include metering, retrofitting, controlling flow, and recycling. Socio-political techniques in a water-demand management context refer to policy and related measures that can be taken by public agencies to encourage water conservation. Techniques include public awareness programmes, laws mandating building codes and appliance standards, and governmental economic policies.

Water demands existing prior to the construction of a water-resources project should be considered in the hydrological design of the project. Failure to consider these demands may cause economic losses as well as social and legal problems in the operation of the project.

51.2 Water use

Water-use data are needed to assess the impact of human activities on the natural hydrologic cycle. Sufficient water-use information can assist in planning water-supply projects, in evaluating the effectiveness of options for water-demand management, and in resolving problems including competing uses for water, water shortages caused by excessive withdrawals, and water shortages during droughts.

In the United States, Congress recognized the need for uniform, current, and reliable information on water use and directed the U.S. Geological Survey to establish a national water-use information program. The U.S. Geological Survey has established national guidelines and standards to meet regional and national needs [2].

Water use can be subdivided into offstream use and instream use [3]. Offstream use is a water use that depends on water being diverted or withdrawn from a surface-water or groundwater source and conveyed to the place of use. In order to determine the total quantity of water used — self-supplied withdrawals and municipal-supply deliveries — five sub-types of use are evaluated:

(*a*) Withdrawal — The quantity of water diverted or withdrawn from a surface-water or groundwater source;
(*b*) Delivery/release — The quantity of water delivered at the point of use and the quantity released after use;
(*c*) Conveyance loss — The quantity of water that is lost in transit, for example, from the point of withdrawal to the point of delivery, or from the point of release to the point of return;
(*d*) Consumptive use — That part of water withdrawn that is evaporated, transpired, or incorporated into products or crops. In some instances, consumptive use will be the difference between the volume of water delivered and the volume released; and
(*e*) Return flow — The quantity of water that is discharged from the point of use and which becomes available for further use.

Offstream-use categories presented in this chapter include municipal water supply, domestic, commercial, irrigation, livestock, industrial, and thermoelectric power. Each category of use typically has different effects on the re-use potential of return flows. Re-use potential reflects the quality and the quantity of water that is available for subsequent use. For example, irrigation return flow may be contaminated by pesticides and fertilizers, and, because of the high consumptive use of water during irrigation, the mineral content of the return flow is often substantially greater than that of the water applied. Consequently, irrigation return flow frequently has little re-use potential. This is a significant contrast to the re-use potential of most water discharged from thermoelectric plants, where the principal change in the water is an increase in temperature.

Instream use is a water use which is not dependent on diversion or withdrawal from surface-water or groundwater sources. Quantitative estimates for most instream uses are difficult to compile. However, because such uses compete with offstream uses and affect the quality and quantity of water resources for all uses, effective water-resources management requires that methods and procedures be devised to enable instream uses to be assessed quantitatively.

Instream-use categories presented in this chapter include navigation, pollution abatement, recreation, aesthetics and tradition, and fish and wildlife conservation. Hydropower is discussed in Chapter 56.

51.2.1 ***Municipal water supply***

Municipal or public water supply refers to water withdrawn by public and private water suppliers and which is delivered to multiple users for domestic, commercial, industrial, and thermoelectric power uses [3]. Information on municipal water supplies can generally be obtained from the individual suppliers by mail surveys or personnel interviews. Data should be obtained on the size of the population served and on the quantity of the withdrawals. Data on deliveries from municipal suppliers to various users are more difficult to obtain, and such information is generally less accurate.

51.2.2 ***Domestic***

Domestic water use includes water for normal household purposes, such as drinking, food preparation, bathing, washing clothes and dishes, flushing toilets, and watering lawns and gardens [3]. Information on deliveries from municipal suppliers to domestic users can be obtained from the municipal suppliers. The number of people served by their own water systems (self-supplied) can be determined by subtracting the number of people served by municipal suppliers from the total population of the area. Self-supplied domestic systems are rarely metered, and few data exist. Self-supplied domestic withdrawals can be estimated by using per capita use coefficients based on a reasonable volume of water per person per day for the study area.

51.2.3 ***Commercial***

Commercial water use includes water for motels, hotels, restaurants, office buildings, other commercial facilities, and civilian and military institutions [3]. Information on deliveries from municipal suppliers to commercial users can be obtained from the municipal suppliers. In many cases, self-supplied withdrawal estimates can be based on the population of the commercial facilities, i.e., the number of students attending a university, inmates in a penal institution, and workers in an office building, or the average occupancy rate of a hotel.

51.2.4 ***Irrigation***

Irrigation water use includes all water that is artificially applied to farm and horticultural crops as well as water used to irrigate public and private lawns, gardens, and golf courses. Irrigation water can be self-supplied or supplied by irrigation companies or districts. The quantity of irrigation water required to produce a crop depends on a number of factors, such as the natural rainfall and other climatic conditions, type of crop, length of growing season, method and scheduling of irrigation, soil properties, etc. Several methods for estimating crop water requirements are in use in different countries [4, 5], but they are usually suitable only for the conditions under which each was developed. Guidelines on this subject are available from the Food and Agriculture Organization (FAO). For site-specific inventories of irrigation water use, an inventory form can be used to collect the necessary water-use information [6]. For large areas and for areas where measurements cannot be made, estimates of irrigation water use may be necessary. Estimates can be made by indirect methods, e.g., statistical samples, land-use mapping, remote sensing, or a combination of these methods [6].

The recent thrust for the efficient utilization of irrigation water has led to a search for more efficient agricultural methods involving the reduction of water demands and return flows, better water quality, and the reduction of monetary expenditures on irrigation, while maintaining or even increasing the level of crop production.

51.2.5 *Livestock*

Livestock water use is defined as water used in association with the production of red meat, poultry, eggs, milk, and wool and animal specialities, such as the raising of horses, rabbits, fur-bearing animals in captivity, and fish farms [3]. Fish farms are primarily engaged in the production of food fish under controlled feeding, sanitation, and harvesting procedures. Most of the water used for fish farms is required in order to maintain acceptable pond levels and water quality.

The quantity of surface water and groundwater withdrawn for use by livestock can be estimated from the numbers of animals in the project area. The number of each type of animal is multiplied by an average water use per animal to obtain water-use estimate. Water use for fish farms is estimated by multiplying pond acreage by an application rate.

51.2.6 *Industrial*

Industrial water use includes water for such purposes as processing, washing, and cooling in facilities that manufacture products [3]. Major water-using industries include, but are not limited to, steel, chemical and allied products, paper and allied products, and petroleum refining. Information on deliveries from municipal suppliers to industrial users can be obtained from the municipal suppliers. Self-supplied industrial withdrawals can be estimated from surveys of individual plants and is fairly constant throughout the year. Good quality water is required in many cases.

Statistical sampling of industrial water users might give some indication of total water use by an industrial sector. It is important to note that a few large industrial users often account for most of the water used. For example, in the United States, the largest industries that represent only three per cent of the total number of industries account for about 95 per cent of the total industrial withdrawals. Another indirect method of estimating industrial water use can be accomplished through the correlation of industrial water use with employment and production.

51.2.7 *Thermoelectric power*

The thermoelectric power category includes water used in the generation of electric power with fossil-fuel, nuclear, or geothermal energy [3], which is also discussed in section 56.3. The estimates of water withdrawals for thermoelectric power should be reliable because relatively complete files are maintained by the power facilities. Most of the water withdrawn by thermoelectric plants is used for condenser and reactor cooling. Plants vary widely as to the techniques used in the disposal of the cooling water after it is passed through the condensers. Less water is required when cooling water is recycled through cooling towers or ponds, but a higher percentage of the cooling water is evaporated (consumptive use), usually more than 60 per cent. When the water withdrawn for cooling is used only once before it is returned to a surface water body, a great deal more water is required, but evaporation is low (less than three per cent). Water-withdrawal estimates can generally be made based on power generation.

51.2.8 *Pollution abatement*

Water quality in many rivers is less than desirable, due to high concentration of pollutants. The situation is usually aggravated during dry periods when the ratio of effluent discharges to streamflow increases. Therefore, pollution abatement may require low-flow augmentation to prevent the pollutants from exceeding a preset maximum level of concentration. Occasional flushing of pollutants by surges of high flows from reservoirs may be an acceptable means of reducing the concentrations of pollutants.

51.2.9 *Recreation, aesthetics, and tradition*

There are many rivers in the world where a specific flow regime is desirable because of scenic and recreational purposes, historical interest, religious activity or other intangible uses. Changes in flow regime in these rivers may provoke strong objections and must be planned and executed carefully.

The recreational demand for water usually requires that it has a reasonable quality, a fairly constant level, a fairly constant velocity, and minor wave activity. Sudden changes in water level can be highly objectionable. It is often difficult to quantify water use for these purposes.

51.2.10 *Fish and wildlife conservation*

In considering fish and wildlife demands for water, it should be considered that a change in regime may cause changes in the populations of various species of fauna and flora. In order to mitigate adverse ecological effects and to strengthen the positive ones in the development of a project, experts should be consulted whenever a change in the natural flow regime is contemplated. The evaluation of these changes is complicated.

51.2.11 *Navigation*

Navigation demands usually centre around the regulation of flow — in order to maintain the minimum required water depth and the velocity below a safe maximum — and the water volumes needed for passage through locks (section 57.1). In some cases, navigation depth requirements have to be met partially or entirely by channel dredging. It is often difficult to quantify water use for these purposes.

51.2.12 *Flood control*

Flood control is not a water use but is generally a demand for a more uniform time distribution of streamflow. This can be partly achieved by various land-use practices, e.g., afforestation of the basin and contour ploughing. One of the most common means of flood control is the reduction of flood peaks by storing the excess water in reservoirs. The basic conflict between the objectives of flood control and water conservation is discussed in section 47.3.

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CHAPTER 52

ESTIMATING RESERVOIR CAPACITY

52.1 General

The examination of the natural variability of streamflow may indicate if a stream will frequently be deficient with respect to the estimated water requirements of a particular management project. Low flows may be augmented by reservoir storage. The effectiveness of a reservoir depends primarily upon the rate of withdrawal, called reservoir draft D, the reservoir storage capacity S, and the time-series structure of the streamflows. The relationship between reservoir storage capacity, draft, and the resulting reliability R of the water supply is called the storage equation [1]. In reservoir design, any two of these three variables can be taken as independent and assigned specific values. The value of the third variable may be computed from the storage equation for the given hydrological regime. There are several methods for the solution of storage equations that depend on the inflow-regime representation, e.g., a historical or a synthetic streamflow record, probabilistic properties of the inflow process, or inflow-duration curves.

The usual task in the design of a low-flow augmentation reservoir is to find the reservoir storage capacity necessary to maintain a given rate of draft with a given reliability, i.e., to solve the storage equation of the form:

$$S = f(D, R) \tag{52.1}$$

where R is expressed either as a percentage of time of non-failure operation, as a risk that a failure in operation will occur within one year or any specified period, or as the amount of water actually supplied in the long run to the consumer, expressed as a percentage of the demand.

The simplest solution is possible if the reliability for the design period can be considered 100 per cent, i.e., if no failures in water supply are allowed. Although such a case never occurs in practice, because of its simplicity, it is often used in preliminary computations.

A more realistic case, in which reliability is less than 100 per cent within the design period, cannot be solved directly in the form of equation 52.1. The usual method of solution is one of successive approximations of the storage equation in the form

R = f(D, S). The solution proceeds in such a way that, keeping one of the independent variables constant, the other is adjusted until the desired value of *R* is obtained.

In many cases, the value of *R* is not specified explicitly, but another criterion of reservoir performance is used, e.g., the maximum expected economic gain, the minimum expected economic regret. However, problems of this category are beyond the scope of this chapter. Approaches to their solutions are presented by Maass, *et al.* in *Design of Water-resources Systems* [2].

52.2 Estimation of water losses from surface-water systems

52.2.1 *Nature of losses*

Water losses, e.g., evaporation and seepage, occur under pre-project conditions and are reflected in the streamflow records used for estimating water supplies. The construction of new reservoirs and canals is often accompanied by additional evaporation and infiltration. Estimation of these losses may be based upon measurements at existing reservoirs and canals. The measured inflows, outflows, and rates of change of storage are balanced by the computed total loss rate.

In terms of a water balance, seepage and infiltration do not constitute a loss because they contribute to groundwater recharge or to discharge downstream from a river-control structure. However, they do constitute a loss as far as the primary purpose of the project is concerned, e.g., the water lost through seepage is lost for power generation or for withdrawal for water supply. Thus, the term loss is to be understood in the water-management, rather than the hydrological, sense.

The depth of water evaporated annually from a reservoir surface may vary from about 400 millimetres in cool, humid climates to more than 2 500 millimetres in hot, arid regions. Therefore, evaporation is an important consideration in many projects and deserves careful attention.

Seepage loss from reservoirs and irrigation and navigation canals may be significant if these facilities are located in an area underlain by permeable strata. The reduction of seepage losses can be expensive, and the technical difficulties involved can render a project unfeasible.

52.2.2 *Losses from irrigated areas*

Water losses in an irrigation system may be several times greater than the water actually utilized by the crops. These losses consist of excess water drained from the land surface or percolating to the groundwater, evaporation from the soil, transpiration by undesirable vegetation, and seepage and evaporation from canals. From 20 to 60 per cent of the water diverted for irrigation may appear as return flow and may contribute either to streamflow or to groundwater recharge. Chemical constituents in irrigation return flows are usually more concentrated than in the original water and may contain additional undesirable elements.

Losses through evaporation from water surfaces and soils may be estimated by various methods, which are reviewed in [3]. Seepage and percolation may be estimated from field observations of groundwater levels, on small pilot or experimental irrigation systems established within the area of interest, or by the water-budget method.

52.2.3 *Evaporation from reservoirs*

Methods for estimating reservoir evaporation from pan observations and from meteorological data are described in Chapter 37. In the absence of pan evaporation or other appropriate meteorological observations at or near the reservoir site, regional estimates of these quantities are used to assess reservoir evaporation.

Prior to its submersion by a reservoir, land loses water by evapotranspiration. For reservoir design purposes, it is desirable to estimate increased water loss from the reservoir area due to formation of a lake, i.e., the difference between estimated reservoir evaporation and estimated pre-project evapotranspiration from the land area to be covered by the reservoir. Direct measurement of evapotranspiration presents a number of largely unsolved problems [3-6]. Indirect methods of estimating evapotranspiration are described in section 9.5.

Whenever practicable, the minimum-storage surface area per unit volume of storage should be sought in the selection of the dam sites. Extensive research has been conducted into evaporation suppression by the spreading on water surfaces of monomolecular films, but major practical problems in the application of these techniques to large storages still remain unsolved [7]. Thermal stratification in reservoirs and the temperature difference between inflow and outflow can have a significant impact on reservoir evaporation.

52.2.4 *Seepage from reservoirs*

Seepage from reservoirs depends on the structure and permeability of the underlying strata and on local conditions. An estimate of expected seepage may be derived from evaluation of seepage at existing reservoirs, from geological investigations at the site, and from the area-depth relationship for a planned reservoir. Following the construction of a reservoir and after collection of flow and other data, seepage or total losses may be evaluated, and a seepage-depth relationship can be derived.

52.3 **Influence of reservoir location**

When the reservoir is to be located at or near the point of diversion or utilization, the estimated flow available for the project may be considered to be the reservoir inflow, while the estimated water requirements and losses may be considered to be the required draft from storage. If, however, the reservoir is to be located some distance upstream, the flow entering the reservoir will represent only a portion of the total flow available. The storage capacity of the reservoir should be based on project water requirements reduced by the amount that can be supplied from uncontrolled runoff from the drainage area between the reservoir and the point of demand.

The procedures described below apply specifically to the case where storage is located at the point of utilization, but with suitable adaptations these procedures may also be applied in most other cases.

52.4 Influence of sedimentation

Sedimentation results in a continual reduction of the reservoir storage capacity. If the rate of sedimentation is small with respect to the capacity of the reservoir, a mean annual volume of sediment can be considered as a constant yearly reduction of storage in the computations. If a large volume of sediment occurs, the decrease in the capacity should be related to the annual streamflow or to each major flood event. More details on sediment transport are provided in Chapter 13.

52.5 Sequential analysis

The time-series used for storage-reservoir design can be either historical streamflow records, a historical streamflow record extended by synthesis from another streamflow or precipitation record (section 32.3.3), or a synthesized reservoir inflow series (section 39.6). Most frequently, the computations are based on time-series of mean monthly flows, mean ten-day flows, or mean daily flows.

52.5.1 *Numerical procedure*

The numerical procedure is best organized in a tabular form as shown in Table 52.1. The computation can be carried out either for a prescribed initial amount of water in storage, e.g., starting with an empty or a full reservoir, or for the so-called steady-state condition, where the initial storage is equal to the final storage at the end of the design period. In the steady-state case, the computations are first carried out with an arbitrary initial storage and are then repeated with the initial storage set equal to the final storage obtained in the first run. The results from the second run represent the steady-state situation.

Table 52.1 shows a segment of computations for a case where the storage capacity $S = 300 \times 10^6$ m^3 is between a minimum $S_{min} = 2.0 \times 10^6$ m^3 and a maximum $S_{max} = 2.3 \times 10^6$ m^3. It may be assumed that the minimum storage is required, for example, to facilitate navigation in the reservoir, while the minimum storage must not be exceeded because of the danger to shore property damage. Thus, whenever the release of the full draft would require the storage to drop below 2 x 10^6 m^3, the outflow must be reduced to a rate that prevents a violation of this constraint. Likewise, should the release of the draft cause the storage to rise above 2.3 x 10^6 m^3, the outflow must be increased to prevent such a rise.

TABLE 52.1

Sequential computations of reservoir operation

Year, Month	*Precipitation, P*		*Evaporation, E*		*Inflow, I*	*Desired draft, D*	*Outflow, O*	*Storage change, ΔS*	*Storage at end of month, S*	*Reservoir area*	*Spills*	*Water deficits*
	mm	*10^3 m^3*	*mm*	*10^3 m^3*	*10^3 m^3*	*10^3 m^3*	*10^3 m^3*	*10^3 m^3*	*10^3 m^3*	*km^2*	*10^3 m^3*	*10^3 m^3*
1	*2*	*3*	*4*	*5*	*6*	*7*	*8*	*9*	*10*	*11*	*12*	*13*
1954												
.												
.												
.									2254	0.56	0	0
Sept.	40	22	90	50	20	150	150	-158	2096	0.54	0	0
Oct.	50	27	70	38	20	80	80	-71	2025	0.53	0	0
Nov.	40	21	50	26	20	50	40	-25	2000	0.52	0	10
Dec.	50	26	30	16	30	30	30	+10	2010	0.52	0	0
1955												
Jan.	40	21	30	16	20	20	20	+5	2015	0.53	0	0
Feb.	60	32	40	21	30	20	20	+21	2036	0.53	0	0
Mar.	80	42	50	26	50	20	20	+46	2082	0.54	0	0
Apr.	90	49	70	38	160	20	20	+51	2233	0.55	0	0
May	70	38	90	50	140	20	61	+67	2300	0.56	41	0
.												
.												
.												

In the present example, the rate of draft varies with the season of the year (column 7 of the Table). The reservoir inflow is represented by a series of monthly inflow totals (column 6). Also given are monthly precipitation and evaporation totals in millimetres (columns 2 and 4).

The volumes of precipitation P and evaporation E (columns 3 and 5, respectively) for a given month are computed by using the reservoir-surface area at the end of the previous month (column 11). Each row of the table represents the reservoir water balance for one month, i.e., a solution to the storage equation:

$$S_i = S_{i-1} + I_i + P_i - E_i - O_i = S_{i-1} + \Delta S_i \qquad (52.2)$$

where the release O_i equals the water demand D_i, subject to the constraint $S_{min} \leq S_i \leq S_{max}$ (the values of P and E are taken from columns 3 and 5).

The violation of the lower constraint is prevented by a reduction of the outflow by the amount $S_{min} - S_i$, which is registered as a water deficit (e.g., column 13 for November). If the constraint S_{min} is removed, the reservoir becomes semi-infinite in the sense of being bottomless. Such an assumption is used to determine the storage capacity required to prevent shortages in water supply for the duration of the inflow series, i.e., for $R = 100$ per cent. The design storage capacity would equal the maximum storage depletion recorded during the design period. The violation of the upper constraint is prevented by increasing the outflow by an amount, $S_i - S_{max}$, registered as a spill (column 12 for May).

