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RESEARCH ARTICLE

A resilience assessment method for urban water systems

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ABSTRACT
Infrastructure planning for Urban Water Systems (UWSs) is challenged by, *inter alia*, increasing uncertainty in both demand and availability of water and aging infrastructure, and this is already impacting the climate-proofing of cities. In this context, the idea of resilience has been gradually embraced by the water sector, but the term itself is not yet universally defined, nor operationalised. Here, we propose a methodology to assess the resilience of a UWS, defining it as the degree to which the UWS continues to perform under increasing stress. A resilience assessment method is then proposed as a 'stress-test' of UWS configurations, under increasingly more stressful scenarios. We then demonstrate a toolbox assembled for the proposed analysis using, as a proof of concept, a semi-synthetic case study. Results are promising, suggesting that the approach could assist in the uptake and evolution of resilience thinking in strategic water infrastructure decision making, leading to water-wiser cities.

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Decision support; future scenarios; resilience assessment; urban water systems; water infrastructure; strategic planning

1. Introduction: water infrastructure planning under uncertainty

Water services are currently (and for the foreseeable future) facing significant challenges in the form of internal and external *pressures*. Examples of pressures can be found (a) at the supply side (in terms of both quantity and quality) due to hydro-climatic changes and resulting uncertainty (b) at the delivery side, as infrastructure itself gets older and less reliable in a context of limited new investment and (c) at the demand side with demographic and socio-economic trends changing demand levels and patterns while levels of service and related customer expectations increase (Brown, Keath, and Wong 2009; Rygaard, Binning, and Albrechtsen 2011). Some of these pressures occur outside the remit of the Urban Water System (UWS) decision maker (e.g. supply-side uncertainties due to large-scale climatic changes), some occur within (e.g. delivery side challenges addressed within an asset management context) and some occur in an intermediate space where the water system decision maker has some influence but no direct control (e.g. demand side changes relying on end user behaviour change). These three interconnected systems (termed external, internal, and transactional, respectively, within this paper) can be seen in Figure 1.

Although the specific aims of the water industry are (and will probably remain for the foreseeable future) centred around customer satisfaction, costs minimisation, optimisation of water and effluent quality, and environmental protection, the way the overall system is designed to perform under different, uncertain conditions across these three interconnected realms, over the longer term, can vary significantly. In this paper, we argue that, although performance of individual technologies and specialised (sub)systems is more or less understood, it is far less clear how overall urban water system performance is affected by a deployment of a portfolio of different technologies, within a given design strategy for a given future or sets of alternative futures. What water companies typically need to know is how their system is likely to behave when faced with changing conditions (climatic trends, asset deterioration, behavioural patterns, etc.) as well as accidents/incidents and/or extreme events (e.g. black swan effects in the physical, social, or economic spheres). The wider the system boundaries and the longer term the thinking, the more important and challenging it is to conceptualise formally the difference between alternatives (Makropoulos 2017). As such we suggest that what is required is an internally consistent, theoretically valid, and computationally robust way to assess different aspects of the overall urban water system's performance under uncertainty, so that options can better be understood and evaluated by water companies in the process of strategic planning.

We further argue, in accordance with current thinking among urban water scholars preoccupied with long-term system performance (see Butler et al. 2017) that the classic response to long-term uncertainty, that of overdesigning systems to be 'full proof' is as expensive as it is futile.

This is where new thinking about the desired properties of a water system that is subject to significant long-term uncertainties is required and where a new language for system design and a

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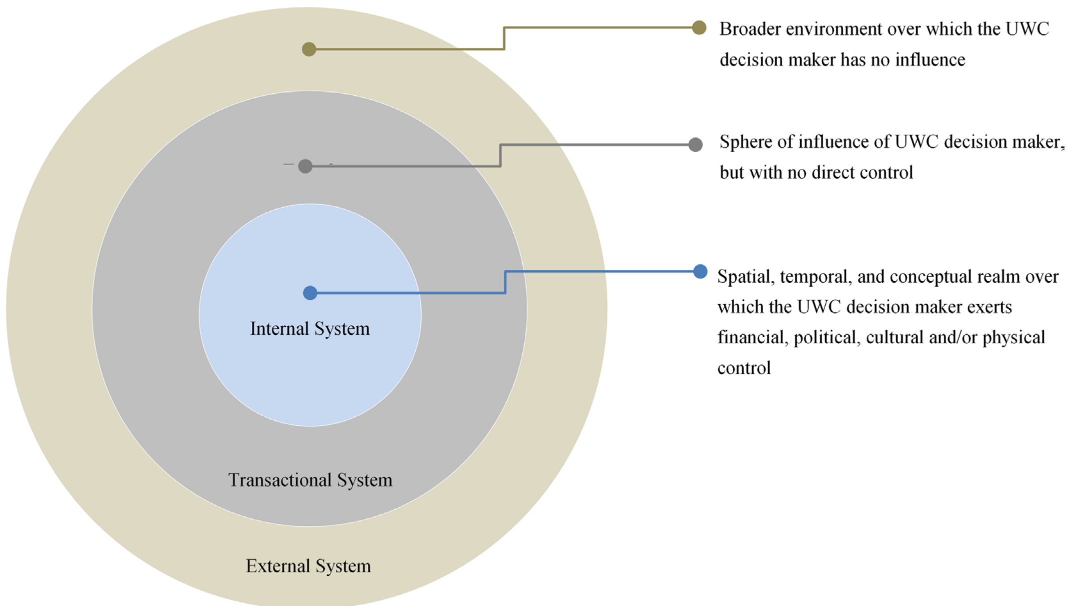

Figure 1. Interconnected systems and UWC decision-maker influence.

way of operationalising this new language comes into play. In short, we argue that the water industry is in need of a methodological shift in long-term strategic planning. This work focuses on the articulation of such a new methodology and its operationalisation through a toolbox that allows its application for different water systems, based on the concept of *resilience*.

2. Resilience: from an elusive concept to an operational method

Resilience has been recently emerging in the policy discourse on 'future-proofing' for a range of systems, from energy to agriculture and from the economy to water systems (Rockström et al. 2014). However, the term remains rather elusive with different authors proposing different definitions, more attune to their different standpoints with the quest for a common, ubiquitously accepted definition is still, arguably, at its infancy (see for example Butler et al. [2014], Mugume et al. [2015], and Pizzol [2015]). That is, however, not to say that some common ground between recent attempts to develop formal definitions of resilience does not emerge from the literature: It is generally agreed, for example, that resilience is a property of the system as a whole, rather than a property of an individual element or unit, and it is also suggested that resilience is a key property for the sustainability of a system. Following this (limited) common ground, different definitions are mostly variations of the following two central themes, both linked to the original definitions of resilience within the realm of ecological systems (Pizzol 2015).

