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Modelling the urban water cycle as an integrated part of the city: a review

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ABSTRACT

In contrast to common perceptions, the urban water infrastructure system is a complex and dynamic system that is constantly evolving and adapting to changes in the urban environment, to sustain existing services and provide additional ones. Instead of simplifying urban water infrastructure to a static system that is decoupled from its urban context, new management strategies use the complexity of the system to their advantage by integrating centralised with decentralised solutions and explicitly embedding water systems into their urban form. However, to understand and test possible adaptation strategies, urban water modelling tools are required to support exploration of their effectiveness as the human–technology–environment system coevolves under different future scenarios. The urban water modelling community has taken first steps to developing these new modelling tools. This paper critically reviews the historical development of urban water modelling tools and provides a summary of the current state of integrated modelling approaches. It reflects on the challenges that arise through the current practice of coupling urban water management tools with urban development models and discusses a potential pathway towards a new generation of modelling tools.

Key words | agent-based modelling, decision-support tools, integrated modelling, urban development, urban water management, water infrastructure

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INTRODUCTION

In examining the developments in urban water systems over the past 100 years we see, in contrast to commonly held perceptions in water infrastructure planning, a complex and dynamic system that is constantly evolving and adapting to changes in the urban environment, to sustain existing services and provide additional ones.

Since the beginning of modern urban drainage infrastructure in the late 19th century and early 20th century, we have seen a massive shift from rural to urban populations, as cities now accommodate 50% of the people, up from 18% in 1900. In total, the urban population has grown from 0.3 billion to 3.2 billion over this time. The urban water system has played a critical role in enabling this rapid growth of cities, by providing potable water and sanitation, which in addition to supplying water resources has prevented outbreaks of cholera and typhoid. These services have also provided water for fire fighting and flood protection (Lloyd-Davies 1906), which has protected humans and property during this rapid growth of the 20th century.

Over this time, however, waterways became increasingly degraded from urban pollution and hydraulic impacts. The Cuyahoga River in Oregon, USA, which frequently caught on fire (Adler 2002), is a case in point. From the 1960s, the public became increasingly concerned about the health of waterways, which led to the development of environmental regulations for protecting receiving waterways by significantly reducing the pollution from point sources, such as wastewater treatment plants (WWTPs) and combined sewer overflows (Brown *et al.* 2009). Today, we continue our efforts to reduce the environmental impacts of urbanisation by integrating stormwater quality treatment measures into the urban environment to reduce pollution from diffuse sources (Wong 2006). We are starting to explore how urban water systems can be embedded in the urban landscape to increase the amenity of growing cities and reduce the impacts of extreme heat through the provision of blue and green infrastructure (Brown *et al.* 2009; Wong & Brown 2009; Ferguson *et al.*

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2013b). Further, we are becoming more aware of the need to enhance the resilience of urban water systems against climate change and urban developments by increasing the adaptability and flexibility of water infrastructure (Ferguson *et al.* 2013b).

Urban water infrastructure, particularly drainage, water supply and sewerage networks, is typically designed and built to have a lifespan of 50 to 100 years. The infrastructures of this nature that are implemented today will see significant contextual changes over their lifespan, as did the systems that were put in place 100 years ago. These include changes to the: (i) urban environment, such as the rapidly growing cities of Asia, South America and Africa, as well as the shrinking cities of Europe and North America; (ii) climate, with more frequent and extreme climatic events, including droughts, floods and heatwaves; (iii) services that the urban water system provides, for example the recent emergence of green and blue technologies for increasing urban amenity; and (iv) development of new technologies such as membranes, which might enable new forms of service provision, such as on-site wastewater recycling. Under such deeply uncertain conditions, designing a system today that will be guaranteed to perform well in the future is a challenging task.

Traditionally, infrastructure design is based on the assumption that key drivers for the urban water infrastructure, such as population growth, water demand and climate change impacts, can be predicted 30 to 50 years into the future. Experience with infrastructure built on these assumptions has revealed it can lead to problematic designs and decisions. For example, after the reunification of Germany in the early 1990s, local municipalities in parts of former East Germany invested massively in the upgrade of water infrastructure systems. Design of the infrastructure was based on the prediction that the economy and population would grow and thereby increase the water demand (Moss 2008). Instead, the water demand dropped by 60% due to rapid deindustrialisation of the economy, shrinking population and technological improvement in water saving technologies. The consequence has been extremely oversized water infrastructure, which has led to operational problems (for example, bacterial growth in the water supply networks and odour from sewer network blockages).

Emerging approaches in urban water management are based on a fundamentally different paradigm. Instead of designing and optimising the water infrastructure for a particular assumed future state, new management approaches seek to increase the adaptive capacity of the urban water system to ensure its resilience, regardless of the future conditions experienced (Pahl-Wostl 2007). For example, the vision of a water-sensitive city understands the city as water supply catchment and makes use of a diversity of water resources to make the urban water system more robust against climate extremes and variability (Wong & Brown 2009). These new approaches understand the urban water system and urban environment as an interwoven system. Instead of simplifying urban water infrastructure to a static system that is decoupled from its urban context, new management strategies use the complexity of the system to their advantage by integrating centralised with decentralised solutions and explicitly embedding water systems into their urban form. In this way, decentralised urban water infrastructure systems can play an important role in providing multiple water services and increasing an urban water system's capacity to cope with changes in key variables, such as climate change and urban development.

To understand and test how well an infrastructure adaptation strategy is likely to perform over time, regardless of the future conditions experienced (i.e. the strategy's robustness), modelling tools are required that allow exploration of a strategy's effectiveness under many future scenarios, while taking into account the coevolutionary dynamics of the human–technology–environment system (Pahl-Wostl 2007).

