GEOSCIENCE FRONTIERS 2(2) (2011) 205–214

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GEOSCIENCE FRONTIERS
journal homepage: www.elsevier.com/locate/gsf

ORIGINAL ARTICLE

A review of regional groundwater flow modeling

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Received 16 December 2010; accepted 21 February 2011
Available online 21 March 2011

KEYWORDS
Regional flow system;
Modeling methodology;
Modeling issues

Abstract Significant advances in regional groundwater flow modeling have been driven by the demand to predict regional impacts of human inferences on groundwater systems and associated environment. The wide availability of powerful computers, user friendly modeling systems and GIS stimulates an exponential growth of regional groundwater modeling. Large scale transient groundwater models have been built to analyze regional flow systems, to simulate water budget components changes, and to optimize groundwater development scenarios. This paper reviews the historical development of regional groundwater modeling. Examples of Death Valley and Great Artesian Basin transient groundwater models are introduced to show the application of large scale regional groundwater flow models. Specific methodologies for regional groundwater flow modeling are descried and special issues in regional groundwater flow modeling are discussed.

1. Introduction

Intensive water resources development in past decades has had large impacts on hydrological systems at basin-scales. Frequently reported negative effects are aquifer depletion, cease of base flow, drying of wetlands, degradation of riparian ecosystem and water quality, and induced land subsidence and ground cracks. Currently, water resources management has to consider a river basin as an integrated system where interactions among surface water, groundwater, water resources use and effects on ecosystems take place. Decision-makers require adequate information on these interactions in order to formulate sustainable water resources development strategies. Groundwater models play an important role in the development and management of groundwater resources, and in predicting effects of management measures. With rapid increases in computation power and the wide availability of computers and model software, groundwater modeling has become a standard tool for professional hydrogeologists to effectively perform most tasks. Groundwater flow models have been used: (1) as interpretative tools for investigating groundwater system dynamics and understanding the flow patterns; (2) as simulation tools for analyzing responses of the groundwater system to stresses; (3) as assessment tools for evaluating recharge, discharge and aquifer storage processes, and for quantifying

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Peer-review under responsibility of China University of Geosciences (Beijing).
doi:10.1016/j.gsf.2011.03.003

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sustainable yield; (4) as predictive tools for predicting future conditions or impacts of human activities; (5) as supporting tools for planning field data collection and designing practical solutions; (6) as screening tools for evaluating groundwater development scenarios; (7) as management tools for assessing alternative polices; and (8) as visualization tools for communicating key messages to public and decision-makers.

This paper presents an overview of regional groundwater flow modeling. A brief history of regional groundwater flow modeling is reviewed, and two large scale regional groundwater modeling case studies are introduced to show how to construct regional groundwater flow models. Special issues in regional groundwater modeling are discussed, and specific methodologies for constructing regional groundwater flow models are then summarized.

2. A brief history in regional groundwater flow modeling

Toth (1963) used for the first time analytical solutions to investigate groundwater flow in hypothetical small drainage basins. He found theoretically the existence of hierarchically nested groundwater flow systems: local, intermediate (sub-regional) and regional (Fig. 1). Topography, geology and climate turned out to be major factors for the formation of three sub-flow systems of gravity-driven flow in a homogenous and isotropic groundwater basin. These flow systems can be identified in the field by investigating recharge and discharge areas, changes of groundwater levels with depth, hydrochemistry patterns, environmental isotopes, vegetations and surface water networks (Toth, 1970, 1971, 1972).

Freeze and Witherspoon (1966, 1967) were the first to use numerical models to simulate steady state regional flow patterns in hypothetical layered aquifer systems. Such numerical models have the advantage in simulating three-dimensional groundwater flow in heterogeneous and anisotropic groundwater basins. Their models were used to analyze the effects of water table configuration and hydraulic conductivity on regional flow patterns and to quantify basin yields (Freeze and Witherspoon, 1968). A transient saturated-unsaturated numerical model was later developed by Freeze (1971) to investigate the relation between infiltration rates, water table rise and base flow hydrograph. The model was further used to predict maximum basin yield as a function of pumping pattern and recharge and discharge characteristics of a hypothetical basin.

Application of groundwater flow models to large scale aquifer system simulation started in 1978, with the Regional Aquifer System Analysis (RASA) program of U.S. Geological Survey (Sun and Johnson, 1994). During the 18 years of the program (1978–1995), 25 regional aquifer systems were intensively studied. These include the famous High Plains aquifer system, the California Central Valley aquifer system and, among others, the Florida and Great Basin aquifer systems. The major contributions of the program were: (1) creation of regional hydrogeological databases; (2) construction of hydrogeological frameworks (conceptual models); (3) understanding of responses of regional aquifer systems to natural stresses (predevelopment) and human interferences (abstraction and land use changes); and (4) the compilation of a national groundwater atlas. Computer-based numerical groundwater flow models were constructed and used to characterize flow systems and to simulate the effects of groundwater development and land use changes. Computer models used in most cases were the USGS 3D finite difference model (Trescott, 1975) and the USGS MODLFOW (McDonald and Harbaugh, 1988). Typical regional aquifer system models covered an area of tens of thousands square kilometers. The models simulated 2–10 aquifer layers with a grid spacing ranging from 6 to 25 km. A steady state model was usually calibrated with data from predevelopment time and a transient model was constructed using the calculated heads from the steady state model as initial conditions. More than 900 reports were published from RASA program in USGS Professional Paper numbered from 1400 to 1428. Finally, a bibliography of the RASA program was compiled listing 1105 reports of various publications (Sun et al., 1997).

The Netherlands has contributed in broadening the concepts and methodologies in hydrological system analysis. An overview of concepts in flow system analysis and case studies in The Netherlands was presented in 1986 (Engelen and Jones, 1986), and case studies of

