Chapter 17

Water Resource System Modelling for Climate Adaptation

Edoardo Borgomeo

Abstract Methods and models for water resource system simulation, risk analysis, and decision analysis provide powerful tools for dealing with the challenge of climate change in the water sector. These models enable learning about the complex behaviour of river basins, testing of alternative adaptation decisions, exploration of uncertainties, and navigation of trade-offs. This paper briefly describes recent advances in decision analysis and simulation modelling for climate adaptation in the water sector. These advances are now relatively mature and are increasingly being applied by practitioners.

Keywords Water resource system analysis · Water supply · Decision-making under uncertainty · Bottom-up vulnerability assessment · Optimization

Introduction

Methods for risk analysis and decision analysis provide powerful tools for informing climate change adaptation in the water sector. Simulation models are at the heart of these methods, and are widely used to improve understanding and assist decision-making in water resource management. The essence of water resource system simulation is predicting the hydrologic, socioeconomic, and environmental consequences of water management, especially in the face of climate change. These are the variables, such as future water availability, the economic value of water, and the reliability of environmental flows, that are important to governments, industries, and the public as they adapt to climate change (Brown et al. 2015). This paper briefly reviews the application of water resource system models for climate adaptation and sketches out some areas for further improvement. A water resources system is here defined as the whole made from connected hydrologic, infrastructure, ecologic, and human processes that involve water. It includes biogeophysical processes (e.g., elements of the hydrologic

E. Borgomeo (✉)

Environmental Change Institute, University of Oxford, 3 S Parks Rd, Oxford OX1 3QY, UK

e-mail: edoardo.borgomeo@ouce.ox.ac.uk

© The Author(s) 2022

Climate Adaptation Modelling, Springer Climate,
https://doi.org/10.1007/978-3-030-86211-4_17

141

cycle and ecosystem functioning), and human processes (e.g., construction, operation, and removal of infrastructure), and other human decisions and actions such as consuming, enjoying, being harmed by, or paying for water (Brown et al. 2015).

Decision Analysis for Water Management Under Climate Change

Faced with climate uncertainties, decision-makers may despair at the prospect of having to make long-term choices about adaptation and water infrastructure. These are indeed difficult decisions, which impact upon future generations and potentially lock-in patterns of development. The recognition of these challenges and of the impacts of climate change on water resources has given rise to a range of methods for decision-making under uncertainty (Maier et al. 2016). As we explain in the following section, all of these methods are underpinned by simulation models of hydrology and the operation of water resources systems (withdrawals, storage, allocation to users, and return flows). Before reviewing the characteristics of water simulators, we review a set of principles shared by these decision analysis methods:

First, they promote the notion of flexibility. Flexibility is broadly interpreted as the ability to switch or change a decision depending on what outcomes materialize. In practice, this means recognizing the extent to which modification of the operation of infrastructure systems can yield very different outcomes or building less infrastructure up front but enabling expansion in the future if needed.

Second, they promote the notion of robustness. A robust decision is a decision that performs acceptably well under a wide range of plausible future conditions. In the presence of uncertainty, it is desirable to seek water decisions that perform reasonably well across a range of possible future conditions, and so are robust to uncertainty. This emphasis upon robustness is in principle quite different to optimizing methods which focus on maximizing expected utility. Promoting a notion of robustness means identifying options that perform acceptably well (i.e., they satisfy a set of criteria) over the widest possible space of possible futures and not that are optimal over a narrow set of conditions.

Third, they emphasize the importance of exposing trade-offs in order to identify and mitigate possible undesirable impacts. The tools of multi-objective optimization are particularly powerful for exploring trade-offs between different attributes of water resource systems. These enable system states (e.g., in different possible future scenarios) to be presented in terms of their performance with respect to multiple objectives (Reed et al. 2013).

Simulation Models for Climate Adaptation in the Water Sector

Simulation modelling is at the core of the decision analysis methods described above. Simulation modelling is particularly powerful because of the capacity to test and explore shocks and scenarios that have never happened, by subjecting a simulator of a water resource system to those conditions ‘in silico’. System stress testing through computer simulation is one of the most important tools for water resources planning in the face of climate change, especially when that is combined with scenario exercises for the multiple stakeholders responsible for a system. This approach, typically referred to as exploratory modelling, uses simulation models to ask ‘what if’ questions, unravelling the implications of different assumptions and hypotheses about future trends on water-related outcomes of concern (e.g., the frequency of water shortages) (Hall et al. 2019).

The purpose of water resource system simulators is to test the performance of the system under changing conditions of climate and demand. System performance within a given future state can be quantified in multiple ways. Since the earlier work of Hashimoto et al. (1982), who defined metrics of vulnerability, reliability, and resiliency, a number of other metrics have been applied to measure the performance of water resource systems. The recent emphasis on decision-making under uncertainty means that metrics that can be related to the principles of flexibility and robustness described above are increasingly being applied (e.g., maximin, optimism–pessimism, max regret) (Giuliani and Castelletti 2016). These metrics are typically quantified across large sets of plausible future climate scenarios (e.g., thousands of scenarios), generated either through downscaling of global climate model projections or through statistical models for direct simulation of hydroclimatic variables (e.g., synthetic hydrology). These metrics are often then traded-off against each other to identify acceptable decisions.