After completing the computations, the water deficits are used to compute the reliability R. The value of R, together with the original values of S and D, represent one solution of the storage equation for the specified input series. Since the same pair of S and D will lead to different values of R for different input series, the value of R which is obtained from the historical record may not be representative of a future period. It is, therefore, advantageous to perform the computations of R for a number (at least 50) of synthetic input series and to take their average as the design value. When confidence limits on R are desired, at least a thousand values should be computed. In such cases, the volume of computations is large, and the tabular form should be computerized. The ease of computerization makes the numerical time-series approach the most flexible and powerful tool for reservoir design [1, 8].

52.5.2 *Graphical procedure*

In a reservoir subject to an inflow I and an outflow 0, the storage S at time t is mathematically defined as:

$$S_t = S_o + \int_o^t (I - 0)\, d\tau = S_o + \int_o^t I d\tau - \int_o^t O d\tau = S_o + I_t^* - Q_t^* \qquad (52.3)$$

Plots of the cumulative sums *I** and *0** represent the inflow and outflow mass curves, respectively, with S_o being the initial reservoir storage. It can be seen in equation 52.1 that the reservoir-storage capacity is the difference between the input and output mass curves. An example of this technique is shown in Figure 52.1 in which the reservoir storage capacity, *S*, is determined for a constant draft, *D*, with the constraint that no failure is allowed during the design period. The procedure employs the concept of a semi-infinite (bottomless) reservoir mentioned in section 52.5.1 and yields the required storage capacity as the minimum storage depletion recorded in an initially full reservoir during the design period. The following graphical procedure applies. The constant draft corresponds to a constant slope of the draft mass curve *D**. A line, parallel to *D**, is drawn through each peak on the inflow mass curve *I**. The design storage capacity *S* is the maximum vertical distance between any point on *I** and any of the lines that are parallel to *D**.

52.6 Probabilistical approach

If streamflow is interpreted as a stochastic process, each realization of this process, i.e., each time-series, is governed by the probabilistical properties pertinent to the given process. If these properties are relatively simple, then it is possible to use them

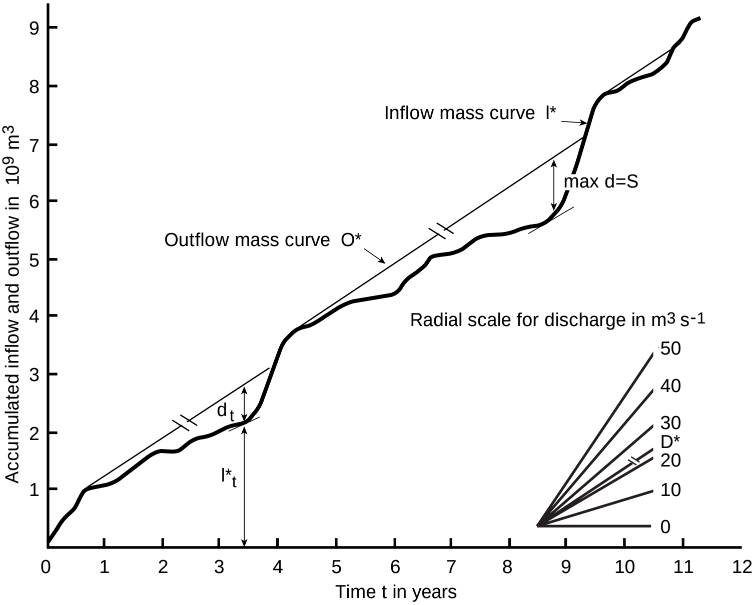

Figure 52.1 — Mass-curve approach for determining reservoir storage capacity.

directly for reservoir analysis without generating time-series. Methods employing this approach are called rigorous and methods ignoring the sequential structure of the process and making use only of its probabilistical distribution are called approximate. Sometimes these processes are called stochastic and probabilistic, respectively [9].

52.6.1 *Rigorous methods*

Only two stochastic methods have been developed to simulate the reservoir-inflow process — the random and the first-order autoregressive-inflow models [10]. The problem has to be posed in the form $R = f(D, S)$. The general procedure is as follows: the storage capacity is divided into k intervals ΔS_i, $i = 1, 2, \ldots, k$, so that $S = \sum \Delta S_i$. Each interval, or storage layer, is represented by one value S_i, usually the interval mid-point. The objective of the computations is to find the probability distribution of storage states $S_1, S_2, \ldots, S_k$ for the given values of S and D. The reliability is obtained from this distribution. In finding this distribution, advantage is made of the fact that, whatever the initial storage, the distribution soon reaches an equilibrium or steady state that is independent of the initial storage. Hence, it is sufficient to find the distribution of storage states for any instant t_m of the equilibrium state of the process by first establishing the conditional probability that the reservoir will be in a given state S_i if it had been in state S_j at the time t_{m-1} for each storage state at time t_m. This probability is called the transition probability p_{ij} and can be determined from the probability distribution of the inflow and the value of D. After knowing all the transition probabilities, it is then possible to compute the probability $P_i^{(m)}$ of reservoir state S_i at time t_m from the equation:

$$P_i^{(m)} = P_1^{(m-1)}\, p_{i1} + P_2^{(m-1)}\, p_{i2} + \ldots + P_k^{(m-1)}\, p_{ik} \tag{52.4}$$

Such an equation is written for each storage state $i = 1, 2, \ldots, k$. This form of analysis can be employed only for a representation of the inflow process by series of annual, seasonal, or monthly flows that can be assumed to be either a random or a first-order autoregressive process.

52.6.2 *Approximate methods*

The design of storage reservoirs intended for delivering relatively low rates of draft must often be based on a detailed time representation of the inflow process. This representation is typically a series of daily flows with a complex stochastic structure that prevents the use of rigorous probabilistical methods. In such cases, the only alternative to the time-series approach is the use of the approximate probabilistical methods that are applied in the preliminary stages of planning and design. The most common of the approximate methods employ low-flow discharge and volume frequencies and are based on the assumption that sufficient dry periods are separated by wet periods to fill the reservoir before the next dry period starts.

The fact that the lowest flows often occur during one period of the year in sequences seldom interrupted by high flows makes it possible to disregard the actual sequential order and to find the approximate storage capacity necessary for raising the lowest flows to some constant level D from the duration curve (section 35.2). The storage capacity is defined as a volume represented by the area of a wedge bounded by that part of the duration curve for which the flow is less than D and a line defined by flow equal to D. A risk assessment of the storage required for seasonal drought conditions can be made by using low-flow frequency curves (section 35.3). For example, if a mean daily discharge lower than 5 m^3 s^{-1} is permitted on the average only once every four years, then the required storage can be determined from curves of the type of Figure 35.1.

Duration curves and low-flow frequency curves should not be used for ephemeral streams. For these streams and for high-flow perennial streams, the discharge-duration frequency curves are more convenient. As an example, if a draft of 3 m^3 s^{-1} is desired from the river, the available volume in 80 per cent of the years can be computed from Figure 52.2.

The volume available for draft at a given discharge is most conveniently determined from volume-duration frequency curves. This method can also be used for a preliminary estimate of storage capacity of a flood-control reservoir. Thus, for example, if mean daily flows higher than 100 m^3 s^{-1} are permitted on the average only once every five years (i.e., with a 20 per cent exceedance probability), then the required detention storage can be determined by means of Figure 52.3.

52.7 Storage-draft reliability relationship

To facilitate comparisons and economic evaluations of various alternatives of reservoir design, it is convenient to solve storage equation 52.1 for a wide range of the three variables involved and represent the solution in a concise manner. The most usual representation for a given site on a stream is to plot the draft as a function of reservoir storage capacity, by using the reliability characteristic as a parameter. Such relationships can be further generalized by expressing both the draft and the storage capacity as ratios to the mean annual inflow (Figure 52.4).

52.8 Multi-purpose reservoirs

Most storage reservoirs serve a number of purposes listed in section 47.2. It is usually not practicable to allocate a fixed portion of storage for each purpose. In most cases, such an allocation is restricted to emergency purposes. For example, a buffer zone is often created immediately above the dead-storage zone and is reserved for use in exceptional circumstances, such as flushing the downstream

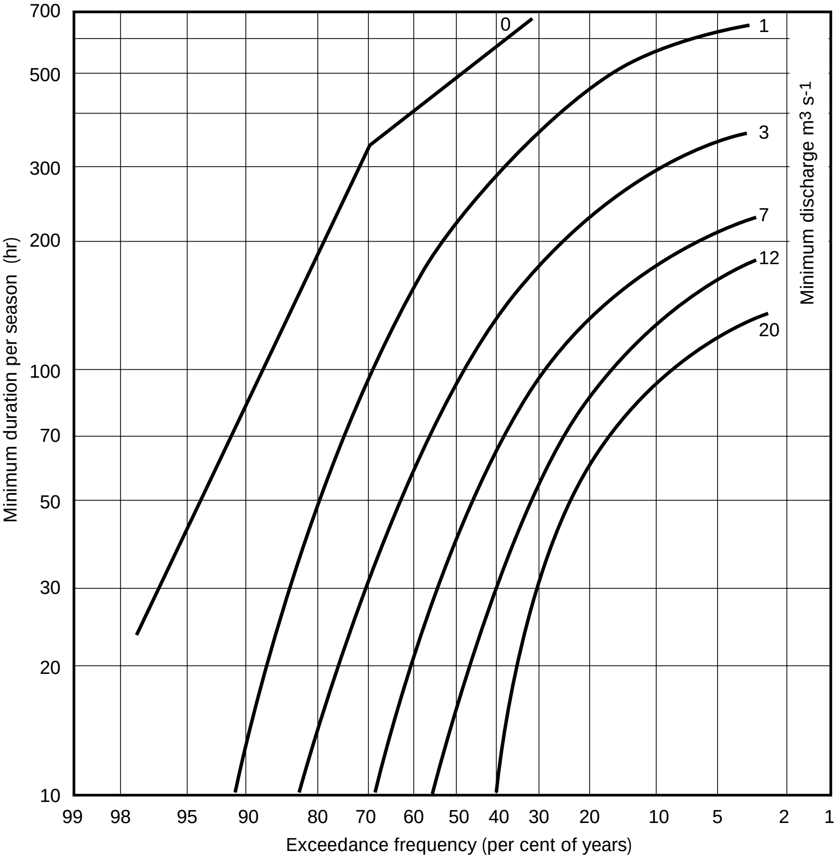

Figure 52.2 — Frequency of occurrence of discharge as a function of duration.

river section in case of some accidental contamination, emergency water supply in case of sudden health hazards, or fire reserve. Similarly, reservoirs may have an ungated emergency flood-control storage to prevent overtopping of the dam. However, most purposes are served from the same storage and their requirements are accommodated by rather complex release rules for reservoir operations. Reservoir releases are often formulated in terms of rule curves that indicate the rate of release as a function of the instantaneous storage and the time of the year. Examples of rule curves are provided by Box and Jenkins in *Time Series Analysis:*

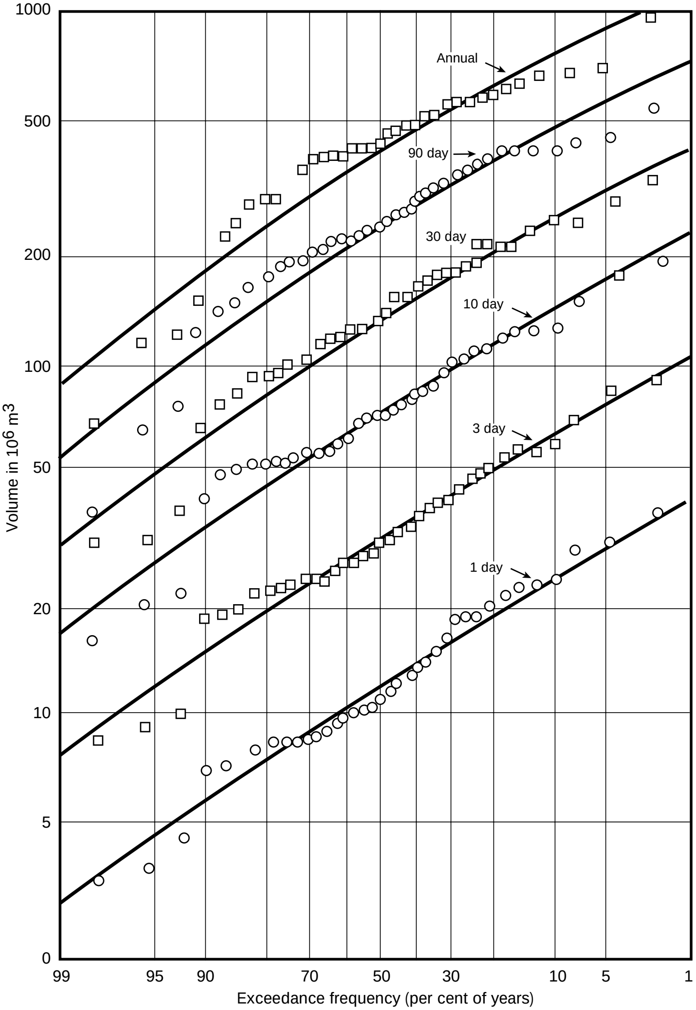

Figure 52.3 — Frequency of occurrence of high volumes as a function of duration.

Forecasting and Control [11] and by Svanidze in *Mathematicheskoe Modelirovanie Gidrologicheskikh Ryadov* [12].

The design and operation of multi-purpose reservoirs require complex analysis, which is usually carried out by iterative methods that involve adjustments of the rule curves and evaluation of the effects on all individual purposes with the aim of

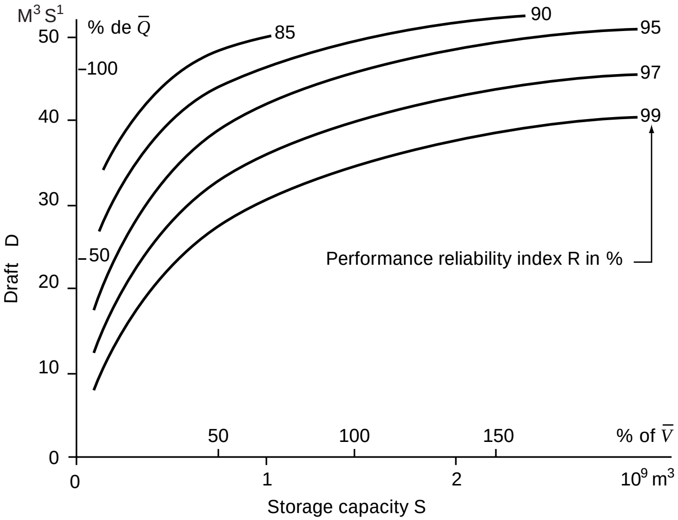

Figure 52.4 — Storage-draft reliability relationship.

optimizing the whole water-management system. In such cases, the classical storage-draft reliability relationships can serve only as a first approximation of the operating policy, which is then gradually refined. Various optimization methods are provided by Maass, *et al.* in *Design of Water-resources Systems* [2].

52.9 Systems of reservoirs

Procedures used in reservoir-system design are similar to those described above for multi-purpose projects. Due to the complex interactions among system components and between supplies and demands at various times and various locations, a direct solution is usually not feasible. Consequently, an initial design is selected by engineering judgement and then improved by successive sequential routings.

The reservoirs in a basin are usually not designed as a system from the start, but the initial reservoir projects are often designed for individual purposes. As the resources of a river basin become more utilized, it becomes necessary to study the operation of all projects as a system and to add new projects to the system from time to time. When this is done, the operation of existing components may be changed, but major changes are usually difficult to implement because of the many legal, political, economic and physical constraints. Accordingly, the level of optimization that can be reached in practice is usually rather low.

At any stage of reservoir-system design, all feasible new storage projects should be evaluated in sufficient detail to determine the order of desirability of the various projects. This order is determined by comparing the cost and the increased service provided. As demands on the reservoir system increase, it is only necessary to determine when to build the next most desirable project. The detailed simulations of multi-site supply and demand require special attention to the presentation of the various statistical and physical relationships among the variables at all sites. Some pertinent simulation techniquesare provided by Box and Jenkins in *Time Series Analysis: Forecasting and Control* [11] and by Svanidze in *Mathematicheskoe Modelirovanie Gidrologicheskikh Ryadov* [12].

52.10 **Incidental effects of reservoirs**

52.10.1 ***Effects on hydraulic and hydrological regimes***

The construction of a reservoir causes a change in the hydraulic and hydrological regimes downstream. Consumptive uses of water reduce the mean flow while reservoir regulation changes the seasonal distribution of flow and usually reduces its variability. The detention of water in the reservoir causes sedimentation and results in the released water being clearer than the inflow, which can cause erosion below the reservoir. The decrease of the river gradient may cause backwater and sedimentation problems in the river channel upstream from the reservoir.

52.10.2 ***Environmental effects***

Environmental effects are of increasing concern in the planning and management of water-resources projects. The creation of reservoirs usually has a very important influence on ecology. In the case where the storage volume is large in relation to annual runoff, eutrophication can have a significant impact on the quality of the water in the reservoir because of long residence times. The reservoir exerts a great influence on the temperature and oxygen content of the release water. The regulation of flow will also change the nature of land use downstream of the reservoir. The increase in water use usually results in an increase in the amount of waste water that may lower the quality of water in the receiving river.

Changes of this nature are of major concern. However, reservoirs also cause changes that have beneficial effects. In many cases, the environment in the vicinity of reservoirs and downstream has been greatly improved by providing recreation, aesthetic, ecological and health benefits. It is of primary importance to assess continuously all environmental effects of storage reservoirs and to provide monitoring facilities for measuring environmental factors both before and after construction.

52.11 **Estimating maximum reservoir levels**

Reservoirs must be designed for water levels somewhat higher than those that may be attained during maximum flood as a safety measure against wind set-up, wave run-up, and periodic undulations of the water surface (seiches). This freeboard cannot be considered as adding to useable storage, although it may provide a factor of safety against floods, which is greater than the maximum design flood. Greater freeboard is usually provided for earth dams, particularly in areas that are subject to earthquake effects or severe frost action.

52.11.1 *Wind set-up*

The result of wind blowing over the water surface of a reservoir is to pile up water at the leeward end of the reservoir and to lower the water level at the windward end. This set-up and set-down is more pronounced in shallow than in deep water and may be represented by an equation of the form:

$$H_s = \frac{ku^2 \ln \cos \theta}{gd} \tag{52.5}$$

where H_s is the height of set-up above still pool level, u is the wind speed measured at an elevation of 10 metres above still pool level, l is the fetch length or straight length of unobstructed water surface exposed to wind action, n is a dimensionless coefficient dependent on the configuration and hydrography of the lake, θ is the angle between wind direction and line along which fetch is measured, g is the acceleration of gravity, d is the average water depth along the direction of wind, and k is a dimensionless shear-stress coefficient. Equation 52.5 is valid for any consistent set of dimensional units. For essentially rectangular lakes of uniform depth, $n = 1$ and $k = 1.45 \text{ x } 10^{-6}$ provided that $u \leq 880d(g/l \cos \theta)$. For wind speeds greater than this, the set-up calculated through equation 52.5 will be larger than the actual set-up.

52.11.2 *Wind-generated waves*

Wind blowing across reservoirs also generates waves that eventually reach and run up on lake shores and the upstream face of the dams. The adequate freeboard to prevent overtopping of a dam by waves is required. The run-up of the waves is a function of wave height, wave length, and the slope of the embarkment. The height of wind-generated waves in water of limited depth may be calculated by:

$$H_s = \frac{0.283u^2}{g} \tan h\left[0.578\left(\frac{gd}{u^2}\right)^{0.75}\right] \tan h\left\{\frac{0.0125\left(\frac{gl}{u^2}\right)^{0.42}}{\tan h\left[0.578\left(\frac{gd}{u^2}\right)^{0.75}\right]}\right\} \tag{52.6}$$

where H_s is the significant wave height (average height of the highest one third of the waves) and u, d, l, and g are defined in section 52.11.1. Detailed lists of the function tan(x) can be found in standard mathematical tables. Equation 52.6 represents the initial height of the wave before it undergoes reflection or refraction within the reservoir.

Reservoir design must normally be based on wind data obtained at land stations with an overland fetch to the recording site. Determining the wind field over the lake from land-based wind observations is a most difficult meteorological problem. The ratio of wind speed over land to wind speed over the lake depends on the stability of the air mass over the lake, which depends on the temperature difference between the water surface and the overlying air. It also depends on the roughness of the topography at the land-based measuring station. Table 52.2 [13] illustrates approximate values of this ratio.

Waves are critical only when a reservoir is near its full-storage level. Thus, only winds that can occur during the season(s) of high water levels need be considered. The height above the still water level to which the water will rise as a result of wave action is termed the run-up. This elevation depends on the embarkment slope and wave steepness and can be estimated from charts provided by Saville, *et al.* in *Freeboard Allowances for Waves in Inland Reservoirs* [14].