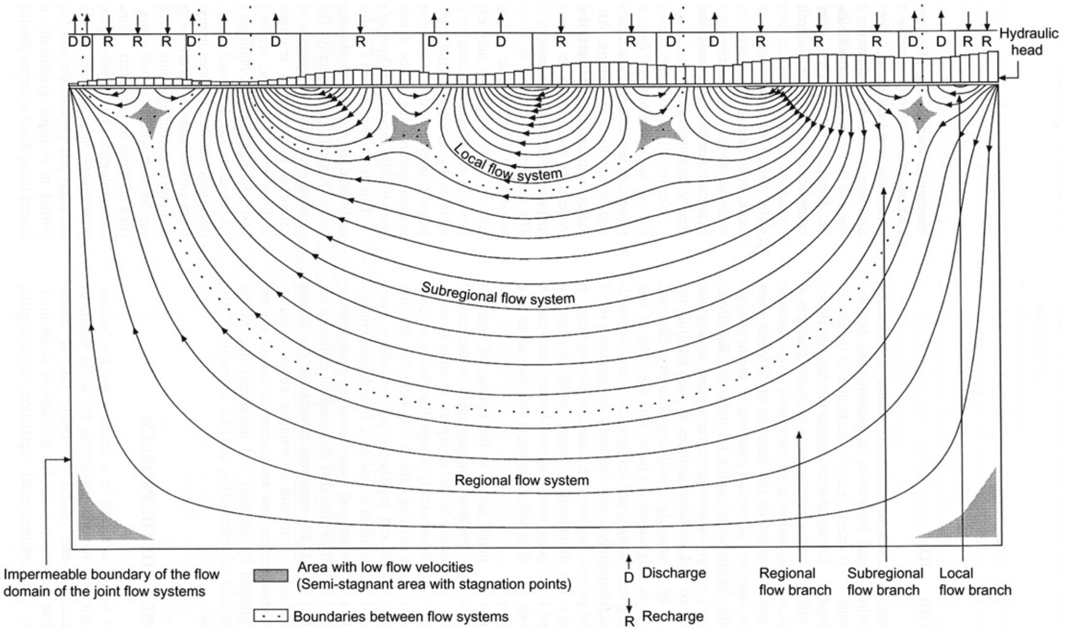

Figure 1 Example of Toth's hierarchically nested groundwater flow systems (after Engelen and Kloosterman, 1996).

national hydrological system analysis in The Netherlands were published in 1996 (Engelen and Kloosterman, 1996).

In China, several regional groundwater models have been constructed in recent years. Among them, a transient groundwater flow model was constructed for the North China Plain in order to assess its groundwater development potential (Shao et al., 2009). The model covers an area of 139,000 km^2 with a uniform grid of 4 km by 4 km. The thickness of the aquifer system ranges from 550 m to 650 m and was simulated with 3 model layers. The model was calibrated with data from 2002 to 2003, with monthly stress periods. A regional groundwater flow model was also constructed for the Cretaceous aquifer system in Ordos Basin (Hou and Zhang, 2008). The model consisted of 3 layers, 330 rows and 160 columns with a uniform grid size of 2 km by 2 km. The model was calibrated under the steady state and used for analyzing groundwater flow patterns and assessing groundwater resources. And, in addition, a 3D transient groundwater flow mode1 was established for the Beijing P1ain in order to analyze groundwater flow systems and water balance (Wang et al., 2009). The transient model simulation time was from l995 to 2005. The model was used to explore options for sustainable groundwater resources development. A limited review of groundwater modeling in China was provided by Wang et al. (2010).

Significant advances in regional flow system analysis were driven by the application of 3D groundwater flow models. Since its release in 1988, MODFLOW has become the industrial standard worldwide for groundwater modeling because of its flexible modular structure, complete coverage of hydrogeological processes and public domain free availability. MODFLOW-88 was progressively updated to MODFLOW-2000 (Harbaugh et al., 2000) and MODFLOW-2005 (Harbaugh, 2005). The 2005 version of MODFLOW family includes the simulation of saturated-unsaturated flow process, groundwater simulation-optimization process, irrigation process, density dependent flow process, parameter optimization process and solute transport process. The future direction of MODFLOW is for it to be developed into an integrated modeling system of coupled surface and groundwater systems (Barlow and Harbaugh, 2006).

Modeling of large groundwater basins became much easier with the rapid development in software engineering, computer capacity and wide use of Geographic Information Systems (GIS). Several Windows-based graphic user interfaces for MODFLOW have been developed in 1990s. The most widely used are Processing Modflow (Chiang and Kinzelbach, 2001), Visual Modflow (Waterloo Hydrogeological, 2001), Groundwater Modeling Systems (GMS) (Brigham Young University, Environmental Modeling Research Brigham Young UniversityEnvironmental Modeling Research Laboratory, 2000), and Groundwater Vista (Rumbaugh and Rumbaugh, 2005). These graphic user interfaces make the modeling process much easier and allow time saving in analyzing model results. At the same time, the capacity of personal computers (storage and speed) has increased greatly, such that a steady state simulation of groundwater flow in a large basin can now be finished in a few minutes on a desktop PC. The application of GIS for data storage, processing, and interpretation further helps both model building and visualization of the model outputs.

An exponential growth of application of numerical models for regional groundwater flow study has been witnessed in last 20 years in the world. Among others, two large scale regional groundwater modeling case studies were carried out. One is the modeling of Death Valley regional groundwater flow; another is the modeling of regional groundwater flow in the Great Artesian Basin of Australian. These two case studies are briefly introduced in the next section.

3. Two examples of large scale groundwater modeling

3.1. Death Valley, California, USA

The Death Valley region of southeastern California includes several large extensional valleys and intervening mountain ranges encompassing approximately 100,000 km^2. The arid landscape is dominated by isolated mountain ranges rising abruptly from broad, alluvial-filled desert basins. Altitudes range from 86 m below sea level in Death Valley to 3600 m above sea level in the Spring Mountains. Climatic conditions are controlled by both altitude and latitude. The northern part forms part of the Great Basin Desert. It is warm and dry in summers and cold and dry in winters. The southern part of the region includes Death Valley and part of the Mojave Desert. It is hot and dry in summers and warm and dry in winters. The central region is called the Transition Desert, which represents a mixing of the two climates. Winter snow is characterized by a low intensity, long duration and it covers large areas. Most summer rains result from localized thunderstorms of high intensity and short duration.

Groundwater flow in the Death Valley region is composed of several interconnected, complex groundwater flow systems (Fig. 2). Groundwater flow occurs in three subregions in relatively shallow and localized flow paths that are superimposed on deeper, regional flow paths. Regional groundwater flow is predominately through Paleozoic carbonate rocks and generally follows the regional topographic gradient; water generally flows toward Death Valley. Most groundwater recharge results from infiltration of precipitation and runoff on the high mountain ranges. Natural groundwater discharge is by flow to springs and wet playas and by evapotranspiration in areas with shallow water table at valley floor.

The underground nuclear test and disposal of nuclear wastes in the Death Valley region have driven numerous intensive groundwater modeling studies from 1982 to the present (Belcher et al., 2004). Models developed in 1980s were steady state and two-dimensional with oversimplified flow processes and lumped hydrogeological parameters. In the early 1990s, two 3-dimensional numerical models of the Death Valley regional groundwater flow system were developed. One model was developed for the Yucca Mountain site being considered for nuclear waste disposal. Another was developed for the Nevada underground nuclear test area. In 1998, the Department of Energy requested the USGS to develop an improved groundwater flow model of the Death Valley regional groundwater system. The purposes of the modeling were to: (1) understand the groundwater flow paths and travel times associated with potential migrating of radioactive materials from nuclear test sites; (2) to characterize the groundwater system in the vicinity of the proposed nuclear waste disposal site in Yucca Mountain; and (3) to address various effects on users down-gradient from these two sites. In this 5 year-long project a 3-dimensional transient groundwater flow model of the Death Valley region was developed (Faunt et al., 2004a).