As this paper will outline, such tools are not yet available but steps have been taken towards developing a new generation of modelling tools for urban water systems and beyond. This paper aims to give an overview of the current state of computational modelling tools used in testing adaptation strategies in urban water management. It discusses limitations of current approaches, particularly the lack of consideration of feedbacks between the biophysical and societal systems and adaptation strategies. This paper proposes a conceptual framework to the urban water modelling community as a pathway forward for testing the implications of urban water management policies in an integrated and dynamic urban system under deeply uncertain conditions.

A BRIEF HISTORY OF URBAN WATER SYSTEM MODELLING

The early focus of modern urban water systems was on providing potable water and sanitation for the urban population, to prevent outbreaks of typhoid and cholera. Sewer systems were designed as combined systems, particularly in Europe, which also provided a certain level of flood protection. Rapidly growing towns and cities at the end of the 19th and beginning of the 20th century increased the need for adequate flood protection (Lloyd-Davies 1906). To provide support to engineers designing these combined and separate drainage systems, a first generation of pen and paper methodologies was developed. Papers published by Mulvaney (1851) in Ireland, Kuichling (1889) in the United States, and Lloyd-Davies (1906) in the United Kingdom significantly improved understanding of the relationship between rainfall and runoff, providing the basis for the rational method (Burian & Edwards 2002), which is still used in the design of drainage systems. Similar 'paper and pen' methods have been published for the design of water supply networks (Walski 2006).

As computers became available in the late 1960s, new methods for designing drainage systems emerged and replaced the pen and paper methods. The US Environmental Protection Agency (US-EPA) was, and still is, a main driver for the development of numerical methods in urban drainage modelling. As Rauch *et al*. (2010) describe, the US-EPA commenced development of the modelling tool SWMM (Storm Water Management Model) in 1969, with the initial release following in 1971 (Metcalf & Eddy Inc. 1971). SWMM enabled assessment of the hydraulic performance of urban drainage systems based on Saint Venant equations, allowing engineers to design more complex and optimised drainage systems (Mikkelsen & Geldof 2012). SWMM is still widely applied and continues to be developed – the latest version integrates low-impact development infrastructure (Rossman 2010) and efforts are being undertaken to increase computational speed (Burger *et al*. 2014). On the water supply front, the first computational methods based on the groundwork of Cross (1936) appeared in the 1960s. In 1993, US-EPA released the first version of EPANET (Rossman 2000), which drove the development in water supply modelling in much the same way as SWMM for drainage systems.

Continued growth of metropolitan areas and increasing environmental awareness during the 1960s led to community concern about the poor health of urban waterways (Brown *et al*. 2009). To tackle the problem of this environmental degradation, new water management strategies and technologies have been developed to reduce the impacts of point and diffuse sources of pollution. Computational models were developed to deepen understanding of the environmental impacts of urban water infrastructure on waterways. This required urban drainage and sanitation to be considered an integrated system, including wastewater treatment plants (Harremoës & Rauch 1996). Several, mainly conceptual, tools were developed that could link components of sewerage and drainage systems, including the receiving water bodies, to assess the hydraulic and environmental impact of stormwater and its pollution (Rauch *et al*. 2002)

Resource limitations, particularly in drought situations, led to development of new management strategies and decentralised water supply technologies (see, for example, Melbourne, as described in Ferguson *et al*. (2013b). These integrated water management strategies aim to harvest water from a diversity of sources, thereby increasing the resilience of the supply system. They also lead to complex interactions, as feedbacks between the traditionally separated water supply, drainage and sewerage systems are introduced through the integration of water harvesting technologies at different temporal and spatial scales (for example, rainwater harvesting on individual lots, sewer mining at a district level, and third pipe reticulation of recycled wastewater across a region). Water balance models have been developed to help understand these interactions, for example, AquaCycle (Mitchell *et al*. 2001; Mitchell & Diaper 2005; Mitchell & Diaper 2006), UrbanCycle (Hardy *et al*. 2005) and UWOT (Urban Water Optioneering Tool) (Makropoulos *et al*. 2008; Rozos & Makropoulos 2013). These tools have led to a good understanding of the integrated urban water cycle amongst the urban water modelling community (see Bach *et al*. (2014) for a comprehensive literature review).

As new decentralised technologies are implemented, integration of water infrastructure with the urban environment becomes increasingly fundamental to the system performance. They affect not only the water system's ability to respond to climate change and urbanisation impacts, but also the urban landscape itself, for example, through providing greater amenity and mitigating the effects of urban heat islands (for example, Gill *et al*. 2007).

In addition to these structural measures, non-structural measures (influencing the societal system, rather than the bio-physical system) make a significant contribution to increasing the sustainability and resilience of the urban water infrastructure system (Ferguson *et al*. 2013c).

To summarise, the modern urban water system needs to be considered as an integral part of the urban environment and intrinsically interconnected with the societal system (Wong & Brown 2009; Ferguson *et al*. 2013b). However, the understanding of these complex and dynamic interactions is still in its infancy and, as the next section shows, is not well supported by current modelling tools (Mitchell *et al*. 2007).