- 'The amount of disturbance that a system can withstand without changing self-organised processes and structures' based on early work by Holling (1973).
- 'The return time to a stable state following a perturbation', see for example Brede and de Vries (2009).

Pizzol (2015) argues that there are two main ideas that literature returns to when resilience is discussed, as follows.

- Resilience depends on both system elements and how these elements are connected to each other. Specific designs of this connectivity lead to increased resilience (for example by increasing the number of connections between elements or their strength – an idea also connected, loosely, with redundancy or overdesign).
- There is a trade-off between resilience and efficiency, with some natural systems favouring resilience while most human systems favour efficiency. What is being argued is that systems can better manage increased stresses by allowing some less-than-efficient aspects to exist, even though this may result in 'a non-efficient performance of their main function'.

It should be noted here that different authors have used these elements differently to derive suitable definitions of resilience specifically for engineering systems. Butler et al. (2014) as well as Mugume et al. (2015), for example, suggest that the key properties of interest in engineering systems are in fact 'continuity and efficiency of system function during and after failure', arguing from a 'function over form' perspective. In other words, they suggest that there is a clear difference between ecological systems (that have emerged through evolution) and engineered systems (that have been explicitly designed for some purpose). Yet, the difference in question is not all that clear: both continuity of performance under stress and efficiency in engineering systems in their own right, are well understood concepts, operationalised through specific performance metrics. We argue that the added value from introducing the concept of resilience specifically for engineering systems comes from a working definition much closer to that of ecological systems. In this work, we adopt the lineage of the term as originally defined by Holling (1973), understanding resilience as 'a measure of the persistence of systems and of their ability to absorb change and disturbance and still maintain the same relationships between populations or state variables'. In the same vein, Walker et al. (2004) discuss resilience as 'the capacity of a system to absorb disturbance … so as still to retain essentially the

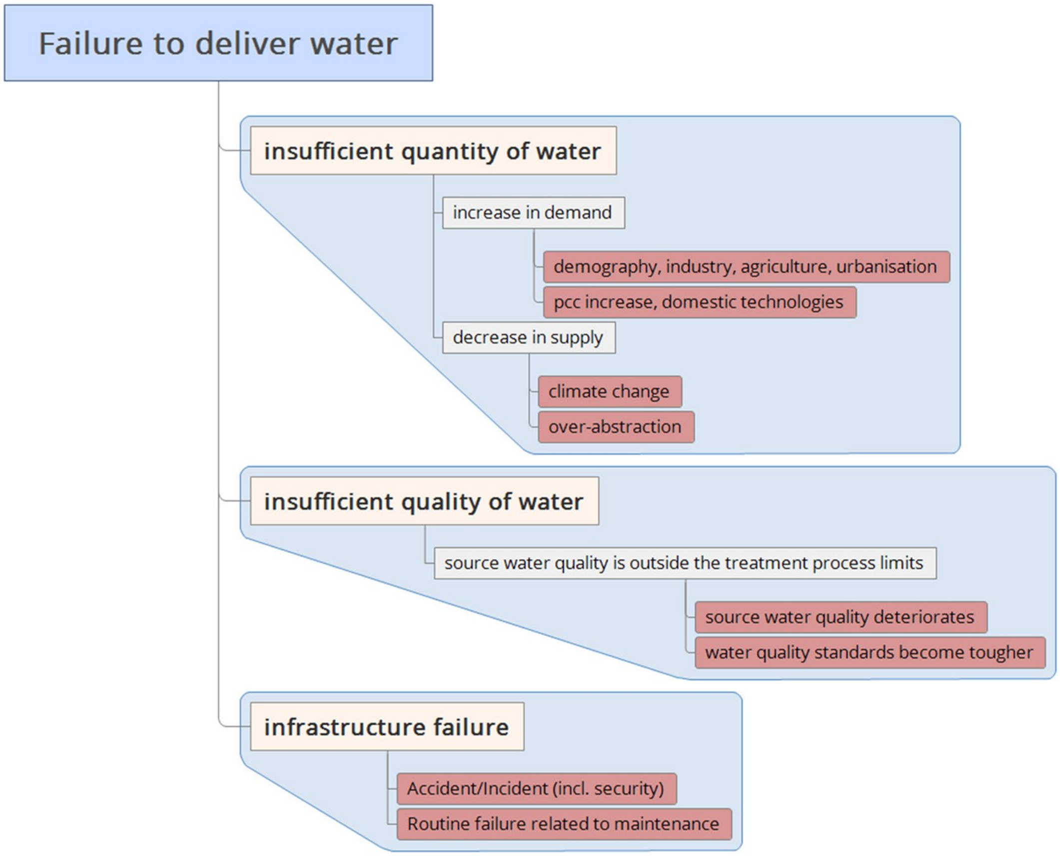

Figure 2. Different functional (quantity and quality) and structural (infrastructure) failure modes of water services for the water quantity objective.

same function, structure, identity, and feedbacks'. This suggests the ability of a system to keep the values of its state variables within a given 'domain of attraction' (Gallopín 2006) in the face of perturbations, and as such could in principle be measured by the magnitude of the perturbation that can be absorbed before the state of the system falls outside that 'domain'.

Following this rationale, we define resilience, for the purposes of this work, as *the degree to which an urban water system continues to perform under progressively increasing disturbance*. To be able to operationalise this definition we need to be able to define and compute its component terms: notably *performance* as a function of *disturbance*.

Performance is quantified here through *reliability*, which is defined for the purposes of our work as 'the ability of the system consistently to deliver its *objectives, considered over a timespan*'. This extension of the term 'reliability' allows us to account for failures beyond the typical use of the term in the literature (see for example Mays [1989]) and across internal, external, and transactional systems, as depicted in Figure 1, and hence to map the effects of different pressures on the resilience of a water system. As an example, Figure 2 presents a set of pressures that could affect the delivery of water, i.e. reduce the ability of a water company to achieve its objective to deliver sufficient quantities of water to customers. The way in which a pressure results in a failure of the system is termed hereafter 'failure mode'.

Water companies, of course, do have other objectives as well, beyond delivering the required quantities of water. The objectives of the Dutch Water Sector are presented as an example in Table 1.

Table 1. Dutch Water Sector objectives (RIVM 2004).