The transient groundwater flow model was constructed using MODFLOW-2000. The finite difference model consists of 194 rows, 160 columns, and 16 layers. The grid cells have uniform size of 1.5 km, and the 496,640-cell model covers an area of about 69,840 km^2. The large grid cell size (2.25 km^2) is quite small

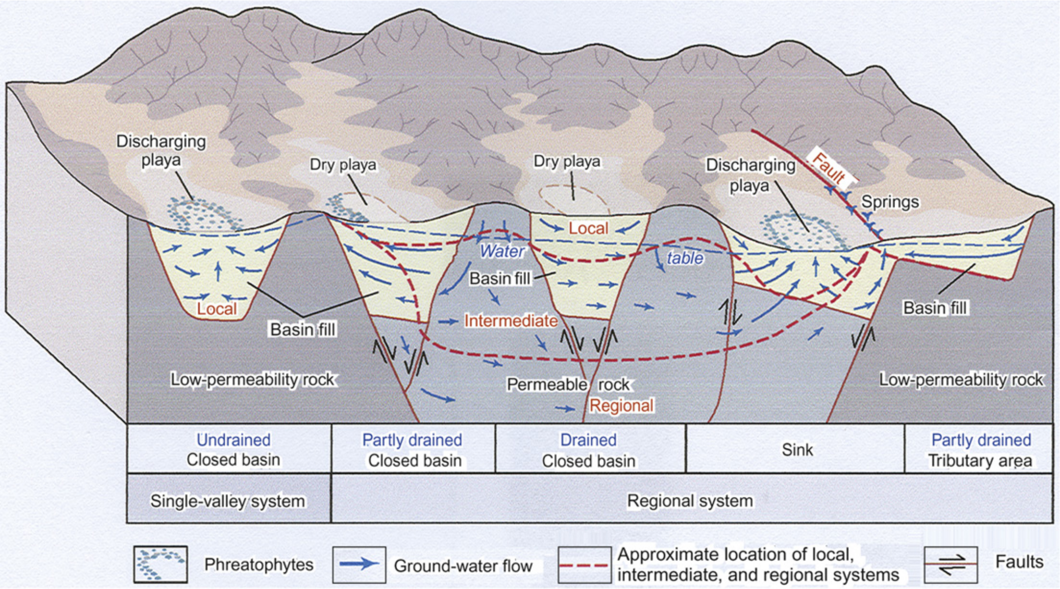

Figure 2 Schematic block diagram of Death Valley (from Faunt et al., 2004b).

compared to the total simulated area. Three factors were considered in determining the cell size: (1) computational efficiency, (2) proper representation of available data, and (3) effective simulation of regional-scale groundwater flow. The layer thickness increases from 50 m at the top to 300 m at the bottom with a total depth of 1700 m. The resolution at the top of the flow model was made higher since there are more field observations of hydrologic and geologic conditions.

A 3D digital hydrogeological framework model (HFM) was developed which defines the physical geometry and materials of hydrogeological units and the hydrogeological structures (Faunt et al., 2004c). Twenty five hydrogeological units were identified and represented in the HFM. The hydrogeological framework model was discretized into numerical flow model input arrays using Hydrogeological Unit Flow package of MODFLOW-2000 (Harbaugh et al., 2000). In this way, the top elevation and material distribution of every model layer were automatically specified. Hydrogeological structures act as relative flow barriers or conduits. The mapped faults were incorporated as relative flow barriers and were simulated with the horizontal flow barrier package in MODFLOW-2000.

Lateral boundaries of physical flow barriers and groundwater divides were simulated as no flow boundaries. Some sections of boundaries were simulated as flow boundaries where hydraulic gradients permit flow across these boundaries through fractures or high permeability zones.

The major source of recharge is from precipitation on the higher mountains. Empirical water balance and distributed-parameter methods were used to characterize the location and amount of recharge in the Death Valley region. For the modeling, a process-based, numerical model was developed to estimate net infiltration (San Juan, 2004). The recharge was simulated with the Recharge package of MODFLOW-2000.

Groundwater discharges are through evapotranspiration (ET) and springs (San Juan, 2004). Regional evapotranspiration was estimated with spectral satellite data combined with micrometeorological measurements. ET zones were identified and the annual ET rate of every zone was computed. The discharge of large springs was recorded. Discharge by ET and springs were simulated with the Drain package of MODFLOW-2000. Extraction of groundwater for irrigation and domestic use started from 1912 and has increased rapidly since the 1950s. Pumping wells were simulated using the Multi-Node Well package of MODFLOW-2000. This package automatically allocates pumping rate to model layers proportional to layer transmissivity.

The simulation time is divided into a steady state period and a transient period. The steady state period is before 1913 in which no pumping was simulated. The transient period from 1913 to 1998 was divided into annual stress period for which pumping rates were defined. The constructed numerical model was calibrated using a nonlinear regression method. Observations of 700 groundwater heads for the steady state, 15,000 water level measurements for transient, and 49 groundwater discharges (ET and springs) were used to compute the weighted residuals, which were minimized by optimizing hydraulic parameters. The model was first calibrated to the steady state flow conditions. The calculated heads were used as initial conditions for the transient model, which was calibrated to simulate transient flow conditions for 1913–1998. During the model calibration, numerous conceptual models were evaluated to test the validity of various interpretations about the flow system. These include: (1) the location and type of flow system boundaries; (2) the definition of recharge areas; and (3) variations in the interpretation of the hydrogeological framework.

The final calibrated model was evaluated by comparing measured and computed groundwater heads and discharges. Good fit to observed groundwater heads occurs in areas of flat hydraulic gradients. Poor fit to the observed groundwater heads is visible in areas with steep hydraulic gradient. Groundwater discharge residuals are fairly random, with as many areas where simulated flows are less than observed flows as areas where simulated flows are greater. The model has not yet been used to analyze the flow systems and to assess potential impacts for which the model was made.

3.2. Great Artesian Basin, Australia

The Great Artesian Basin (GAB) is a confined groundwater basin that occupies 1.7 million km^2 — one-fifth of the Australian continent — and includes most arid and semi-arid regions of

Queensland, New South Wales, South Australia and the Northern Territory. Most of the Basin comprises low-lying inland basins bounded to the east by the tablelands and uplands of the Great Dividing Range. The land surface generally slopes toward the main topographic depressions of Lake Eyre and Lake Frome in the southwest. Drainage in the north is predominantly into the Gulf of Carpentaria. The GAB is generally located in semi-arid to arid landscapes with very dry, warm to hot climates prevailing in the central and western parts of the Basin. Subtropical climates are prevailing along most of the eastern margins. The northeast area of the basin has tropical conditions. The south-western part of the Basin is very dry with a mean annual rainfall less than 200 mm. Average annual rainfall increases toward the east and northeast to more than 600 mm. Annual rainfalls reaches 900 mm near the Gulf of Carpentaria.