Understanding cities and water infrastructure as complex adaptive systems (Batty 2005, 2008; Dawson 2007; Pahl-Wostl 2007) and considering these complexities in the infrastructure planning process can help to avoid problematic decisions, as well as identify opportunities for

Table 1 | Integrated modelling attempts

Paper	Application	Planning horizon	Scale	Urban water system: Spatial representation	Urban water system: Scale	Urban water system: Future infrastructure	Urban water system: Performance assessment
Rozos *et al.* (2011)	Supply and demand strategies for the total urban water cycle using decentralised technologies	2020	City	Four categories of urban properties; two types of water system; conventional or innovative	100 × 100 m	Either conventional or innovative	Water cycle for each category UWOT (Makropoulos *et al.* 2008)
Zellner (2007)	Land use planning on regional to city scale, focus on groundwater management	–	Region	Conceptual over cell either septic tank or connected to municipal water and sewer supply	Regional 255 × 255 m	–	Groundwater integrated (Reeves & Zellner 2010) Modflow
Huang *et al.* (2007)	Pollution management of an urban catchment	2040	City	Schematic	City scale	The infrastructure is modified according to current conditions with an agent-based model	Regional water balance including pollution to assess the pollution in the receiving water body
Polebitski *et al.* (2010)	Water demand forecast under different water pricing scenarios	2090	Region	–		–	Water demand model considering the urban form and water pricing
Ward *et al.* (2012)	Cost–benefit of centralised/decentralised management options	2031	City	Schematic within each tile	250 × 250 m	Static, sustainable urban drainage system in each tile	Supply–demand balance
Veerbeek *et al.* (2012)	Impact of urban development on water pollution	2060	Regional	–	–	–	Pollution load for stream network
Fu *et al.* (2009); Astaraie-Imani *et al.* (2012)	Impact assessment of new developments on receiving water bodies	– (Sensitivity analysis)		Schematic	Regional scale	Static	River quality
Doglioni *et al.* (2009)	Impact of new developed area	5 years		Pipe networks and WWTP	Spatially explicit	Static	Hydraulic and water quality assessment (SWMM)
Willuweit & O'Sullivan (2013)	Demand and pollution forecast; management options	2026		Schematic in cell clusters of cells; different parameter for land use types	200 × 200 m	Percentage of rain and grey water systems as timeline	Water cycle
Urich *et al.* (2013)	Adaptation of urban drainage systems using on-site infiltration systems	2030	City	Combined sewer system	Spatially explicit	New developed areas are connected to the drainage network (Urich *et al.* 2010)	Hydraulic (SWMM)
Dawson *et al.* (2011)	Non-structural flood risk management measures	2100	Regional	–	–	–	Hydraulic model
Urich & Rauch (2014)	Adaptation of urban drainage systems using on-site infiltration systems	2040	City	Combined sewer system	Spatially explicit integrated into complex network	New developed areas are connected to the drainage network (Urich *et al.* 2010)	Hydraulic (SWMM)

[(1)] Not shown. UDM: Urban development model; CA: Cellular automata; ABM: Agent-based model; D: Dynamic; S: Snapshots; E: Exploratory; S: Scenarios; F: Forecasting.

	Urban environment						
Societal	**Link**	**Biophysical**	**Societal**	**Calibration**	**Validation**	**Uncertainties**	
–	Linear, aggregated number of categories at city level	Grid based 100 × 100 m; occupancy and buildings per cell	CA	–	Conventional or innovative system; one population growth scenario	D	F
–	Feedbacks. Agents are located on the grid, extract water and change the landscape, affecting other agents' decisions	Grid based 255 × 255 m conceptual	ABM	–	Different zonings, irrigation for agriculture	D	E[1]
–	Feedbacks. The population dynamics is influencing the performance and therefore affecting the agents' decision	Time line of population growth at city level	–	–	Different decision strategies for infrastructure adaptation, possible to run for various input scenarios[1]	D	E
Impact of water pricing; integrated into urban development model	Linear, urban form (housing type) aggregated at city level	Parcel level (aggregated to traffic analysis zones)	ABM UrbanSim (Waddell 2002)	Integrated. Based on water demand data for a 12 year period	Different water pricing scenarios	D	F
–	Linear, technologies placed in the urban form on tile, new, retrofit	Grid based, a tile can hold single building type and different development stages	Spatial equilibrium based on spatial zones (Echenique *et al.* 2013) converted into tiles	UDM	Different development scenarios[1]	S	F
–	Linear	Grid based 500 × 500 m	CA	UDM. Based on 10 year period	Different development scenarios[1]	D	F
	Linear, empirical relation between housing density and impervious area	Sub catchment level; population and housing densities	Population for sub-catchment is sampled out of uniform distribution	–	Population as range for one sub-catchment	S	E
–	Linear, based on population and housing data	Grid based 100 × 100 m, cells contain housing and population	CA	–	Different development scenarios[1]	S	S
–	Linear, via land use	Cells with 200 × 200 m single land use	CA MOLAND (Engelen *et al.* 2007)	Integrated. Based on water demand (5 year period) and stormwater runoff (1 year)	Different development scenarios[1]	D	F
–	Linear, empirical relation between population densities and impervious area	Grid based 250 × 250 m	UrbanSim	–	Generates many algorithmic generated case studies	D	E
Flood insurance policy considered in household location choice (part of UDM)	Urban development policies can be constrained by flood-prone areas	Census wards	Spatial interactions model based on (Lowty 1964)	UDM	Four UK foresight scenarios	S	E
	Feedbacks. Urban and water infrastructure development are part of the same network	Complex network	Agent-based model; agents physically alter the urban environment	–	Explore many possible future scenarios	D	E

adaptation (Gersonius *et al.* 2012), possible consequences and potential conflicts with other infrastructure systems (McEvoy *et al.* 2006).

CURRENT STATE OF INTEGRATED MODELLING

Recently published papers are starting to explore the interaction between the urban water system and the urban environment for testing water management strategies. Table 1 provides an overview of the first modelling approaches to couple the urban water infrastructure more closely with its urban environment with the aim of scenario and strategy testing.

The reviewed models each aim to support long-term planning using different lenses to understand the dynamics of different aspects of the urban water system. The following approaches were identified: (i) tools that support impact assessment of different urban development and climate change scenarios, to increase understanding of the complex system behaviour to inform strategy planning; (ii) tools that assess the potential of structural measures, particularly decentralised technologies; and (iii) tools that test the potential of non-structural measures to assess the impact of land use policies or water pricing.