52.11.3 ***Periodic undulations of the water surface***

In restricted bodies of water, such as reservoirs, periodic water-surface undulations may be caused by either variations in the rate of inflow or outflow, wind action, sudden changes in atmospheric pressure, or by earth temperature. Depending on the physiographical characteristics of the reservoir, these waves may be reflected either from shorelines, or at places where abrupt changes occur in the reservoir width or depth. In a long, narrow body of water, a series of waves may be set up with several nodes and antinodes.

There is no method for computing the height of waves due to such causes as a sudden change in atmospheric pressure, or to earthquakes. Total freeboard allowance for these phenomena may vary from several centimetres up to about one metre depending on the size and the importance of the reservoir. The antinodal

TABLE 52.2
Nearshore wind-speed adjustment

Wind direction	*Location of wind station*	*Ratio**
Onshore	5 to 75 kilometres offshore	1.0
Onshore	At coast	0.9
Onshore	12.5 to 25 kilometres inland	0.7
Offshore	At coast	0.7
Offshore	25 kilometres offshore	1.0

* Ratio of wind speed at location to over water wind speed (both at 10-metre elevation).

height of a wave generated by a sudden change in the rate of reservoir inflow or outflow may be approximated by the equation:

$$H_a = \frac{\Delta q}{bv} \tag{52.7}$$

where H_a is the height of wave above or below still water level, Δq is the change in the rate of flow into or out of the reservoir, b is the surface width of reservoir where the antinodal point of the wave occurs, and v is the wave velocity.

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CHAPTER 53

ESTIMATING DESIGN FLOODS

53.1 General

Most structures built on, across, or near rivers are potentially exposed to damage caused by floods. Since absolute flood protection is usually impossible or economically infeasible, rational design of these structures must take into account the risk of flooding. For design purposes, it is necessary to define a flood corresponding to the maximum tolerable risk. This flood, called the design flood, is defined as the flood hydrograph or the instantaneous peak discharge adopted for the design of a hydraulic structure or river control after accounting for economic and hydrological factors. It is a flood that a project can sustain without any substantial damage, either to the objects which it protects or to its own structures. The risk of damage is equivalent to the probability of occurrence of floods larger than the design flood. The decisive factor in the determination of a design flood is that feature or parameter of the flood that can be identified as the major cause of potential damage. The decision as to which is the most relevant flood parameter for a particular project rests with the planner and the designer and should be based on an engineering analysis of the given situation.

Usually, the decisive parameters are as follows:

(*a*) Peak discharge in the case of culverts, bridge openings, spillways, and outlets of weirs and small dams;
(*b*) Peak stage in the case of levees, clearance under bridges, flood-plain zoning, and design of roads and railways in river valleys;
(*c*) Flood volume for the design of flood-control reservoirs and, generally, for all cases where flood attenuation by water storage can be significant, e.g., for the design of spillway capacities and freeboards on dams; and
(*d*) Flood hydrograph shape in cases where superposition of several floods must be considered, e.g., flood protection downstream from the mouth of large tributaries or for reservoir operation during floods.

53.2 Design flood and its types

The following types of design floods are commonly used in water-resources engineering practice:

(*a*) Spillway design flood — A term often used in dam design to identify a flood that a spillway must be able to pass to provide the desired degree of protection to a dam [1];
(*b*) Construction flood — A flood for which reasonable precautions will be taken to avoid flooding of construction sites and thereby to prevent damage to a project during its construction;
(*c*) Probable maximum flood (PMF) — The greatest flood that may be expected at a site, taking into account all pertinent factors of location, meteorology, hydrology and terrain (section 27.3). It has essentially an infinite return period and could be selected as the design flood to prevent a disaster; and
(*d*) Standard project flood (SPF) — A flood resulting from the most severe combination of meteorological and hydrological conditions that are considered reasonably characteristic of the geographical region involved, excluding extremely rare combinations. It has a long but unspecified return period and may be selected as a design flood for structures of great importance.

53.2.1 ***Magnitude and methods of computation***

The general rule for the selection of the magnitude of the design flood is to reduce the risk of flooding (increase the design flood) which is inversely proportional to the extent of possible material damage. For structures involving low-damage risk, such as culverts and secondary roads, the design flood may be calculated by empirical methods because knowledge of its exact return period is of relatively low importance. For structures or projects involving large potential damage, but without the danger of the loss of life, design floods should be computed, if possible, by methods allowing an evaluation of their return periods so that optimization methods could be used for the selection of the design-flood magnitude. For situations involving a danger of loss of human life, the aim is to provide maximum protection, and the maximum probable flood or the standard project flood is usually adopted as the design flood.

53.2.2 ***Design life of a project***

In the wide range of cases in which the design flood is selected by optimizing the relation between the expected flood damage and the cost of flood-protection measures, the resulting optimum level of the calculated risk depends to a certain degree on the length of the period over which the performance of the project is evaluated. This period is called the design life or planning horizon of the project and is determined in the project-planning stage on the basis of the following four time spans [2]:

(*a*) The physical life, which ends when a facility can no longer physically perform its intended function;
(*b*) The economic life, which ends when the incremental benefits from continued use no longer exceed the incremental cost of continued operation;

(*c*) The period of analysis, which is the length of time over which a facility may be expected to function under conditions that can be relatively accurately foreseen at the time of the analysis — any operation in the distant future that is subject to a high degree of uncertainty is excluded from consideration; and

(*d*) The construction horizon, which is reached when a facility is no longer expected to satisfy the future demands (functional obsolescence).

The optimum level of calculated risk and hence the design return period for each of these periods may be different, and the final selection of the design flood cannot be made without a consideration of political, social, environmental, and other non-quantifiable criteria.

53.2.3 ***Design floods for large reservoirs***

The selection of design floods for spillway design for large storage reservoirs must be given special attention because the reservoir may change considerably the flood regime, both at the reservoir site and in the downstream section of the river.

The basic flood-related effect of a reservoir is flood attenuation. Its estimation requires a knowledge of the original flood-hydrograph shape. When the hydrograph is not known, a hypothetical shape (often triangular) is assumed and fitted to the selected flood volume and peak discharge. In evaluating the effect of flood attenuation on the reduction of spillway capacity and freeboard of a dam, it is imperative to adopt a conservative approach and to consider only those effects that can be guaranteed at all times. Thus, only the effect of the ungated spillway should be considered. All gated outlets should be assumed to be closed and the reservoir filled to the crest of the fixed spillway at the beginning of the flood.

In addition to flood attenuation, the flood regime downstream must be analysed carefully from the point of view of changes in the timing of flood peaks, the effects of changed shapes of flood hydrographs, and the effects on the river channel caused by an increased scouring tendency of the virtually sediment-free water leaving the reservoir through the spillway.

The type of dam structure must also be considered because it is of prime importance in determining the vulnerability of the dam in the case of its overtopping. Vulnerability is highest for earthfill dams, which usually collapse when overtopped.

53.2.4 ***Probable maximum flood (PMF)***

The probable maximum flood is computed from the probable maximum precipitation (section 29.4) or from the most critical combination of maximum snow-melt inflow rates and the probable maximum rainfall that could occur during the critical melting period (section 31.7). Since the rainfall usually accounts for a major portion of the PMF runoff, special consideration must be given to the conversion of rainfall to runoff. This conversion is done by deterministic rainfall-runoff models (sections

33.3 and 39.3), but their application for this purpose involves certain modifications designed to accommodate the extreme magnitude of the rainfall event that is being used as input. The most important modifications are as follows:

(*a*) The effect of the initial soil-moisture conditions and of the variation of the infiltration rate during the rainfall on streamflow is greatly reduced as compared to their effect in streamflow simulation under normal conditions. Hence, the refined methods employed in most models for estimating infiltration indices can be considerably simplified. A common practice is to use the minimum infiltration capacity or the maximum runoff coefficient, for a given soil type and vegetal cover, throughout the entire storm;

(*b*) When a unit hydrograph is used to transform the maximum precipitation, it should be remembered that the validity of the underlying assumption of linearity is limited to conditions similar to those for which the unit hydrograph was derived. An analysis of floods in a number of basins [3] has shown that the peak ordinates of unit hydrographs derived from major floods (greater than 125 millimetres of runoff over the basin area) are often 25 to 50 per cent higher than peak ordinates derived from minor floods (25 to 50 millimetres of runoff). It is important to bear in mind that the adjustment of the unit hydrograph for the computation of the PMF must be guided by the necessity of making a conservative estimate; and

(*c*) In the case of drainage basins larger than 500 km^2, or even smaller basins where their different parts have widely different runoff characteristics, it is usually necessary to derive separate unit hydrographs and PMFs for several sub-areas and to obtain the PMF for the whole basin by routing the component floods downstream to the project site. It must be remembered that the same positioning of the isohyetal pattern of the design storm over the catchment, which yields the maximum flood if a single unit hydrograph is used for the whole catchment, need not yield the maximum flood if the catchment is subdivided into several sub-areas. Thus, for each different catchment subdivision, an optimal positioning of the design storm (i.e., the position yielding the most unfavourable combination of the relevant parameters of the PMF) must be found separately subject to the restrictions, due to orography, discussed in section 29.4.

Although no specific return period can be assigned to the PMF, its parameters should be compared with the respective frequency curves fitted to historical floods to make sure that they have extremely long return periods unequalled by any historic flood event.

53.2.5 ***Standard project flood (SPF)***

The standard project flood is usually about 50 per cent of the PMF [1]. Its determination is governed by similar considerations as those relevant to the PMF. The standard project flood is usually determined by the transformation of the transposed largest rainstorm observed in the region surrounding the project, rather than from a meteorologically–maximized rainstorm as in the case with the PMF. In spite of this, the standard project flood should represent a very rare event and should not be exceeded by more than a few per cent the major floods experienced within the general region [1].

53.3 Data preparation

Basic data for determining design floods are the records collected by regional or national Hydrological and Meteorological Services. These data exist in the form of stage recordings and discharge measurements that form the basis for the computation of rating curves. Since the magnitude of the design flood depends primarily on the measurements of high discharges, special attention should be given to their evaluation and to the extension of rating curves.

For a proper assessment of the flood regime, it is essential to obtain sufficient information on historic floods. The basic element of such information is stage. In compiling information on flood stages, use can be made of traces of materials deposited by floods, flood marks on bridges, buildings, and river banks, recollection of long-time residents, photographs taken during floods, archived materials, articles in the press, and memoirs.

In order to convert flood stages determined by such investigations into discharges, hydraulic computations must be based on reconstructed river cross-sections, longitudinal profiles, the slope of water surface, and channel roughness. All the known modifications of the river channel should be taken into account (e.g., dredging, embankments, channel straightening). Due to the limited accuracy of the reconstructed river characteristics, the application of the Manning and Chézy formulae is usually satisfactory for hydraulic computations of this kind.

53.4 Techniques for the computation of design floods

The selection of computational techniques for the determination of design floods depends on the type, quantity, and quality of the available hydrological data. In general, the best technique is that which allows the extraction of the maximum amount of relevant information from the given data. It must be emphasized that a technique or method with a higher degree of refinement needs not be the most appropriate one in a particular situation. For example, while it is true that by fitting a three-parameter probability distribution to a data sample one can obtain a better fit than by fitting with a two-parameter distribution, it would be wrong to assume that a three-parameter model is always preferable to a two-parameter one. The preference of one over the other depends on the size of the data sample. The relative effectiveness of a three-parameter model generally decreases with decreasing sample size because, for a small sample, the amount of noise (sampling error) in the third parameter may be much larger than the amount of information. Sampling error may lead to a less adequate fit than if the third parameter were ignored.

In order to extract maximum information from scarce or inaccurate data, it is advisable to apply several different methods, to compare the results, and then to choose the design parameters based on engineering judgement. Sensitivity analysis can be useful in making the final decision because it may show the impact of potential errors on the magnitude of the design variable.

53.4.1 ***Empirical methods***

Empirical flood formulae attempt to obtain simple forms of relationships between flood variables (usually the flood peak) and flood-producing factors characterized by various geomorphological and meteorological variables. A common type of formula expresses the peak discharge Q as a power function of catchment area A:

$$Q = CA^n \tag{53.1}$$

where coefficient C and exponent n vary within wide limits, the values for a particular study being selected on the basis of empirical data [4].

The application of empirical formulae is usually limited to the region for which they have been developed, and they should be used with great caution and only when a more accurate method cannot be applied. Another drawback of empirical formulae is the difficulty in assessing the return period of the computed peak flow.

An envelope curve enclosing maximum observed peak flows can be plotted against catchment areas for a large number of stations in a meteorologically — and geomorphologically — homogeneous region. Such curves provide useful information, especially in cases where few data are available at any single station. Attempts have been made to refine the technique by constructing different envelopes related to different climatological and/or geomorphological factors [5]. However, the return periods of the peak flows remain unspecified.

53.4.2 ***Deterministic models***

Deterministic models are used to synthesize design floods by simulating the physical processes that govern flood formation. The models used for this purpose are basically the same as those used for general streamflow synthesis (Chapters 33 and 34). However, because the emphasis here is on flood events rather than on a continuous streamflow record, the choice, calibration, and application of models for design-flood computation may differ from those for a general-purpose streamflow synthesis. In particular, the models should provide an accurate representation of individual flood peaks, volumes, and hydrograph shapes that correspond to actual rainfall events and snow-melt conditions. Their ability to predict the exact position of the flood hydrograph on the time axis would be of a secondary importance.

Depending on whether the design flood is to be synthesized from precipitation and/or snow melt or from known flood hydrographs at upstream points, the deterministic models of interest fall into two broad categories:

(*a*) Rainfall-runoff models, as described in Chapter 33; and
(*b*) Streamflow routing models, as described in Chapter 34.

53.4.3 ***Probabilistic methods***

One of the main concerns in design-flood synthesis is an evaluation of the risks associated with the occurrence of floods higher than the design flood. Knowledge of these risks is important because of their social, environmental, and economic implications, e.g., the determination of flood-insurance rates, flood-zoning policies, or water quality implications. Since floods are stochastic phenomena, their magnitudes and the times of their future occurrences cannot be predicted. The only possibility is to assess them on a probabilistic basis, i.e., to assign a probability to the possibility that a flood of a given magnitude will be exceeded within a specific period of time. A variable that has a probability of exceedance p has a return period $T= l/p$.

Guidance for general frequency analysis is provided in Chapter 27 and for flood-frequency analysis, in particular, in Chapter 36.

The probability of exceedance of a given magnitude of event, as derived from a probability distribution model, pertains to each future event. Thus, if an annual flood series is considered, the exceedance probability p_n defines the risk that the given magnitude will be exceeded in any one year. However, it is often necessary to calculate a probability p_n that a given event (e.g., the exceedance of a particular flood peak) will occur at least once in n years, e.g., during the design life of a project. If the assumption of independence of floods in individual years is satisfied, this probability is:

$$p_n = 1 - (1 - p)^n = 1 - \left(1 - \frac{1}{T}\right)^n \qquad (53.2)$$

where T is the return period. It may be noted that the risk of an event occurring at least once during its return period follows from equation 53.2 for n equal to T. Where T is large, this risk approaches the asymptotic value $1 - e^{-1} \cong 0.63$.

From equation 53.2, it is possible to express T as a function of n and p_n, i.e., to calculate a return period such that the risk of occurrence of the event during a period of n years will have a specified value p_n. This return period is called the design return period T_d and is:

$$T_d = 1/[1 - (1 - p_n)\ 1/n] \qquad (53.3)$$

A useful approximation to this formula is:

$$T_d = n\left(\frac{1}{p_n} - \frac{1}{2}\right) \tag{53.4}$$

Some values of the variables T_d, n, and p_n are shown in the Table below. In order to illustrate its use, assume that the design life of a dam is 50 years and that the designer wishes to take only a 10 per cent risk that the dam will be overtopped during its design life. Thus n equals 50, p_n equals 0.10, and the dam must be designed to withstand a flood that has a return period T_d = 475 years, i.e., a probability of exceedance $p = 1/T_d \approx 0.2$ per cent.

Required design return period T_d of an event whose risk of occurrence in n years is equal to p_n

p_n	*n year* *2*	*10*	*50*	*100*
0.01	199.0	995.0	4975.0	9950.0
0.10	19.5	95.4	475.0	950.0
0.50	3.4	14.9	72.6	145.0
0.75	2.0	7.7	36.6	72.6

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CHAPTER 54

FLOOD MITIGATION

54.1 General

Flood-control works may consist of levees and flood walls along the course of a river designed to confine the stream to a particular channel or direct it along planned floodways, and reservoirs designed to store a portion of the flood flow to reduce the flood peak downstream from the reservoir. For levees and flood walls, special attention must be given to requirements for associated interior drainage facilities. Major pumping installations and ponding areas may be required.

54.2 Flood-control reservoirs

The volume of storage that must be provided in a reservoir will depend on the degree of flood abatement required and on the flood characteristics of the stream. If flooding occurs only during certain periods of the year, the reservoir level may be drawn down before the danger of flooding begins and may be refilled after the danger has passed. In such cases, flood abatement is achieved largely through reservoir-operation schedules rather than by providing additional storage. However, in areas where a flash flood may occur at almost anytime during the year, storage capacity must be held in reserve at all times for temporary storage of flood waters.

Storage capacity to be held in reserve for flood-control purposes can be provided either in on-stream or off-stream reservoirs, while multi-purpose storage is usually provided in on-stream reservoirs. An on-stream reservoir is a reservoir behind a dam constructed across a river, whereas an off-stream reservoir is situated beside a river and is connected to it by canals, sills, etc.

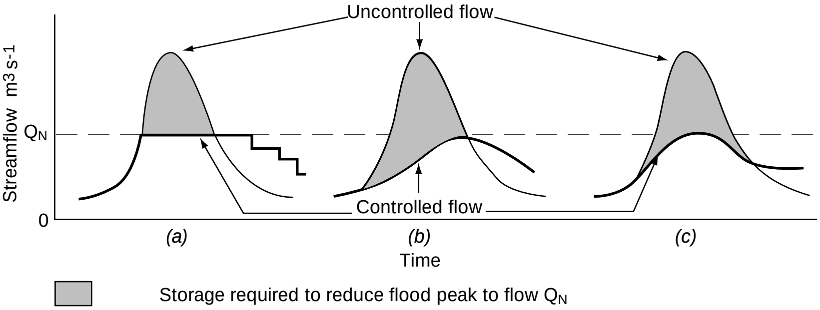
54.2.1 *The design problem*

Flood abatement is achieved by detaining and storing a portion of the flood water. The amount of storage required (the detention storage) is usually specified as that part of the reservoir storage that can produce a given reduction in a flood peak of a given magnitude or of a given probability of recurrence.

The following basic types of storage can be distinguished:

(*a*) Regulated storage, either in an on-stream or in an off-stream reservoir;
(*b*) Unregulated storage in an on-stream reservoir; or
(*c*) Unregulated storage in an off-stream reservoir.

The storage capacity needed to achieve a given effect will depend on the type of storage used. The flood-transformation effects of each of the types, when the same reduction of flood peak is desired, are shown in the Figure below and are discussed in the following subsections. In actual practice, the effect of a flood-control reservoir is usually a combination of the regulated and unregulated types.



Effects of reservoirs on floods (*a*) regulated storage, (*b*) unregulated on-stream storage, and (*c*) unregulated off-stream storage.

54.2.1.1 *Regulated detention storage*

Full control over the flood-detention storage of a reservoir provides the highest efficiency of flood mitigation because it is possible to start storing water only after the highest permissible flow (also called the non-damaging flow) has been reached downstream from the reservoir. Thus, only that portion of flood water that is apt to cause damage is stored.

Control over storage is achieved by the regulation of gated outlets in the case of an on-stream reservoir and of gated intakes and outlets in the case of an off-stream reservoir. In an on-stream reservoir, full control is achieved only if the outlet has a capacity sufficient to release the non-damaging flow when reservoir storage is at its minimum, and if the release of water from the detention storage can be fully regulated.

In an off-stream reservoir, full control is achieved only if the intake has a sufficient capacity to prevent the rise of flow in the downstream section of the river above the non-damaging flow, and if the release of the detained water can be regulated.

The design flood for the determination of the flood-detention storage capacity of a reservoir need not be the same as the design flood used for the design of its spillway because the safety requirements for the dam itself are usually different from the normal flood-protection requirements downstream from the reservoir.