The GAB is covered by Cenozoic continental sediments and the hydrogeological basement comprises older sedimentary, metamorphic and igneous rocks. In general terms, the basin is comprised of a multi-layer system of five major confined aquifers separated by aquitards. These aquifers are largely continuous across the extent of the Basin and extend down to 3000 m below land surface in the central depressions. Discovery of Artesian groundwater resources in the 1880s, has been a key element in the development of pastoral industry in the region. Natural Artesian springs support diverse wildlife in the arid regions. Groundwater resources are increasingly exploited for drinking water supply, agricultural irrigation, and water supply for oil, gas and mining developments.

Over the past 100 years, about 3000 free-flowing Artesian wells and 35,000 sub-Artesian wells have been developed in the Basin. Uncontrolled well discharge flowed to drains and was exhausted by seepage and evaporation losses. Close to 570 million m^3 of groundwater is currently abstracted yearly by wells, of which the pastoral industry accounts for 90%. Major issues related to the sustainable use of groundwater resources in the GAB are: (1) groundwater pressures have declined in some regions and 1500 Artesian wells have ceased to flows. Spring flows have declined significantly and some springs have dried up; (2) up to 90% of Artesian groundwater is wasted due to the use of the large number of uncontrolled Artesian flowing wells and the open earth drains for water distribution; (3) there is a potential of groundwater pollution with intensive land use in recharge zones.

The Great Artesian Basin Borehole Rehabilitation Program was initiated in 1989, to place control valves on free-flowing Artesian wells and to replace open drains with piped distributed systems. The effects of this program on the pressure recovery of Artesian groundwater were predicted with a groundwater model. The model is called GABFLOW, a 2D steady state groundwater flow model developed by the Bureau of Rural Sciences, Department of Agriculture, Fisheries and Forestry (Welsh, 2000).

Fig. 3 illustrates that the GAB is vertically divided into several confined aquifers separated by aquitards. The first and highest aquifer (Winton–Mackunda) consists of lithic sandstones, siltstones, and mudstones with high salinity groundwater. The main producing aquifer is the second aquifer consisting of sandstones of the Cadna–owie–Hooray formation. This aquifer and the first aquifer are separated by the Cretaceous Allaru Mudstone, which is the thickest confining unit for the GAB. A third, lower aquifer (Hutton) consists of Jurassic continental quartzose sandstone with good groundwater quality. This aquifer and the second aquifer are separated by an aquitard consisting of the late Jurassic Westboure formation. Since most production wells are located in the second aquifer, only groundwater flow in this aquifer was simulated. The first and the third aquifers provide vertical leakage water to the second aquifer through aquitards. These two aquifers were simulated as external sink/sources.

MODFLOW-88 was used to construct the groundwater flow model of the GAB. The basin was discretized with a uniform grid size of 5 km × 5 km, resulting in a model grid of 359 rows and 369 columns. There are more than 60,000 active cells, covering a model area of 1.54 million km^2. The grid is aligned N–S and E–W. The northern boundary of the model is the coastal line of the Gulf of Carpentaria and the Gilbert River, which was simulated as a constant head boundary. The remaining boundaries were no flow boundaries. The modeling was carried out for steady state hydrogeological conditions assumed for 1960, as it was believed that a new equilibrium state between recharge and discharge had been established during the period from 1950 to 1970.

Most recharge occurs along the elevated eastern margin of the basin where its sandstones are exposed. The aquifers also receive episodic recharge along the western margin of the basin. The recharge flux was determined as a percentage of mean annual rainfall, ranging from 0 to 35 percent. The average percentage of all recharge cells is 1.3% and the mean average recharge over all recharge cells is 5.4 mm/year. The area of the model receiving recharge is about 134,000 km^2. The total recharge from rainfall in the model is then 1,937,394 m^3/day. The recharge was simulated with the MODFLOW recharge package.

Natural discharge occurs as localized outflow from springs. There are more than 600 spring complexes in 12 major groups around the margins of the basin. The springs are generally associated with faults or structural features. A total of 303 natural springs or spring groups were simulated in the model with the well package of MODFLOW. The total spring discharge was estimated to be 93,531 m^3/day. Artificial discharge is by means of pumped and free-flowing wells. Almost 2300 wells were simulated in the

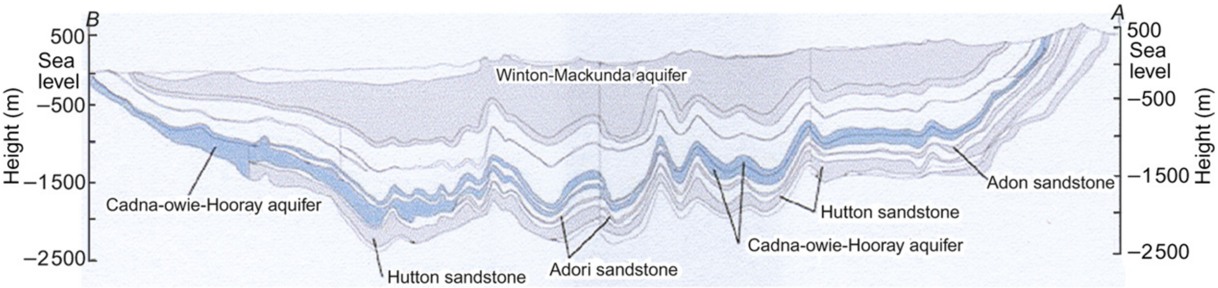

Figure 3 Cross-section of the Great Artesian Basin (from Radke et al., 2000).

model with a total well discharge of 1,372,471 m^3/day. The combined total discharge of springs and wells amounted to 1,466,002 m^3/day.

Leakage mostly occurs as distributed discharge upward from deeper higher pressure aquifers to shallow lower pressure aquifers. Leakages between the modeled aquifer and both the overlying and underlying aquifers were simulated implicitly in the model with the MODFLOW's general head boundary package. Groundwater heads in the overlying and underlying aquifers were estimated from hand contour maps. Leakage parameters of two separating aquitards were estimated from their thicknesses and vertical hydraulic conductivities.

Two databases were developed to assist data input. A borehole database called GABMOD was created using an Oracle relational database. Information for 55,530 boreholes in the model area is stored in the database. A GIS spatial database was created which extracts relevant information from data tables of GABMOD to prepare input data files for thickness, hydraulic parameters, initial heads, and spring and well discharges. GMS was used to process input data files from the GIS spatial database to the specific data files required by MODFLOW. Model outputs were also visualized using GMS.

The model was calibrated with a trial-and-error method to reduce the difference between the modeled and measured groundwater head surface. During model calibration, hydraulic conductivities of the modeled aquifer and recharge from precipitation were adjusted. The Root Mean Square (RMS) error was used to measure the accuracy of the model calibration. The RMS error of the final model is 4.5 m with individual values ranging from −13.1 to +12.8 m.

