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Introduction to the Special Issue on "Adaptation and Resilience of Water Systems to an Uncertain Changing Climate"

Suraje Dessai · Alison Browne · Julien J. Harou

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Reliable water supply is fundamental to human health and wellbeing. Climate change has the potential to affect water systems in a number of ways: through changes in the water available for abstraction and storage, through altered drought frequency and intensity, and through changes in demand and changing risk of infrastructure failure. While the precise details of these changes may be uncertain, there is high confidence that global climate is changing, thus making adaptation to an uncertain changing climate unavoidable. Water managers have often planned under the assumption of a stationary climate. This assumption is no longer valid under a changing climate and other socio-economic changes.

This special issue demonstrates the value of multidisciplinary and interdisciplinary approaches to addressing the future adaptation and resilience of water systems. The range of articles in this special issue, largely based on work from the UK, offers an interdisciplinary perspective on the issues associated with the adaptation and resilience of water systems to an uncertain changing climate. Such themes will resonate with a broad international audience interested in water resources management and adaption to climate change. This special issue has in large part emerged from research associated with the Adaptation and Resilience in a Changing Climate (ARCC-Water) project funded by the EPSRC (Engineering and Physical Sciences Research Council) with co-funding by the ESRC (Economic and Social Research Council). As such it includes the findings and thoughts from a number of universities, research institutions, consultancies, and government and non-government stakeholders involved in the ARCC-Water project. Some of the papers (Browne et al., Korteling et al., Matrosov et al.,

S. Dessai (✉)
Sustainability Research Institute, School of Earth and Environment,
University of Leeds, Leeds, UK
e-mail: S.Dessai@leeds.ac.uk

A. Browne
Sustainable Consumption Institute, The University of Manchester,
Manchester, UK

J. J. Harou
Department of Civil, Environmental and Geomatic Engineering,
University College London, London, UK

Pearce et al., von Lany et al.) were presented at a session entitled “Sustainable water management under an uncertain changing climate” at the Royal Geographical Society (RGS)-IBG Annual International Conference 2011 in London. The session was convened by Suraje Dessai and Brett Korteling and sponsored by the RGS’s Climate Change Research Group.

The interdisciplinary nature of the review papers, research articles and invited editorials presented in this special issue demonstrate the wide variety of themes that are of interest when it comes to climate change adaptation of water systems. These include uncertainties associated with the impact of climate change on droughts (Rahiz and New), water resources (Wade et al.) and freshwater environments (Fai et al.), the uncertainties embedded in current approaches to forecasting demand (Parker and Wilby), and the use of quantitative approaches for water resources planning under deep uncertainty (von Lany et al., Korteling et al., Matrosov et al.). The articles in this special issue also emphasize that future water system will be as much influenced by climate as by legislative and regulatory environments affecting the water consumers and producers (Browne et al., Pearce et al.), and encourages the multidisciplinary readership of Water Resources Management to engage with these diverse social, political, and economic issues and reflect upon how the sum of these different interdisciplinary parts will influence current practice and policy. Finally, given the UK focus of this special issue, we invited three experienced scholars from three different continents (Sofoulis; Mujumdar; Gober) to share their thoughts and wisdom on the topic of this special issue.

1 Exploring Critical Social Science Approaches to Water Demand Research

The invited editorial provided by Sofoulis, reflecting on the Australian experience of water resources management in the face of drought and early climate change, advocates an interdisciplinary, multidisciplinary approach which prioritizes conceptual and methodological experimentalism and reflexivity; but reflects on the difficulties for humanities and social science research ‘to count’ due to the privileging of positivist science. She also reflects on the need to continue developing the emergent ‘partnership model’ which focuses on the co-management of water resources. These issues are addressed in various degrees in the other social science papers in this special issue.