Simulating a water resource system involves coupling several different models (Hall et al. 2019):

Climatic boundary conditions: Information on climatic variables (rainfall, temperature) is a first key input to simulate water resource system behaviour under climate change. As described in Nazemi and Wheeler (2014), this typically involves choosing one or more scenarios for future greenhouse gas concentrations to force one or more global climate models (GCMs) and then transferring the GCM projections of climate variables to the river basin of interest using one or more downscaling techniques. This process generates the climatic boundary conditions. Using climate models as the ‘upstream’ boundary of a water system simulator is attractive because (i) it enables simulations from climate models to be used (if necessary after appropriate downscaling) to test possible future climatic conditions and (ii) climate model outputs implicitly represent spatial and temporal dependencies between the several climatic variables that influence water resource systems—most notably precipitation and the variables that determine evapotranspiration. However, the reliability of GCM outputs for adaptation planning in the water sector has been questioned because of

their inadequacy in terms of the scale of global and regional biases (Stainforth and Calel 2020). To overcome this challenge, climatic boundary conditions can also be generated through direct simulation of either weather (rainfall, temperature) (Stein-schneider and Brown 2013) or hydrological (streamflow) variables (Borgomeo et al. 2015). Direct simulation of climatic boundary conditions is based on sampling and perturbation of the statistical distribution of historical observations.

Surface and groundwater hydrology: Hydrological models transform climatic inputs (notably rainfall) into quantities of water that may be withdrawn from rivers and/or groundwater at specified locations, taking into account topographical and land-use characteristics. Because the quantity of water at a given location is an aggregation of a complex series of spatial–temporal processes, these are dynamical models, though the representation of spatial complexity varies, from lumped catchment models to spatially explicit gridded models. These models are also increasingly capable of simulating water quality, which is known to influence water supplies for urban and rural users.

Water supply infrastructure (withdrawals, storage, pumping) and allocation rules: This is the core of a water resource system simulator. Water resource system models simulate the functioning of the water supply infrastructure, typically on daily or monthly timescales. System simulation models can represent rules for withdrawal of water from water bodies, operation of storage (e.g., dams), and allocation of water to different users. They take as input observations or projections of water demand and can also simulate the amount by which demand may be voluntarily or forcibly reduced during times of scarcity through water use restrictions.

Water use: A variety of methods exist for projecting water demands from households, agriculture, and other economic sectors. Traditionally, models focus on low time resolution data on consumption acquired through billing or limited measurement campaigns and employ deterministic forecast methods (House-Peters and Chang 2011). Recent advances in smart metering technology provide a promising avenue to advance residential water demand modelling and thus significantly improve the ability of water resource system simulators to model users' response to restrictions and other demand-side measures (Cominola et al. 2015). Advances in economic analysis also allow for an improved understanding and modelling of the impact of water use restrictions on multiple users (Freire-González et al. 2017). This understanding is crucial as it feeds directly into the cost–benefit assessment of policy options needed to reduce the risk of water shortages.

Adaptation Practices in the Water Sector: Simulating London's Water Security

The process illustrated above has been applied in London to adapt the city's water supply system to the expected impacts of climate change and population growth.

Simulators of London's water systems show that if no action is taken, London is indeed set to experience more frequent and severe water shortages in the future as early as 2030 (Borgomeo et al. 2018). This is mainly down to population growth, but climate change complicates things further as it will mean more frequent and intense droughts.

Through the use of simulators, water managers in London have identified aggressive demand management to reduce consumption and losses in the distribution system (called leakage) is a priority to be implemented immediately (Water 2019). However, they have also identified options to augment supplies in the long-term. These include recycling wastewater and transferring water from other parts of Southern England (Borgomeo et al. 2018; Water 2019). These options have been identified through the application of water resource system simulators designed to optimize system performance along four objectives: (1) least cost, (2) least environmental impact, (3) robustness, and (4) least emissions. London's approach to climate adaptation required water managers and regulators to move away from a decision model focused on identifying the least cost solution to close the water supply–demand gap. Instead, they expanded their decision objectives to incorporate other aspects such as sustainability and robustness which are key to adapt to climate change and which can be modelled through water system simulators.

The Expanding Boundaries of Water Resources System Modelling

Technological advances, institutional innovations, and behavioural change are some of the factors pushing the boundaries of water resource system modelling. Following Hall et al. (2020), we identify the following:

New data sources: The proliferation of sensors in water resource systems is providing an opportunity to fill persistent data gaps. For example, the introduction of smart water meters in homes is providing much more precise information on the characteristics of water usage.

Economics: There is a growing body of empirical research that seeks to quantify the interplay between water and the economy, in particular in economies that are highly dependent upon agriculture (usually, but not exclusively, poor countries) and are subject to large hydrological variability. Another strand of research examines the productivity of water and hence the wide economic effects of water shortages (Freire-González et al. 2017). This is a challenging research because water is so pervasive in the economy, so its effects are difficult to isolate.