The model was used to evaluate the effectiveness of the GAB Sustainability Initiative with the aim to restore the pressure heads under different management scenarios. Three scenarios were simulated: (1) well discharges in selected high usage zones were restricted to 4 L/s; (2) all wells with higher free-flowing discharge were capped to reduce well discharge to less than 4 L/s; (3) most wells with higher free-flowing discharge were capped, but the maximum discharge per well in some management zones was allowed above 4 L/s.

The simulation indicated that the control of free-flowing wells with a high discharge is an effective method to save valuable groundwater from being wasted and to recover Artesian pressure. Scenario (3) is the most realistic option for implementation. It can save a total flow of 212 million m^3/year and the maximum groundwater level recovery is 26 m. The output of the modeled scenario was used for the prioritization of the management zones. The map of maximum groundwater level recovery created from the model output was used by the state water authorities as a basis for their target recovery maps.

The GABFLOW steady state model has been updated into a 2D transient model for the shallowest Artesian (Cadna–owie–Hooray) aquifer of the GAB (Welsh, 2006). MODFLOW-2000 was used to construct the transient model. The transient model simulates groundwater flow from 1965 to 1999, using the year as the stress period. The vertical leakage from the top and bottom aquifers was simulated as net recharge in the recharge package. Around 8750 water wells and 207 petroleum well fields were simulated in the model. Measurements of groundwater heads from 254 water bores were used to calibrate the model. Because of data limitation, the fit of the transient model to measured heads was not good.

Deficiencies of the GAB groundwater model as a predictive tool to simulate the effects of management scenarios are as follows:

1) Spring discharges were fixed and simulated with the MODFLOW well package. However, spring discharges would increase when groundwater levels recover under management scenario to control free-flowing well discharges. Springs can be better represented with the MODFLOW drain package so that spring discharge will be calculated depending on the variation of groundwater levels.
2) Leakages from and/or to the overlying and underlying aquifers were simulated using the MODFLOW general head boundary package with fixed groundwater levels in the overlying and underlying aquifers for the steady state model. Groundwater levels in the overlying and underlying aquifers would change corresponding to groundwater level changes in the modeled aquifer under management scenarios. The 2D model of the main production aquifer should be expanded into a quasi-3D model simulating groundwater flows in three aquifers and leakage through two aquitards.

4. Methodologies of regional flow modeling

4.1. Characteristics of regional groundwater model

Any useful groundwater model for groundwater resources assessment and management should simulate the whole groundwater basin and, therefore, has to be at basin-scale. Such a large regional model must include characteristics of groundwater discharge and recharge and the aerial distribution of multiple aquifer systems. Distinct features of basin-scale groundwater flow and flow models are: (1) differences in topographic elevation provide the principle driving force for regional flow. Groundwater recharges occur at mountain ranges and their margins; groundwater is discharged as springs and seepage to rivers and by evapotranspiration at low depressions at the basin floor; (2) leakage through aquitards forms an essential element of regional flow systems. The model layers should include major regional aquifers and aquitards; (3) groundwater and surface water are essentially the single resource. The intensive river and groundwater interactions should be simulated as line sources/sinks; discharge and flow-through lakes should be simulated as head-dependent discharge or constant head (especially useful for a steady state model).

The model grid size for a basin-scale model can range from a kilometer (for a basin of thousands of square kilometers) to several kilometers (for a basin of tens of thousands square kilometers). When a model cell is several square kilometers, the additional considerations are: (1) effective cell hydraulic conductivity should be aggregated from small scale values with a proper up-scaling method; (2) the computed cell hydraulic head represents the average value over an area of several kilometers and can't be considered as a point value; (3) for evaluating model calibration, contour maps of the computed heads should be compared with contour maps of measured regional heads; however, the measured discharges (spring and evapotranspiration) are more useful for model calibration; (4) local grid refinement can no longer be used to increase the resolution at places of local interests (well fields, pollutant transport); the telescopic approach should be used to convert a regional model to a local model with the required grid refinement.

4.2. Hydrogeological conceptual model approach

In the traditional grid-based modeling approach, a 3D model grid is designed according to the complexity and data availability of the conceptual model. Afterward a large amount of data is entered cell-by-cell into model grids. The process of data input is tedious and error-prone. In the last few years, a conceptual model approach has been developed for constructing a complex regional groundwater model. In this model approach (Fig. 4), a conceptual hydrogeological model of the study area is created using feature objects (points, arcs and polygons) and stored in the modeling system. Once the model grid is generated, inputs to model grids are automatically transferred from the conceptual model. This approach is especially suited to basin-scale groundwater modeling.

There are numerous benefits using the conceptual model approach as compared to the traditional grid-based model approach. First of all, the model can be defined independently of the grid resolution. For example, the modeler does not need to waste valuable time computing the appropriate conductance to assign to a river cell based on the length of the river reach within the cell. This type of computation is performed automatically. Furthermore, transient variables such as pumping rates of wells can also be assigned independently of model discretization. Transient variables are entered as a curve of the stress versus time. When the conceptual model is converted to the numerical model, the transient values of the stresses are automatically assigned to the appropriate stress periods by interpolation. Since the conceptual model is defined independently of the spatial and temporal discretization of the numerical model, the conceptual model can be quickly and easily changed and a new numerical model can be generated in short time. This allows the modeler to evaluate numerous alternative conceptual models in the space of time normally required to evaluate one, resulting in a more accurate and efficient modeling process. A further advantage of storing attributes with feature objects is that the method of applying the boundary conditions to the grid cells reduces some of the instability that is inherent in finite difference models such as MODFLOW. When the user enters individual values for heads and elevations, entering cell values one cell at a time can be tedious. It is also difficult to determine the correct elevation along a river segment at each cell that it crosses. The temptation is to select small groups of cells in series and apply the same values to all of the cells in the group. This results in an extreme stair-step condition that can slow or even prevent convergence of the numerical solver. With the conceptual model approach, it is possible to interpolate values at locations along a linear boundary condition such as a river. The user insures then that there will be no abrupt changes from cell to cell—thus minimizing the stair-step effect. It also produces a model with boundary conditions that more accurately represent real world conditions.

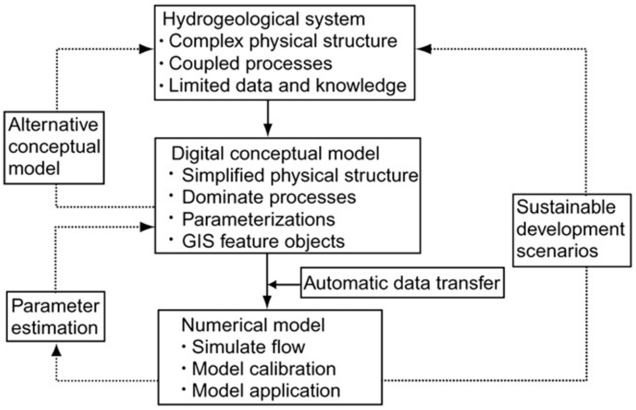

Figure 4 Modeling procedure of a conceptual model approach.