54.2.1.2 *Unregulated on-stream detention storage*

The storage above a fixed-spillway crest of an on-stream reservoir is generally regarded as unregulated for design purposes although it may be partially regulated by release through gated outlets and turbines. However, for the design of the unregulated detention storage, these releases are either considered constant during the passage of a flood, or the outlets are considered closed. The former condition is usually adopted for the assessment of the normal downstream flood-control effects of the reservoir, while the latter condition is applied for the assessment of the dam safety.

The unregulated detention storage plays an important role in the safety of a dam against overtopping. Its design is interlinked with the design of the dam spillway and must be based on the same design flood as the spillway itself. Safety considerations in spillway design require that the reservoir be regarded as filled up to the spillway crest at the beginning of the design flood.

As the comparison of parts (*a*) and (*b*) of the Figure indicates, unregulated storage is less efficient in flood-peak reduction than in regulated storage. This is because unregulated storage begins filling before it is needed.

54.2.1.3 *Unregulated off-stream detention storage*

Unregulated off-stream detention storage arises in off-stream reservoirs (sometimes called “polders” because of structural resemblance to real polders) constructed by enclosing a part of a flood plain by a dyke whose crest at the upstream end is lowered to form a sill, i.e., an intake into the enclosure. When the river stage at the upstream end rises above the sill crest, the polder starts filling by overflow over the sill. The fact that the river bypasses the reservoir makes the unregulated off-stream storage more efficient than unregulated on-stream storage because unnecessary filling starts later (parts (*b*) and (*c*) of the Figure).

54.2.2 ***Operation considerations for design purposes***

Flood-detention storage is frequently provided in multi-purpose on stream reservoirs with gated outlets with a capacity sufficient to provide a high degree of control of the reservoir storage. These reservoirs always have some ungated flood-detention storage and, in many cases, they also have a designated part of the gated storage reserved for flood detention. In addition, storage designated for other uses may occasionally be used for flood-control purposes. This diversity offers flexibility and makes the flood reduction strongly dependent on the mode of reservoir operation. Therefore, it is necessary, in such cases, to analyse many different operation modes during the early stages of design because the results affect the selection of the design variables for the project.

54.2.3 *Further considerations concerning reservoirs*

54.2.3.1 *Time interval between successive floods*

The use of storage reservoirs to reduce floods raises the question of a possible occurrence of two or more floods in close succession and, hence, the possibility that the detention storage filled by one flood may not be emptied before the arrival of the next flood. The problem is essentially one of frequency distribution of the times between flood events of specified magnitudes and can be solved by frequency analysis (section 27.2) of historical streamflow records, synoptic weather patterns, or synthetic streamflow records derived from precipitation records via deterministic models (section 33.3). However, care must be taken in extrapolating the frequency curves of the between-flood intervals to prevent the violation of physical constraints.

54.2.3.2 *Sedimentation effects*

The deposition of sediments in a reservoir reduces its storage capacity and the reservoir's ability to perform its function. Most reservoirs have a certain part of their storage capacity designated for sediment deposition to prevent premature reduction of the active storage. However, it can happen that this storage is inadequate. The flood-detention storage can be affected significantly because it occupies the upstream part of the reservoir where sedimentation first occurs. Thus, the flood-reduction efficiency of a reservoir generally decreases with time. This should be considered in long-term flood protection planning so that alternative measures can be developed in time.

54.2.3.3 *Effects of upstream development*

The design of a flood-control structure is based upon analyses of floods that have occurred in the past, although the structure is to control future floods. The growth of population and increases in standards of living result in intensified land development. Forests may be transformed into agricultural lands, and drainage of agricultural lands can be improved. The change from manual labour to mechanization in agriculture, and the extension and intensification of urbanization, often contribute to increased volumes and discharges of surface runoff and sediment transport. The application of sound soil-conservation practices contributes to their decrease. The evaluation of the hydrological effects of land development is difficult, yet the hydrologist should be aware of its effects of increasing flood risk.

54.3 **Other structural measures**

54.3.1 ***Diversion***

Diversion of flood waters from one river to another involves the following hydrological considerations:

(*a*) Determination of design-flood hydrographs for both rivers;

(*b*) Separation of the part of the flood hydrograph to be diverted;
(*c*) Flood routing of the diverted flow through the diversion canal;
(*d*) Combination of the diverted flow with floods occurring in the receiving river; and
(*e*) Estimation of the new flood frequencies at the downstream segments of the two rivers concerned.

Care should be taken to evaluate the phasing of the superimposed floods in the receiving river as well as the backwater effects that may cause an increase in the flood risk in the reach upstream from the diversion-discharge point in the receiving river.

54.3.2 ***Channel modification***

Channel modification is usually aimed at an increase in channel capacity by deepening and widening, by cutting meanders and shortening the channel length, and by cleaning and possibly lining a channel to reduce its resistance to flow. The result is an increase in flow velocity and a lowering of stage in the reach concerned with a consequent effect of flood reduction along the modified reach, which causes increases of flood peaks downstream. The effects of channel modification can best be assessed by hydraulic-routing methods (Chapter 34) with the proper consideration of the interaction between the floods in the main channel and in the tributaries downstream. An incidental effect of channel modification is increased scouring in, and upstream from the modified reach, and an increased deposition downstream.

Opposite effects can be achieved by reducing the channel capacity by various river training structures. By obstructing the flow, they cause increased flooding upstream and flood reduction downstream. They function similar to an unregulated on-stream reservoir (section 54.2.1.2).

54.3.3 ***Levees and flood walls***

Flood levees, either parallel to the streams or surrounding riparian areas, are major flood-protection measures, particularly on flat lands and along large rivers. They can be combined with other methods (e.g., by-passes, retention basins, emergency reservoirs, zoning). Levees are constructed mainly from earth and should be resistant to flood levels, wave actions, and seepage, e.g., sand boiling and internal erosion.

The design of levees requires:

(*a*) The design flood levels established according to the economic value of the protected area;
(*b*) The design freeboards against overtopping and wave attacks;
(*c*) The duration of the flood levels for calculating seepage and hydraulic gradients in earth dykes and underground; and
(*d*) The probability of ice jams and subsequent backwater.

Design water levels should be calculated on the basis of ice-free observations if the flow regime is natural. On rivers where human activities influence the water regime (upstream reservoirs, dykes, or barrages), the design water level should be calculated on the basis of hydraulic conditions [1].

The probability of the design water level for levees is normally in the range of 2.1 or 0.1 per cent (50, 100 or 1 000 years flood) depending on the value of the protected area. On rivers subject to frequent ice jams, water levels should be calculated according to the highest backwater levels caused by downstream ice jams.

Freeboards above the design flood level should ensure that extreme floods cannot overtop the dyke, that seepage cannot cause significant flow within the body of the dyke, and that waves cannot spill over the crest of the dyke. Depending on wave conditions and the slope of the dyke on the water side, the freeboard should normally be in the range of one to two metres. Freeboard can also be ensured by constructing flood walls on the crest of the dyke.

The loading of the levees depends on the duration of the floods. Thus, a statistical analysis of the duration of certain water levels may help to design and construct seepage-resistant dams.

The alignment of the levees, e.g., the width of the unprotected flood plains, influences the upstream water levels. Heavy constrictions may cause a serious flood-level rise. Thus, the design of the flood levees should consider the new water levels upstream. The dimensions of the freeway of flood plains also require due attention to the change of hydraulic resistance from vegetation.

Risks of levee breaches cannot be eliminated completely. The area that would be inundated by spillage through breaches can be estimated on the basis of previous experience. Emergency warnings for the population can be prepared if such studies have been made. Emergency planning is an important activity for the protected areas where evacuation or isolation of inundations may become necessary.

54.4 **Non-structural measures**

54.4.1 ***Flood-plain control***

Flood plains attract agricultural, municipal, industrial, and transportation development because of high soil fertility, because of the proximity of water and construction materials such as sand and gravel, and because of their flatness, which facilitates construction and accessibility. Their development is encouraged by the fact that the intervals between major floods are sometimes long. For these reasons and because of the high cost and limited effectiveness of flood-protection structures, it is becoming increasingly necessary to regulate the development of flood plains by appropriate zoning and flood insurance.

The function of the hydrologist is to delineate the areal extent of floods of various return periods. This task can be accomplished by routing design floods of different frequencies through the flood plain, the determination of flood stages, and drawing flood lines on topographic maps.

54.4.2 *Flood warning*

For enhanced flood mitigation, it is necessary to adopt an active attitude towards flood-damage reduction rather than to rely passively on the effect of the existing structural, zoning, and other measures. The active approach consists of the adoption of various ad hoc measures that might be appropriate in the case of a specific flood, e.g., an evacuation of the endangered area, removal of valuable equipment, and temporary flood proofing by sand bags combined with pumping. For this purpose, it is essential to develop an efficient flood-warning system (section 44.3.1), which would indicate, with sufficient lead time, the expected extent and duration of flooding. An important point to be emphasized in this connection is the necessity of a continuous operation of the flood-warning system despite the fact that it may be used only rarely. A system that is activated only once in many years may be likely to fail when it is needed. A continuous operation would keep the hardware, software, and the organization in good working condition and may lead to gradual improvements of the system. In order to make the continuous operation economical, the flood-warning system may be combined with other activities, such as the routine daily weather forecasting, regular hydrometric measurements, and traffic control.

54.5 Design of urban and small rural watershed drainage works

54.5.1 *Drainage system features*

The design of drainage systems for urban and small rural watersheds differs from the design for natural catchments for the following reasons:

(*a*) The drainage area in urban catchments is usually very small;
(*b*) Urban catchments usually have a high portion of impervious areas which give rise to high runoff;
(*c*) The process of flood generation is usually more rapid in urban catchments than it is in large rural catchments;
(*d*) The water is usually not drained by rivers but rather by closed conduits and canals;
(*e*) Discharge measurements are usually unavailable in urban catchments.

Due to the general shortage of runoff data for small rural watersheds and urban areas, the design of storm drainage systems must usually begin with an analysis of the frequency of rainfall of various intensities (Chapters 28 and 29).

In general, it is not economical to design urban or agricultural drainage systems (sewers, road and airport drains, culverts, pumping stations for low-lying areas, etc.) to cope with the most intense precipitation — more exactly, to cope with the most critical discharges — which could occur during their lifetime.

These systems are thus normally designed to provide protection against a rainfall intensity-duration combination of specified probability, rather than against the probable maximum precipitation. The design discharge for a system would be determined from consideration of such factors as the estimated damage resulting from overtaxing of the works by large, but infrequent, discharges and the additional cost of designing and building the system to cope with these rare discharges.

A discussion on agricultural drainage is included in Chapter 55.

54.5.2 *Calculating discharges from drainage systems*

Discharges in the terminal site of a drainage system caused by precipitation of a given intensity are frequently estimated by the so-called rational method, which is described in detail in handbooks and manuals [2, 3]. This simple method used in practice for planning and designing systems for more than a century is based on data on maximum precipitation intensity over the time of concentration and the runoff coefficients depending on the relief of watershed. However, this method is applicable only to small areas with a brief concentration time. It is used to calculate only the value of maximum discharge but not the runoff volume and the shape of the hydrograph.

The rational method is not adequate for the description of the behaviour of a urban watershed which contains several branches of sewers. In this case, where records are available, a unit hydrograph (section 33.3.1) can be formulated for existing sewer networks. Where records are not available, or in the design of a modified network, a time-area curve can be formulated for the system using one of the many techniques available [4, 5, 6].

The design and operation of a sewer network for a large city may warrant the use of distributed system models. These models have been undergoing rapid development and many different types are now available [7, 9].

The present trend in the design of urban and small rural drainage systems is to proceed from the analysis of meteorological data to the synthesis of design storms which are then used as inputs when using deterministic models to obtain design flood hydrographs for individual inlets into the river system or for different parts of the watershed. These hydrographs are then routed through the drainage system with the aid of streamflow routing methods, thus producing the final design flood hydrographs for particular points within the system. A description and assessment of some recent hydrological models for urban catchments are presented by Marsalek in *Urban Hydrological Modelling and Catchment Research in Canada* [8] and by Maksimovic and Radojkovic in *Urban Drainage Modelling* [9].

54.6 **Effects on the hydrology cycle**

Drainage systems in urbanized areas exert a pronounced effect on the hydrological cycle — the hydrographic network and relief are modified as well as the hydroclimatic elements (local climate, precipitation, evaporation, etc.), surface and subsurface accumulation, surface and ground runoff, water quality, erosion and sediment transport. The water balance in the regions subjected to urbanization is transformed. The meteorology for quantitative estimation of these changes are set out in the UNESCO *Manual on Drainage in Urbanized Areas* [2] and in the *Manual on Urbanization Effects on Hydrology and Water Quality* [3].

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CHAPTER 55

IRRIGATION AND DRAINAGE

55.1 **Irrigation**

A major objective of the management of an irrigation system is to maximize the crop yields per volume of water consumed by the system. In practice, four basic types of irrigation are used — surface, sprinkler, subsurface, and drip or trickle. Where water is scarce and costly, the use of drip or trickle irrigation may become attractive.

The water consumed is needed:

(*a*) To meet the crop water requirement, which is defined by the Food and Agriculture Organization (FAO) [1] as:

> "the depth of water needed to meet the water loss through evaporation of a disease-free crop growing in large fields under non-restricting soil conditions including soil water and fertility and achieving full production potential under the given growing environment";

(*b*) To satisfy losses caused by:

- (i) Evaporation from weeds;
- (ii) Evaporation from the wet surfaces of vegetation and saturated soil;
- (iii) Evaporation from moist soil;
- (iv) Drainage of soil water; and
- (v) Seepage, leaks, and evaporation from associated reservoirs and water-distribution canals.

Water management is directed toward ensuring that crop water requirements are met while minimizing other water losses.

55.1.1 ***Crop water requirements***

Crop water requirements are usually estimated either from a knowledge of evaporation demand and crop characteristics or, more recently, from direct measurements of the soil-water status or the physiological stress of the plants.

The Food and Agriculture Organization [1] describes how the pan-evaporation, radiation, Penman, and Blaney-Criddle methods can be used to calculate a potential reference crop evaporation, which, when multiplied by an appropriate crop coefficient, gives an estimate of the crop water requirement. Additional information on the first three of these methods is provided in Chapters 9 and 38. In the former

USSR, the heat-water-balance method, based on data from a standard hydrometeorological network and developed by the State Hydrological Institute, has been applied widely [2].

55.1.1.1 *Blaney-Criddle method*

Blaney-Criddle is one of the most widely used methods of estimating crop water requirements. An adaptation of this method is suggested in the FAO *Guidelines for Predicting Crop Water Requirements* [1] to calculate the reference crop evapotranspiration for areas where only measured air temperature data are available. The original Blaney-Criddle approach involves temperature and percentage of daylight hours as climatic variables to predict the effect of climate on evapotranspiration. An empirically-determined consumptive-use crop coefficient is then applied to establish the consumptive water requirement, which is defined as the amount of water potentially required to meet the evapotranspiration needs of vegetative areas so that plant production is not limited from lack of water.

However, crop water requirements will vary widely between climates having similar air temperature, for example, between very dry and very humid climates, or between generally calm and very windy conditions. Thus, the effect of climate on crop water requirements is not fully defined by the temperature and day length. Consequently, the consumptive-use crop coefficient will vary not only with the crop, but also with climatic conditions. Its value is both time and place dependent, and local field experiments are normally required for its determination.

The Blaney-Criddle consumptive-use factor f is calculated in the following way:

$$f = p\,(0.46\,t + 8.13) \tag{55.1}$$

where p is the mean daily percentage of annual daylight hours for a given month and latitude and t is the mean of the daily temperatures, in °C, during the month considered. The factor f is expressed in millimetres per day and represents the mean value for the given month. This adaptation of the Blaney-Criddle method should be used only when temperature data are the only weather data available. The empiricism involved in any evapotranspiration prediction from a single weather factor is inevitably high. Only for weather conditions similar in nature does a generally positive correlation seem to exist between f values and the reference crop evapotranspiration.

The use of the Blaney-Criddle method to calculate mean daily evapotranspiration should normally be applied for periods no shorter than one month. Unless verification of the general prevailing weather conditions — e.g., daytime minimum humidity, the ratio of actual to maximum possible sunshine hours, and daytime wind conditions at two metres height — can be obtained, predictions are highly questionable. Thus, considerable care is needed in the use of this method because, for a particular month, actual sunshine hours may vary greatly from year to year. Hence, it is suggested that evapotranspiration should be calculated for each calendar month for each year of record rather than by using mean temperatures based on several years' records.

This method should not be used in equatorial regions where temperatures remain relatively constant while other weather variables change. Nor should it be used for small islands where air temperature is generally a function of the surrounding sea-surface temperature and shows little response to seasonal change in radiation. At high altitudes, the daytime radiation levels may be higher than under the conditions from which the method was derived. Also, in climates with a high variability in sunshine hours during transition months, e.g., monsoon climates and mid-latitude climates during spring and autumn, the method can be misleading.

55.1.1.2 *Soil moisture*

Tensiometer and neutron-probe soil-moisture meters have been used to monitor soil moisture and to calculate application requirements based on the measurement of soil-moisture deficit. They can also be used directly to schedule and control application amounts by turning irrigation on and off when predetermined levels of soil moisture have been reached [3, 4]. Detailed information on the use of these instruments is provided in Chapter 15.

55.1.1.3 *Water quality*

Water for irrigation is required not only in sufficient quantities, but must also meet certain quality criteria. Plants are particularly sensitive to the level of dissolved salts in irrigation water. A high salt content in water and soil, and irregular irrigation can produce problems of salinization of irrigated lands, which are common in many regions of the world.

55.1.2 ***Water losses***

Water losses are influenced by the particular configuration of an irrigation scheme and can be minimized by management practices that can result in considerable savings in the operational costs of the scheme. The drainage of soil water should not be regarded solely as a loss. A minimum drainage is required to remove salt accumulation from the soil. Where seasonal rainfall is insufficient to flush out accumulated salts, application rates should be increased to satisfy both the crop and the leaching requirements. Details on how this increment can be calculated from a knowledge of the quality of the irrigation water and the crop water requirement are provided in the FAO *Guidelines for Predicting Crop Water Requirements* [1].

The choice of method of irrigation will also influence evaporative losses. Overhead sprinkler systems will wet vegetation surfaces, and the loss rates of intercepted water are likely to be higher — in the case of tall crops this will be many times higher — than transpiration from dry crop.

Surface irrigation will result in evaporative losses from the wet soil surface, but this is not likely to be a significant proportion of the crop water requirement unless the surface is maintained wet for a significant proportion of the time, as in a rice paddy. It is of more concern that an oversupply of water may be necessary — in ridge and furrow application — to meet the crop water requirement, and the drainage losses may be large and spatially variable.

With drip or trickle irrigation, there is maximum potential for managing water applications to minimize both surface evaporation losses and drainage losses in excess of leaching requirements. By siting the drip points close to the crop, both weed growth and evaporative losses from the weeds can be minimized. Drip irrigation systems can be used in both large-scale irrigation schemes and on small-scale, gravity fed, small-holder irrigation schemes. Except for subsurface irrigation, which may not be cost effective in many circumstances, drip irrigation methods offer the highest potential for water-use efficiency [5].

55.2 **Agricultural drainage**

55.2.1 ***Definition***

Agricultural drainage is the removal of excess groundwater or water from the land surface to create more favourable conditions for plant growth. Surface drainage can remove excess precipitation from the land surface at a rate that will prevent long periods of ponding or flooding without excessive erosion so that pasture or crops will have the best possible moisture conditions. Information on the design of drainage works for small watersheds is provided in Chapter 54.

Subsurface drainage lowers the water table so that it will not interfere with root development and it promotes leaching to maintain the proper salt balance in the soil. Detailed discussion on this subject is provided by Richards and Marsh in *Irrigation Based on Soil Section Measurements* [4].

55.2.2 ***Factors affecting drainage***

Agricultural-drainage needs vary considerably because of differences in climate, geology, topography, soils, crops, and farming methods. Visual evidence of inadequate drainage includes surface wetness, lack of vegetation, undesirable vegetation — such as marsh grass, sedge, or swamp trees — crop stands of irregular colour and growth, variations in soil colour, and salt deposits on the surface of the ground. The topography, geology, man-made obstructions, or soils of a site and its surrounding area, may result in conditions that retard water movement and cause poorly drained sites. Site factors can be placed in several categories. These may exist separately or in various combinations. The following are some of the more important factors:

(*a*) Lack of a natural drainage way or depression to serve as an outlet. Such sites are common in glaciated and coastal-plain areas where natural-drainage systems are in the process of development;

(*b*) Lack of sufficient land slope to cause water to flow to an outlet. Such sites can be found in the irregular and pitted surfaces of glaciated land, above constrictions and natural barriers of valley flood plains, and above dams;
(*c*) Soil layers of low permeability that restrict the downward movement of water. Many soils have a heavy subsoil, rock formation, or compact (hardpan) layer below the surface in the normal root zone of plants;
(*d*) Man-made obstructions, such as roads, fence rows, dams, dikes, bridges, and culverts with insufficient capacity, which obstruct or limit the flow of water;
(*e*) Natural surface barriers that cause local concentrations of water in sufficient amounts to aggravate the drainage problem; and
(*f*) Subsurface drainage problems in irrigated areas caused by deep percolation losses from irrigation and seepage losses from the system of canals and ditches serving the irrigated lands. Deep percolation losses from irrigation fall in the general range of 20 to 40 per cent of the water applied. Seepage losses from canals and ditches vary widely and may be in the range of zero to 50 per cent of the water applied.