Objective	How is this quantified?
Water quantity	Ability to deliver water (substandard supply minutes, customer minutes lost)
Water quality	Ability to meet water quality standards (fraction of samples not meeting standards)
Environment	Ability to protect the environment (total emissions, limits set by environmental legislation – such as meeting Good Ecological Status)
Customers	Ability to meet customer expectations (partly related to the three objectives above – but also with other key issues such as, *inter alia*, the relationship between customers and water service providers

Although in this paper we will demonstrate the proposed methodology looking only at the water quantity objective, in principle the same method can be applied for any of the objectives of Table 1 (or any other objectives of this type that can be quantified in terms of reliability). It should be noted, however, that even when considering the 'water quantity' objective only, one needs also to take into account water quality and other pressures that could deter a water company from delivering the required quantity (as seen in Figure 2). In the case study presented below, these pressures and their associated failure modes are indeed taken into account.

Reliability itself can be calculated in different ways: in the case of The Netherlands, for example, a widely-used reliability definition is the cumulative duration of failure to deliver water to the customer (in minutes lost). However, one can also define reliability by focusing on either the frequency of disruptions or the volume of water not delivered, or indeed some other undesirable quantitative water supply aspect, each providing different insights into the water system's performance (Atkinson et al. 2014).

In this work, we use the following two reliability metrics in order to quantify performance in terms of water quantity and use in order to calculate resilience. The first reliability metric, which can also be termed *Volumetric Reliability* (R_V), is expressed as

$$R_V = 1 - \frac{\Sigma \text{ deficit}}{\Sigma \text{ demand}}, \quad (1)$$

where 'deficit' is the volume of water not delivered in each simulation timestep and 'demand' is the volume of water requested by all users in each simulation timestep, summed over all simulation timesteps.

The second reliability metric is a more typical definition of reliability related to the frequency of interruptions (henceforth termed *Frequentistic Reliability* (R_F) and is expressed as

$$R_F = 1 - \frac{\text{number of failures}}{\text{number of simulation timesteps}}, \quad (2)$$

where 'number of failures' is the counter of all simulation timesteps in which a failure to meet supply occurred (irrespective of volume not delivered) divided by the number of timesteps in the complete simulation.

It should be noted that other scholars have proposed that water quantity reliability metrics such as volume not delivered (Equation 1) could in fact be considered measures of resilience per se (e.g. Butler et al. [2014]). Here we would argue that, from an Ockham's razor (terminological parsimony) viewpoint, it would be preferable to keep all variants of metrics related to water quantity provision (volume and frequency) as part of reliability, regardless of whether loading conditions are normal or exceptional, and reserve the term resilience for a higher property of the system (its behaviour under pressure – as discussed above). It should also be noted that in our definitions we have explicitly avoided including efficiency as part of the discussion of a system's resilience. That is because, although efficiency is certainly a desired property of an engineered system (Butler et al. 2014), we tend to agree with Pizzol (2015) in his realisation of a trade-off between efficiency and resilience. We find that often enough resilience, in the way defined in this work, comes at the expense of efficiency and that this is a major insight of work into resilience for engineering systems, which could change the design paradigm of these systems in a fundamental way. As such, we propose that efficiency needs to be kept separate, as an independent variable of a configuration under study, to allow the trade-off to be observed explicitly and decisions to be reached using a multi-objective, Pareto optimality approach, where the independent properties to be maximised for a given system would be resilience and efficiency (the later possibly including the capital and operational costs of the configurations under study).

Before we proceed with linking our (expanded) working definition of reliability to the concept of resilience, we introduce one more related term, which can also be quantified using the proposed approach: that of *robustness*. *Robustness* is a term often associated with performance and resilience (Herman et al. 2015; Jeuland and Whittington 2014). It is a desired trait of a system in the sense that a resilient system can absorb stresses by being robust. While resilience refers to the ability of the system to cope (well or otherwise) with failure, robustness is the level of pressure that the system can take *without* failing (Redman 2014). Given that for engineered infrastructure (and water systems in particular) a certain amount of failure is always acceptable and is foreseen in the system's design (e.g. dimensions of water system elements are defined for given return periods of hydrologic events), hereafter robustness is defined as *the extent to which a system can keep performing within design specifications under increasing stress*. This is also consistent with the popular image of robustness in the 'palm tree versus the sycamore tree' (Read 2005) analogy, while both accounting for and providing a useful (i.e. actionable) distinction between resilience and robustness, as different aspects of the behaviour of a given system under pressure. As such, a robust system is also resilient, but the converse does not necessarily hold: a system can be resilient without being robust.

With these definitions in mind, we now attempt to visualise what a change in the relevant behaviour (i.e. the performance) of the system under stress would look like. The graphical expression of performance, quantified through (any) one of the possible metrics of reliability, can be seen in Figure 3, termed a *resilience profile* graph hereafter for the purposes of our work. The graph is, essentially, a stress–strain diagram, with the behaviour of the system under increasing disturbance communicated through the area under the curve. Each point of the graph is a calculation of the reliability of a given objective being met (*y*-axis), under the conditions specified by a particular stress scenario (*x*-axis). The *x*-axis of the resilience profile graph is constructed as a series of progressively more extreme disturbances in the form of scenarios and is therefore by definition an ordinal scale. Note that these disturbances cover, in principle, the entire extent between stresses *within* design standards and stresses (well) *beyond* design standards. To scale resilience and robustness to a maximum of one, we propose that the area under the curve is divided by the area of a 'completely robust' system, and that robustness is divided by the number of points in the resilience profile diagram (i.e. the number of scenarios analysed). Observe that, in Figure 3, *increased* strain (resulting from increased stress) is depicted as a *decrease* in reliability. This representation has the advantage of allowing larger areas under the curve to represent increased resilience, which is a visually intuitive result. It should also be noted that the idea of depicting resilience in different forms of stress–strain diagrams is gaining traction lately as seen for example in Butler et al. (2017) for urban wastewater networks.

A graphical summary of the proposed terminology, arising from the proposed definition of resilience, can be seen in Figure 4.

To produce such resilience profile graphs for a given water system, we propose the following methodological steps.