Pearce, Dessai and Barr in their article *Re-framing Environmental Social Science Research for Sustainable Water Management in a Changing Climate* explore what they see to be a bias towards anthropocentric demand-side management in current approaches to water management and climate change adaptation in the UK, and how this is brought through into current conceptual and methodological approaches in the water industry in dealing with the individualised consumer. They also identify how this creates a dichotomy in the ‘twin track’ mantra of demand and supply within current approaches to water management in the UK. Following a strong history of social science research from Australia, the UK, and Europe they problematise this current framing of the location of adaptation and change ‘within the individual’ highlighting how this framing inadvertently re-emphasizes the importance of developing more resilient infrastructure in the face of the ‘average consumer’ who it is uncertain whose consumption can be ‘controlled’. They overview the way that these problematic framings that is, a “dystopian disaster frame and the results were viewed through a behaviour frame” are brought into the actual content of current government funded research in the UK and used to develop fairly inaccurate typologies and segmentations of customers (which are then used to shape ‘interventions’ and ‘demand reduction strategies’) based on attitudes to the environment and climate change rather than actual reflections of water related practices (and associated services provided by water) and their relationship to actual water use consumption. The authors propose that Classic Grounded Theory could be used as a potential approach to bridge the positivist and postpositivist divide that has previously been observed as existing in ‘social’ and ‘hard’ research on water resource management in the UK, and may be a way of sprouting interventions related to water use from actual context of study (that is patterns of actual water use) rather than it being inferred from non-related theory (that is attitudinal and economic theory). They suggest that this should be attractive to funders of water efficiency and demand research and policy as “an intervention that grows from a substantive theory is likely to be much more useful and beneficial in the short-term”.

Browne, Medd and Anderson in their article *Developing novel approaches to tracking domestic water demand under uncertainty—A reflection on the* “*up scaling*” *of social science approaches in the United Kingdom* present an initial piece of work focused on developing methodologies for tracking actual water use practices. It similarly advocates the use of alternative methodological perspectives to be developed to support the critical social sciences studies of water consumption and demand management in a way that address actual practices and habits associated with water use rather than approaches to the typologies of the domestic consumer that are shaped by psychological, economic and environmental framings highlighted in the article by Pearce, Dessai and Barr. However, rather than follow the more qualitative route as suggested by Pearce et al., they advocate for playful and experimental use of quantitative methodologies to stretch out and up conceptual approaches to critical social science research (namely practice theory and an idea of ‘distributed demand’) that have largely been conducted through qualitative approaches. While also recognizing the limitations of current approaches to framings of the consumer, they also recognise the limitations of critical social science in not developing methodological approaches that are at the same time critical of, and useful to, the current water resource management system. They argue for linking studies of actual consumption as identified by Parker and Wilby, with more qualitative and grounded research advocated by Pearce et al. as well as scaling this qualitative research in such a way to identify changes at population levels to the drivers of consumption. They outline potential strategies for tracking the drivers of demand, which could be used as proxy measurements to identify change to water demand at a population level, which could be then used to inform research and policy strategies.

Parker and Wilby in their article *Quantifying household water demand*: *A review of theory and practice in the UK* provide a comprehensive overview of the current approaches to demand forecasting and prediction in the water industry in the UK, largely exploring the use of household and other demographic variables as a method of assessing per capita consumption, and potential changes related to a range of technological and other outcomes. Through this review they highlight the paucity of research addressing the relationship between weather variables and actual consumption, and highlight the flaws in current approaches that attempt to predict and forecast future household consumption related to weather and climate variability. They use the Anglian Water Services ‘Golden 100’ data set to illustrate the significant practical and conceptual issues faced when mining household demand data for weather signals. The errors that are carried through in these large data sets are highlighted, as are the fact that these datasets were always intended for other applications, not for exploring the relationship between demand and weather. Nevertheless they have identified a range of potentially interesting demand and weather relationships at various levels of analysis—from stratification to linear regression analyses. This reveals that there is often a non-linear relationship between weather variables and demand profiles. The practical and analytical learnings from this research could be used to inform approaches to water demand estimation and forecasting over the short (daily to season) and long term (years to decades).

