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Special Issue

Sustainable Water: Uncertainty, Risk and Vulnerability in Europe

Context and aims

This special edition of HESS presents key results from the project SWURVE (Sustainable Water: Uncertainty, Risk and Vulnerability in Europe), which contributed to the EU Energy, Environment and Sustainable Development Programme of the Fifth Framework and was additionally supported by the Swiss Office of Higher Education. The SWURVE project ran from 2001 to 2004, with the guidance of the European Commission's Project Officer, Panagiotis Balabanis.

The last decade has seen much research aiming to assess the impacts of changes and variability in climate on hydrological and hydraulic systems used in diverse areas including water supply, flood risk management, urban drainage, agriculture, fisheries and hydropower. Such systems can be extremely vulnerable to climate change but two major problems have affected the assessment of their vulnerability and planning for how it can be mitigated or avoided:

- There is great uncertainty inherent in future climate change. This is well documented and arises from various sources, including prediction of greenhouse gas emissions, imperfect climate models and incomplete understanding of how global climate change relates to regional and local climates. It is now widely recognised that dealing with this uncertainty requires probabilistic consideration of the whole range of possible future scenarios rather than a 'best guess' or arbitrarily selected set of scenarios but there is no consensus on how best to manage this process;

- The risk of failure of various systems, and subsequent vulnerability, is difficult to quantify, as it may depend on the occurrence of extreme events, either singly, in sequence or in combination with other events. Since extreme events by definition occur infrequently, they are difficult to characterise. Quantifying this risk, therefore, also calls for a probabilistic framework using large ranges or long time series of hydro-meteorological scenarios and possible consequences; this demands the development of novel statistical simulation methodology.

The SWURVE project followed a two-fold strategy to address these problems in the context of designing and planning for sustainable water and associated sectors in Europe:

1. the development of a probabilistic framework for the treatment of future scenarios and their impacts, resulting in assigning probabilities of various critical outcomes and risks, rather than single central estimates;
2. the development of a quantitative and transferable methodology for the measurement of long term sustainability using statistical measures such as reliability, resilience and vulnerability.

The first part of this strategy was one of the central recommendations of the EU ECLAT-2 *Concerted Action Workshop on Uncertainty* (Carter *et al.*, 1999): "Formal probabilistic assessments linking climatic, hydrologic and management uncertainties are required. In particular, methods or expert guidance must be developed for assessments where probability density functions are unknown."

The second part was a central recommendation of the Task Committee on Sustainability Criteria, Water Resources Planning and Management Division, of the American Society of Civil Engineers and Working Group of UNESCO/IHP IV (ASCE and UNESCO, 1998): "Droughts and floods of various magnitudes and durations will no doubt continue to occur, and global warming may actually result in increasing those magnitudes and durations. What statistical measures for various criteria could be used to measure long-term sustainability? ……Sustainability implies robustness, the ability of systems to adjust to changes in system parameters or inputs without requiring excessive expenditures and without losing their ability to meet demands of current and future generations."

Following this recommendation, Lettenmaier *et al*. (1999) carried out a performance assessment of several water resource systems in the USA using statistical measures for present and future climates. An immediate aim of SWURVE was to make a similar effort Europe-wide and transfer it to related aspects of the water environment.

Methodology

SWURVE was conceived as a methodological development combining a probabilistic scenario framework with means of assessing impacts using a sustainability metric. This approach was made possible by using simulation approaches for impact assessment, allowing a wide range of possible scenarios to be tested. This range derived firstly from the Hadley Centre's HadRM3 simulations, augmented by multi-model scenarios made available by the EU project PRUDENCE (Prediction of Regional scenarios and Uncertainties for Defining EuropeaN Climate change risks and Effects). These were further augmented by the use of stochastic modelling methods to generate long representative rainfall series.

The general approach to hydrological impact assessments was as follows:

- take General Circulation Model (GCM, or climate model) outputs for future climate scenarios already dynamically downscaled to 50 km resolution using Regional Climate Models (RCMs);
- where appropriate, further downscale rainfall using stochastic rainfall models and provide consistent temperature and PET (potential evapotranspiration) data;
- apply these scenario data to hydrological models (e.g. rainfall-runoff models, or water resource system planning models);
- analyse the system performance and impacts using a sustainability metric.

The sustainability metric that was applied to the case studies follows the RRV (reliability-resilience-vulnerability) methodology, developed by Hashimoto *et al.* (1982) in the context of performance assessment of water resource systems. The method combines easily defined criteria of reliability, resilience and vulnerability which are especially useful in the selection of water resource system capacities, configurations, operating policies and targets. RRV methods are particularly appropriate for use within the context of climate change and uncertainty (Lettenmaier *et al*., 1999). SWURVE has applied the method across a range of water-sector applications, demonstrating its versatility, as well as allowing cross-comparison of impacts on systems with different operating constraints, parameters and procedures.

Case studies and applications

Five case study regions considered in SWURVE are reported here: the Rhine river basin, the Tejo and Guadiana river basins in Spain/Portugal, north-west England, the Mauvoisin catchment and the Jura lakes (Switzerland). Where possible, consistent methods have been applied using the same base climate scenarios, and several downscaling methods have been compared, including direct use of RCM output, use of change factors from RCM outputs and use of stochastic rainfall models fitted to predicted rainfall statistics. The RRV methodology has been applied to a range of contrasting cases, allowing conclusions to be drawn for very different applications such as flooding, drought and fish habitat.

