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Robust optimization to secure urban bulk water supply against extreme drought and uncertain climate change☆

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ABSTRACT

Urban bulk water systems supply water with high reliability and, in the event of extreme drought, must avoid catastrophic economic and social collapse. In view of the deep uncertainty about future climate change, it is vital that robust solutions be found that secure urban bulk water systems against extreme drought. To tackle this challenge an approach was developed integrating: 1) a stochastic model of multi-site streamflow conditioned on future climate change scenarios; 2) Monte Carlo simulation of the urban bulk water system incorporated into a robust optimization framework and solved using a multi-objective evolutionary algorithm; and 3) a comprehensive decision space including operating rules, investment in new sources and source substitution and a drought contingency plan with multiple actions with increasingly severe economic and social impact. A case study demonstrated the feasibility of this approach for a complex urban bulk water supply system. The primary objective was to minimize the expected present worth cost arising from infrastructure investment, system operation and the social cost of "normal" and emergency restrictions. By introducing a second objective which minimizes either the difference in present worth cost between the driest and wettest future climate change scenarios or the present worth cost for driest climate scenario, the trade-off between efficiency and robustness was identified. The results show that a significant change in investment and operating strategy can occur when the decision maker expresses a stronger preference for robustness and that this depends on the adopted robustness measure. Moreover, solutions are not only impacted by the degree of uncertainty about future climate change but also by the stress imposed on the system and the range of available options.

1. Introduction

In the review of the challenges to better solve water resources problems using evolutionary algorithms, Maier et al. (2014) observe that uncertainty affects all aspects of water resources management and that the key sources of uncertainty need to be made "visible" to the optimization process in order to ensure the optimizer does not "have an overinflated sense of control and produce solutions that are likely to be suboptimal and possibly reckless". There are different types of uncertainty, of which deep or severe uncertainty is particularly challenging to handle because it is not amenable to conventional statistical analysis. This study explores the challenge of finding robust optimal solutions that secure real urban bulk water systems against extreme drought in the presence of deep uncertainty about future climate change.

Recent studies on impacts of climate change on water resources have highlighted the potential threat of shifting climate on urban water supply (Brekke et al., 2009; Buytaert and De Bièvre, 2012; Cha et al., 2012; Raje and Mujumdar, 2010; Vicuna et al., 2010). With the prospect of continuing population growth in major cities, the provision of secure water supply will become more pressing and, even more so, if the future climate becomes drier.

Despite advances in climate modelling over the last decade the science of climate change is such that the accuracy of model projections of future climate change is limited (e.g. Randall et al., 2007; Stainforth et al., 2007; Koutsoyiannis et al., 2008, 2009; Blöschl and

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☆ Thematic Issue on the Evolutionary Algorithms.
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Montanari, 2010; Montanari et al., 2010). Moreover, the absolute likelihoods of future climate change scenarios cannot be determined (Brekke et al., 2009). This uncertainty about future climate change is described as "deep uncertainty" because the planning for secure urban water supply involves "parties to a decision [who] do not know or do not agree on the system model(s) relating actions to consequences or the prior probability distributions for the key input parameters to those model(s)" (Hall et al., 2012, p.1665).

Urban bulk water systems are typically required to supply water with high reliability and, in the event of extreme drought, maintain sufficient supply to enable the urban area to avoid catastrophic economic and social collapse. They typically have a complex infrastructure network that harvests water from multiple surface and groundwater sources, stores water in reservoirs, treats and transfers water to consumption zones. The decision space is complex and nonlinear and often there are multiple conflicting objectives. Mortazavi et al. (2012) showed that coupling a Monte Carlo simulation model based on network flow programming with multi-objective evolutionary optimization offers the prospect of finding practically useful optimal solutions for complex urban bulk water systems. They used historical data to calibrate a stochastic model for generating long time series to ensure the bulk water system was subjected to extreme drought. Of particular relevance here was their finding that the cost of optimal future investment portfolios can be very sensitive to the return period of the design drought (that is, the most severe drought the system can survive without collapse) and that the bulk water system can be extremely vulnerable to droughts with return periods in excess of the design return period.