As Table 1 shows, building on the urban water modelling traditions, current approaches focus on impact assessment and analysis of structural measures. Particular focus is given to the dynamic impacts of urban development and climate change on existing water infrastructure systems and how decentralised technologies can be used to adapt the urban water system while increasing its technical resilience.

Simultaneously, emerging approaches developed by Dawson *et al.* (2011) and Polebitski *et al.* (2010) aim to understand the impact of non-structural measures on the urban water system. Non-structural measures or 'soft measures' (Dawson *et al.* 2011) are adaptation measures targeted at the human system and, due to the complex nature of these systems, are inherently difficult to model.

As Dawson *et al.* (2011) and Ferguson *et al.* (2013c) discuss, a successful strategy consists of a portfolio of structural and non-structural measures. However, none of the frameworks reviewed in Table 1 currently supports the consideration of combined strategies.

The following section describes the modelling approaches in Table 1 in more detail to review how they each consider feedbacks between the biophysical and societal systems across the urban environment and the urban water system. We then discuss how structural and non-structural adaptation measures are considered and whether the approaches support feedbacks between the urban system and adaptation strategies to test their robustness. Lastly, we discuss the model applications that assess strategies under deeply uncertain conditions. Figure 1 shows an overview of the dimensions reviewed for each model listed in Table 1.

Model integration

A common approach to combine different modelling domains (in this paper the urban environment, the urban water system and the adaptation strategies) is the use of integrated modelling (Voinov & Shugart 2012). This integrated modelling approach links existing models developed for specific domains; the models in Table 1 focus primarily on the coupling of the biophysical dimension of the urban water system and the urban environment.

To consider feedbacks between integrated models, a translation between the domains is required. This means that the output of the urban development model needs to be translated into input for the urban water management model and vice versa. The advantage of such an integrated modelling approach is that it allows the coupling of existing modelling tools and can therefore build on the knowledge base of well-tested software tools. One difficulty lies in the data translation, since the modules are usually designed for their own purpose and therefore do not necessarily contain the data required or use a different spatial and temporal resolution. For this reason, the integration of feedbacks between different models is difficult (Zellner *et al.* 2008). Voinov & Shugart (2012) provide a good discussion of these issues. The models in Table 1 hardly consider feedbacks.

The models developed by Huang *et al.* (2007); Urich & Rauch (2014) and Zellner (2007) build on integral modelling approaches. In all three approaches the decision-making unit representing the societal system spans across the different modelling domains. This has the advantage that it allows a coherent description of the biophysical and societal systems. The disadvantage is that these models do not build on existing well-established tools. Therefore the processes simulated in these models are often simplified compared to well-established models of a specific domain.

Biophysical system

Urban environment

For most approaches in Table 1, the utilised urban development model determines the granularity of the urban

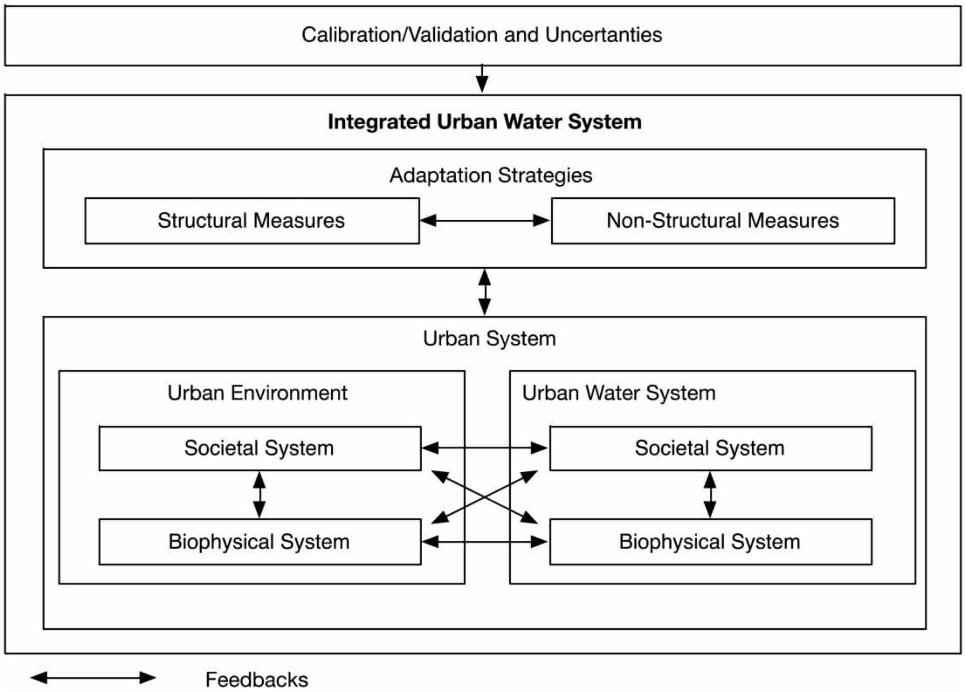

Figure 1 | Dimensions and linkages of modelling the integrated urban water system.

environment. They are mainly based on a raster-based description of the urban environment, which is common for urban development modelling. The grid-cell size varies from 100 to 500 m and each grid-cell holds information about its current land use and population and additional information such as housing densities. The data contained in these cells are aggregated and lack information about the spatial layout of the urban form such as streets, parcels or building geometries. Nevertheless, this spatial dimension is important when considering decentralised technologies, since the urban form provides local constraints for their design and placement. Further, important parameters such as impervious area and roof area highly depend on this spatial dimension. Therefore deriving these data is a substantial part of linking the urban environment with the water infrastructure system.

An exception is the approach by Polebitski *et al.* (2010), which uses a more detailed description at parcel-level detail. However, this significantly increases the complexity of the urban development model, affecting its computational intensity and data requirements.