(i) Select an urban water system to test and identify its current (benchmark) state.
(ii) Set up alternative configurations for the same water system, where different design philosophies and interventions are applied to support them (including technical and non-technical measures), see for example Makropoulos and Butler (2010).
(iii) Build one or several models for each configuration. In this work, we will demonstrate this with the Urban Water Optioneering Tool (UWOT) model (Makropoulos et al. 2008; Rozos and Makropoulos 2012, 2013; Rozos,

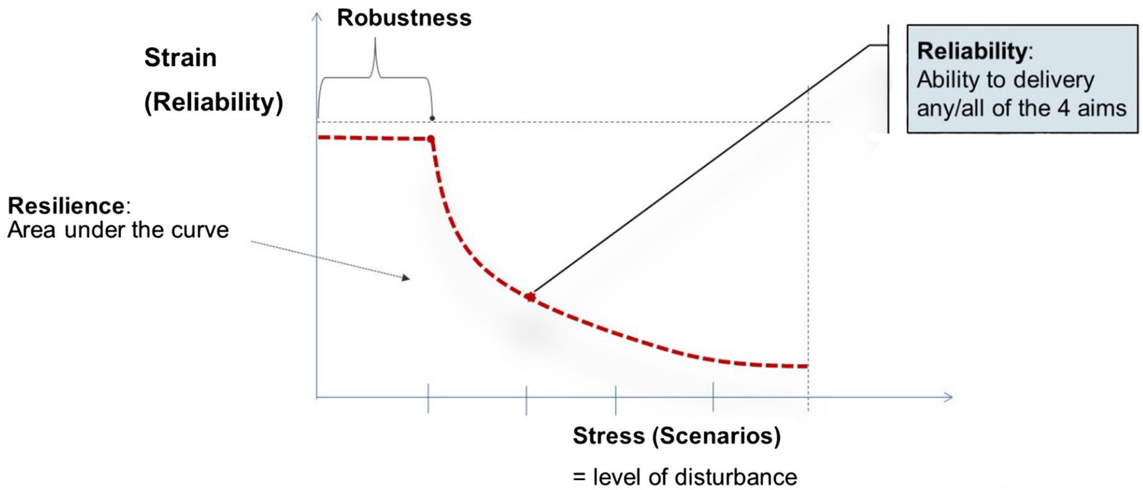

Figure 3. Resilience profile graph.

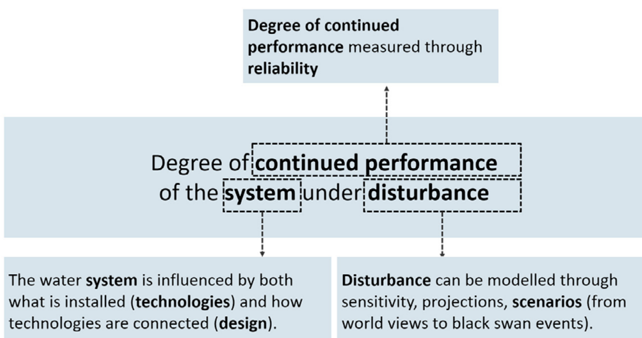

Figure 4. A graphical summary of the proposed methodology.

Makropoulos, and Maksimović 2013) as discussed in next section.

(iv) Develop a set of scenarios following a vector of increased disturbance (see the next section) and present a narrative linking a set of external variables that are expected to influence the internal system through two 'pathways':

(a) either directly affecting some variable of the internal system (e.g. a climate scenario affecting rainfall that affects resource availability in the simulation); or

(b) affecting some variable of the transactional space (Figure 1), which then influences an internal system variable, e.g. socio-economic climate (external) affecting customer behaviour (transactional) leading to the adoption of water efficient appliances (internal).

(v) Subject eachmodel to the *same scenarios* to allow for the performance of the system to be evaluated.

(vi) Plot *a resilience profile graph* of the tested system for every alternative intervention set.

(vii) Explore a number of pertinent questions, including for example:

(a) testing different interventions to see which improve the system's resilience more;

(b) testing the same interventions under different scenarios.

In the following sections, two software tools developed and customised to allow these steps to be implemented are briefly presented. The tools are then used to develop resilience profile graphs for a semi-hypothetical water system, based on a typical Dutch City, as a proof of concept.

3. A toolbox for developing resilience profile graphs

Two main tools were developed and customised in this work for calculating the resilience profile graph (Figure 3) of a given urban water system: (a) the Scenario Planner Tool for developing the *x*-axis and (b) the Urban Water Optioneering Tool for calculating the reliability of a given system on the *y*-axis. In the following sections, we will briefly describe each tool, giving more emphasis to the former, as the latter has been presented in detail in previous publications.

3.1. Scenario planner

Our research investigates and explores the scope of future socio-metabolic circumstances within which the urban water cycle, and the actors who manage it, may need to function. By definition, future socio-biophysical phenomena involve non-actualised possibilities and unexercised powers (Patomäki 2006). Thus, the future is 'open', but not 'empty' (Adam and Groves 2007). This means that the future is partially subject to shaping via the agency of (human) actors but that there are also parts of the future that are already 'on the way' although they have not yet materialised due to lag in the systems. These 'futures in the making' are also considered to be 'actual', even though they have not materialised into an 'empirical' form. This classification is important to our methodology because we are looking to explore future socio-metabolic circumstances for which no direct empirical observation is possible. Complexity and uncertainty are, of course, key aspects of this endeavour and different approaches to future exploration exist for different levels of complexity and uncertainty (Figure 5).

The approach adopted in this work is one of exploratory scenarios, allowing us to look into diverse future socio-metabolic circumstances for which 'simple' parameter sensitivity, or even extrapolations of historic parameters, are not applicable. The central idea is to simulate the performance of various options

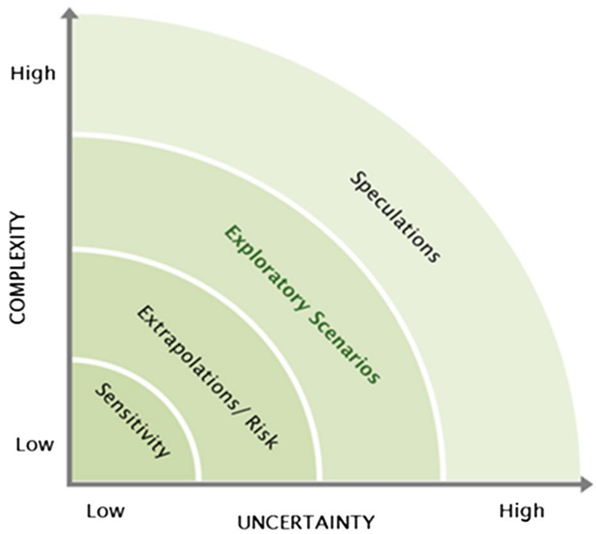

Figure 5. Different approaches to future exploration for varying degrees of uncertainty and complexity (adapted from Zurek and Henrichs [2007]).