A significant shortcoming of the Monte Carlo approach used by Mortazavi et al. (2012) was that it assumed the instrumental hydrological record is representative of the future. Given the prospect of anthropogenic-induced climate change impacting water availability, conditioning the optimization of the urban bulk water system on the assumption of a stationary climate runs the risk of exposing the system to unwanted vulnerability in the event that the climate in the planning period tracks a trajectory less favourable than that assumed. This study seeks to address this problem of dealing with "broken assumptions" (Weaver et al., 2013) arising from deep uncertainty about future climate change. Its main contribution is to fuse a number of existing approaches to demonstrate a methodology that helps the decision maker identify the operating rules, drought contingency plan and investment portfolio that trade-off sensitivity to "broken" assumptions about uncertain future climate change against expected economic efficiency. Its key contributions in the context of urban bulk water planning are: 1) the incorporation of the Monte Carlo approach of Mortazavi et al. (2012) into the robust optimization framework of Mulvey et al. (1995) with deep uncertainty about future climate change scenarios; 2) the construction of extreme drought sequences under different future climate change trajectories; and 3) the use of a comprehensive decision space that integrates decisions controlling system operation, determining investment in new sources and source substitution, and defining the drought contingency plan that represents a set of staged decisions responding to a drought emergency.

The paper is organized as follows: Section 2 reviews the concept of robustness and robust optimization and then selects a robust optimization framework that facilitates the exploration of the trade-off between efficiency and sensitivity to different climate change scenarios. Section 3 presents the case study involving an Australian urban bulk water system with a complex decision space involving a comprehensive drought contingency plan involving normal and emergency rationing, source augmentation and substitution, operating rules and capital investments. It describes the construction of a stochastic model to generate long sequences of multi-site streamflow representative of a plausible range of future climate change scenarios. Section 4 presents and discusses results for two demand scenarios using two different measures of robustness and different decision spaces. Section 5 presents the conclusions.

2. Robustness and robust multi-objective optimization

Urban water agencies are tasked with the responsibility of planning and operating bulk water systems in a way that minimizes economic, social and environmental costs while providing an acceptable (and usually very high) level of drought security. The management of urban drought security typically involves a two-pronged strategy:

1. *Risk mitigation*: This involves development of medium to long-term strategies that affect water use efficiency and behaviours, and long-lead time water source infrastructure associated with surface and subsurface water storage, harvesting and recycling, to manage the risk exposure to severe drought.
2. *Drought contingency*: Once a drought develops, trigger events, whose probability of occurrence is determined by the risk mitigation strategy, initiate short-term responses such as restrictions/rationing and short-lead time (and usually very expensive) source augmentation.

The number of feasible solutions can be very large. The typical goal is to identify solutions which maximize drought security, minimize operating and investment costs and minimize social impacts. Because these objectives are conflicting, there is no one best solution. Multi-objective optimization identifies the Pareto optimal set of solutions where each solution cannot be improved with respect to any objective without worsening at least one other objective (Deb, 2001). The Pareto optimal set presents the optimal trade-offs between competing objectives.

However, use of multi-objective optimization in itself is not sufficient. If the optimal solutions are based on assumptions about the future trajectory of the system about which there is deep uncertainty, risk-averse decision makers will shun solutions that are optimal for a particular trajectory but produce poor or unacceptable outcomes for other plausible trajectories – McInerney et al. (2012, p.549) liken such optimality as "dancing on the top of a needle". Considering the risks posed by climate change, Matalas and Fiering (1977) introduced the concept of robustness to the water resources field, describing it as 'the insensitivity of a system design to errors, random or otherwise, in the estimate of those parameters affecting design choice'. Robust solutions should be found so that they can be adaptable to a range of "wait and see" strategies "with some economic efficiency or optimality traded in favour of adaptability and robustness" (Matalas and Fiering, 1977). Dessai and Hulme (2007) argued that decisions will and must continue to be made even "in the absence of accurate and precise climate predictions". In the face of deep uncertainty, they argue that overreliance on projections made by climate models is unwise. Consequently, solutions should be robust across a range of possible futures.

There are several definitions of robustness. However, Hall et al. (2012, p.1657) observe that "most capture the idea of satisficing over many plausible future states of the world". Moreover, there are number of different approaches to making robust decisions. Lempert and Collins (2007) present an insightful case study involving deep uncertainty to compare three robust decision making approaches – the first trades some measure of optimal performance in return for less sensitivity to different plausible futures, the second for satisficing solutions which produce acceptable

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