Urban water system

As for the urban environment, urban water models frequently use a grid- or cell-based representation of water infrastructure to reduce complexity, particularly for the integration of decentralised technologies. For example, Rozos *et al.* (2011) use grid-cells with either conventional or innovative water infrastructure systems. Ward *et al.* (2012) use grid-cells to identify potential opportunities for the placement of decentralised technologies. In both cases the urban water infrastructure within the grid-cells is considered conceptually (rather than spatially) down to tap-level detail. Although these approaches consider a wide range of different decentralised technology options, the representation of centralised networks is weak and the cells are not connected with each other to represent catchment- or regional-scale infrastructure systems. They are therefore limited in their capacity to consider the interaction between centralised and decentralised systems.

Willuweit & O'Sullivan (2013) developed a more generic, tile-based model to describe the urban water infrastructure. While the model does not physically represent the urban water infrastructure system, it allows for conceptual consideration of the shift from centralised to decentralised water systems. In addition, the model can combine several tiles in a cluster to represent parts of the water infrastructure system, such as water recycling plants, at the district scale and beyond. However, it does not consider dynamics across tiles to represent the whole system.

Doglioni *et al.* (2009) and Urich *et al.* (2013) use a spatially explicit representation of the centralised drainage and sewer systems, but the consideration of decentralised technologies is limited. Further, the evolution of infrastructure networks is limited to pre-defined layouts.

Linking

Different methods to derive key parameters from the urban environment are available, depending on the level of detail considered in the urban water model. Sitzenfrei *et al.* (2010) (not considered in Table 1 since the model does not include a urban dynamics) use a simple regression model, presented in Chabaeva *et al.* (2004), to derive the impervious area from land use and population data. Similar relations can be found between housing densities and impervious area (Butler & Davies 2004), used for example by Fu *et al.* (2009) or Doglioni *et al.* (2009).

When considering the placement and design of decentralised technologies, especially for stormwater treatment solutions that are embedded in the urban landscape, more detailed information about the urban form is required (Mitchell & Diaper 2005; Liu *et al.* 2012; Bach *et al.* 2013). A common approach is to derive key parameters needed for the selection of decentralised technologies from stylised tiles that uniformly represent a particular building structure, such as single family houses or apartment units (see, for example, Rozos *et al.* 2011; Ward *et al.* 2012; Willuweit & O'Sullivan 2013). Nevertheless, as Bach *et al.* (2013) show, reconstructing the urban form to derive required parameters is not straightforward.

Such linking enables changes in the urban environment to be reflected in the parameters for the urban water infrastructure system, and therefore its performance. However, as the review showed, current modelling capabilities to dynamically adapt physical structures are still limited.

Societal system

As discussed above, consideration of the dynamic nature of the urban system and the water infrastructure is crucial for testing the success of adaptation strategies. The dynamics of an urban system's biophysical elements are largely determined by human decisions and interactions (Ferguson *et al.* 2013a).

The modelling approaches in Table 1 mainly focus on the evolution of the urban environment as the driver for the water infrastructure. To evolve the urban environment, the approaches mostly employ cellular automata or agent-based models. Both approaches have been widely applied and allow the integration of feedbacks between the societal and environmental systems (see Haase & Schwarz (2009) for a detailed review of different urban development approaches that consider feedbacks with the urban environment). Nevertheless, the consideration of feedbacks from the urban water system in the urban development model is not considered by the reviewed models, with the exception of Dawson *et al.* (2011). Their model considers floodplains in land use planning as a non-structural measure; however, it does not update the water infrastructure system with dynamic inputs from the urban environment.

There is little consideration of the societal dynamics in relation to the urban water system in the modelling approaches of Table 1. Only Dawson *et al.* (2011) considers the effect of flood insurance on urban development in flood-prone areas, and Polebitski *et al.* (2010) considers the impact of water price on demand. As such, consideration of the societal system as a driver for the urban water infrastructure system is still in its infancy in modelling approaches.

Adaptation strategies

An important application of the modelling approaches in Table 1 to inform decision-making is to test adaptation strategies. This requires the approach to enable strategy and policy options to be adjusted in response to changes in the urban system (Kwakkel *et al.* 2012). Most of the reviewed models do not allow this adjustment to be made.

Huang *et al.* (2007) and Zellner (2007) are the exceptions, considering such feedbacks to enable testing of flexible adaptation strategies. As Huang *et al.* (2007) show, this is a powerful method for identifying triggers and signposts in the urban system to develop a strategy that will be robust under deeply uncertain future scenarios.

Calibration/validation

Calibration and validation is a major challenge for integrated modelling approaches, particularly for models that integrate different modelling domains and use many different input parameters (Voinov & Shugart 2012; Bach *et al.* 2014). For a more detailed discussion of current challenges in calibrating and validating integrated models see Bach *et al.* (2014) and Voinov & Shugart (2012). To produce reliable modelling results for long-term planning, the calibration and validation should also be based on long-term observations. However, such data are often difficult to obtain or not available. Another challenge is that due to feedbacks between the integrated components the calibration of individual components is not sufficient to calibrate the whole integrated model (Voinov & Shugart 2012).

Many of the models in Table 1 have been used without calibration or validation and, as Bormann *et al.* (2007) discussed, the interpretation of such studies is therefore restricted to the model behaviour. Most of the applications in Table 1 used, compared to the planning horizon, only short historical periods to calibrate and validate the model. For example Polebitski *et al.* (2010) used a 10-year calibration period to assess the water demands until 2090. Polebitski *et al.* (2010) and Willuweit & O'Sullivan (2013) calibrated the response of the model integration across domains. Model applications by Dawson *et al.* (2011), Veerbeek *et al.* (2012) and Ward *et al.* (2012) calibrated only the urban development component, and the urban water system is without calibration. Therefore the integrated component of these models should be considered as not calibrated.