2 Predicting the Impact of Climate and Weather Variability on Water Systems

In his invited editorial, Mujumdar, notes that not even a small proportion of the large impact literature has reached into policy interventions and decision making in the developing world. He attributes the lack of use of climate impact studies by water managers to large uncertainties and their long-term focus. Near-term decadal projections and the reduction of uncertainties could benefit water resources planning. Mujumdar further highlights the challenge of adapting urban water systems in developing countries where demand is increasing.

In their article *21st century drought scenarios for the UK*, Rahiz and New construct scenarios of future meteorological drought to better understand their spatial and temporal behaviour. The scenarios are based on the 11-member perturbed-physics ensemble of the Met Office Hadley Centre's regional climate model, which underlies the UK Climate Projections 2009. They use a drought severity index over 23 water resource regions to investigate four main drought characteristics: intensity, drought covariance, frequency of drought months and frequency of drought events at a given duration. Ensemble-mean change shows an increase in drought intensity over England and Wales with larger change occurring for the 2050s and 2080s, for moderate droughts (70th percentile) and during the wet season (October-March). There is large uncertainty in projections over England during the dry season (April-September). Results also show that droughts can persist over long durations. However, the projected frequency of droughts at longer durations is low compared with droughts with shorter duration of persistence.

Using a sensitive chalk river in the south east of England (the river Itchen) to illustrate their approach Fung, Watts, Lopez, Orr, New and Extence in their article *Using large climate ensembles to plan for the hydrological impact of climate change in the freshwater environment* explore the range of potential consequences of climate change on freshwater ecosystems focusing on the macro-invertebrate community impacts. The environmental impact matrix that they develop (using 246 transient climate series from 1920 to 2080 through the CATCHMOD rainfall-run-off model) suggests that failure to meet environmental flow targets in this river would lead to irreversible changes to the invertebrate community. This model highlights the importance of developing large ensembles to improve the understanding of climate change impacts, and how this approach represents a wider range of possible ecosystem change which, if communicated effectively could be useful for decision makers in exploring a wider range of policy and regulatory responses to address climate impacts.

Wade, Rance and Reynard's article *The UK Climate Change Risk Assessment 2012*: *Assessing the Impacts on Water Resources to Inform Policy Makers* reports on the water sector study of the UK's first Climate Change Risk Assessment. In order to assess the impacts of climate change on the UK water sector, Wade et al. took a number of approaches: stakeholder engagement, literature review, expert elicitation and broad-scale quantitative analysis to develop ten climate change risk metrics. The ten metrics were grouped into: direct biophysical effects (e.g., relative aridity and change in low flows), water availability (e.g., change in deployable output and demand for water), water quality and environment (e.g., numbers of sites with unsustainable abstraction) and assets. The UK Climate Projections 2009 and future population projections from the Office for National Statistics were used to create scenarios for the analysis. Overall the assessment showed that there is likely to be increased pressure on water resources in the UK. In the near term, the impacts on low flows are projected to be the greatest in the east of England. In the north and west changes are smaller and not dissimilar from conditions experienced in the past, but these changes could still be significant in some sensitive catchments. However, some of the consequences for water supplies may be offset by making use of surplus winter flows that are expected to increase under most scenarios.

3 Different Approaches to Planning Water Supply Systems Under Uncertainty

In her invited editorial, Gober argues that too much attention has been given to quantifying climatic uncertainty and too little attention directed to accommodating uncertainty and change. She suggests that a way "forward is to embrace principles of decision making under uncertainty, including exploratory modeling of alternative futures, searching for robust strategies that work well across a range of future climate conditions, and using foresight and flexibility to anticipate adaptation strategies and monitor change". These principles are explored in the remaining three papers of the special issue.