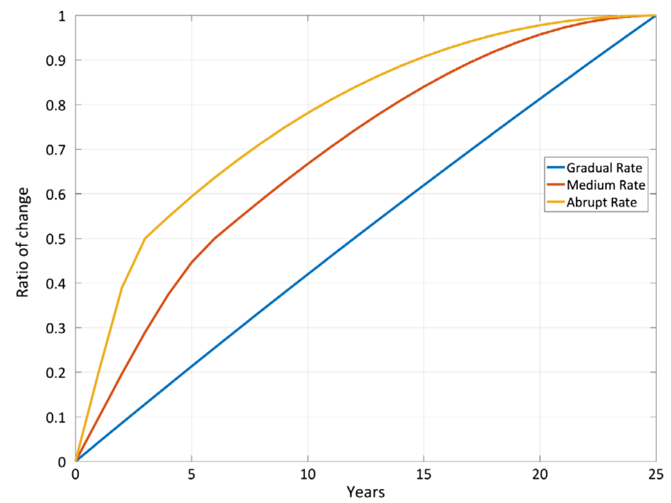

Figure 6. Ratio of change over an example simulation horizon of 25 years for specified rates of change: gradual, medium, and abrupt. All three rates refer to the same magnitude of change over the same period.

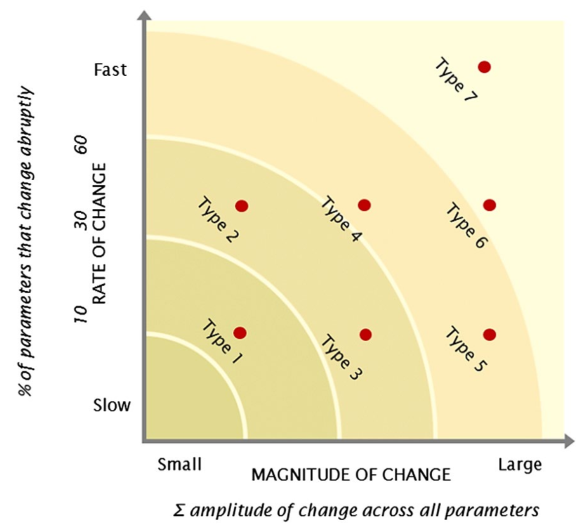

Figure 7. Types of future scenarios as a function of rate and magnitude of parameter change. Type 1 is the mildest, Type 7 is the most extreme.

and configurations of a water system, under future 'real world' conditions. However, as the futures we are considering are open-ended and complex, there are implications for how we define the categories and parameters needed to describe a future scenario. The ultimate goal here is to perceive various real-world entities as parameters appertaining to a specific category. The three basic categories we distinguish here are taken to be the sociocultural, the biophysical, and the socio-biophysical (see also Fleetwood [2005]). A distinction is made between these three categories because of the different mechanisms by which they influence structural elaboration either via reproduction (morphostasis, no change) or transformation (morphogenesis, change). These 'static' categories are integrated into a model of morphogenesis to reflect our understanding of how change occurs in complex, socio-biophysical systems.

The model of morphogenesis we used in this work employs two attributes to describe the relative change of each parameter over a specified horizon, namely *rate* and *amplitude*. Rate can be simplified to duration: within how many units of time did the given amplitude of change occur? To distinguish between linear and exponential change, we adapt this definition: within how many units of time did the majority (> 50%) of the given amplitude of change occur? The rate is thus relative to the time horizon: for 'gradual' change, most of the given amplitude of change occurs over most of the time period; for 'abrupt' change, most of the given amplitude of change occurs within a short time window. A 'medium' rate of change is somewhere in between. Three different rates of change that were used in this work are presented in Figure 6. These categories are only meant to structure the scenario space in a systematic and replicable manner. A scenario that includes a greater percentage of parameters that change 'abruptly' is taken to represent more severe structural elaboration with a greater 'rate' of change. These percentages are used to rank the scenarios and thus structure the scenario space. For scenario ranking purposes, the 'rate' of change is considered to have greater impact on an UWS than the 'magnitude', because it determines the window of time that is available to the decision maker for taking adaptive measures. For defining the types of scenarios that are considered interesting to explore, we include types with equal 'magnitudes' and different 'rates'. For example, as can be seen in Figure 7, Type 1 and Type 2 scenarios are characterised by equal 'Magnitudes' of change but in Type 2, more than 30% of the parameters changed abruptly compared to 10% for Type 1. In our work, Type 1 scenarios involve the least severe types of change with Type 7 being the most severe.

To demonstrate the methodology, a sample set of parameters from the transactional and external space was selected and operationalised (Table 2). Once the parameters had been defined and the scenario space had been structured, the next step was to define a method for choosing the range of values for each parameter. Attempts have been made in the scenario-development literature at making the estimation of values for scenario parameters less subjective. For example, once the parameters

Table 2. The complete set of parameters[a] used to demonstrate the methodology.

Parameter	Operationalisation	Rationale
Population growth	% of change in population	Growth or decline of the population affects, *ceteris paribus*, demand for resources, goods and services
Number of households	% change in households	In some cases, a more relevant unit for utility companies. Can increase even when population does not
Age distribution	% of people over 65 in cities	Age is an important factor in lifestyle. Can be associated with increase in water demand and increase in medicine use
Ethnic composition	% of non-western immigrants in cities	Cultural aspects of lifestyle can have an effect on water demand, consumption patterns, attitude towards government
Knowledge development	% of GDP for scientific research	High rate of knowledge development can be associated withmore availability of technology, higher educated workforce
Electricity Price for heavy users	% change (euro¢ per kW h, 2000 prices)	Will have an effect on operating costs
GDP (per capita) of city	% change (€)	Much used measure of the size of the economy, will through taxation have an effect on amount of public income
Public finances	% of GDP public expenditure	Determines in part the money available for public services
Temperature	% change (°C)	Has impact on all kinds of socio-biophysical process and on the city's socio-metabolism
Average rainfall summer/winter	% change (mm/year)	Has impact on all kinds of socio-biophysical processes and on the city's socio-metabolism
Industry water demand	% change (hm^3/year)	Adds to overall water demand
Horticultural water demand	% change (hm^3/year)	Adds to overall water demand
Domestic water use (behavioural)	% change (l/p/d)	Signifies the effect of behaviour on domestic water use, assuming technology to be constant
Water governance	Form of governance	Affects how the water sector is perceived by citizens and other organisation
Risk acceptance	The extent to which risk is accepted	Affects the expectation citizens have of government and companies in terms of risk
Trust in corporations	Ordinal scale (low/medium/high)	Affects interaction between citizens and corporations
Trust in government	Ordinal scale (low/medium/high)	Affects interaction between citizens and government
Quality standards drinking water	Ordinal scale (low/medium/high)	Quality standards determine the minimum quality that needs to be delivered and thus form part of the failure mechanism
Surface water quality parameters[b]	Probability distribution	These parameters provide an overall indication of the quality of the water of the incoming river in WaterCity. They form a mix of microbiological, biochemical and chemical components