Most soils in arid regions contain some salts, varying in concentration from slight to strong. High water-table conditions caused by deep percolation from irrigation tend to concentrate salt accumulations in the root zone. One of the primary functions of subsurface drainage is to lower the water table and to keep the level of salt concentration below the root zone. Much of the subsurface-drainage work in arid regions is actually for salinity control.

There is no danger of over-drainage of most soils with poor internal drainage. Close spacing of drains in soils in poor physical condition aids in the establishment and growth of vegetation needed for soil conditioning even though this intensity of drainage may not be necessary in the same soil if it were in good physical condition. The removal of free water in the soil eliminates moisture in excess of that held by capillary action. Drainage does not remove the capillary water used by growing plants. The depth of the drains controls the height of the water table. If the water table is low in soils with low capillary suction, then moisture may not move upward into the root zone. This is a desirable condition in irrigated saline, saline-alkali, and alkali soils.

There is a possibility of over draining some extremely sandy soils and some peat and muck areas. These soils have a particular depth of water table that is best for plant growth that should be considered in designing the drainage system.

55.2.3 ***Benefits of farm drainage***

The removal of free water, which promotes bacterial action in the soil that is essential for the manufacture of plant food, allows air to enter the soil. The roots of plants, as well as the soil bacteria, must have oxygen. Drainage accomplishes this by providing air space in the soil. Rainfall passing downward in the soil removes carbon dioxide and permits fresh air to infiltrate. Thus, drainage provides needed soil aeration.

Surface drainage removes ponded water quickly, thereby allowing the remaining gravitational water to move through the soil.

The removal of free water by drainage allows the soil to warm more quickly because more heat energy is required to raise the temperature of wet soil. Soil warmth promotes bacterial activity, which increases the release of plant food and the growth of plants. Soils that warm up sooner in the spring can be planted earlier. Better germination conditions for seeds are also provided.

The removal of groundwater improves the conditions for root growth. For example, if free water is removed only from the top 25 centimetres of soil, crop roots will feed in this confined area, but if free water is removed from the top metre, this entire depth of soil is available as a root zone from which plants can obtain nutrients and moisture.

55.2.4 ***Basic types of drainage***

Drainage is accomplished by establishing or accelerating gravity flow within the site, by diverting flow from the site, or by a combination of these two.

55.2.4.1 *Relief drainage*

Establishing or accelerating the flow of excess water within and from a site is referred to as relief drainage. Surface flows are removed by surface ditch systems and land grading. Subsurface flows are removed by relief drains, which are lateral drains located parallel, or approximately so, to the flow of groundwater.

55.2.4.2 *Interception drainage*

Interception ditches or drains located across the flow of groundwater (or seepage) are installed primarily for intercepting subsurface flow moving down a slope. While this type of drainage intercepts and diverts both surface and subsurface flows, the removal of surface water is generally referred to as diversion drainage and the removal of subsurface water by this method is referred to as interception drainage.

55.2.5 ***Methods of artificial drainage***

55.2.5.1 *Surface drainage*

Surface drainage may be accomplished by open ditches and by shaping land surfaces for the movement of water to the disposal ditches. Drainage by this method applies to flat sites where:

(*a*) Soils are of low permeability throughout their profiles, e.g., low permeability clays;
(*b*) Soils are shallow (20 to 50 centimetres) over low permeability subsoil or rock;
(*c*) Soils would be responsive to subsurface drainage but lack free subsurface outlet;

(*d*) Subsurface drainage is not economically feasible; and
(*e*) Surface drainage supplements subsurface drainage.

55.2.5.2 *Subsurface drainage*

Subsurface drainage may be accomplished by various types of buried drains, by mole drains, and open ditches. Subsurface drainage is applicable to saturated-soil conditions where it is physically and economically feasible to use underdrains to remove free water from the root zone. The fertility of the soil must be such that sufficient drainage will result in additional yields of crops to justify the expense of installing the drains.

The need for, and the design of, subsurface systems are related to the amount of excess water entering the soil, the permeability of the soil and the underlying subsoil, and the crop requirements. In general, fine textured soils have low permeabilities. In such soils, the pore spaces are so small and clogged with colloidal material that gravitational flow into the drain is obstructed, which restricts it to removal of the free water only from a limited area.

In some sandy, peat, and muck soils, the pore spaces are large and the movement of water is rapid. Wetness occurs because of high water table, particularly in the spring in nonirrigated areas and in the fall, or after the irrigation season, in irrigated areas. This must be corrected by drainage if maximum crop yields are to be produced. Soils of this type can be successfully drained, but many of them present installation and maintenance problems.

In some fine, sandy soils, there is insufficient colloidal material to hold the particles together, and there is danger of excessive movement of the sand particles into the drains. These soils require special precautions in drain construction. Open ditch subsurface drainage may be practical.

In peat and muck soils, there is some tendency for the fine soil particles to enter the drain, there is danger of a tile drain shifting due to the unstable nature of the soil, and there is a tendency for newly drained muck and peat soils to settle considerably. For these reasons, it is recommended that drainage of these soils by buried drains be delayed until initial settlement has taken place. Mole drainage and open ditches may be used for initial drainage of this type of soil.

In very porous soils, such as coarse sands and some peats, excessive lowering of the water table may cause a moisture deficiency during periods of drought. Such soils, being very porous, have low capillary suction and are unable to draw water up into the root zone of certain crops if the water table falls much below the root zone.

There are other soil conditions where drains are hazardous or impractical. In some soils, boulders or stones make drainage costs prohibitive. In other soils, the top soil is satisfactory, but it is underlaid with unstable sand at the depth where drains should be installed, thus making installation more difficult or impossible. In other soils (as those containing glauconite, iron oxide, or magnesium oxide), there is a tendency for the drain joints or perforations to seal due to chemical action.

55.2.6 *Economic factors*

Some soils can be drained satisfactorily, but the installation costs are so great that the benefits derived do not justify the expense. In most instances, drain spacing of less than 15 metres for relief drainage cannot be justified unless high-value crops or substantial indirect benefits are involved. Indirect benefits should be considered when, for example, the drying out of orchards makes it possible for spray rigs to be used without bogging down.

Some soil can be drained satisfactorily, but inherent productivity is so low that yields do not justify the expense. Suitable outlets may not be available and can be obtained only at prohibitive cost.

In some cases, the financial ability of the farmer may not permit substantial indebtedness, even though returns from increased crop yields and reductions in the cost of production might pay for drain installation within a five- to 10-year period.

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CHAPTER 56

HYDROPOWER AND ENERGY-RELATED PROJECTS

56.1 General

Energy is one of the most important commodities for the satisfaction of physical needs and for providing economic development of modern society. Energy needs are continually growing. To date, the world energy market has depended almost entirely upon the non-renewable, but low cost, fossil fuels. Energy produced by hydroelectric developments throughout the world provides approximately one-fifth of the world's total electrical energy.

Electric-power generation constitutes a major demand on water resources, so that hydrological data and information are essential to planning the exploitation of both renewable and non-renewable electrical energy sources. Although water is one of the two essential components in the production of hydroelectric energy, this is essentially a non-consumptive use as well as a non-polluting one. In the production of thermal-electric energy, water is required in practically all technical stages from the boring of test wells in oil and gas exploration to the transformation of fossil and nuclear fuels into electrical energy at thermal power stations — uses which are largely consumptive and/or polluting.

Recently, new problems have evolved with the exponential growth of electrical energy demands. These are the issues of water supply for energy production and the impact of energy developments on climate and the global environment.

56.2 Hydroelectric power

Hydropower is a source of electrical energy that is continually renewed and available in the runoff segment of the hydrological cycle. Energy from flowing water offers something unique to a nation's economic development — sustainability, which has been defined by the Bruntland Commission as "economic activity that meets the needs of the present generation without jeopardizing the ability of future generations to meet their needs" [1]. Hydroelectric schemes are diverse, not only as a result of the different natural conditions to which they may be adapted, but also because of the diversity of circumstances related to power demand and utilization. Hydroelectric power is frequently developed as part of a multi-purpose project so that the project may involve the full range of water-resources considerations, e.g., flood control, navigation, irrigation, municipal and industrial supplies, recreation, and fish and wildlife enhancement. Rarely does a project concern a local area only. Usually, an entire river basin is under investigation, which entails regional, national, and even international considerations. In considering any magnitude of development, the planning phase must take into consideration all water-resources needs of the region and the ways in which such needs are to be met. The effects of a proposed hydroelectric development on the resources and various needs in a region, and the capacity to meet those needs, must be carefully evaluated.

Although hydroelectric projects have become increasingly larger during the past quarter-century, small hydroelectric plants of up to a few megawatts (MW) can economically exploit the energy at potential sites on small streams, or they can often be integrated into existing dams or artificial waterways.

56.2.1 *Advantages*

Although hydroelectric developments throughout the world provide a relatively small percentage of the global electrical-energy demand, the importance of their outputs is proportionally greater than that from other sources. It is especially significant as an economic stimulus in developing countries and as an important part of complex power systems in more industrialized countries. Its importance will not diminish because:

(*a*) Hydroelectric energy is derived from a continuously renewable resource powered by the energy of the sun, which sustains the hydrological cycle;
(*b*) Hydroelectric energy is non-polluting — Significant heat or noxious or greenhouse gases are not released in its production;
(*c*) Hydroelectric plant efficiencies can be close to 90 per cent, whereas fossil-fired thermal plants attain efficiencies of only 30 to 40 per cent;
(*d*) Hydroelectric plants have a long, useful life;
(*e*) Hydroelectric technology is a mature technology offering reliable and flexible operation, and its equipment is readily adapted to site conditions;
(*f*) Water in storage provides a means of storing energy and may be available for other purposes;
(*g*) Hydroelectric plants are capable of responding, within seconds, to changes in electrical demands; and
(*h*) Hydroelectric generation has no fuel costs and, with low operating and maintenance costs, it is essentially inflation proof.

Of course, a potential hydroelectric development may be subject to geopolitical constraints, e.g., flooding of upstream areas, to create a head and/or storage, as well as environmental impacts, e.g., changing a riverine to a lacustrine ecology.

56.2.2 *Site potential*

Hydroelectric energy is developed by the transformation of the energy in water falling from a higher level to a lower level, into mechanical energy on the turbine generator shaft and thence into electrical energy through the generator rotor and stator. The power potential of a site, in kW, is:

$$P = 9.81\ Q\ h\ e \qquad (56.1)$$

where Q is discharge in $m^3\ s^{-1}$, h is the net head (fall) in metres and e is the plant efficiency. The head to be utilized may result from control of the natural characteristics of the watercourse, such as steep gradients, rapids and falls, or it may be created artificially by the construction of a dam that may create a substantial storage or reservoir area that can be used to regulate or change the natural flow regime of the stream. The flow available for use is, allowing for losses, the flow of the watercourse on which the plant is constructed, but this flow may be modified in several ways:

(*a*) By regulation;
(*b*) By means of reservoirs;
(*c*) By diversions from contiguous river basins; and
(*d*) By pumping to enable an upstream reservoir to be used for energy storage.

The amount of capacity to be installed at a potential site depends not only upon the magnitude and the regime of the streamflow and the available head or fall through which that flow may be utilized, but also upon the size of available storage capacity, the lengths of the waterways, operating limitations imposed in the interests of other water uses and, very importantly, upon the magnitude and characteristics of the power markets to be served.

The gross head on a hydroelectric plant is the difference between headwater (forebay) elevation and tailwater (tailrace) elevation when the plant is in operation. The gross head will vary with the magnitude of flow in the stream and the reservoir, or pond, water levels. In considering the economic feasibility of a project, it is important to know the average gross head that may be expected for computing average energy, as well as the minimum gross head to enable an estimate of the firm or dependable energy, i.e., the energy that can always be supplied to consumers on demand. The average gross head is dependent upon the flow in the river below the site. Under low-flow conditions, the tailwater level would be low so that the head is usually near its maximum value, whereas, under high-flow conditions, the tailwater level would be high so that the head would be in the minimum range. A low-head plant on a river subject to periodic, large flood flows may have such a minimum reduced gross head under flood conditions that operation of the plant would be impaired to the extent that it might have little or no firm (dependable) capacity, and its operation would have to be interrupted.

While most of the gross head can be utilized in producing electrical energy, there are hydraulic losses in the intake water passages, which convey the water from the forebay to the turbines, as well as losses in the exit water passages, i.e., from the turbines through the draft tube into the tailrace. The draft tube is designed to regain most of the kinetic energy of the water at its exit from the turbine runner. Within limits, all of the foregoing losses are controllable because they decrease with the increasing size of water passages or with the type of design.

The net or effective head in a hydroelectric plant is the gross head minus all losses upstream of the entrance to the scroll case that surrounds the reaction-type turbine and at the exit from the draft tube, or to the base of the nozzle in the case of the impulse-type turbine. Thus, the net head is a function of the gross head and discharge through the plant — because velocity-head losses increase approximately as the square of the discharge — as well as the flow in the river immediately below the power site.

In order to enable a reliable estimate to be made of the energy that can be generated at a selected site requires an adequate record of streamflow along with related information and hydrological data, as follows:

(*a*) Daily and/or monthly streamflow data for an extended period of time, at least 10 years;
(*b*) Streamflow diversions upstream from the dam or intake works;
(*c*) Flow-duration curves;
(*d*) Drainage areas;
(*e*) Evaporation losses from proposed reservoir surfaces;
(*f*) Stage-discharge relationship immediately below proposed site;
(*g*) Spillway design-flood hydrograph;
(*h*) Dam, spillway, and outlet rating curves;
(*i*) Project purposes, storage available, and operating rules;
(*j*) Seepage losses, fish-ladder requirements, and diversions from storage;
(*k*) Reservoir elevation-duration information;
(*l*) Annual peak-discharge data to assess risks associated with spillway design; and
(*m*) Minimum-flow requirements downstream from the site.

Examples of techniques used in analysing hydrological data to extract relevant information for design purposes are given in Part D of this *Guide.* The *Hydrological Operational Multipurpose System* (*HOMS*) *Reference Manual* provides information on the availability of software packages for the application of these techniques.

Probably the most useful tool in hydropower feasibility studies is the flow-duration curve (section 35.2). A flow-duration curve based on the day as a unit will give a more accurate curve, particularly for those portions near each end of the curve, than one based on the month. The differences will be more obvious for streams with little or no natural surface storage. The area under the curve is equivalent to the mean flow of the stream for the period of the data. A very useful form of the flow-duration curve is one that is dimensionless and can be obtained by expressing the ordinate as a ratio to the mean flow. Since the general form of this curve is much the same for different streams in a similar hydrological region, it provides a means of approximating a flow-duration curve with only an estimate of the mean flow of a stream. This approach might be necessary if few or no streamflow records are available, but data on precipitation and general hydrological conditions are at hand to establish a reliable estimate of the mean yearly flow for the stream under study, and adequate flow records are available for the construction of flow-duration curves for other streams in the region.

The capacity of the turbines to be installed in a development will usually be of a magnitude that could utilize the flow available 20 to 40 per cent of the time. However, design plant capacity will be determined by comparing the cost of different sizes of plants, their resulting outputs, and the value of this power to the system. The value of hydropower to a power system is dependent upon the cost of obtaining equivalent energy from an alternative source at that time. On the other hand, the cost of energy varies with time. At times of low energy demand, such as at night, only the most efficient plants of the system would be operating so that the incremental energy cost would be small, but, under the much larger day-time demands, less efficient equipment would be used so that the incremental cost of energy would be larger during these periods.

The area under the flow-duration curve up to the turbine discharge capacity will give the average yearly flow that can be utilized, which, with the net head, will provide the basis for computation of the available power from the proposed installation. The effect of storage (pondage) on a flow-duration curve would be to raise the curve to the right of the mean and to lower it to the left of the mean flow. If it were possible to provide complete regulation, the duration curve below the storage reservoir would become a horizontal line corresponding to the mean flow of the stream.

Storage permits within-day and within-week fluctuations in output to respond to fluctuating demand. Peaking is a term used for within-day fluctuations. Hydroelectric plants are particularly well suited for peaking operations. Load changes may be handled in a matter of seconds by altering turbine gate openings. This capability can mean significant fuel savings as well as greater security of supply in a mixed hydro/thermal system. However, should the reservoir have sufficient capacity to meet not only daily and weekly fluctuations but also greater energy production during those seasons of the year when electrical energy is in greater demand, the project should be provided with seasonal storage. For example, in many regions, energy demands are greatest in winter when the river flow may be lowest. Storage of the generally high flows from snow-melt runoff during the spring season could then augment the winter flows. Occasionally, carry-over storage can be provided for extended drought periods of one or more years.

The determination of storage-yield relationships is one of the basic hydrological analyses associated with the design of reservoirs (Chapter 52). Physical constraints may include limits on the area that may be flooded, i.e., on the maximum water level, on the minimum level because of the location of the low level intakes, on the discharge capacity, and on the downstream channel capacity. Constraints may also require the maintenance of fisheries during spawning or for species of wildlife dependent on water levels for their survival. In northern regions, for example, the maintenance of an ice cover or the prevention of ice jams may require the establishment of appropriate discharge maxima during the winter period.

When the reservoir capacity is fixed by conditions at the site (it usually is), the firm flow which the runoff regime from the contributing area, together with available storage space, could sustain may be determined by a mass-curve analysis (section 29.2). The firm yield is the sum of the usable storage in the reservoir and the usable inflow during the critical low-flow period. It may not always be a simple matter to select the critical-flow period. A combination of two moderately dry years in series may be more serious than a single, isolated, very dry year.

For the planning of hydropower utilization and for the design hydropower stations, a special duration curve should be derived, which is the resultant duration of the corresponding heads and discharges and corresponds to the planned plant efficiency. This output-duration curve can be produced by the successive application of equation 56.1 for selected corresponding points (Q,h) of their respective duration curves.

Another valuable product for estimating hydropower resources is the hydroenergetic longitudinal profile, which corresponds to the potential energy content of the river that can be generated in an average dry or wet year. This is based on the discharge records of the stream and on the corresponding water-level slopes (or the energy line).

56.2.3 ***Rule curves*** **[K75]**

The water demands for conservation storage, in a multi-purpose storage project, may be partially complementary or they might be competitive so that it is necessary to make proper capacity allocations among the competing demands by removing or resolving conflicts as far as possible. From the standpoint of power generation, it is desirable to use the water according to the electric power demand by maintaining the storage level as high as possible and by generating electrical energy under the resulting higher head. For irrigation, the required water is expected to be available during the irrigation season, and municipal and industrial water will be required throughout the year. In most instances, water used for power generation is discharged into the river and can be reused in the lower reaches. Thus, there is no essential conflict between power generation and water supply, but, among other purposes, basic conflicts can exist. If, for example, water is diverted from the reservoir by gravity canal for irrigation purposes, it would be in direct conflict with power generation. Even though the return flow from the irrigation project would eventually find its way back into the river, such use could be in direct conflict with downstream water-supply and navigation because a substantial quantity of diverted water would have been consumed in the irrigation project and its quality may have deteriorated. Therefore, where multiple-purpose reservoirs are contemplated, reservoir-capacity planning becomes much more complex. Each objective function adds to the complexity because each use must be evaluated and the final result must be obtained by a process of optimization.

Rule curves or operational criteria should be established to minimize the conflicts between purposes. A rule curve is a guideline for reservoir operation and is generally based on a detailed sequential analysis of various critical combinations of hydrological conditions and water demands. When hydroelectric energy is a principal output of the reservoir operation, a detailed flow analysis is required to coordinate energy production with other reservoir uses to determine the project's average energy output. This also will establish the firm power and energy over the critical period, particularly when the conservation storage is relatively large and the head can be expected to fluctuate over a fairly wide range. Various operational plans may be tried in an attempt to maximize energy output while meeting other uses. When the optimum output has been achieved, a rule for operation can be developed and tested during critical low- and high-flow periods.

