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Exploring critical pathways for urban water management to identify robust strategies under deep uncertainties

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ABSTRACT

Long-term projections for key drivers needed in urban water infrastructure planning such as climate change, population growth, and socio-economic changes are deeply uncertain. Traditional planning approaches heavily rely on these projections, which, if a projection stays unfulfilled, can lead to problematic infrastructure decisions causing high operational costs and/or lock-in effects. New approaches based on exploratory modelling take a fundamentally different view. Aim of these is, to identify an adaptation strategy that performs well under many future scenarios, instead of optimising a strategy for a handful. However, a modelling tool to support strategic planning to test the implication of adaptation strategies under deeply uncertain conditions for urban water management does not exist yet. This paper presents a first step towards a new generation of such strategic planning tools, by combing innovative modelling tools, which coevolve the urban environment and urban water infrastructure under many different future scenarios, with robust decision making. The developed approach is applied to the city of Innsbruck, Austria, which is spatially explicitly evolved 20 years into the future under 1000 scenarios to test the robustness of different adaptation strategies. Key findings of this paper show that: (1) Such an approach can be used to successfully identify parameter ranges of key drivers in which a desired performance criterion is not fulfilled, which is an important indicator for the robustness of an adaptation strategy; and (2) Analysis of the rich dataset gives new insights into the adaptive responses of agents to key drivers in the urban system by modifying a strategy.

1. Introduction

Urban water systems are coming under significant pressure, with extreme weather events associated with climate change, rapidly growing cities in Asia, shrinking cities in Europe, and an increased community demand for a higher level of amenity and access to green and blue infrastructure. Likewise, new approaches to stormwater management focus on integration

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with the planning of urban landscapes. Instead of draining stormwater through large pipes out of the city, it is kept as a feature in the landscape to provide pollution control and create blue and green areas, which serve to enhance urban amenity (Brown et al., 2009; Ferguson et al., 2013a). These new management strategies not only affect the existing water infrastructure, they involve close interactions with the urban environment and therefore influence its planning and design. All this significantly increases the complexity of urban water infrastructure systems, particularly by integrating centralised and decentralised infrastructure systems to provide multi-functional services (Marlow et al., 2013). Nonetheless, this mix of technologies provides promising solutions for increasing the robustness of the urban water system (Ferguson et al., 2013b; Marlow et al., 2013). Water scholars and practitioners are still facing the question of how to adapt the increasingly complex urban water infrastructure to future challenges such as climate change and urban development (Ferguson et al., 2013a; Marlow et al., 2013).

A common planning approach to address this question is to develop a handful of storylines or scenarios (typically three or four) for how the future could evolve and assess the potential impact on the water infrastructure for each (e.g. Semadeni-Davies et al., 2008; Ashley et al., 2005; Nie et al., 2009). As discussed by Lempert et al. (2004) and Gersonius et al. (2012a,b), the quality of the results of these so-called *predict-then-act* approaches are highly dependent on the quality of the assumptions and projections. Yet the models adopted for climate change and urban development projections still reveal fundamental uncertainties in the understanding of the relationship between the human interaction and the urban environment (Gregersen and Arnbjerg-Nielsen, 2012), and therefore in their results. Therefore a planning process based on deeply uncertain predictions provides only a crude approximation of the future and is a weak basis for robust decision-making.[1] As history has shown, this can result in problematic infrastructure decisions, such as high operational costs and lock-in effects (Dominguez and Gujer, 2006; Moss, 2008; Tillman et al., 1999).

In addition to these limitations in the number of future scenarios that are typically investigated in planning processes, the temporal and spatial dynamics of the urban environment and of the water system is rarely considered. The system performance is usually only assessed at a particular point in the future and the transition from the present to this future state is both unknown and left disregarded (e.g. Semadeni-Davies et al., 2008; Ashley et al., 2005; Nie et al., 2009). However, these dynamics are critical for linking an adaptation strategy to changes in the urban environment (e.g. by timing adaptations to water infrastructure with renewal cycles of buildings (Gersonius et al., 2012a,b). Further, the spatial and temporal dynamics associated with integrating decentralised systems and existing centralised systems can cause unforeseeable consequences and disturbances during their implementation (Larsen and Gujer, 1997).

To overcome the limitations of *predict-then-act* methodologies, recent development of *assess-risk-of-policy* approaches take a fundamentally different view (Lempert et al., 2004). In such approaches, policy assumptions are tested against key drivers and the likelihood of reaching a specific target (Gersonius et al., 2012a,b). Based on these ideas, Lempert et al. (2006) developed the formalised robust decision making (RDM) method. RDM uses exploratory modelling (Bankes, 1993) to assist policy analysis in systems with deep uncertainties. In exploratory models the implications of assumptions and hypotheses are tested by means of computational experiments. This type of modelling approach does not claim to predict the future accurately, but gives insight into the system behaviour, aiming to identify robust policies that perform well under many future scenarios. RDM has already been successfully applied to identify policy relevant scenarios in the context of water resources management (Groves and Lempert, 2007). However, to apply RDM in the context of urban water management, special modelling tools are required that enable testing of adaptation strategies under many scenarios in an evolving urban environment.

Newly developed urban water modelling tools couple urban development models with water infrastructure models. For example Rozos et al. (2011) and Willuweit and O'Sullivan (2013) couple a conceptual tile based water systems model with a cellular automata urban development model. Another example is Urich (2014), which combines agent based modelling and procedural modelling approaches to simulate the coevolution of the urban environment and its water infrastructure at parcel level detail. A critical review of current integrated modelling approaches can be found in Urich and Rauch (in press). In this paper, we now take the next step in this emerging area of research by exploring the potential of this innovative approach to be used as an exploratory model through RDM analyses to test adaptation strategies. In doing so, the robustness of a strategy can be investigated against key drivers for the urban water system by spatially evolving many futures. Specifically, this paper demonstrates how these methods can be applied to:

- consider the spatial and temporal dynamics of adaptation strategies
- identify clusters of critical future scenarios that lead to problematic infrastructure performance
- design an adaptation strategy that significantly increases the robustness of urban water infrastructure against climate change and urban development

The developed modelling approach is demonstrated through application to an illustrative case study of the combined sewer system in Innsbruck, Austria. The adaptation strategy of implementing on-site infiltration systems to reduce the drained impervious area is tested to investigate whether the adapted system can cope with climate change and urban development impacts.

The rest of this paper proceeds as follows: Section 2 describes the research methods adopted to explore the approach's potential; Section 3 presents the model's development to enabling evolution and analysis of many pathways; Section 4 applies the approach to demonstrate that the

[1] In the context of this paper a robust decision is defined as being relatively insensitive to most of the key uncertainties (Groves and Lempert, 2007).