RHINE BASIN

The Rhine occupies a central position in Europe, both economically and geographically. Estimates of future discharges of the river Rhine were made to inform assessment of impacts on flooding and navigability. Considering a very large basin with discharges controlled by seasonal snow melt and periods of prolonged heavy precipitation was a challenging task. Two different methods were used: one was based on the model output of the future climate run (direct approach) and the other on perturbation of the present-day HadRM3H time series (delta approach). Both methods show major increases in winter discharge (30%) and decreases in summer discharge (40%) as well as increases in the 100-year flood flows (10 and 30% respectively). There are serious implications for all aspects of management of the Rhine ranging from navigation to flooding.

TEJO AND GUADIANA BASINS

Impacts on river flows in two important trans-national river basins were assessed primarily for information on water resource availability. Here again, major challenges included the large area of the basins as well as the effects of increased management over recent decades. Future scenarios were constructed using two contrasting techniques (i) using RCM output directly, with monthly mean bias-correction calculated from observed rainfall records, and (ii) using a circulation-pattern based stochastic rainfall model. Year-round major reductions in rainfall and streamflow are projected using both approaches; this outcome differs from that of previous studies which projected winter increases. Despite uncertainties in the representation of heavily managed river systems, projected impacts pose major threats to the maintenance of bi-partite water treaties between Spain and Portugal.

NORTH-WEST ENGLAND

Two studies are reported here; they consider, firstly, water resource availability and, secondly, the physical habitat for salmon fisheries. Although the north-west of England is relatively wet, it suffered a serious drought in 1995/96 which tested to the limit the complex conjunctive-use water supply system. The assessment here shows that, although the performance of individual sources may alter substantially under climate change, the overall yield is not affected so severely, because the system has great flexibility. Other systems in the UK and elsewhere are less flexible and will require considerable adaptation to exploit any increased mean winter rainfall within the context of decreased summer and annual rainfall.

The second study addressed the impact of changes in flow regimes on the Atlantic salmon, *Salmo salar*, in an upland river. Simulated flows across the catchment were assessed in terms of hydraulic indicators and compared with ranges suitable for salmon. An RRV analysis showed that significant reductions in suitable habitat for spawning are likely, with implications for the species which require new management strategies for setting ecologically acceptable flows.

MAUVOISIN

Impacts on hydropower production were assessed, together with quantification of modelling uncertainties in a complex application to the Mauvoisin dam in the southern Swiss Alps, a high altitude system with inputs from a highly glaciated catchment. Four linked simulation steps were required, with modelling uncertainties characterised and quantified separately for each: regional climate change scenarios, a discharge model, glacier surface evolution and hydropower management. It was found that potential climate change has a significant negative effect on the system performance.

JURA LAKES

An ambitious application was carried out for three interconnected lakes, providing a joint quantification of the climate change impact uncertainty induced by the global-mean warming scenarios and the regional climate response. Impacts were assessed using the RRV methodology using indices relating to flows, agriculture and ecology. It is shown that future climates could have a significant influence on the performance of the system and that a large part of the uncertainty is contributed by inter-RCM variability.

Conclusions

Broadly, the SWURVE assessments of climate change impacts on water sector activities are consistent with those from other studies. For example, summer warming and decreases in precipitation are expected to exert pressure on water resources and ecological flows, which are generally not compensated for by increased winter precipitation. There are also consistent indications of increased extremes in precipitation, particularly in the winter, which are liable to generate increased flooding. The use of the RRV sustainability metric has allowed useful cross-comparison of impacts in widely different sectors.

However, the novel outcomes of SWURVE lie more in the findings on uncertainties and differences in methods rather than in any 'central' impact estimates. For example, systematic differences are found between rainfall regimes from circulation pattern downscaling and the regime taken 'direct' from RCM outputs. Furthermore, there are considerable differences between the spatio-climate change patterns of different global climate model simulations. Over and above any change signals, for precipitation — and particularly for extreme precipitation — natural variability is often the largest source of uncertainty.

Clearly considerable challenges remain in the field of climate change impact assessment and formulation of policy for sustainable water management. At the outset of the SWURVE project, it was recognised that the uncertainty inevitably associated with regional climate change posed a major obstacle to meaningful analysis. It has become apparent throughout the project, and from other recent research, that this issue is becoming more acute as larger ensembles of climate simulations become available.

With these larger ensembles comes the prospect of better defined probability density functions (PDFs) than were achievable in SWURVE. There are fundamental remaining problems of how to understand and utilise such PDFs, not least of which is how to account for the sometimes poor ability of climate models to reproduce the baseline climatology in many instances. However, progress can be made by bringing methodologies from other fields to bear. Early approaches (e.g. Palmer and Räisänen, 2002) applied equal weighting to the results from different models in the production of PDFs. However, more recent approaches take the principle that non-uniform weighting may be more appropriate as models may have unequal skill or simulation. These include the use of Bayesian statistical frameworks in model weighting and construction of PDFs for regional scale change (e.g. Tebaldi *et al*., 2004, Greene *et al*., 2006). Greene *et al.* (2006) combine the ensemble of models by calibrating their past trends at regional scales to the observed trends, and use these calibrations to derive probabilistic projections of future trends. Tebaldi *et al.* (2004, 2005) use the two criteria to weight models: bias — performance with respect to current climate — and convergence — a measure of each model's agreement with the majority.

Although these new methods show promise for use in the impacts field, some obstinate problems, such as the need for continuous time-series simulation of hydrological systems with memory, remain and preclude straightforward statistical analysis of impacts for many applications. The participants in SWURVE hope that their results will at least provide useful directions in this challenging research field.

C.G. Kilsby
School of Civil Engineering and Geosciences
Newcastle University
United Kingdom

c.g.kilsby@ncl.ac.uk

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