[a]A list of data sources used to quantify these parameters can be found in the supplemental data for this article, which can be accessed at https://doi.org/10.1080/1573062X.2018.1457166

[b]Nitrogen (mg litre^{-1}), E. coli (CFU 100 ml^{-1}), Viruses/protozoa/bacteria, Chloride (mg litre^{-1}), Arsenic (µg litre^{-1}), Cadmium (µg litre^{-1}), Lead (µg litre^{-1}), Glyphosate (µg litre^{-1}), Carbendazim (µg litre^{-1}), Carbamazepine (µg litre^{-1}).

have been defined, parameter values can be estimated using fuzzy set theory (Kok et al. 2015) or fuzzy cognitive maps (Jetter and Schweinfort 2011). For the proof-of-concept application presented in this work, we used values from existing exploratory scenarios that had already been developed by Dutch authorities for other purposes.

The construction of these scenarios, which should be developed for all practical applications in collaboration with the UWS decision makers themselves, was facilitated in this work by a custom-built tool (called the scenario planner) that allows for (a) the selection of the parameters of interest for a set of scenarios and (b) the selection of the specific combination of parameter values that forms a specific scenario. An interface of the scenario planner tool can be seen in Figure 8. Further presentation of this tool, which is still under further development, is beyond the scope of this article, as the aim here is to showcase the general method rather than the specific tools used to implement it.

3.2. The Urban Water Optioneering Tool (UWOT)

UWOT was used as the main model for the simulation of the entire water system and the assessment of its performance in terms of the quantity objective (with its various failures modes). UWOT is a bottom up, micro-component based, urban water cycle model, which simulates the demand at arbitrary time steps and multiple network scales (from the household to the hydrosystem. Unlike typical urban water models, which employ a dual approach (simulating outgoing flows directly and assuming incoming flows to be equal to demand), UWOT adopts a simulation methodology that is based on a single approach for all urban water flows: as every urban water flow is caused by a demand (demand for potable water, demand to drain storm water, demand to dispose of wastewater, etc.), UWOT simulates the generation, aggregation, and transmission of demand signals, which, under normal (non-failure) conditions, are met accordingly by a flow. The routing of the demand signals extends from the household water appliances 'upstream' all the way to the water resources and 'downstream' to the disposal at the water bodies. More information on UWOT can be found in the publications of Makropoulos et al. (2008), Rozos and Makropoulos (2012, 2013), and Rozos, Makropoulos, and Maksimović (2013).

4. Case study

A synthetic case study was developed for purposes of proof of concept of the methodology. The case was termed 'WaterCity' (Figure 9) and is based on a typical but anonymised Dutch city. To demonstrate the method, we developed the following three alternative water system configurations.

(a) A current state, business as usual (BAU) model of the system (following standard practices of the Dutch Water Sector).

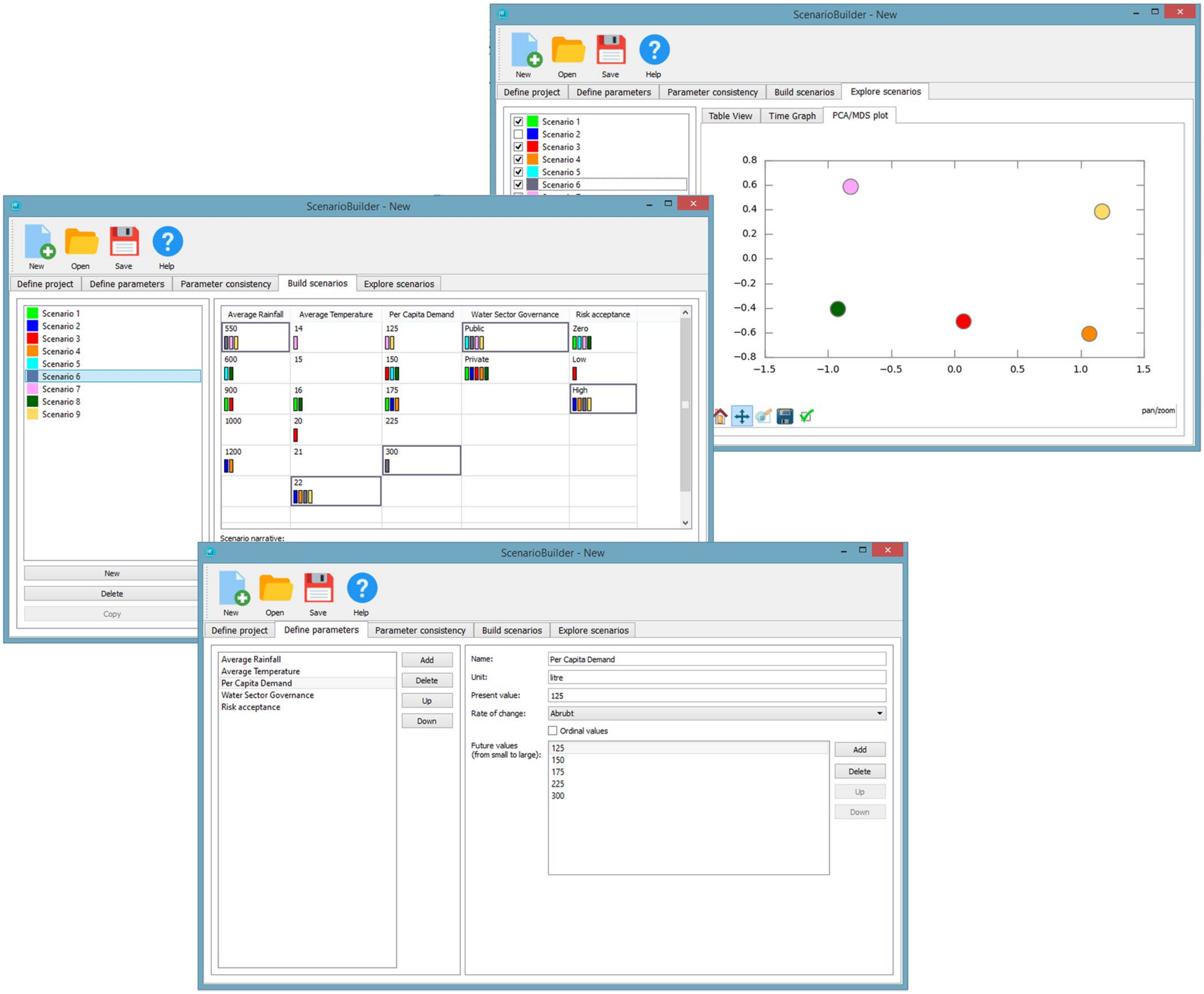

Figure 8. Screenshots of the Scenario Planner Tool. The user can compose scenarios based on a defined set of parameters, add values, and perform internal consistency checks. Once defined, a scenario is visualised. The user can then export the scenarios for use in UWOT.