A simple rule curve for power operation of a single-purpose storage project will show the reservoir elevation or storage volume required to assure the generation of firm power at any time of the year. Variations of the rule curve may be developed with an upper and lower curve corresponding to whether or not the reservoir supplies are above or below normal. Hydrological forecasts will assist in maximizing energy output by minimizing spillage of water. Flow restrictions may be necessary where there are downstream constraints due to flooding. The rule curve can be adapted to reflect such constraints. Probability analysis of supplies may be employed to guide the operator on whether or not to favour the upper or lower rule curve.

56.2.4 ***Water quality***

Water quality is not usually a major concern for hydropower projects, either with respect to the inflow or the outflow. Current environmental considerations ensure that biomass degradation and reduction in flow aeration in the reservoir reach are minimized. In some rivers in tropical regions, the water may be dangerously acidic and corrosive to such an extent that it may attack the runner blades and other parts of the turbine machinery. The sediment load of a river may also be a factor in designing and in limiting the useful life of a reservoir, as well as of the embedded and moving parts of the hydraulic turbine.

56.3 Energy-related projects

Although the major use of water in electrical-energy production is hydroelectric, it is also essential in the thermal production of energy and is necessary in practically all of its technological stages from the boring of test wells in oil and gas exploration to the transforming of fossil and nuclear fuels into electrical energy at thermal-power stations. The following descriptions provide a guide to the quantity and quality of water required for processing and consumptive use and the quality of the effluent flow from such projects. The Table below provides a summary of the general ranges of water requirements and consumption for a number of processes related to energy production.

56.3.1 *Fossil-fuel and nuclear-power generation*

Uses of water for electrical generation from fossil and nuclear fuels are similar. All such power plants use water for steam and condensate system make-up, general service, and potable and miscellaneous water systems. The rate of use is dependent upon the condenser-cooling and waste-heat rejection systems. In the case of coal-fired generating stations, water is also needed for ash transport, which requires about 0.00095 m^3 s^{-1} MW^{-1} and, where appropriate, flue-gas desulphurization requiring about 0.00019 m^3 s^{-1} MW^{-1}. However, water for condenser cooling is the single, most significant use, and the quantity required is typically in the range of 0.032 to 0.044 m^3 s^{-1} MW^{-1} based on an 8°C temperature rise across the condenser. The principal waste-heat rejection systems include once-through cooling, evaporative-cooling towers, and dry-cooling towers. The application of regulations controlling thermal pollution of watercourses is resulting in a decline in the use of once-through cooling. Evaporative-cooling towers are the largest water consumer and contributors of effluent water. Dry-cooling towers dissipate waste head from a power plant directly to the atmosphere by means of air-cooled heat exchangers without the addition of heat to, or consumptive use of, natural bodies of water. Plants using this system, however, require increased fuel consumption and additional plant capital cost.

As is typical of any complex system, nuclear-power plants are subject to a wide variety of unplanned occurrences that may interfere with their normal operation and, in extreme cases, endanger the health and safety of the public. The probability of occurrence of more serious accidents is undoubtedly quite small in view of the large factors of safety and safeguards that are an inherent part of the design of nuclear power plants. Volume II of the WMO *Meteorological and Hydrological Aspects of Siting and Operation of Nuclear Power Plants* [2] describes the various types of nuclear power plants that are now part of many electric utility systems. It discusses hydrological and related water-resources problems that may be encountered in planning, designing, operating, and decommissioning nuclear power plants.

Summary of water requirements for energy-related uses other than hydropower

Process	*Process water consumption*			*Energy development water requirements*	
	Standard unit	*Water consumption m^3/standard unit*	*Comment*	*Standard production rate*	*Water requirement m^3/standard production rate*
	(product)	*(typical values)*		*(product)*	*(typical values)*
Coal mining (surface and underground)*	tonnes	0.01-0.06	-	million t/yr	0.0003 - 0.0019
Coal mining (hydraulic)*	tonnes	0.08-0.14	15% makeup	million t/yr	0.0025 - 0.0044
Coal processing*	tonnes	0.4-1.5	10% makeup	million t/yr	0.0127 - 0.0475
Coal slurry pipelines	tonnes	0.95	-	million t/yr	0.0301
Coal liquefaction	tonnes	2.4-3.8	-	million t/yr	0.0761 - 0.1204
Tar sands extraction	bbl	0.88	-	bbl/d	1.02×10^{-5}
Crude oil refining	bbl	0.163	-	bbl/d	1.88×10^{-6}
Fossil fuel power plant	MW-h	0.9-5.4	-	MW	0.00025 - 0.0015
Nuclear power plant	MW-h	1.5	-	MW	0.00043
Uranium milling					
- Ontario and Newfoundland	kg	0.67	low grade ore	t/yr	2.11×10^{-5}
- Saskatchewan	kg	0.4	high grade ore	t/yr	1.27×10^{-5}
Methanol production (synthesis gas and biomass)	tonnes	1.75-3.5	14%-25% makeup	t/d	2.03×10^{-5} 4.05×10^{-5}

Source: Acres International, 1982.

*Coal mining is divided into mining and coal processing. Therefore, to determine the water requirements of a coal mine operation, surface and underground mining or hydraulic mining values must be added to coal processing values to determine the total water requirements of the developments.

In view of the diversity and complexity of such problems, this publication provides some examples of techniques that could be useful in solving the most significant problems. Not only the very high but also the very low flows carry a special significance for the operation and safety of a nuclear power plant. From a safety point of view, highly reliable water supplies are essential for the emergency core-cooling system, the cooling of the spent fuel, and for the ultimate heat sink [3]. Of particular importance is the requirement for protection against flooding from any conceivable source, because flooding may cause common-mode failure, i.e., failure of two or more systems, that could reduce the efficiency of system safety measures [4]. It is imperative, therefore, that the best available system of hydrological forecasting of the regime of water bodies affecting a nuclear power plant be applied and also that periodic reviews of the hydrological assumptions of the planning and design of the station be carried out.

In most energy-related projects, water quality considerations are not the determining factor in the viability of development, but they may be a contributing factor in the sizing, process design, economic siting, or attractiveness of the project. The composition of water arising from different sources varies widely both in the amount of dissolved salts and in the dissolved gases that it contains. Surface waters usually contain suspended matter and often organic matter in solution or suspension, derived from either decayed plant material or sewage. The increasing use of synthetic detergents, some of which are not readily destroyed in sewage-treatment processes, has resulted in measurable amounts of these chemicals being present, even in public water supplies. Rain water in industrial areas and for considerable distances downwind of emission sources, such as coal and oil-burning furnaces, may have a low pH and be potentially corrosive. Most waters, however, can be treated to make them suitable for condenser cooling, general service, ash transport, and flue-gas desulphurization. However, very pure water, containing no more than a trace of dissolved salt, is required for boiler-feed make-up purposes. The cost of preparing this pure water will, in general, increase in proportion to the total dissolved salts that the natural water contains.

A fossil-fuel thermal power plant generates a variety of waste water streams, the most important of which are cooling-water discharge and blowdown. The largest waste water stream is cooling water from a once-through cooling system. For coal-fired power plants, approximately 6,000 BTU's of heat must be dissipated by means of cooling for every kilowatt-hour of electricity generated. Cooling-water discharges are often six or nine degrees Celsius higher than the temperature in the receiving stream. In recent years, cooling towers have become necessary in many installations to prevent thermal pollution of natural watercourses. The next largest waste stream in a fossil-fuel power plant is the cooling-tower blowdown of an evaporative cooling system. Blowdown water contains high dissolved amounts of calcium, magnesium, sodium, chloride, and sulphate. It also contains other agents introduced for corrosion control.

Radioactive wastes are encountered in nuclear power generation and are due, to a large extent, to such factors as leakage, blowdown, maintenance, refuelling, and other mechanisms. Circulating reactor water is used as a source of heat, and corrosion products formed in the system are the primary source of radioactive isotopes in the reactor water. It is mandatory that the water used for cooling purposes, as well as that used as the source for steam, be exceptionally pure because any salts or other impurities in the water may capture neutrons and become radioactive. Another potential source of radioisotopes in the reactor water is the fission products formed within the fuel elements. The quantity of radioactive isotopes in the reactor water depends, therefore, on corrosion rates, frequency of failure of fuel-element cladding, and the rate of removal by condensate and reactor clean-up demineralizers. The possible presence of radioactive isotopes in the water necessitates waste-treatment precautions. In the primary circulating system, great care is required to maintain the water at a high level of purity in order to minimize build-up of excessive radioactivity caused either by impurities or by corrosion products. No primary water is wasted but a portion is removed, purified and recirculated. The danger of stress corrosion requires that the boiler water contains very low concentrations of oxygen and chlorides. To achieve this, raw water is de-aerated and evaporated to reduce oxygen and chloride levels to less than 0.03 and 0.3 mg l^{-1}, respectively.

56.3.2 ***Coal mining and processing***

Very little water is used in either open-pit or underground mining for the extraction of coal. In fact, seepage water is usually a nuisance, and considerable effort and cost may be expended in removing it from mine workings. Coal-preparation plants use large quantities of water to clean coal, but recycling systems are generally used with the result that about 10 per cent makeup water is required.

Coal-slurry technology has been available since just prior to the turn of the century. Slurry pipelines may be economical over certain large-volume, long-distance routes, but following separation of the pulverized coal product, the water must be treated prior to discharge into a natural watercourse. Effluent-treating facilities will depend on the quality of the coal (i.e., its sulphur content, ash, and minerals) proposed for transport, the chemical additives required to inhibit corrosion in the pipeline and associated equipment, and the coagulating-agent chemicals used in dewatering.

Runoff from coal-mining sites contains high levels of metals, suspended solids, and sulphate from pyrite and/or marcasite, which is commonly associated with coal, shale, and sandstone deposits. Upon exposure to air, these minerals form both sulphuric acid and ferric-hydroxide compounds. Acid mine drainage can result from tailings ponds, waste-rock piles, and wherever coal is stockpiled. Impacts to receiving waters can include high acidity (pH of 2 to 4) and high concentrations of aluminium, sulphate, iron, and trace levels of heavy metals.

The result of deforestation, establishing access roads, and the mining process itself will create increased erosion, siltation, and nitrate and cation leaching into the receiving waters. Impacts are nutrient loading and increased turbidity in the receiving waters.

56.3.3 *Uranium mining and processing*

The use of water in both underground and open-pit uranium mining is generally small and is mostly required for potable supply. The total water usage during uranium milling is not large, with most of the water being used for wet grinding.

The processing of uranium ore in concentrating mills generates wastes and effluents that are both radioactive and non-radioactive. Solid, liquid, and gaseous effluents are released into the environment to a greater or lesser extent, depending on the process-control and waste-management measures instituted.

56.3.4 *Petroleum production*

Water supply and availability, cost, energy conservation, and environmental considerations have all had an impact on petroleum refining. Modern refineries are designed with the objective of reducing water intake to a magnitude of 1/50th of the older once-through systems. The emphasis is now on air cooling, rather than water cooling and multiple use of water (water recycling). The extent of water utilization depends on refinery complexity, which tends to be directly related to capacity, with the larger refineries being more complex. Unit water intake capacities can range from 0.1 to 3 m^3 bbl^{-1} depending on size, complexity, and design approach.

Discharges from petroleum production and refining operations require treatment prior to release into natural watercourses. These treatment processes typically constitute settling of solids and oil/water separation. Due to the large volumes of water required in some processes, recycling design is becoming essential in new refineries.

56.3.5 *Methanol production*

The conversion efficiency for producing methanol fuel from wood or natural gas is approximately 60 per cent. Thus, a large proportion of the heat content of the original carbon-rich source materials must be rejected during the process of converting them to methanol. Approximately half of the heat loss can be rejected via an evaporation cooler, requiring approximately 3 m^3 of water to be evaporated for every tonne of methanol produced. Alternatively, if direct cooling is used, and a 10°C temperature rise is permitted, then 170 m^3 of water would be passed through the heat exchanger to remove this heat with an induced evaporation loss of 1.5 m^3/tonne of product. Clearly, if water is scarce or costly, the process designer must chose a water-conserving method of heat rejection.

By far the largest effluent stream in the manufacture of methanol from either natural gas or wood is cooling water. The degree of contamination of cooling water for these processes is minimal, and the main consideration in waste water disposal is thermal pollution of the receiving waters.

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CHAPTER 57

NAVIGATION AND RIVER TRAINING

57.1 Application of hydrology to navigation

Inland navigation is one of the forms of water use. During the early stages of navigation's development, the transport facilities were primarily adapted to the rivers or river reaches concerned. Later, increased requirements for transportation and the need to avoid expensive transhippings led to the construction of more uniform conditions for navigation along many of the major river sections by means of river canalization or river training.

During early periods of river navigation, the depth and width of a waterway were considered to be its basic parameters. Later on, the number of parameters taken into account increased and interactions between shipbuilding and waterway shaping became more prevalent.

Some of the factors that influence navigation, mostly those referring to the general characterization of the waterway, are more or less constant through time and can be characterized well by more or less permanent measurements. The other factors, however, characterize the temporal conditions of navigation that depend on the runoff regime of the river. Hence, these two groups of factors will be considered separately.

There are two primary facets of river navigation in which hydrology plays a key role:

(*a*) The characterization of river reaches with respect to the types of vessels that can regularly use them for navigation; and
(*b*) The description of current hydrological conditions that influence the operations of the vessels.

These two facets are discussed in the following sections.

57.1.1 *Application of hydrological data to the characterization of waterways*

The goal of the investigation of any waterway for the purpose of characterizing its potential for navigation is to determine the seasonal likelihoods of navigation for various categories for vessels of the individual reaches of the waterway. This may be accomplished by using a system of categories that are based on the magnitudes of the various relevant parameters, as has been done by the United Nations Economic Commission for Europe. The definitions of several of these parameters are given below:

Waterway — The part of the river passable by ships and ship caravans, marked by means of navigation signs (buoyage) (Figure 57.1);

Navigation clearance — The complexity of factors characterizing the depth, width, height, and sinuosity of the waterway, required for a regular and safe navigation by vessels of given dimensions;

Minimum depth of waterway (h) — The minimum depth at the navigable low stage that ensures the required width of the waterway;

Minimum width of waterway (B) — The minimum width at the navigable low stage that ensures the required depth of the waterway;

Prescribed vertical clearance (H) — The minimum vertical difference across the entire width of the waterway between the lower edge of any structure (e.g., bridge) and the navigable high stage;

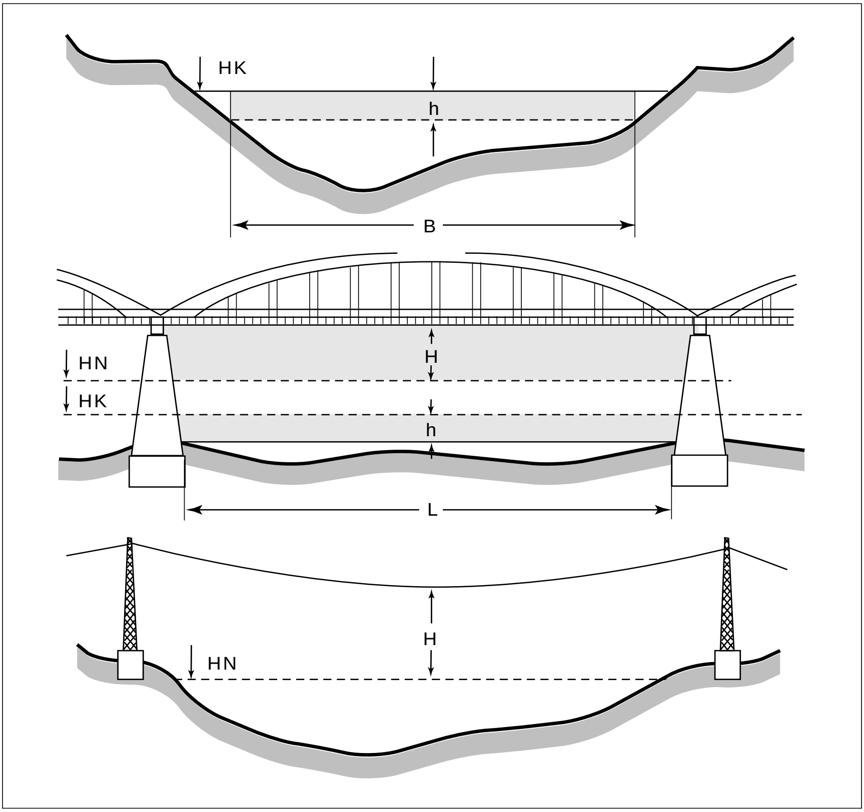

Figure 57.1 — Geometrical elements of the waterway.

Minimum sinuosity radius (R) — The prescribed lower limit of the sinuosity radius of a river bend measured to the axis of the waterway during navigable low stage;
Navigable low stage (HK) — The critical stage ensuring the prescribed value of water depth and width;
Navigable high stage (HN) — The critical stage generally ensuring the prescribed clearance;
Water demand of navigation — The discharge required to ensure the depth required for untroubled navigation;
Minimum discharge for navigation — The discharge ensuring the navigable low stage in a given cross-section;
Maximum discharge for navigation — The discharge ensuring the navigable high stage in a given cross-section;
Navigation season — The part of the year during which navigation is not hampered by ice;
Ford — The transition reach with small depth between two bends of a river; and
Top ford — The shallowest ford along a given navigation reach.

The procedures for describing these parameters are described in the following subsections.

57.1.1.1 *Geometric parameters*

For the determination of the depth and width available for navigation, a closely spaced series of cross-sections along the river is indispensable. The minimum stage at which the minimum width of navigation is still available has to be identified for each cross-section. The navigable low stage for each cross-section is determined by adding the minimum depth of navigation (prescribed for the given river) to its minimum stage. The sinuosity radius should be determined graphically from a contour map of appropriate scale and accuracy.

In the case of investigating the possibility of navigation on a river, it is advisable to carry out this procedure for several values of minimum navigation width so that the navigation category of the natural river can be specified.

57.1.1.2 *Hydrological parameters*

To determine the degree that the runoff regime corresponds to the navigable low stage, flow hydrographs and duration curves of water stages (or flow discharges) are required.

The flow hydrographs should be determined from daily data of a time series with a minimum length of 50 years. They should be computed for a number of probabilities of exceedance (Figure 57.2). The periods during which the prescribed minimum depth of waterway is expected with a given probability can be determined by superimposing the level of navigable low stage on these curves. The durations of

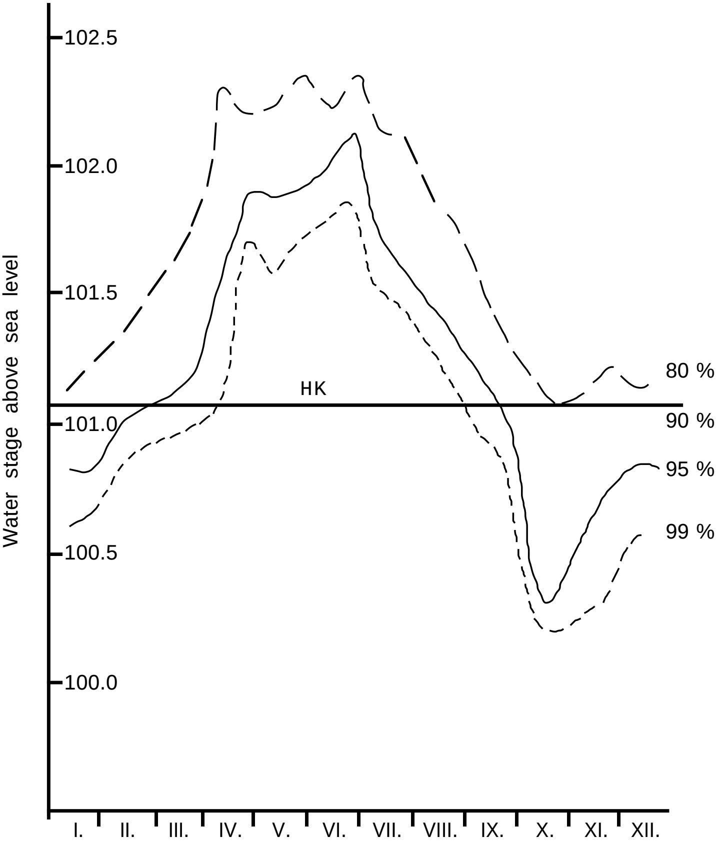

Figure 57.2 — Average flow hydrographs in the cross-section at the 1695th kilometre of the Danube river.

these periods can be obtained by computing durations and/or probabilities. Since the homogeneity of stage data is not always guaranteed, the durations of discharges should be determined and then converted to stage by means of a current stage-discharge relationship (section 12.5). It is possible to find the minimum duration of the navigable low stage along the given river reach by comparing the navigable low stage with the flow hydrographs in various cross-sections. For example, according to investigations carried out for the Danube river, the navigable low stage corresponds to the water stage of 94 per cent duration, as computed for the series of ice-free stage data (Figure 57.3).