4.3. Application of GIS

Modeling of groundwater basins requires large sets of data on the hydrogeological framework, hydraulic parameters, hydrological stresses and measured groundwater heads. All these data are stored and presented in many different forms and scales such as maps, graphs, tables, computer databases, or spreadsheets. A Geographical Information System (GIS) represents a powerful set of tools that can significantly improve the processing of spatial data.

Coupling GIS and groundwater models can be achieved using three techniques: loose coupling, tight coupling, and embedded coupling (Gogu et al., 2001). Loose coupling is when GIS and the model represent distinct software packages and the data transfer is made through input/output model predefined files. The GIS software is used to pre-process and post-process the spatial data. An advantage of this solution is that the coupled software packages are independent systems, facilitating potential future changes in an independent manner. Most applications of GIS in groundwater modeling use the loose coupling technique. In tight coupling, an export of data to the model from GIS is performed, but the GIS tools can interactively access input model subroutines. In this case, the data exchange is fully automatic. An example of this coupling is the groundwater model link (Steyaert and Goodchild, 1994) between the ERMA spatial database scheme and MODFLOW, MODPATH, and MT3D finite difference software packages. When a model is created using GIS programming language or when a simple GIS is assimilated by a complex modeling system, embedded coupling is used. Argus ONE's (Argus Interware, Inc., 1997) numerical modeling environment and the Groundwater Modeling System (GMS) are examples of this system.

5. Special modeling issues

5.1. Simplicity versus complexity

All groundwater flow models are simplifications of real hydrogeological systems. First, complex geological formations are simplified into a limited number of aquifer and aquitards layers. Types and values of physical boundaries of the groundwater basin are usually assumed; even artificial boundaries are sometimes used. Second, flow processes are simplified; only dominant flow processes are included in the model simulation. Third, parameter zones are defined to simplify the input of model parameters and to satisfy the parsimony for the model calibration.

Historically, groundwater models have been very simple. With the rapid increase of computer power, groundwater models have become more complex. In some cases the model complexity is beyond the availability of data and the necessity of the model objective. Neither very simple models, nor very complex models, are likely to provide accurate predictions. The principle of parsimony calls for keeping a model as simple as possible while representing major system characteristics and dominant flow processes needed for the prediction. The strategy of model development is to start with a simple model and build model complexity slowly as warranted by the available data and model predictions (Hill, 2006). There are several advantages to start with a simple model. With a simple model, it is easier to understand the simulated flow processes and the model misfit. Execution time of a simple model is short (less than 30 min according to Hill, 2006) so more time can be allocated for analyzing model results and for investigating alternative models. Reduction of model execution time can be achieved through (1) better representation of heterogeneity contrast; and (2) better linearization of water table nonlinearities (Hill, 2006).

5.2. Model calibration and multi-model analysis

Model calibration is viewed as a process to develop a useful groundwater model. Effective model calibration includes the entire modeling process. Guidelines for effective model calibration using automatic parameter identification (nonlinear regression) have been proposed by Hill and Tiedeman (2007).

Because of limits to our understanding of the regional groundwater flow system due to a lack of data, uncertainties in conceptualizing the aquifer layers, boundary conditions, parameter distributions and dominant stresses may result in multiple plausible conceptual models. Evaluation of the alternative models becomes inevitable. Assessment of alternative conceptual models has received increased attention (Neuman, 2003; Ye et al., 2004; Hojberg and Refsgaard, 2005; Poeter and Anderson, 2005; Refsgaard et al., 2006, 2007). A general purpose computer software for multi-model analysis has recently been developed (Poeter and Hill, 2007). These methods have been applied to the northern Yucca Flat area of the Nevada Test Site located within the Death Valley Regional Flow System (Ye et al., 2010). A total of 25 alternative groundwater flow models were produced (as the result of combinations of the five recharge and five geological models). All of these models were calibrated and evaluated using the information criteria and prediction uncertainties. The results show that conceptual geological models have a more significant effect on groundwater flow simulations than the recharge estimation methods. Model uncertainties resulting from parameter uncertainties are much less when compared to conceptual model uncertainties.

5.3. Data for groundwater modeling

The bottleneck for building regional groundwater flow models is usually the lack of sufficient data. Three main categories of data are required to construct useful transient regional groundwater models: static data for constructing 3D hydrogeological framework model (HFM); dynamic data for assessing groundwater recharges and discharges; and time series of groundwater levels in major aquifers.

The 3D hydrogeological framework model is a digital representation of hydrogeological units and geological structures which control the regional groundwater flow. Spatial extension, thickness and hydraulic properties of each hydrogeological units and structures are defined in the HFM. GIS and stratigraphical modeling tools are used to construct the HFM. Data sources for

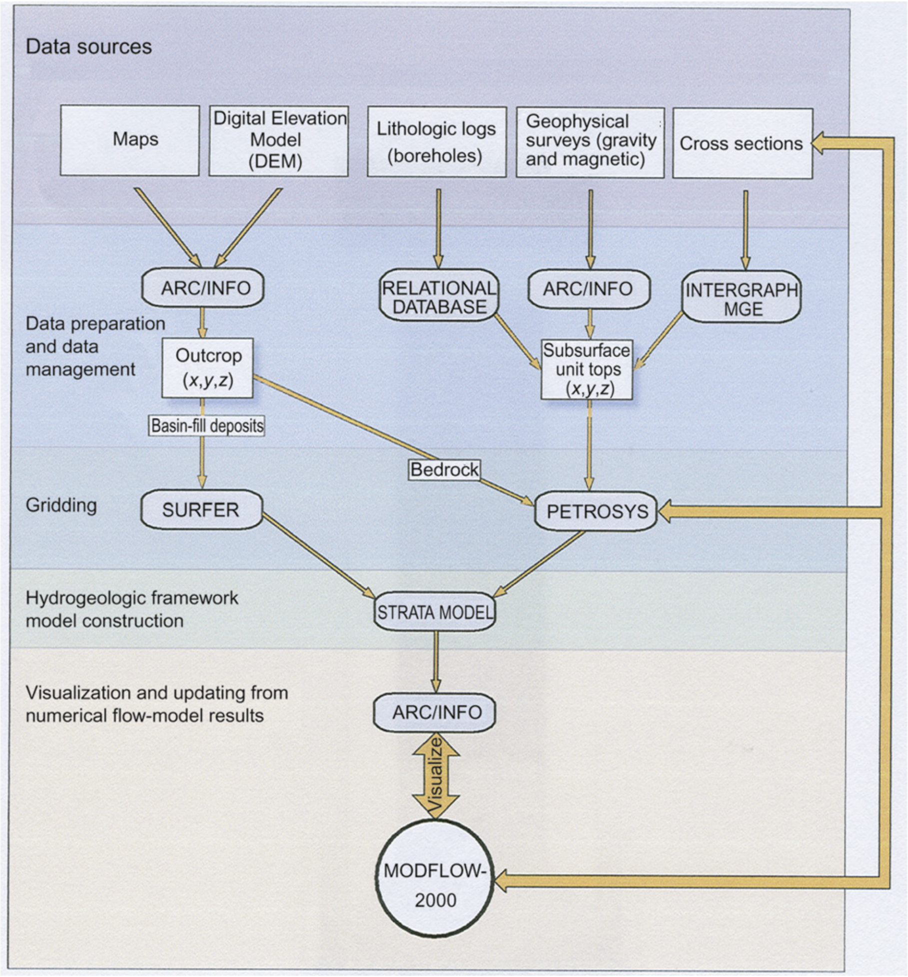

Figure 5 Development of the Death Valley hydrogeological framework model (from Faunt et al., 2004c).

