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Screening robust water infrastructure investments and their trade-offs under global change: A London example

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ABSTRACT

We propose an approach for screening future infrastructure and demand management investments for large water supply systems subject to uncertain future conditions. The approach is demonstrated using the London water supply system. Promising portfolios of interventions (e.g., new supplies, water conservation schemes, etc.) that meet London's estimated water supply demands in 2035 are shown to face significant trade-offs between financial, engineering and environmental measures of performance. Robust portfolios are identified by contrasting the multi-objective results attained for (1) historically observed baseline conditions versus (2) future global change scenarios. An ensemble of global change scenarios is computed using climate change impacted hydrological flows, plausible water demands, environmentally motivated abstraction reductions, and future energy prices. The proposed multi-scenario trade-off analysis screens for robust investments that provide benefits over a wide range of futures, including those with little change. Our results suggest that 60 percent of intervention portfolios identified as Pareto optimal under historical conditions would fail under future scenarios considered relevant by stakeholders. Those that are able to maintain good performance under historical conditions can no longer be considered to perform optimally under future scenarios. The individual investment options differ significantly in their ability to cope with varying conditions. Visualizing the individual infrastructure and demand management interventions implemented in the Pareto optimal portfolios in multi-dimensional space aids the exploration of how the interventions affect the robustness and performance of the system.

1. Introduction

Many urban water systems across the globe face future stresses such as reduced or shifted water availability due to climate change, increased water demands, more demanding regulatory regimes and heightened service expectations (Ferguson et al., 2013; Hallegatte, 2009; Pahl-Wostl, 2009). Water supply infrastructure in many major cities globally relies on aging assets designed and constructed over a century ago (Boyko et al., 2012). Refurbishment of existing infrastructure and capacity expansion is needed to cope with future pressures. Moreover, the uncertainty in future conditions motivates novel approaches that help discover which combinations of interventions would work well under a wide range of plausible futures.

Instead of defining "optimality" under historical or narrowly defined conditions, planners have recently been seeking "robustness" for planning under uncertainty (Ben-Haim, 2000; Haasnoot et al., 2013; Herman et al., 2015; Lempert et al., 2003). Robustness as a planning goal is well suited to situations where the probabilities that govern uncertain future states are uncertain themselves. Such uncertainties are known as 'deep' or Knightian uncertainties (Knight, 1921). For example, assigning probabilities to population growth or the effects of climate change on systems is problematic (Walker et al., 2013). A robust system is one that performs well or satisfactorily well over a broad range of plausible future conditions rather than optimally in one. Robustness is

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increasingly incorporated as a goal in many-objective water systems planning studies (Giuliani et al., 2014; Hamarat et al., 2014; Herman et al., 2014; Kasprzyk et al., 2013, 2012). Planning approaches seeking robustness have also been investigated in the UK's water resource planning context (Borgomeo et al., 2014; Korteling et al., 2013; Matrosov et al., 2013a, 2013b) but none of those explored the implications of many-objective decision-making and how the trade-offs change when multiple sources of uncertainty are considered. Recently, dynamic robustness (Walker et al., 2013) that specifically considers the value of flexibility and adaptation has been explored using the Dynamic Adaptive Policy Pathways approach for pre-specified strategies (Haasnoot et al., 2013; Urich and Rauch, 2014) and in multi-objective optimization (Hamarat et al., 2014; Kwakkel et al., 2014). Application of such frameworks by water system planners will require them to understand and accept the benefits of embedding the search for robustness within automated investment filtering approaches which historically only considered cost. In our study we focus on demonstrating how performance trade-offs between investment packages change when uncertainties are considered within complex real-world water systems. Our goal is to communicate to policy makers the increase in understanding and judgement they can obtain by incorporating uncertainty into automated intervention evaluation methods.