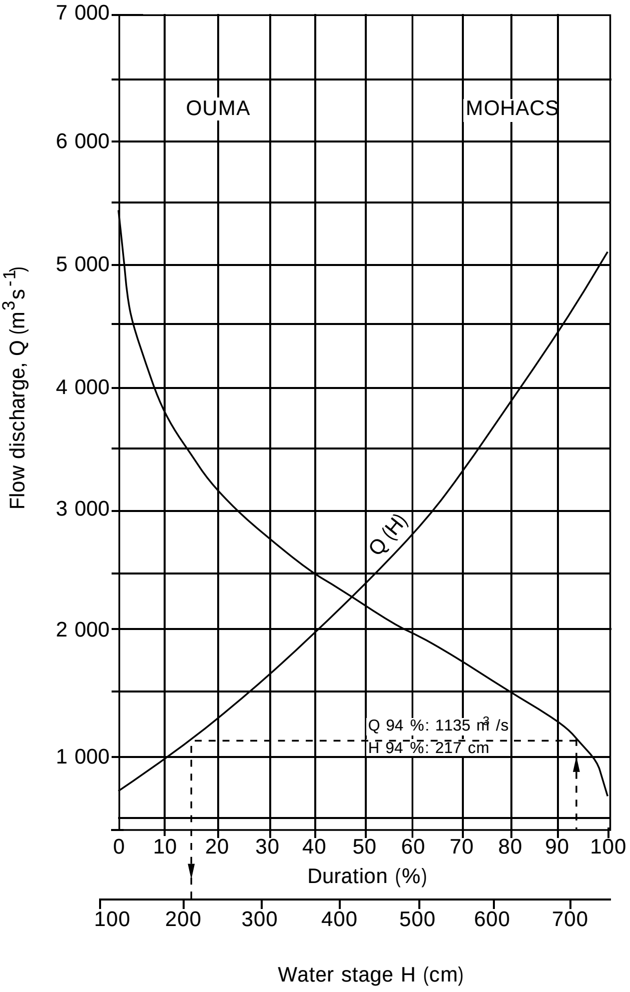

Figure 57.3 — Determination of navigable water stage and flow discharge of a given duration.

In temperate and arctic climatic zones, the length of the navigation season is primarily determined by the ice regimes of the rivers. On the basis of observed data of the various ice phenomena, e.g., ice drift, complete freezing, ice break-up, and ice cessation (section 14.2), the values of the various phenomena expected with given probabilities can be computed, and the length of forced interruption of navigation by river ice can be estimated. The results of such a calculation for the Hungarian reach of the Danube river are shown in Figure 57.4.

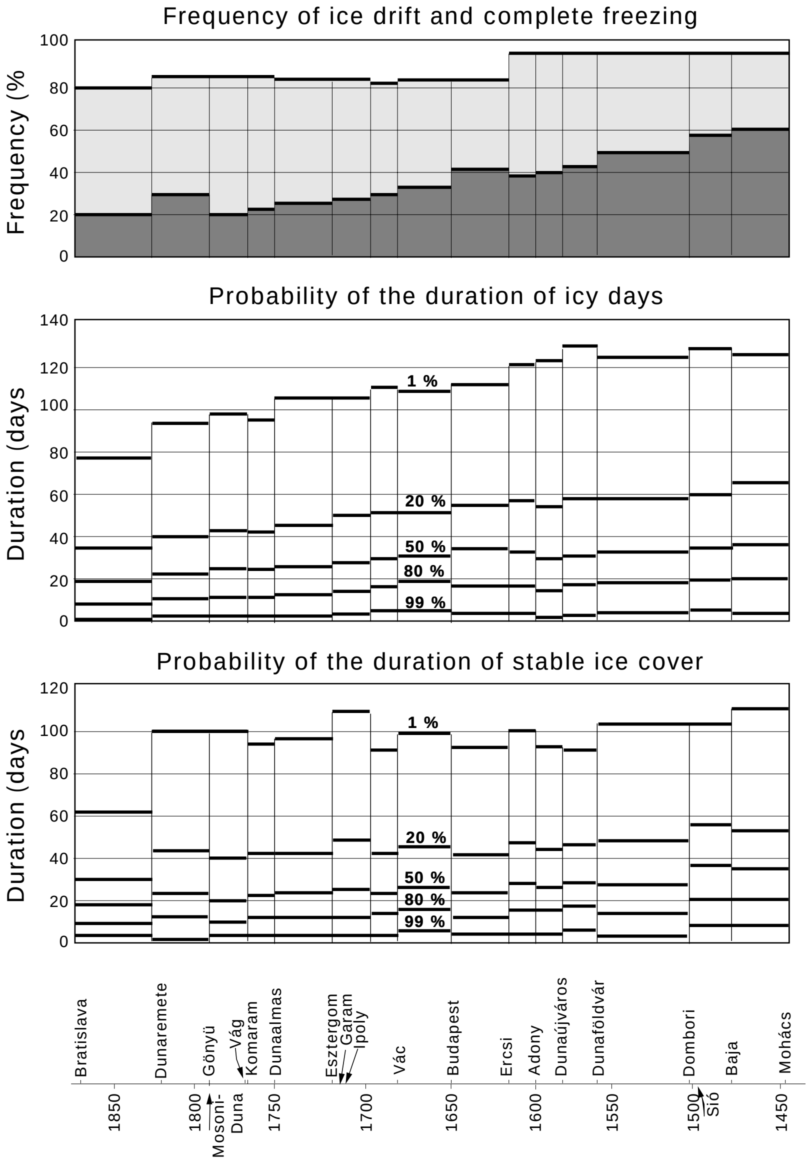

Figure 57.4 — Ice conditions along the Hungarian reach of the Danube river.

From the viewpoint of the efficient operation of ice-breakers, the processing and analysis of observations of ice thickness are also of major importance.

57.1.1.3 *Hydraulic parameters*

Investigation of the flow regime, as described in the foregoing chapter, can be carried out for only selected cross-sections. It is necessary that the navigable low and high stages determined for these cross-sections be interpolated for the river reaches between them. The most reliable method of interpolation, especially in the case of the navigable low stage, is the development of water-level profiles, which requires knowledge of hydraulic parameters, like slopes and roughnesses of the various river reaches between the cross-sections (Chapter 34).

57.1.2 ***Application of hydrological data to operational navigation***

Inland navigation is a complex economic activity that is highly dependent on natural factors. Without reliable knowledge about the state of the river bed, the streamflow, the ice regime, and their expected changes, the planning and operation of navigation activities would be seriously hampered. In order to provide this information, it is necessary to collect continuously data about the hydrological regime, to predict expected changes, and to transfer regularly both data and forecasts to their users.

57.1.2.1 *Data collection*

Navigation utilizes a wide range of data collected by the hydrological services. They include:

(*a*) Data collected on the river basin, e.g., rain and snow;
(*b*) Data collected at the gauging sections, e.g., stage, discharge, water temperature, air temperature, suspended-sediment load, bed load, and ice phenomena; and
(*c*) Data collected along river reaches, e.g., ford depths, flow direction and velocity, water-surface profiles, and ice phenomena.

For a majority of the data needed for navigation, observation methods are those used in general practice (Part B). Some differences arise primarily in connection with the observations and measurements carried out along the river sections between gauging stations.

Measurements of ford depths should be conducted frequently whenever the water depth above the ford does not reach the prescribed value. The depths should be measured along the ford’s crest. As a result of these measurements, the width of the waterway has to be determined for the shallow river reach. The length of the river reach in which the water depth is less than the minimum navigable depth should be stated.

To enable reliable manoeuvres of ship caravans, measurements of flow direction and velocity are also required along the shallow river reaches as well as in the vicinity of ship locks. Surface velocity is measured by means of floats, while the directions and velocities of currents within the water body are measured by current meters equipped with direction finders.

Standard ice observations performed as routine work in the gauging cross-sections are far from being satisfactory for navigation. This activity has to be complemented with respect to both the places where observations are made and the phenomena that are observed. Namely, the observations have to be extended to river reaches between the gauging stations such that, at least at every five to 10 kilometres an observation point should be established. The most important task is to observe river reaches regularly, particularly for ice jams. During periods of drifting ice and at times of freeze over and break up, observations should be made daily, while during the period of fixed ice cover and unchanged flow regime, observations made every five to 10 days may be satisfactory. Reliability of ground observations can be enhanced considerably by aerial surveys and photos. It is recommended that ice maps be drawn at least every five to 10 days.

For ice predictions for navigation purposes, it is indispensable to observe the first crystallized formations and then the development of brink ice. Where hydraulic conditions support the forming of frazzle ice, the density of frazzle ice should be characterized according to the following three degrees: 0-33 per cent, 34-67 per cent and 68-100 per cent of the depth of the river. The density of drifting ice is characterized according to the degrees of 0-10 per cent, 11-20 per cent, ..., 91-100 per cent of the surface area of the river.

57.1.2.2 *Forecasting*

The efficiency and safety of inland navigation depend on the reliability of hydrological forecasts of water stages, ice phenomena, and water depths at fords. There is a need for both short- and long-range forecasts. Navigation is particularly interested in forecasts with lead times equal to the water's travel times along the navigable stretches of rivers.

In addition to the general methods of hydrological forecasting (Part E), navigation often uses monthly forecasts (compiled by taking into account the water volume stored in the river network). Because navigation is particularly sensitive to the reliability of stage forecasts during low-flow periods, the confidence bands of the forecasts should be narrow. For example, for the Danube river, the following values are applied:

Duration of water stage	*Width of confidence band*
60 to 70%	50 cm
70 to 80%	40 cm
80 to 100%	30 cm

57.1.2.3 *Transmission of data and forecasts*

The data collected along a navigable river and the forecasts based thereon can only be utilized if they reach the navigation companies and the shipmasters in a timely manner. In order to ensure this, a well-organized system for the collection and transmission of information is indispensable. Such a system is of particular importance on international rivers like the Danube, which crosses eight countries. In conformity with the recommendations of the Danube Commission, the data collected in the Danube basin are transferred every day by telex. In order to avoid errors, the codes HYDRA and HYFOR (section 4.4) were adopted for data transfer. Announcements reach the shipmasters partly by radio and partly in the form of daily hydrological bulletins.

57.1.3 *Navigation on lakes and canal rivers*

The following differences between navigation on lakes and canals and navigation on rivers, as describes above, can be identified:

(*a*) The importance of the geometrical and hydrological regimes for ensuring navigation conditions is considerably lower because the control structures provide stability of these conditions;
(*b*) On lakes and impoundments, the duration of ice cover is longer, and hence the navigation season becomes shorter;
(*c*) While problems due to fords are reduced or fully eliminated, problems can arise due to silting around lock heads and harbour structures;
(*d*) Wind affecting navigation increases on lakes and impoundments; and
(*e*) There is a heavier dependence of navigation operations upon the operation rules of locks and other structures;

The security of navigation on lakes and canals requires a broadening of the range of observations:

(*a*) On the shores of lakes and river impoundments, wind-measuring stations should be established and operated;
(*b*) In order to investigate the siltation, the amounts of sediment entering and leaving the impoundments should be measured systematically;
(*c*) Since barrages create favourable conditions for frazzle ice, regular observations should be carried out in the vicinity of the structures; and
(*d*) Automated stage recorders should be installed at the cross-sections that are particularly unfavourable to navigation, along any reach influenced by peak-load power generation.

In order to be useful, these data must reach the shipmasters in a timely manner.

57.2 Application of hydrological data to river training

River training, or river regulation, is an activity of continuous character aiming at the formation of the river bed to facilitate navigation, bank protection, and flood control.

Rivers in their natural state often change their beds and by doing so hinder both navigation and the discharge of ice and floods. River training strives to make the river form its own bed with reasonably constant geometrical and hydraulic characters.

The purpose of minor bed regulation is to ensure navigation and ice passage during low-flow periods. Mean bed regulation strives to form a uniform river bed at mean flow that is free of sediment accretion. Flood bed regulation has essentially the same goal as flood control, i.e., the facilitation of flood discharges without significant damage or loss of life.

In addition to hydrological data, a great number of other physical, geographical, morphological, meteorological, and hydraulic data and/or relationships are required for the design of river-training measures. Since the scope of this *Guide* is not to undertake a detailed explanation of many of these variables, only variables that entail operational hydrology will be discussed.

57.2.1 *Evolution and characterization of river bends*

Natural watercourses generally tend to form irregular channels that deviate back and forth across their flood plains. This phenomenon is explained by the fact that each river is a system striving for dynamic equilibrium, in which one of the components of change is the formation of river bends or meanders.

A considerable number of theories have been offered to explain the physical reasons of meandering. Although there are differences among them, most include the following common points:

(*a*) One of the components of meandering is sediment movement;
(*b*) Natural rivers strive to achieve a state of dynamic equilibrium; and
(*c*) The character of meandering, the development degree of bends, and the frequency of their occurrence vary from river to river.

The primary task of river training is to find an optimal path which is suitable to the nature of the given river, i.e., the selection of bends from which the creation of a new dynamic equilibrium can be expected. In order to be able to do so, it is indispensable to study the bends that are still in a natural state.

The sinuosity of river bends can be characterized most easily with circular arcs (Figure 57.5). The following parameters must be determined:

L — The length of the arc, as measured along the central line, between the two inflexion points;
H — The chord length of the bend;
A — The amplitude of the bend;
R — The sinuosity or radius of the bend; and
α — The central angle of the river bend.

Depending on the degree of its development, a river bend can be (Figure 57.6):

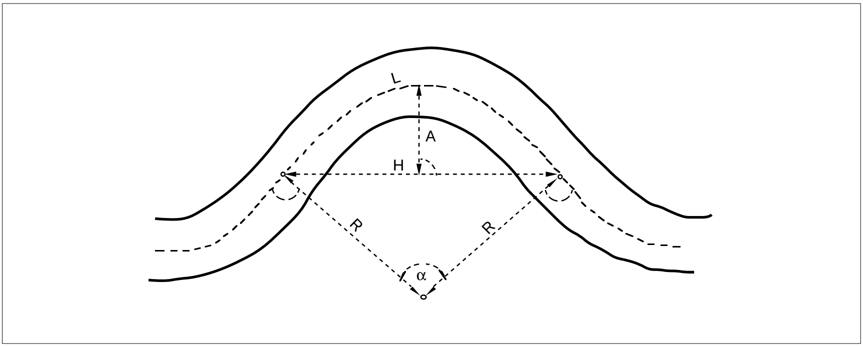

Figure 57.5 — Definition sketch of the parameters of river bends.

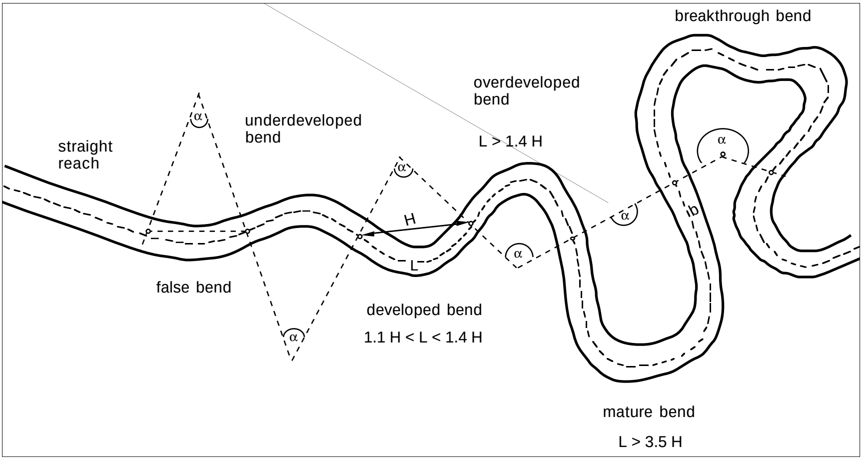

Figure 57.6 — The various degrees of development of river bends.

(*a*) A straight reach;
(*b*) A false bend, when the straight line connecting the two neighbouring inflexion points does not intersect the convex bank line, but remains between the two bank lines;
(*c*) A true bend, which in turn may be:
  (i) An underdeveloped bend, if in each of the two neighbouring inflexion cross-sections, there is at least one point from which that of the other section is visible;
  (ii) A developed bend, if $1.2\ H < L < 1.4\ H$ and $\alpha < 120°$;

(iii) An overdeveloped bend, if 1.5 $H < L < 3.5 H$;
(iv) A mature bend, if $L > 3.5 H$; or
(v) A breakthrough bend, if the distance between the counterbands is less than the width of the river bed.

The sinuosity characteristics of Figure 57.5 can be plotted as a longitudinal profile or can be investigated as random variables by statistical methods.

The geometrical characteristics of the river bed are the following:

(*a*) The area of the cross-section (F);
(*b*) The width of the cross-section (B);
(*c*) The wetted perimeter (P);
(*d*) The hydraulic radius ($R = F/P$); and
(*e*) The average water depth ($h_k - F/B$).

The geometrical characteristics of the river bed change both in time and along the river. On the basis of regular river-bed surveys, the geometrical characteristics can be investigated either as functions of the water stage or, with relative frequencies, of the various variables computed for different river reaches. Figure 57.7 is an example showing the variation of the width of the cross-section along the Danube river downstream of Budapest.

On the basis of such data, the cross-section that optimally suites the nature of the given river reach can be selected, and its dimensions can be determined by using hydraulic methods.

57.2.2 ***Determination of design discharges and stages***

57.2.2.1 *Determination of the design discharge for flood bed regulation*

Characteristic flood data can be determined and flood discharges, with various probabilities, can be computed by using the methods described in Chapters 27 and 36. The outputs of these computations are the basic data necessary for selecting the design discharge for flood bed regulation.

In present practice, the design discharge is given as a magnitude of given probability, or given average return period, of the ice-free annual-peak discharges. The probability depends on the demographic and economic conditions of the area to be protected.

57.2.2.2 *Determination of the design discharge for mean bed regulation*

The dimensions of the mean bed are related closely with the flow and sediment regimes. Both regimes and, consequently, the evolution of the river bed are processes that are changing in time. The task is to determine the formative discharge (or design discharge) that has the greatest impacts on the natural and/or planned dimensions of the river bed.

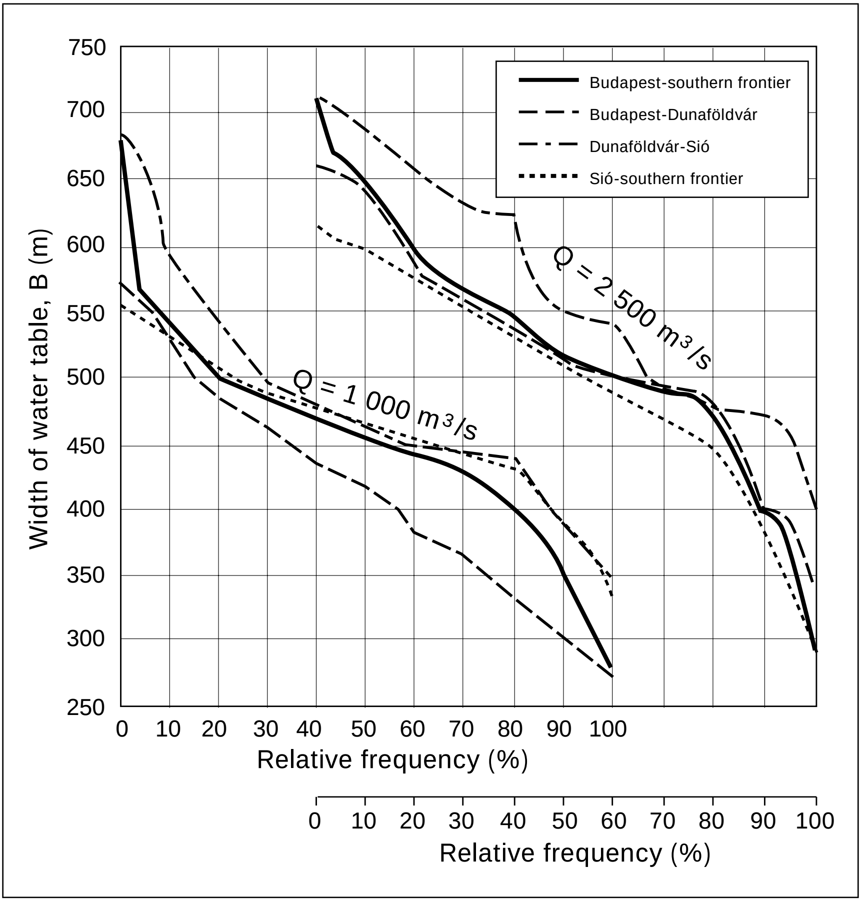

Figure 57.7 — Relative frequency of cross-section widths on the Danube river.