constructing the HFM come from topographic data, geological and hydrogeological maps, borehole lithology data, geophysical surveys, cross-sections, geological structures and aquifer test data. Fig. 5 shows the development of the HFM for the Death Valley groundwater flow model. Several tools were used to process data from various sources to the digital HFM.

Determination of distribution and volumes of groundwater recharge and discharge components is another important but difficult task of constructing regional groundwater models. Groundwater recharge generally includes precipitation infiltration, surface water leakage, irrigation return flow and lateral inflow. Meteorological data, vegetation and soil characteristics are necessary to estimate net groundwater recharge from precipitation infiltration. Irrigation return flow depends on amount of irrigation water, crop evapotranspiration and evaporation loss. Water levels in the lakes and rivers are required to determine recharge from surface water. Contour maps of groundwater levels are constructed to determine lateral groundwater inflow and outflow. Groundwater discharge generally consists of evapotranspiration, spring discharge, discharge to surface water, lateral outflow, and abstraction. Apart from direct measurement, remote sensed data are used to determine actual evapotranspiration. Measurements of spring discharges are especially important for hard rock aquifers. Separation of river hydrograph is an important method to determine groundwater discharge to rivers. Abstraction is not only difficult to obtain, but also alternate natural recharge (induce more recharge) and discharge (decrease discharge). Therefore, whenever it is possible, a groundwater balance for predevelopment period should be established first as a reference for pumped conditions. The natural water balance components are also necessary to construct a steady state regional groundwater model.

Measurements of groundwater levels are not only required for the calibration of groundwater models, but also for the analysis of groundwater flow systems. Integration of contour maps of groundwater levels, water balance components and hydrogeological framework model can identify 3D groundwater flow systems and flow patterns. Groundwater chemistry, isotope and temperature data can be used to ascertain the groundwater flow paths. A useful regional groundwater model should not only to fit the measured groundwater heads at observation wells, but more importantly to reproduce the inferred 3D groundwater flow patterns and simulate changes of water balance components under pumped conditions. A regional groundwater level monitoring network is essential to provide time series of groundwater levels for the flow system analysis and calibration of groundwater models. The regional flow model in turn can be used to identify important locations for monitoring of groundwater levels.

6. Conclusions

Groundwater model has become a commonly used tool for hydrogeologists to perform various tasks. The rapid increase of computing power of PCs and availability of user friendly modeling systems has made it possible to simulate large scale regional groundwater systems. Experiences from Death Valley and Great Artesian Basin transient groundwater models are useful to guide the construction of regional groundwater models in China. However, the bottleneck for building regional groundwater flow models is usually the lack of sufficient data. Geological, hydrogeological and geophysical surveys are necessary to get data for constructing 3D hydrogeological framework models. Continuous measurements of water budget components and groundwater levels will build up databases required for analysis of regional flow systems and construction of regional transient groundwater models. The model should be used to simulate impacts of human activities on groundwater flow systems, to formulate sustainable groundwater resources development scenarios, and to communicate the results to public and decision-makers.

References

Argus Interware, Inc., 1997. Argus Open Numerical Environments – A GIS Modeling System, Version 4. Argus Holdings, Limited.

Barlow, P.M., Harbaugh, A.W., 2006. USGS directions in MODFLOW development. Ground Water 44 (6), 771–774.

Belcher, W.R., D'Agnese, F.A., O'Brien, G.M., 2004. Introduction, Chapter A of Death Valley Regional Groundwater Flow System, Nevada and California-Hydrogeological Framework and Transient Groundwater Flow Model. U.S. Geological Survey. Scientific Investigation Report 2004–5205.

Brigham Young University, Environmental Modeling Research Laboratory, 2000. Groundwater Modeling System (GMS), GMS 3.1 Tutorials.

Chiang, W.H., Kinzelbach, W., 2001. 3D-Groundwater Modeling with PMWIN: A Simulation System for Modeling Groundwater Flow and Pollution. Springer-Verlag, New York, 346 pp.

Engelen, G.B., Jones, G.P., 1986. Developments in the Analysis of Groundwater Flow Systems. IAHS Publication, No. 163, 365 pp.

Engelen, G.B., Kloosterman, F.H., 1996. Hydrological system analysis: methods and application. In: Water Science and Technology Library, vol. 20. Kluwer Academic Publishers, p. 149.

Faunt, C.C., Blainey, J.B., Hill, M.C., D'Agnese, F.A., O'Brien, G.M., 2004a. Transient Numerical Model, Chapter F of Death Valley Regional Groundwater Flow System, Nevada and California-Hydrogeological Framework and Transient Groundwater Flow Model. U.S. Geological Survey. Scientific Investigation Report 2004–5205.

Faunt, C.C., D'Agnese, F.A., O'Brien, G.M., 2004b. Hydrology, Chapter D of Death Valley Regional Groundwater Flow System, Nevada and California-Hydrogeological Framework and Transient Groundwater Flow Model. U.S. Geological Survey. Scientific Investigation Report 2004–5205.

Faunt, C.C., Sweekind, D.S., Belcher, W.R., 2004c. Three-dimensional Hydrogeological Framework Model, Chapter E of Death Valley Regional Groundwater Flow System, Nevada and California-Hydrogeological Framework and Transient Groundwater Flow Model. U.S. Geological Survey. Scientific Investigation Report 2004–5205.

Freeze, R.A., 1971. Three-dimensional, transient, saturated-unsaturated flow in a groundwater basin. Water Resources Research 7 (2), 347–366.

Freeze, R.A., Witherspoon, P.A., 1966. Theoretical analysis of regional groundwater flow: 1. Analytical and numerical solutions to the mathematical model. Water Resources Research 2 (4), 641–656.

Freeze, R.A., Witherspoon, P.A., 1967. Theoretical analysis of regional groundwater flow: 2. Effect of water table configuration and subsurface permeability variation. Water Resources Research 3 (2), 623–634.

Freeze, R.A., Witherspoon, P.A., 1968. Theoretical analysis of regional groundwater flow: 3. Quantitative interpretations. Water Resources Research 4 (3), 581–590.