Urban water supply planners have commonly employed narrowly defined, least-cost decision frameworks to guide capacity expansions subject to maintaining required service levels (e.g., Hsu et al., 2008; Padula et al., 2013). Planning that does not capture key concerns or preferences across major stakeholder groups increases the likelihood that policies are viewed as performing poorly (McConnell, 2010) and maladaptative. The optimality assumptions implicit to least-cost approaches assume a central planner for whom expected aggregated costs fully describe their preferences amongst water supply alternatives. One vision of optimality inevitably forces a decision maker to prior judgments without the knowledge of the decision's wider implications (Cohon and Marks, 1975). In real planning contexts, an increasingly diverse range of stakeholder perspectives must be addressed with major public investments and plans (Vogel and Henstra, 2015); this is particularly the case with decisions involving natural resources management (Jackson et al., 2012; Orr et al., 2007; Voinov and Bousquet, 2010). The emphasis is no longer only on one vision of optimality (e.g. least-cost) but on converging on a plan that addresses major concerns and acceptably allocates benefits between the major stakeholder groups and economic sectors (Loucks et al., 2005). Generating multiple alternative solutions that are good with respect to multiple objectives but differ from each other enables explicit examination of the alternatives and gaining insight and knowledge about the system (Brill et al., 1982). Methods that clarify the trade-offs across the various benefits and impacts of portfolios of different supplies and water conservation actions have garnered a more significant role in recent published work (Arena et al., 2010; Beh et al., 2015; Herman et al., 2014; Kasprzyk et al., 2009; Matrosov et al., 2015; Mortazavi et al., 2012; Zeff et al., 2014).

Simple capacity expansion approaches such as least-cost yield planning (Padula et al., 2013) are being renewed in many areas of resource management to incorporate the planning approaches described above. The current UK approach does not consider a portfolio's robustness, cost, and social and environmental acceptability explicitly (Dessai and Hulme, 2007). Water planners and regulators recognize the limitations of the current approach and are actively seeking to improve the statutory planning framework (Defra, 2011). Our study aims to reflect the necessity of the current water planning policy changes that are being considered. These include a move from solely least-cost solutions to planning for resilience and robustness against a wide range of plausible future conditions whilst considering wider impacts of decisions beyond cost (Environment Agency, 2015). However, the current water supply system planning framework (Padula et al., 2013) requires water companies consider intervention yields, i.e., the maximum daily water supply an intervention can provide, based on historical flow data. This paper describes a planning approach that explicitly considers both multiple sources of uncertainty and multiple evaluation objectives. We show how considering only historical data can lead to poorly performing system designs under hydrological futures considered plausible by national climate model results (Centre for Ecology and Hydrology, 2015). In our proposed system design screening framework the goal of robustness and resilience is incorporated explicitly into an automated intervention selection process. This contrasts with common approaches where robustness and resilience are evaluated post-optimization using sensitivity analyses (e.g. Thames Water, 2014). This provides analysts with a high performing set of robust system designs and the associated trade-offs in benefits implied by intervention choices. The benefits of incorporating multiple sources of uncertainty into a multi-objective decision making process are demonstrated.

Trade-off analysis has some, but limited, prior history of inclusion in water resource planning regulations (e.g. California Department of Water Resources, 2008; UKWIR, 2016). Here we seek a visually communicable approach which enables stakeholder deliberation about benefits achievable by the water system and its engineered assets that is compatible with the resilience and participatory aspirations of UK water planning (Environment Agency, 2015). Our study demonstrates the importance of understanding how benefit trade-offs change when diverse sources of uncertainty are considered. From a policy perspective the trade-offs and broader performance requirements help to avoid the myopia of least-cost decision making (Herman et al., 2015). Results aid policy makers to orient their investment strategies towards their key requirements and aspirations.

Our study proposes a multi-scenario multi-objective decision-making approach which addresses some limitations of the current planning approach. Several conflicting performance goals including the financial, engineering and environmental performance are considered explicitly. Multiple sources of uncertainty in the form of scenarios considered relevant by stakeholders are used in an automated search for robust combinations of interventions. The ensemble of scenarios consists of climate change impacted hydrological flows, plausible water demands, environmentally motivated abstraction reductions, and future energy prices. The approach is demonstrated by exploring portfolios of alternative water infrastructure and conservation investments for London's water supply for an estimate of conditions in 2035. We use visual analytics to investigate the trade-offs between performance goals and communicate the influence of specific interventions on a portfolio's performance. Robust portfolios from a multi-scenario search are compared to those developed when considering only historical conditions to highlight the benefits of explicitly considering multiple futures within the investment portfolio search. Visualizing the individual interventions implemented in the identified portfolios from both single and multi-scenario search aids the exploration of how the options affect the robustness of the system. The proposed multi-scenario efficient trade-off analysis is a valuable investment screening tool for utility planners identifying robust infrastructure and conservation investment bundles that provide benefits over a wide range of future conditions. We believe such an approach is particularly valuable where decisions on resource development are contested and trade-offs need to be negotiated with stakeholders interested in a diverse set of definitions for desirable system performance.