(b) 'Next step' (NS) interventions, that could be implemented tomorrow (or be included in the next five-year plan and are to a large extent dependent on internal system variables), where a mix of novel but tested technologies are installed, together with a shift towards new design philosophies and smarter management of existing technologies and systems.

(c) 'Further ahead' (FA) interventions that need more time (and possibly more investment), which would typically need 10 or more years to be implemented.

The general properties, common to all configurations, are briefly described in Table 3.

The three water system configurations are described next.

In the case of BAU, the urban water cycle configuration is characterised by a conventional Dutch layout: water treatment is based on surface water and infiltrated water, wastewater treatment plants are large and centralised, and the city has some areas with separate systems for wastewater collection only. The technological 'bundles' included in the BAU system have the following key properties.

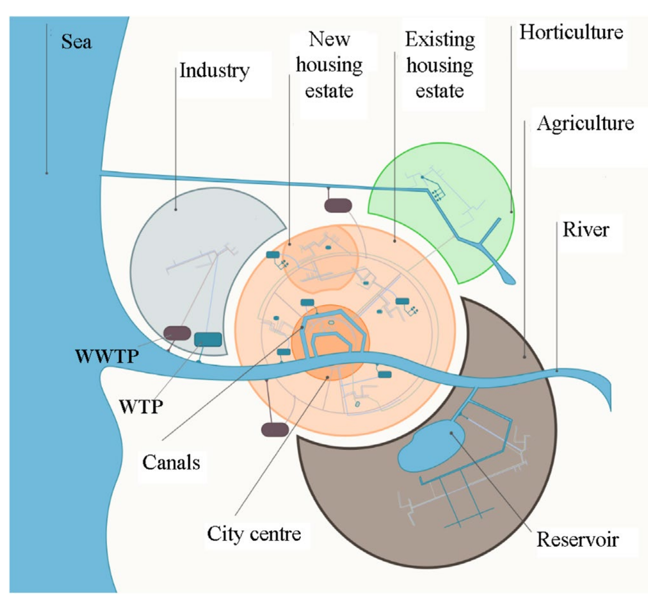

Figure 9. Schematic outline of the WaterCity.

Table 3. WaterCity general attributes.

Water bodies/sources	Areas and water users	Annual water demands[a]
• Close to the sea • Rain fed river (mean flow 300 m^3/s) • 10 hm^3 reservoir • Phreatic groundwater (type A) • Brackish groundwater (type B) • Confined groundwater (type B) • 850 mm mean annual rainfall • Potential for wastewater reuse	• Total area 230 km^2 • 500,000 inhabitants – 200,000 houses • Three different districts: Centre; existing housing estate; new housing estate • Agricultural & horticultural activities upstream of the river (225 km^2) • Industrial activities close to the sea (4 km^2)	• Drinking water 22.8 hm^3 (BAU, FA) or 16 hm^3 (NS) • Wastewater treatment and storm runoff • Industrial uses 5 hm^3 • Agricultural uses 22.8 hm^3 • Horticultural uses 22.8 hm^3

[a]All activities compete for the same resources.

- *Drinking water treatment.*
  - Groundwater (type U) abstraction bundle. The average required extraction is 11.5 hm^3/y, hence 50% of drinking water demand is produced from groundwater. The average flowrate is 1300 m^3/h (1.5 daily peak factor) and the installed capacity is 1950 m^3/h. Permitted annual extraction (concession) is 12.5 hm^3/y. Redundancy: abstraction in two well fields close to the river, east in the city.
  - Surface water bundle for drinking water production using a drinking water reservoir. The average flowrate is 1300 m^3/h, and the installed capacity is 1950 m^3/h. Redundancy: the entire treatment plant is divided in two production routes.
- *Wastewater treatment* is achieved by an activated sludge bundle. There is one central plant close to the river, west of the city. The performance margin is designed at 40 l/person/day.
- *Drinking water transport:* the bundle contains a primary network, a secondary network, and a tertiary network being 90% looped.
- *Wastewater transport* occurs through two bundles: a combined gravity sewers bundle is used in the urban areas (90%) and a combined pressurised sewer bundle is used in rural areas (10%).

The NS urban water cycle configuration differs from the BAU in a number of key features: local treatment of grey water at the household level is foreseen, as well as a central drinking water production plant using sea water as a source, also supported by Aquifer Storage and Recovery (ASR) technology for horticultural uses.

- *Wastewater treatment*. Wastewater treatment is now more decentralised. The bundle includes interventions at the household level, such as vacuum toilets, leading to reduced drinking water demand and local treatment of grey water. The drinking water demand is reduced by 30%.
- *Drinking water production from seawater*. One central drinking water treatment plant is located close to sea. The redundancy margin is set to a daily factor of 1.5. The entire treatment plant is divided in two production routes. We assume a price of 5 €/m^3 for the concentrate. The Reverse Osmosis (RO) step has significant losses (60%), hence the installed (influent) capacity is 6836 m^3/h, the average influent flowrate is 4558 m^3/h, and the concentrate flowrate is 2735 m^3/h.
- *Drinking water transport bundles*. This bundle resembles the BAU transport bundle, with central drinking water production and transport. It contains the looped primary and secondary networks and the tertiary network, which is 100% branched.
- *Storm water bundles.*
  - Centralised collection and transport of storm water. We assume that the required bundle equals the gravity sewer bundle.
  - *ASR water collection bundle* for horticultural water demand: the horticulture site collects the storm water locally and uses ASR for storage and reuse. The amount of collected storm water is sufficient to cover the horticultural water demand.

The FA urban water cycle configuration differs from the previous configurations in the following key features: drinking water production occurs at a local scale; wastewater treatment is expanded with advanced resource recovery.