Each of the geometrical parameters of the river bed vary in a different way, depending on the durations of the different discharges. Thus, one discharge will be the dominant one with respect to the width of the mean flow bed, while a different discharge will be dominant for its depth. For each of the geometrical parameters, a discharge value can be found whose effect on that parameter will be the strongest, but there is certainly no single formative discharge that would equally form all river-bed variables.

Because the sediment regime also plays an important role in the formation of the river bed, the characteristics of sediment transport should be considered. For example, a coupling of the characteristics of flow and sediment regimes has been described in connection with the regulation of the Niger river. The formula serving for the determination of the water stage for the formative discharge was:

$$h_o = \frac{\int_T h_i \, G_i \, dt}{\int_T G \, dt} \tag{57.1}$$

Another method, applicable either graphically or numerically, for determining the design discharge Q_D at a given cross-section of a river, is the following. The vertical axis of an orthogonal coordinate system is calibrated for water stages H (m) and, on the horizontal axis, four different calibrations appear: water stage frequency f (m^{-1}), flow discharge (m^3 s^{-1}), average flow velocity (m s^{-1}) and the product $P = \Delta f \, Q \, v$ (m^4 s^{-2}). In this coordinate system, the curves representing the relationships $Q(H)$, $v(H)$, and $f\,(H)$ are first plotted. While $Q(H)$ and $v(H)$ are generally concave curves, as seen from Figure 57.8, $f(H)$ is a more or less asymmetric, histogram or bell-shaped curve whose basis is the vertical H axis, and the area enclosed between the $f(H)$ curve and the H axis is unity. The H axis is then to be subdivided, within the area between the minimum and maximum water stage recorded, into a sufficient number of (e.g., equidistant) intervals ΔH (m). At the medium stage H_i of each interval ΔH_i, the values $Q_i = Q(H_i)$ (m^3 s^{-1}), $v_i = v(H_i)$ (m s^{-1}) and $f_i = f(H_i)$ (m^{-1}) are read from the respective curves and the products $\Delta f_i = \Delta H_i f_i$ are computed. Finally, for each water stage H_i, the product $P_i = Q_i \, v_i \, \Delta f_i$ (m^4 s^{-2}) is calculated, which is proportional to the kinetic energy of the flowing water, and the location of the resultant P_D of the parallel (horizontal) "powers" P_i is determined, e.g., by using the (graphical) funicular polygon method or the (numerical) momentum equation, both of which are well-known methods in statics. At the water stage H_D corresponding to the resulting "power" P_D, the required value of the design discharge $Q_D = Q\,(H_D)$ can be read from the curve $Q(H)$. The results thus obtained should be checked in river reaches that are presumed to be stable.

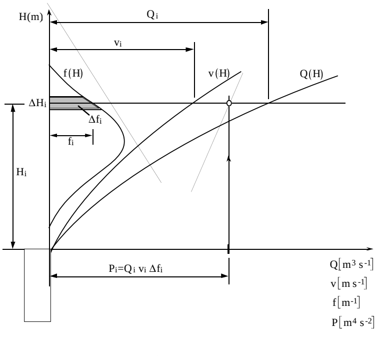

Figure 57.8 — Graphical method for the determination of design discharge.

CHAPTER 58

URBAN WATER-RESOURCES MANAGEMENT

58.1 General

When considering water flowing through an urban environment, it is important to try to detect the origin of its quantity and quality because the choice of the proper strategy in the design, reconstruction (rehabilitation), maintenance, and management of storm-drainage systems is highly dependent on this knowledge. The origin of the water in an urban area may be from:

(*a*) Runoff from the upstream areas;
(*b*) Runoff from adjacent areas;
(*c*) Baseflow from groundwater;
(*d*) Runoff from rainfall over the area considered;
(*e*) Tides and surges; or
(*f*) Used water (sanitary, industrial, etc.).

The flooding caused by runoff from natural and rural areas, as well as groundwater movement, are analysed in the other chapters. This chapter will deal only with surface runoff caused by local rainfalls and with its interaction with receiving water bodies.

Municipal and industrial water supply and management are related to urban drainage as a source of the polluted (sanitary and industrial) waste water. Daily variations in the quantity and quality of waste water from these sources have to be monitored because they serve as inputs to:

(*a*) Drainage-system design, maintenance, and rehabilitation;
(*b*) Design and management of waste water treatment plants; and
(*c*) Assessment of the impacts of the polluted (and treated) water on the receiving water bodies.

The monitoring and management of groundwater in urban areas is very specific because of the variety of ways in which human activities interact with its balance and quality. Groundwater is often a major source of drinking water for urban areas. However, groundwater recharge in urban areas is usually reduced because of increased percentages of impervious areas, which cause lower infiltration rates and faster surface runoff. On the other hand, groundwater in urban areas is subject to pollution by both point and non-point sources.

Therefore, the goals of integrated water management could be:

(*a*) To provide adequate quantities and quality of drinking and industrial water at optimal economic conditions and with minimum adverse effects on the environment;
(*b*) To minimize pollution and adverse changes of groundwater levels;
(*c*) To minimize the costs of floods and damage caused by storms by providing adequate storm drainage based upon the combination of improved drainage networks and real-time control of auxiliary structures (retention and detention basins, pumping stations, etc.); and
(*d*) To minimize the adverse effects of treated or untreated urban waters (sanitary, industrial, and storm) on the receiving water bodies.

Since urban storm drainage is an area that is strongly affected by meteorological conditions, it will be treated in some detail.

58.2 Urban storm-drainage practice

Urban areas are exposed to storms that are stochastic in nature. Therefore the design of the systems is based on storms of a certain return period. Rainfall depth for a certain return period is normally taken from rainfall intensity-duration frequency curves that have been established for many cities. Although common practice is to apply a two-year return-period storm as an input for rainfall-runoff analysis, other return periods are sometimes applied depending on the importance of the area to be protected and the possible damages that can be caused by floods.

Most present-day models used in the design of the storm drainage use either historical (recorded) or synthetic storms as an input. Rainfall intensity is normally taken as a function of time.

Urban-drainage catchments are different from natural ones in many respects. The following are some of the differences:

(*a*) Land-use patterns are different and generally better documented than in natural catchments;
(*b*) The percentage of impervious areas is higher;
(*c*) Unless special techniques for runoff reduction are applied [1, 2], floods are generated rapidly with higher peaks;
(*d*) Water is drained from the catchments by combinations of surface collectors and underground drainage systems; and
(*e*) Drainage areas are usually small, but in large metropolitan areas they tend to be large and with complex systems of buried pipes, pumping stations, and, in recent years, large underground storage facilities.

During the 1970s and 1980s, there were significant programmes for measuring both rainfall and runoff [3], which have enabled the development and calibration of complex, often physically-based, models for rainfall and runoff analysis and storm-drainage system design [4]. Although the drainage systems are normally designed to provide flood protection from storms of a specified probability, most of the present-day models are capable of simulating the consequences of surcharged flow combined with surface flow on the streets (open-channel flow).

58.3 Modelling of rainfall, runoff, and storm-drainage systems

Although simple classical models, e.g., the rational formula, and time-area and unit-hydrograph methods, are still in the use, most of the advanced systems use more complex deterministic approaches. Based on tests with data from the urban drainage models data bank [4], it is sufficient, in most cases of surface flow, to apply kinematic-wave approximations of the governing equations (mass and momentum conservation laws). The same approximations suffice for gutter flow. Generally, good agreement between modelling and measurements of runoff can be achieved if the proper calibration of model parameters is applied [5].

In complex urban-drainage systems in big cities, simulation models are just one component of the sophisticated flood-protection systems that consist of several modules (activities):

(*a*) Real-time precipitation forecasts based on combinations of radar images and raingauge data;
(*b*) Application of computerized databases (network, land use, information on the status of structures and regulation devices, etc.) for real-time control of water quality treatment and monitoring of disposal into receiving water bodies;
(*c*) Links to other municipal services for providing coordination and integrated water management; and
(*d*) Efficient training of staff based on higher levels of information processing and the application of decision-support systems [6].

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CHAPTER 59

SEDIMENT TRANSPORT AND RIVER-BED DEFORMATION

59.1 General

The transport of sediment by the water flowing in rivers and channels is an important factor in the planning, design, and operation of water-management projects. It affects the function of storage reservoirs, the stability and conveyance of river channels, the design of structures that are in contact with the flowing water, and the suitability of the water for various uses. A proper assessment of the effects of sediment transport and of the measures that may be necessary for its control requires a knowledge of the processes of sediment erosion, transportation, and deposition, and of their interaction with the hydrological processes in the catchment.

59.2 Erosion of catchments

The most significant agent for eroding sediments from land is running water. Other agents of land erosion include wind, ice, and gravity. The processes by which water degrades the soil are complicated and depend upon the rainfall properties, soil properties, land slope, vegetation, agricultural methods, and urbanization process. The last two factors account for the most important effects of man's activities on erosion.

Empirical equations have been developed for the determination of soil loss (sheet erosion) from agricultural lands. One of them, developed by Musgrave for conditions prevailing in the United States [1], is given as an example:

$$E = IRS^{1.35}\, l^{0.35}\, p^{1.75} \qquad (59.1)$$

where E is the mean annual soil loss, in millimetres, I is the inherent erodibility of the soil, in millimetres, R is a land-cover factor, S is the land slope, in per cent, l is the length of the slope, in metres, and p is the 30-minute, two-year rainfall depth, in millimetres. The values of the parameters I and R are determined empirically from regional studies.

59.3 Channel erosion

Channel erosion is caused by the forces of the concentrated flow of water. Its rate depends on the hydraulic characteristics of channel flow and on the inherent erodibility of channel materials. In non-cohesive materials, the resistance to erosion is affected by the size, shape, and specific gravity of the particles and by the slope of the bed. In cohesive materials it also depends on the bonding agents. The relationships between the hydraulic variables and the parameters influencing the erodibility of channels are not fully understood and are often expressed by empirical formulae [1, 2]. Stream- and river-control works may have a serious local influence on accelerating channel erosion if they cause an increase in channel depth, flow velocity, change the direction of the flow, or reduce the natural sediment load. The latter effect occurs frequently below dams and may persist for many kilometres downstream.

Bare land and badlands may develop gullies with rates of advance that can be computed by empirical formulae containing such parameters as the drainage area of the gully, slope of the approach channel, depth of rainfall, and clay content of the eroding soil [3].

59.4 Transportation of sediments in channels

59.4.1 *Suspended-sediment transport*

Fine (suspended) sediments transported in rivers originate mainly from the topsoil of the catchment and from the banks of the channels. However, fine sediments also originate from sewage and other return flows, e.g., such sediments comprise about one-third of the suspended-sediment load in the lower Rhine river. A large portion of the transported material comes to rest on flood plains [4], especially upstream from hydraulic structures. The settled material undergoes compaction and other physical and chemical changes that can sometimes prevent its re-erosion by flows that would have carried it previously. A decrease is usually found in the mean annual sediment transported per unit area of the catchment as the area of the catchment increases. The concentration of suspended sediment in runoff is described by formulae such as [2, 5]:

$$log\ c_s = C\ log\ Q + B \tag{59.2}$$

in which c_s is the concentration expressed in weight per unit volume of water, Q is the water discharge, C is a dimensionless coefficient, and B is a function of the rainfall depth, of the antecedent discharge, or of other meteorological and hydrological variables.

The concentration of suspended sediment varies within the channel cross-section. It is relatively high in the lower portion and may also be non-uniform laterally [2] so that its sampling at several points or along several verticals of the cross-section is often necessary for obtaining its mean. The mean concentration should be evaluated to yield the total sediment weight per unit time when multiplied by the water discharge. The graph of suspended sediment against time usually has a peak that does not occur simultaneously with the peak discharge. This lag is a result of the specific conditions in a watershed, and no generalization has yet been formulated for the evaluation of this difference.

59.4.2 *Bed-load transport*

Coarse sediments (bed load) move by sliding, rolling, and bouncing along channels and are concentrated at or near the channel bed. The variables that govern transport are the size and shape of the particles and the hydraulic properties of the flow. As a consequence of the interaction between the hydraulic forces and the coarse sediment, the channel bed assumes different configurations known as plane, ripples, dunes, flat, standing waves, and antidunes. They exert resistance to the flow of water that varies within a wide range and assumes a maximum value for the dune configuration [3, 6]. An empirical formula for the rate of coarse sediment transport proposed by Du Boys in 1879 [1] is still in use. The formula has the form:

$$q_s = c\frac{\tau_o}{\gamma}\left(\frac{\tau_o}{\gamma} - \frac{\tau_c}{\gamma}\right) \tag{59.3}$$

where $\tau_o = \gamma R_h S_e$ and q_s is the sediment transport rate per unit width of the channel, in kg s^{-1} m^{-1}, τ_o is the shear stress at the channel bed, in kg m^{-2}, τ_c is an empirical value for the minimum τ_o required for transporting the sediments considered, γ is the specific weight of the water, in kg m^{-3}, c is a dimensional coefficient, in kg m^{-3} s^{-1}, S_e is the energy slope of the water, and R_h is the hydraulic radius, in metres, which, for wide rivers, may be replaced by the mean depth of water. Values of the coefficients for equation 59.3 are given in the Table below [1].

Coefficients for the Du Boys equation

Classification	*Mean diameter (mm)*	*c (kg m^{-3} s^{-1})*	*τ_c (kg m^{-2})*
Fine sand	1/8	8 370 000	0.0792
Medium sand	1/4	4 990 000	0.0841
Coarse sand	1/2	2 990 000	0.1051
Very coarse sand	1	1 780 000	0.1545
Gravel	2	1 059 000	0.251
Gravel	4	638 000	0.435

A more theoretically-based formula was developed by Meyer-Peter [1]:

$$q_s = \left\{\frac{(\gamma q)^{2/3} S_e - AD}{B}\right\}^{3/2} \tag{59.4}$$

where q is the water discharge per unit width of the channel in m^2 s^{-1}, γ is the specific weight of water in kg m^{-3}, S_e is the energy slope, D is the representative grain size, in metres, q_s is the bed-load discharge per unit width of the channel, in kg m^{-1} s^{-1}, B is a dimensionless constant that assumes the value of 0.40 in a consistent unit system, and A is a dimensional constant that assumes the value of 17.0 in the kg-m-s unit system. If the transported sediments are of diverse sizes, D is replaced by D_{35}, which is the mesh size through which 35 per cent of the weight of the bed load would pass. Equation 59.4 yields results that are reliable particularly for sand-bed channels.

59.5 **Sedimentation**

When approaching its mouth, the flow velocity of a river decreases along with its ability to carry sediment. Coarse sediments deposit first, then interfere with the channel conveyance, and may cause additional river meanders and distributaries. The area of the flowing water expands, the depth decreases, the velocity is reduced, and eventually even fine sediments begin to deposit. As a result, deltas may be formed in the upper portion of reservoirs. The deposited material may later be moved to deeper portions of the reservoir by hydraulic processes within the water body.

Sediments are deposited in accordance with their settling velocity. A relationship between the grain size and the settling velocity is shown in the Figure below [1]. A significant concentration of suspended sediments may remain in the water column for several days after its arrival in a reservoir. This may interfere with the use of the stored water for certain purposes, e.g., for water supply or recreation.

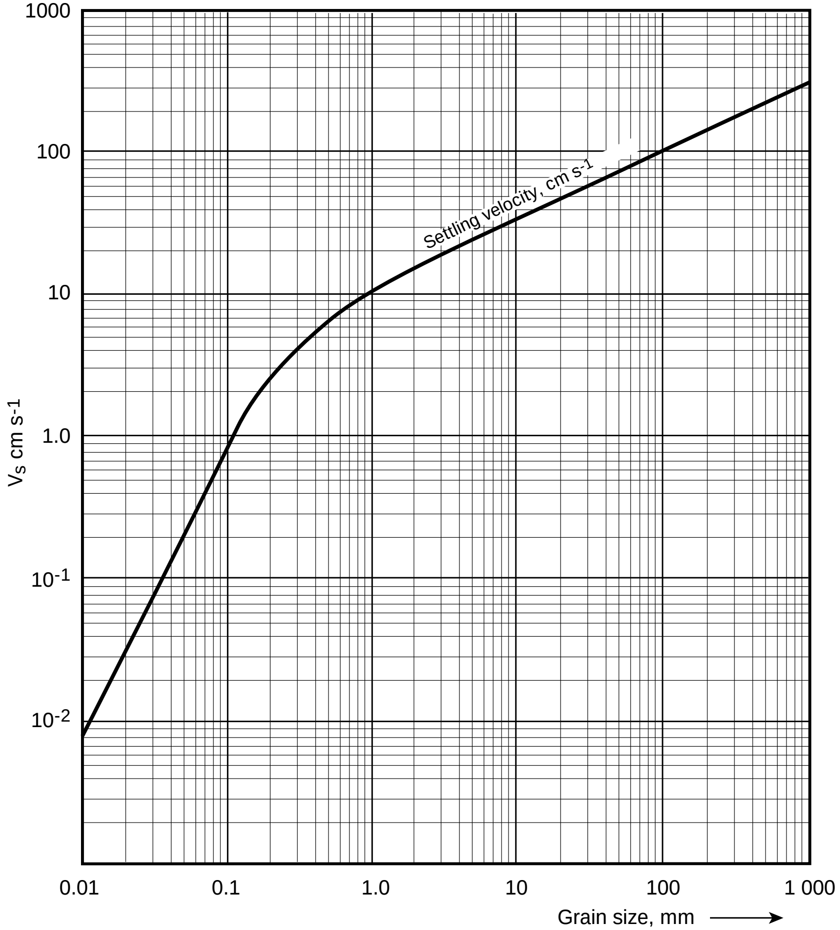
It should be emphasized that not all of the sediment deposits in a reservoir. A large portion of it remains in the upper zones of the watershed, some is deposited upstream from reservoirs, and some is carried downstream by the released water. The sediment-trapping efficiency in a reservoir depends upon the hydraulic properties of the reservoir, the nature of the sediment, and the hydraulic properties of the outlet. The density of newly deposited sediments is relatively low but increases with time. The organic component in the sediment may undergo changes that may reduce its volume and enhance biochemical processes in the stored water.

59.6 **Sediment-control measures**

Sediment-control measures fall into two broad categories:

(*a*) Land-treatment measures for watershed protection; and
(*b*) Structural measures.

Their detailed description are provided by Vanoni in *Sedimentation Engineering* [7]. The aim of land-treatment measures is to reduce erosion in the watershed and thereby the rate of sediment formation by improving the protective cover on the soil surface, reducing surface runoff, and increasing infiltration rates. These measures include:



Settling velocity of quartz grains.

(*a*) Vegetative treatment of land by agronomy and forests, e.g., the use of crop rotation and grazing exclusion in critical runoff and sediment-producing areas; and

(*b*) Appropriate field practices, e.g., contour farming on sloping land, development of gradient terraces on steep slopes, grading and lining of natural waterways, irrigation and drainage ditches, and depressions.

Structural measures are aimed at providing protection beyond that afforded by land-management measures. They include channel improvement and stabilization works, reservoirs, debris and sediment basins, levees, dykes, floodways, and floodwater diversions.

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J15 Combined streamflow forecasting and routing models
J22 Seasonal flow forecasting
J28 Forecasting low flows
J32 Forecasting soil moisture
J45 Ice forecasts
J54 Forecasting surface water temperature
J55 Forecasting surface water quality
J65 Forecasting sediment yield
J80 Analysis of model performance

K Hydrological analysis for the planning and design of engineering structures and water resource systems.
K10 Regional analysis
K15 Site-specific flood studies
K22 Rainfall-runoff simulation models
K35 Streamflow simulation and routing
K45 Routing through reservoirs and lakes
K54 Water temperature studies
K55 Water quality studies
K65 Sediment studies
K70 Evaluation of water-resource projects
K75 Design and operating policies of reservoirs

L Groundwater.
L10 Analysis of data from wells and boreholes
L20 Aquifer simulation models
L22 Calibration and verification of groundwater models
L30 Groundwater forecasting

X Mathematical and statistical computations
X00 Mathematical and statistical computations.

Y Training aids in operational hydrology
Y00 Training aids in operational hydrology.