Planning under uncertainty is universal but the context is always somewhat unique; in England and Wales water supply systems were privatized and a national regulatory system is in place to help ensure water company investments serve customers, striking the right balance between guaranteeing supplies and keeping costs low. Since over a decade companies use a two-phased approach: first, water resource simulation models are used to estimate the safe yield ('deployable output') of existing and proposed supply and demand schemes and to estimate safety factors ('headroom') around these yields. Secondly the selection of options is optimised to demonstrate to regulators that proposed plans follow the least cost annual schedule of system upgrades to achieve the supply demand balance. Von Lany, Choudhury, Hepworth and Akande's paper *Applying Optimisation and Uncertainty Analysis to Help Develop an Integrated Water Resources Plan for South East England* describes a regional application of this two-phased 'Economics of Balancing Supply and Demand' (EBSD) approach. In that effort a group of six water companies and the environmental and economic regulators have joined together to economically optimize supply–demand investments across South East England over a 26-year time-horizon. South East England is the UK's most water scarce area and has its largest and fastest growing population. The paper shows bulk water transfers and opportunities for sharing resource development schemes could reduce supply–demand imbalances across the region more cost-effectively than is possible within individual water company plans. The scenario which allowed for cooperation between companies produced savings on the order of £800 M (a 45 % reduction) compared to when companies develop resources independently.

Korteling, Dessai and Kapelan in their contribution *Using Information-Gap Decision Theory for Water Resources Planning Under Severe Uncertainty* explore the use of Information-Gap decision theory to improve planning under deep uncertainty. Their aim is to evaluate the performance of a proposed water resource plan beyond the bounded uncertainty range that would be considered in the EBSD approach. Info-Gap decision theory offers a method to sample future design at successively wider range of uncertainty and as a result, evaluate the performance of water resource management options under conditions of severe uncertainty. This paper utilizes an integrated method based on the Info-Gap approach to quantitatively assess the robustness of various supply side and demand side management options over a broad range of plausible futures. Findings show that beyond the uncertainty range explored with the headroom method, a preference reversal can occur, i.e. some management options that underperform at lower uncertainties, outperform at higher levels of uncertainty. The study also showed that when 50 % or more of the population adopts demand side management, efficiency related measures and innovative options such as rainwater collection can perform equally well or better than some supply side options. Generally the paper illustrates how an Info-Gap based approach can offer a comprehensive picture of potential supply/demand futures and a rich variety of information to support adaptive management of water systems under severe uncertainty.

Matrosov, Padula and Harou contrast the EBSD economic optimization approach described above with 'Robust Decision Making' (RDM), an approach which like info-gap seeks to help make decisions under uncertainty by detailed simulation of a restricted set of future conditions. Their paper entitled *Selecting Portfolios of Water Supply and Demand Management Strategies Under Uncertainty—Contrasting Economic Optimisation and* '*Robust Decision Making*' *Approaches* describes an application of both methods to the Thames regional water resource system (including London). The economic optimization 'EBSD' approach considers hundreds of independent supply and demand options and their interdependencies and generates the least cost schedule of investments to meet projected annual demands. Uncertainties on scheme yields are aggregated into safety factors which means robustness across multiple futures is not evaluated. RDM begins with ensemble simulation (with or without probability distributions), which allows tracking multiple criteria of system performance for different system designs (plans) under multiple futures. A 'scenario discovery' phase uses cluster finding algorithms to reveal combinations of uncertain factors which cause plans to fail, thus allowing them to be iteratively improved. Benefits of RDM include detailed plan evaluation according to several metrics and simultaneously sampling a wide variety of conditions and assessing their impact on proposed plans; limitations include computational intensiveness which limits the number of plans and factors of uncertainty that can be considered. The paper concludes that the economic optimsation and RDM approaches are complementary, providing different answers and fulfilling different goals. Joint use is suggested as a possible way to improve water planning until a method that unifies the benefits of both is found.

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