Uncertainties

Most modelling approaches are used to test the response of the system for a few scenarios only. As discussed earlier, exploring only a handful of scenarios when the future conditions are deeply uncertain gives limited insight and can lead to problematic infrastructure decisions.

Huang *et al.* (2007) take an alternative modelling approach, based on the ideas of exploratory modelling (Bankes 1993). Their model allows different adaptation strategies for reducing pollution of Dianchi Lake to be tested under various future scenarios. For the model to revise an adaptation strategy, agents can observe key parameter states in the simulation. This enables the author to develop adaptation strategies that dynamically react to changes in the simulation and to test their effectiveness under a variety of different scenarios (although this was not shown in the paper). It also enables integration of feedbacks in the system at a regional scale. However, due to its coarse level of detail at the city scale, the modelling approach is not applicable for testing adaptation strategies in urban water infrastructure systems.

The approaches by Fu *et al.* (2009) and Astaraie-Imani *et al.* (2012) test the sensitivity of the urban water system to its key drivers, such as population growth and climate change. Urich & Rauch (2014) shows that reducing the sensitivity of a strategy to key drivers can significantly improve its robustness.

As this overview shows, the developed modelling approaches reviewed in this paper and summarised in Table 1 have fundamental limitations with regard to simulating the coevolution of the urban environment and urban water systems. The consideration of feedbacks and the biophysical and societal dynamic of the urban system is particularly underdeveloped, and application of these models under deeply uncertain conditions has had little modelling attention.

THE NEXT STEP – TOWARDS AN INTEGRATED MODELLING APPROACH

The urban water modelling community has just started to explore pathways towards an integrated modelling approach and the literature review reveals significant gaps. This section presents a potential pathway forward for modelling tools to support strategic planning in urban water management under deeply uncertain conditions. We draw on literature about socio-ecological system models that use agent-based models, to address limitations in regards to the complex dynamics of the urban system. Additionally, we suggest the use of emergent procedural modelling algorithms to overcome current limitations of the spatial dynamics of the biophysical system. As Figure 2 shows, we propose a modelling framework that, based on a coherent description of the urban system as a complex adaptive network, combines these approaches in an integral modelling tool. This tool:

- considers feedbacks between the urban water infrastructure and the urban environment to be able to identify and to assess multi-functional benefits across both systems;
- models interactions between centralised and decentralised water infrastructure systems at parcel-level detail to identify potential opportunities and conflicts;
- considers structural and non-structural adaptation strategies that can be updated in response to changes in the urban system.

Interlinked urban system

As the previous section highlighted, the biophysical and societal description of the urban environment and the urban water system in different modelling domains makes the integration of feedbacks difficult. Of particular difficulty is the translation of parameters describing the urban environment into input parameters for the urban water system, as well as the consideration of societal interactions

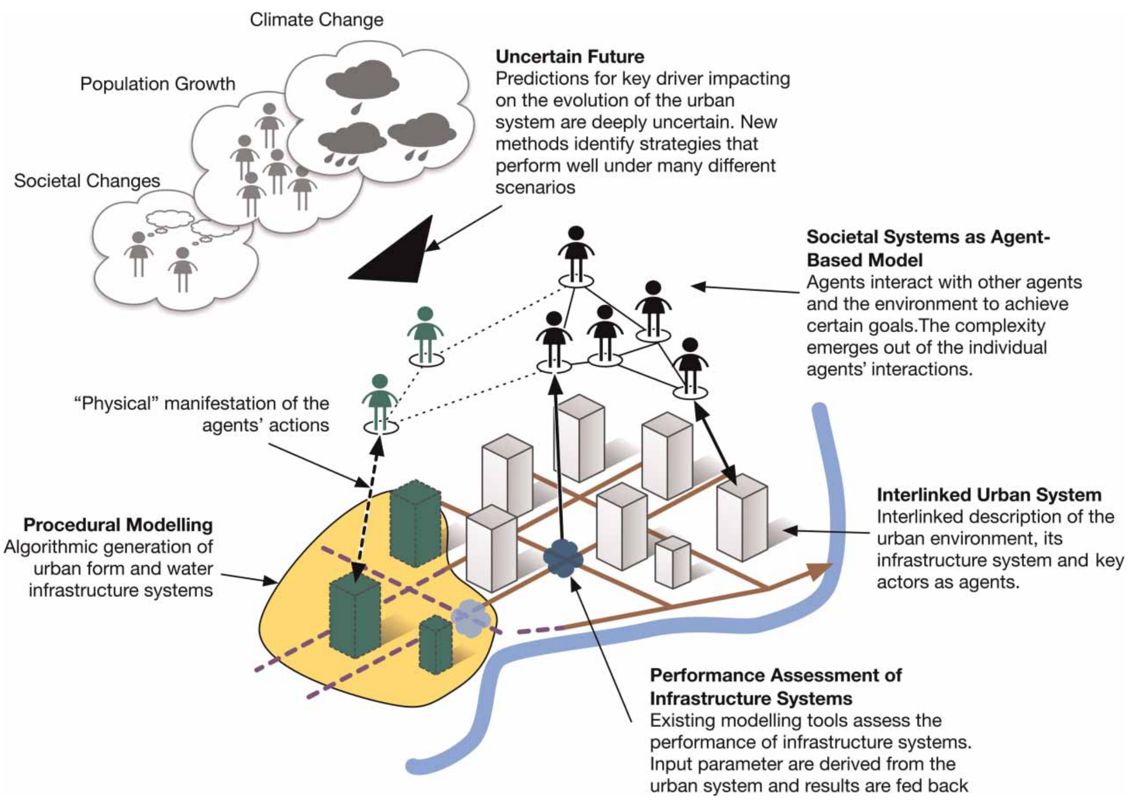

Figure 2 | The dynamics of integrated modelling – modelling the water system as part of the city: a concept for a new generation of modelling tools.