Gogu, R.G., Carabin, G., Hallet, V., Peters, V., Dassargues, A., 2001. GIS-based hydrogeological databases and groundwater modeling. Hydrogeological Journal 9, 555–569.

Harbaugh, A.W., 2005. MODFLOW-2005, the U.S. Geological Survey's Modular Ground Water Flow Model – The Groundwater Flow Process. Techniques and Methods 6–A16. U.S. Geological Survey, Reston, Virginia.

Harbaugh, A.W., Banta, E.R., Hill, M.C., McDonald, M.G., 2000. The U.S. Geological Survey's Modular Ground Water Flow Model – User Guide to Modularization Concepts and the Ground Water Flow Process. U.S. Geological Survey. Open-File Report 00–92.

Hill, M.C., 2006. The practical use of simplicity in developing groundwater models. Groundwater 44 (6), 775–781.

Hill, M.C., Tiedeman, C.R., 2007. Effective Groundwater Model Calibration, with Analysis of Sensitivity, Predictions and Uncertainty. Wiley, New York, 480 pp.

Hojberg, A.L., Refsgaard, J.C., 2005. Model uncertainty—parametric uncertainty versus conceptual models. Water Science and Technology 25 (6), 153−160.

Hou, G.C., Zhang, M.S., 2008. Exploration and Study of Groundwater in the Ordos Basin, 563 pp. Geological Publishing House, Beijing (in Chinese).

McDonald, M.G., Harbaugh, A.W., 1988. A Modular Three-dimensional Finite-difference Ground-water Flow Model. Open-File Report 83−875. U.S. Geological Survey. Book 6.

Neuman, S.P., 2003. Maximum likelihood Bayesian averaging of alternative conceptual-mathematical models. Stochastic Environmental Research and Risk Assessment 17 (5), 291−305.

Poeter, E., Anderson, D.R., 2005. Multimodel ranking and inference in groundwater modeling. Ground Water 43 (4), 597−605.

Poeter, E.P., Hill, M.C., 2007. MMA: A Computer Code for Multi-Model Analysis. TM6−E3. U.S. Geological Survey Techniques and Methods, Reston, Virginia, 113 pp.

Radke, B.M., Ferguson, J., Cresswell, R.G., Ransley, T.R., Habermehl, M.A., 2000. Hydrochemistry and Implied Hydrodynamics of the Cadna-owie-Hooray Aquifer Great Artesian Basin. Bureau of Rural Sciences, Canberra, Australia, 229 pp.

Refsgaard, J.C., van der Sluijs, J.P., Brown, J., van der Keur, P., 2006. A framework for dealing with uncertainty due to model structure error. Advances in Water Resources 29, 1586−1597.

Refsgaard, J.C., van der Sluijs, J.P., Hojberg, A.L., Vanrolleghem, P.A., 2007. Uncertainty in the environmental modeling process—a framework and guidance. Environmental Modeling and Software 22 (11), 1543−1556.

Rumbaugh, J., Rumbaugh, D., 2005. Groundwater Vistas 5.0, 1996−2005. Environmental Simulation, Inc..

San Juan, C.A., Belcher, W.R., Laczniak, R.J., Putnam, H.M., 2004. Hydrological Components for Model Development, Chapter C of Death Valley Regional Groundwater Flow System, Nevada and California-Hydrogeological Framework and Transient Groundwater Flow Model. U.S. Geological Survey. Scientific Investigation Report 2004−5205.

Shao, J.L., Zhao, Z.Z., Cui, Y.L., Wang, R., Li, C.Q., Yang, Q.Q., 2009. Application of groundwater modeling system to the evaluation of groundwater resources in North China plain. Resources Science 313, 361−367 (in Chinese).

Steyaert, L.T., Goodchild, M.F., 1994. Integrating geographic information systems and environmental simulation models: a status review. In: Michener, W.K., Brunt, J.W., Stafford, S.G. (Eds.), Environmental Information Management and Analysis: Ecosystem to Global Scales. Taylor & Francis, Inc., Bristol, PA, USA, pp. 333−356.

Sun, R.J., Johnson, R.H., 1994. Regional Aquifer System Analysis Program of the U.S. Geological Survey, 1978−1992. U.S. Geological Survey. Circular 1099.

Sun, R.J., Weeks, J.B., Grubb, H.F., 1997. Bibliography of Regional Aquifer System Analysis Program of the U.S. Geological Survey, 1978−1996. U.S. Geological Survey Water Resources, Austin, Texas. Investigation Report 97-4074.

Toth, J., 1963. A theoretical analysis of groundwater flow in small drainage basins. Journal of Geophysical Research 68 (16), 4795−4812.

Toth, J., 1970. A conceptual model of the groundwater regime and the hydrogeological environment. Journal of Hydrology 10, 164−176.

Toth, J., 1971. Groundwater discharge: a common generation of diverse geological and morphological phenomena. Bulletin of the International Association of Scientific Hydrology XVI, 9−24. 1.3.

Toth, J., 1972. Properties and manifestations of regional groundwater movement. In: Proceeding of 24th International Geological Congress, Montreal, Section 11, 153−163.

Trescott, P.C., 1975. Documentation of a Finite Difference Model for Simulation of Three Dimensional Ground-Water Flow. U.S. Geological Survey, Open-File Report 75-438, p. 48.

Wang, L.Y., Han, J.P., Liu, J.R., Ye, C., Zheng, Y.J., Wan, L.Q., Li, W.P., Zhou, Y.X., 2009. Modeling of regional groundwater flow in Beijing plain. Journal of Hydrogeology and Engineering Geology 36 (1), 11−19 (in Chinese with English abstract).

Wang, H., Lu, C.Y., Qin, D.Y., Sang, X.F., Li, Y., Xiao, W.H., 2010. Advances in method and application of groundwater numerical simulation. Earth Science Frontiers 17 (6), 1−12 (in Chinese with English abstract).

Waterloo Hydrogeological, 2001. Visual MODFLOW Pro, 3D Groundwater Flow and Contaminant Transport Modeling, V.3.1.

Welsh, W.D., 2000. GABFLOW, A Steady State Groundwater Flow Model of the Great Artesian Basin. Land and Water Sciences Division, Bureau of Rural Sciences, Department of Agriculture, Fisheries and Forestry, Australia.

Welsh, W.D., 2006. Great Artesian Basin Transient Groundwater Model. Bureau of Rural Sciences, Department of Agriculture, Fisheries and Forestry, Australia.

Ye, M., Neuman, S.P., Meyer, P.D., 2004. Maximum likelihood Bayesian averaging of spatial variability models in unsaturated fractured tuff. Water Resources Research 40 (5). doi:10.1029/2003WR002557 W05113.

Ye, M., Pohlmann, F.F., Chapman, J.B., Pohll, G.M., Reeves, D.M., 2010. A model-averaging method for assessing groundwater conceptual model uncertainty. Ground Water 48 (5), 716−728.