Society: The study of the interplay between society and water has recently acquired the new title of socio-hydrology (Sivapalan et al. 2014). The emergence of socio-hydrology re-emphasizes a perennial need to better understand the complex human dimensions of water and incorporate these in the scientific analysis of water resource systems. These interactions operate at a very wide range of scales, from the

choices made by individuals in households, through to the nature of water-related political conflicts in transboundary river basins.

Environment: Looking to the future, much more sophisticated understanding of the resilience of aquatic ecosystems is to be expected. This understanding can hopefully be used in a more dynamic way to inform water resources management decisions.

Conclusions and Recommendations

This paper reviews some of the current and future challenges and opportunities facing water resource system models for climate adaptation. Water resource system models and decision analysis methods are mature, and now see increasing application. However, there is still less uptake in practice than might be expected. This can be attributed to the approaches being conceptually quite challenging and not always easy to align with existing decision-making processes. On the other hand, intensifying calls for ‘outcomes-based’ management of water resources and for reporting of climate-related risks (e.g., climate-related disclosures in business) are now providing a powerful motivator for the wider adoption of these approaches.

References

- Borgomeo E, Mortazavi-Naeini M, Hall JW, Guillod BP (2018) Risk, robustness and water resources planning under uncertainty. *Earth's Future* 6(3):468–487
- Borgomeo E, Farmer CL, Hall JW (2015) Numerical rivers: a synthetic streamflow generator for water resources vulnerability assessments. *Water Resour Res* 51(7):5382–5405
- Brown CM, Lund JR, Cai X, Reed PM, Zagana EA, Ostfeld A, Hall J, Characklis GW, Yu W, Brekke L (2015) The future of water resources systems analysis: toward a scientific framework for sustainable water management. *Water Resour Res* 51(8):6110–6124
- Cominola A, Giuliani M, Piga D, Castelletti A, Rizzoli AE (2015) Benefits and challenges of using smart meters for advancing residential water demand modeling and management: a review. *Environ Model Softw* 72:198–214
- Freire-González J, Decker C, Hall JW (2017) The economic impacts of droughts: a framework for analysis. *Ecol Econ* 132:196–204
- Giuliani M, Castelletti A (2016) Is robustness really robust? How different definitions of robustness impact decision-making under climate change. *Climatic Change* 135(3–4):409–424
- Hall JW, Borgomeo E, Bruce A, Di Mauro M, Mortazavi-Naeini M (2019) Resilience of water resource systems: lessons from England. *Water Secur* 8:100052
- Hall JW, Borgomeo E, Mortazavi-Naeini M, Wheeler K (2019) Water resource system modelling and decision analysis. *water science, policy, and management: a global challenge*, pp 257–273
- Hashimoto T, Stedinger JR, Loucks DP (1982) Reliability, resiliency, and vulnerability criteria for water resource system performance evaluation. *Water Resour Res* 18(1):14–20
- House-Peters LA, Chang H (2011) Urban water demand modeling: review of concepts, methods, and organizing principles. *Water Resour Res* 47(5)

- Maier HR, Guillaume JH, van Delden H, Riddell GA, Haasnoot M, Kwakkel JH (2016) An uncertain future, deep uncertainty, scenarios, robustness and adaptation: How do they fit together? *Environ Model Softw* 81:154–164
- Nazemi A, Wheeler HS (2014) Assessing the vulnerability of water supply to changing streamflow conditions. *Eos, Trans Am Geophys Union* 95(32):288–288
- Reed PM, Hadka D, Herman JD, Kasprzyk JR, Kollat JB (2013) Evolutionary multiobjective optimization in water resources: the past, present, and future. *Adv Water Resour* 51:438–456
- Sivapalan M, Konar M, Srinivasan V, Chhatre A, Wutich A, Scott CA, Wescoat JL, Rodríguez-Iturbe I (2014) Socio-hydrology: Use-inspired water sustainability science for the Anthropocene. *Earth's Future* 2(4):225–230
- Stainforth DA, Calel R (2020) New priorities for climate science and climate economics in the 2020s. *Nat Commun* 11(1):3864
- Steinschneider S, Brown C (2013) A semiparametric multivariate, multisite weather generator with low-frequency variability for use in climate risk assessments. *Water Resour Res* 49(11):7205–7220
- Water T (2019) Draft water resources management plan. Thames Water plc., Reading UK

Open Access This chapter is licensed under the terms of the Creative Commons Attribution 4.0 International License (<http://creativecommons.org/licenses/by/4.0/>), which permits use, sharing, adaptation, distribution and reproduction in any medium or format, as long as you give appropriate credit to the original author(s) and the source, provide a link to the Creative Commons license and indicate if changes were made.

The images or other third party material in this chapter are included in the chapter's Creative Commons license, unless indicated otherwise in a credit line to the material. If material is not included in the chapter's Creative Commons license and your intended use is not permitted by statutory regulation or exceeds the permitted use, you will need to obtain permission directly from the copyright holder.