across domain boundaries. For this reason, we suggest the use of a coherent description of the urban system, including the biophysical and the societal system as a complex network. As Batty (2008) discusses, such a description allows the gap between the biophysical and societal systems to be bridged. For the proposed framework, this paper suggests using nodes to represent biophysical and societal entities of the urban system. Nodes hold attributes that describe the entity, and edges between nodes represent relationships, collectively forming a complex network. Entities that represent key actors of the urban systems are able to alter the network. For example, a residential developer builds a building, which becomes a new node in the network that is linked with the existing parcel. The interlinked nature of the network allows changes to be tracked through the network, which in this case means that the newly constructed building increases the impervious area of the linked parcel. Since the parcel is connected to the drainage network, the increased impervious area potentially causes flooding. If the adaptation strategy of the city council (which is represented as an entity in the urban system) is linked to the flooding performance, the newly constructed building may trigger consideration of new strategy options.

This coherent description of the urban system reduces the translational costs when linking the urban environment with the urban water system (attributes needed are derived from connected nodes). Further, feedbacks across the biophysical and societal systems are an inherent part of the network and do not need explicit consideration.

Procedural modelling

Water infrastructure is usually considered to be static in existing models, and cannot be dynamically adapted to changes in the urban system. In the proposed framework, we suggest procedural modelling be used to spatially manifest the agents' actions in the biophysical system.

Recent advances in computer visualisations allow the generation of entire virtual cities, including streets and buildings at a high level of detail (Parish & Müller 2001; Müller *et al.* 2006). The idea is to generate objects, such as streets, buildings, trees and so on, based on a simple set of rules. A commonly used methodology is L-systems (Prusinkiewicz & Lindenmayer 1990); for example Parish & Müller (2001) and Chen *et al.* (2008) used L-systems to generate artificial street networks. Another approach is shape grammar (Alexander *et al.* 1978), a methodology used by Greuter *et al.* (2003) and Müller *et al.* (2006) to create a variety of different buildings. These methodologies were originally developed to generate virtual worlds for computer games, but have now become increasingly popular for visualising future urban layouts (van Delden *et al.* 2011; Sugihara & Kikata 2012).

In contrast to the common regular grid models applied in land use change modelling, Weber *et al.* (2009) demonstrate how procedural modelling combined with an urban development model can be used to create a detailed three-dimensional city that evolves over time, including roads and buildings. Such an approach overcomes limitations of traditional urban development tools that use either a conceptual representation of the urban environment, based on land use and population densities, or parcel-based models such as UrbanSim (Waddell 2002) and iCity (Stevens *et al.* 2007) that evolve along predefined parcels. Procedural modelling can therefore offer a powerful tool for addressing the limitations of existing modelling approaches, to enable the dynamic evolution of urban water infrastructure systems.

In urban water management, a lack of available case studies led to the development of artificial water infrastructure systems. For example, Ghosh *et al.* (2006) and Möderl *et al.* (2009) used fractal geometry to generate artificial urban drainage networks. For water supply networks, Möderl *et al.* (2011) developed a graph-based approach to generate virtual case studies. While these approaches allow many case studies to be generated, they focus on the water infrastructure without integration into the urban environment, and the dynamic expansion of the generated systems is not possible.

Sitzenfrei *et al.* (2010) and Urich *et al.* (2010) enhanced this approach by generating entire urban environments. These virtual environments can be used as the basis for creating artificial water systems (Sitzenfrei *et al.* 2013a). Sitzenfrei *et al.* (2013b) showed how their approach can be used to generate an entire urban system, coupled with a combined sewer and water supply network, to assess the impacts of decentralised solutions on the existing centralised water infrastructure systems.

Coupling these algorithms with decision-making processes of key actors allows the evolution of the urban system to be modelled at parcel-level detail, thereby increasing the granularity of the approaches used so far. In addition, the integration of procedural modelling allows derivation of parameters needed to model interactions between the urban form and decentralised and centralised urban water systems from 'physical' entities, simplifying the translation process.

Societal system

Socio-ecological systems modelling has made significant progress in the understanding of complex adaptive systems by applying agent-based modelling techniques (Filatova *et al.* 2013). These models simulate the complex interactions amongst actors in a spatially explicit environment. Agents are defined as entities that have a specific aim. To achieve their aim, agents can sense their environment and other agents. Based on this information and on a set of rules, agents make decisions to work towards their aim (Batty 2005). An agent's decision can influence the environment and other agents and therefore influences other agents' decision-making processes. Although the rules can be simple, the complexity of the simulation emerges out of the agents' interaction with the environment and amongst themselves.

In the context of water management, several agent-based models have been applied at catchment scale (Moglia *et al.* 2010) or regional scale (Barthel *et al.* 2005). For example, Barthel *et al.* (2008) represented key actors (such as households, industries, businesses and municipalities) as agents, coupled with an integrated water balance model. This enabled the water cycle to be modelled as a whole, including its biophysical and socio-economic components and the long-term changes for the Upper Danube river basin under climate change. The agent-based approach also enabled the complex interactions between supply and demand to be modelled. It was therefore possible to more realistically represent how actors might react to changes in the water system on a regional scale (e.g. climate or demographic changes). However, although these models consider the societal system at great level of detail (household level), the water infrastructure is highly conceptualised.

Likewise, agent-based models can simulate the adaptation of water infrastructure systems. For example, the earlier discussed model developed by Huang *et al.* (2007) uses an agent-based modelling approach to test flexible adaptation infrastructure strategies based on observed parameters in the urban water system. Tillman *et al.* (1999) use a simple agent-based model simulating an engineer's decision-making process, to increase the capacity in a water supply system.

Agent-based models are also widely applied in urban development modelling to improve understanding of the complex dynamics of the evolving urban environment (Crooks *et al.* 2008). In contrast to the often used cellular automata models like SLEUTH (slope, landuse, exclusion, urban extent, transportation and hillshade) (Silva &

Clarke 2002), agent-based models such as UrbanSim (Waddell 2002) represent the key actors and their actions as agents in the urban environment and support the evolution of the urban environment at parcel-level detail, although consideration of the spatial dynamic is limited to a predefined layout.

As this brief overview shows, agent-based models are widely applied to describe complex adaptive systems. The integration of feedbacks between the environment and agents is straightforward (Verburg 2006), allowing simulation of the influence of human decision-making on the urban system. Further, the exploratory power of agent-based modelling approaches is an important asset (Lempert 2002) and one of the advantages compared to cellular automata approaches (Grimm *et al.* 2006). Agent-based modelling has also been applied across domain boundaries and has the potential to provide a unifying platform for considering the societal dynamics in relation to the urban system.

An important aspect in modelling societal systems is that it is assumed that building predictive models is impossible (see Moss *et al.* (2001)). This has important limitations on the model application. Also questions of verification, calibration and validation of agent-based models are challenging and still debated in literature (Crooks *et al.* 2008). Consequently, the predictive capabilities of the proposed framework are limited. Hence, the proposed framework does not aim to forecast the future of the urban system; instead it aims to increase the understanding of how adaptation strategies affect the resilience of the urban system, to identify robust solutions. Especially, the exploratory power of agent-based modelling approaches is therefore an important asset of the proposed framework (Lempert 2002).

To summarise, applying an agent-based modelling approach in the context of urban water management offers a promising way forward for describing the complex feedbacks within the urban water system, the urban environment and the societal system.

Application under deep uncertainties

The uncertainty and complexity of key drivers is rarely considered in traditional infrastructure design and planning processes, which rely heavily on projections of key parameters like population growth and climate change. Problematic decisions can result, since projections that do not come to be realised can mean the water infrastructure has been designed with over- or under-capacities, thereby adding additional construction and operational costs. In the proposed framework we propose that, instead of forecasting the system performance, the robustness of adaptation strategies should be tested.

To overcome limitations of the traditional 'predict-then-act' planning frameworks, new policy frameworks for assessing risks have been developed (Lempert *et al.* 2004). These approaches are fundamentally different in that they develop adaptive strategic plans that will perform well under a wide range of future scenarios, for example, robust decision-making (Lempert *et al.* 2006) or adaptive policy making (Walker *et al.* 2001). A review of literature on different adaptive planning approaches can be found in Walker *et al.* (2013). These adaptive planning approaches have in common that the performance of a strategy is tested against a large number of future scenarios, to identify pathways that achieve desired objectives, regardless of how the future might unfold (Walker *et al.* 2013).

Formalised modelling approaches for implementing these adaptive planning ideas are based on the principles of exploratory modelling. Bankes (1993) introduced this concept to assist policy analysis in systems that have significant uncertainties. Exploratory models test the implications of varying assumptions and hypotheses through computational experiments. This type of modelling approach does not claim to predict the future of the system, but it provides insight into the system and helps to identify robust policies. Based on the ideas of exploratory modelling, new formalised methodologies emerged for assessing the risk of a policy option and, therefore, enabling robust decision making (Lempert *et al.* 2004). Some of these methods have been applied in the context of water management. For example, the info-gap method was developed by Ben-Haim (2006) and applied for flood risk management (Hall & Solomatine 2008; Hine & Hall 2010). The robust decision-making method was developed by (Lempert *et al.* 2006) and applied for water resource management (Groves & Lempert 2007). A comparison of these two methods is found in Hall *et al.* (2012).

Such methodologies provide promising solutions to support decision-making processes under deep uncertainties. However, the applicability for urban water management is yet to be demonstrated in the literature.

CONCLUSION

Computational modelling tools play an important role in management and design of urban water infrastructure systems. The evolution of the modelling tools is closely linked with the increasing complexity of the urban water system as new challenges are addressed. While in the beginning 'pen and paper' methods were sufficient to support the design of water systems, today's advanced software tools enable the urban water system to be simulated from 'source to tap' to better understand the increased complexity in the interwoven urban water system.

Climate change, urban development and the demand for additional water services, such as urban amenity through blue and green infrastructure, are putting increased pressure on the management and design of urban water systems. New decentralised technologies increase the complexity within the urban water system and couple the urban water system more closely with the urban form. Testing the potential of these new technologies requires a new generation of modelling tools able to represent the complex interactions both within the water infrastructure and between the water system, its urban environment and the societal system in a dynamic coevolving urban system.

The urban water modelling community has recently been attempting to couple urban development models with existing urban water system models. However, the utilised approaches show fundamental limitations, particularly the representation of the dynamics in the urban water infrastructure system, as well as the consideration of feedbacks between the urban environment, the water infrastructure and the societal system.

To tackle the problem of the dynamics and complexity in modelling the urban water system, we investigated current lines of research. First, in modelling socio-ecological systems, significant progress has been made in using agent-based models. Secondly, procedural modelling approaches developed for the purpose of creating virtual environments and computer visualisations enable the algorithmic generation and alteration of entire virtual cities, including streets, buildings and water infrastructure systems. Thirdly, exploratory modelling approaches provide a promising way forward to identify robust strategies under deeply uncertain scenarios. We conclude that a new generation of modelling tools that combine these approaches is necessary to create a tool that enables the implications of adaptation strategies to be tested under many future scenarios, thereby allowing robust and resilient strategies to be identified.

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