- *Drinking water production*. Drinking water production is based on a multisource RO bundle. There are 100 multi-source RO drinking water plants, using locally available sources to produce drinking water. We assume one abstraction well per plant. The capacity is 40 m^3/h per plant. Hence 5000 people, or approximately 200 households, are served by one plant. The required collection bundles are:
  - 20 phreatic groundwater sources;
  - 20 brackish groundwater sources;
  - 20 surface water sources;
  - 20 'sewage' storm water sources, from the collected waste and storm water in the city;
  - 20 sea water sources.
- *Drinking water transport*. The transport of drinking water only requires a tertiary network. All drinking water production units and the tertiary network are connected.
- *Wastewater treatment*. There are two central resource recovery plants (nutrient factories). One is on the north, the other one is in the south of the city. Installed capacity per plant = 1300 m^3/h.
- *Wastewater transport.* The transport of wastewater occurs through a separate sewer system.
- *Storm water collection*. A separate centralised storm water network is required. This system resembles the BAU gravity sewer bundle. The storm water is used to feed a big central ASR system for horticulture and to provide source water for local drinking water treatment; the excess of the storm water is discharged to the environment.

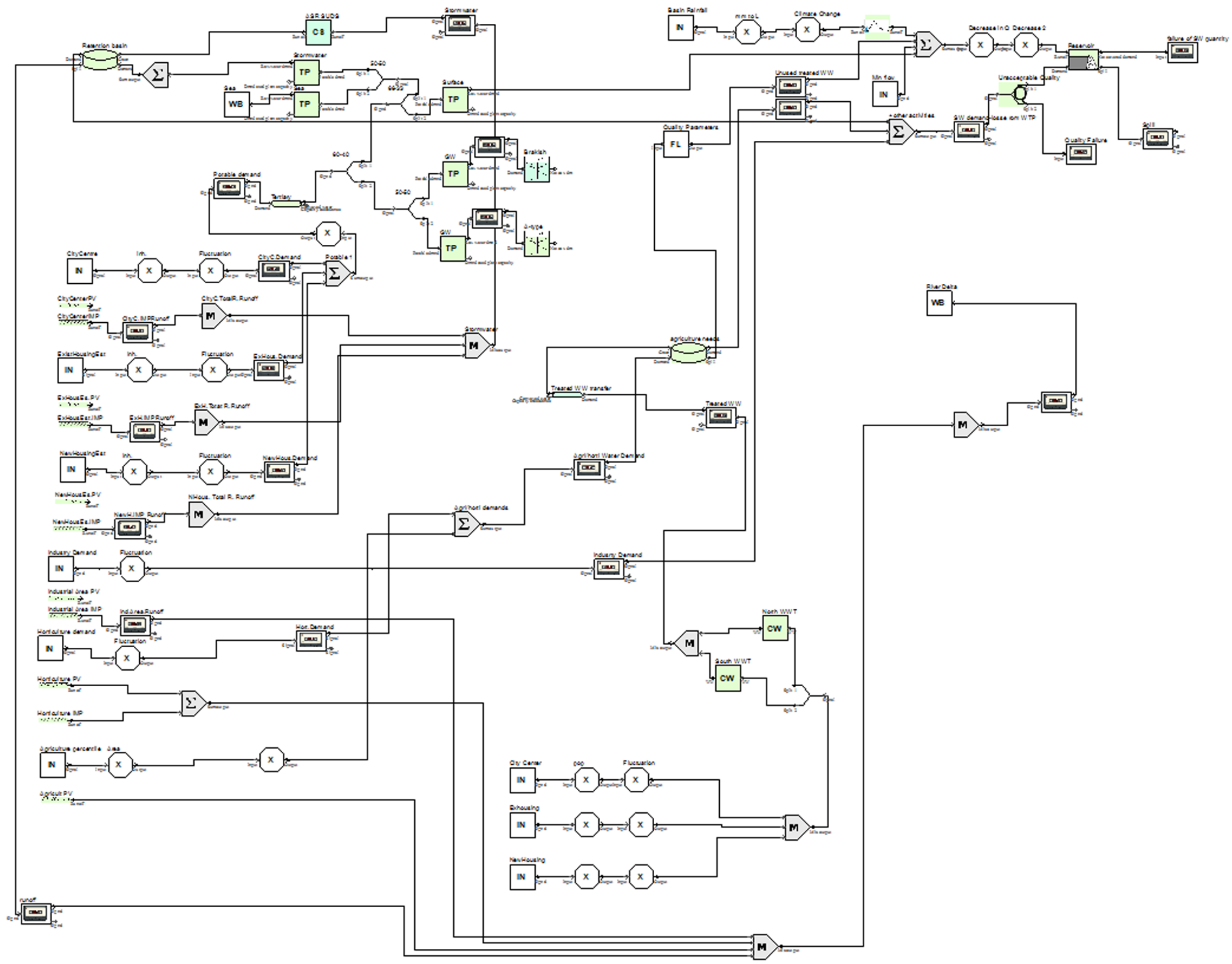

Figure 10. The FA configuration of the WaterCity system modelled in UWOT.

The FA configuration schematic in the UWOT environment is shown in Figure 10, as an example of a water system topology in UWOT.

A UWOT model of the BAU configuration of the WaterCity is made available through an open online repository to facilitate further work (Makropoulos and Nikolopoulos 2018).

The scenario parameters are incorporated in the UWOT models of the configurations either directly (e.g. the population parameter as a timeseries) or indirectly: some parameters affect general per capita water use (e.g. age distribution) or affect a system failure mechanism (e.g. quality parameters affect what is considered a water quality failure; public finances affect component maintenance and therefore affect component failure frequencies). A complete description of scenario parameter mapping onto model inputs is outside the scope of this paper. Seven future change scenarios as well as one no-change baseline were constructed and imposed on each configuration for a timeframe of 25 years, taken to be between 2015 and 2040. Figure 11 presents a summary of the main narratives behind these scenarios, focusing mostly on their differences. Note that each scenario contains the same parameters, which change in a different way (in terms of both rate and magnitude, as discussed earlier) on the basis of their own narrative. Examples of the parameter values used in two scenarios (specifically, Scenarios 5&6, termed 'Of old people and things past') and the information sources on which these specific values were based, are included in the supplemental data for this article, which can be accessed at https://doi.org/10.1080/1573062X.2018.1457166.

5. Results

Indicative results from the implementation of the method (stress-testing the three configurations of the WaterCity with the seven scenarios) can be seen in Figure 12. All three configurations are reasonably robust for the first three scenarios (Basic, 1, and 2). Looking closer, the BAU and NS configurations marginally suffice to cover completely the demand for the whole timeframe (2015–2040) since capacity reduction due to aging infrastructure results in some failures towards the end of the simulation period. These two configurations from scenarios 3 and upwards, characterised by demand increase, exhibit significant reduction in reliability in terms of potable water coverage. It is interesting to note that the FA configuration exhibits a (small) reduction in reliability even at 'low pressure' scenarios due to the

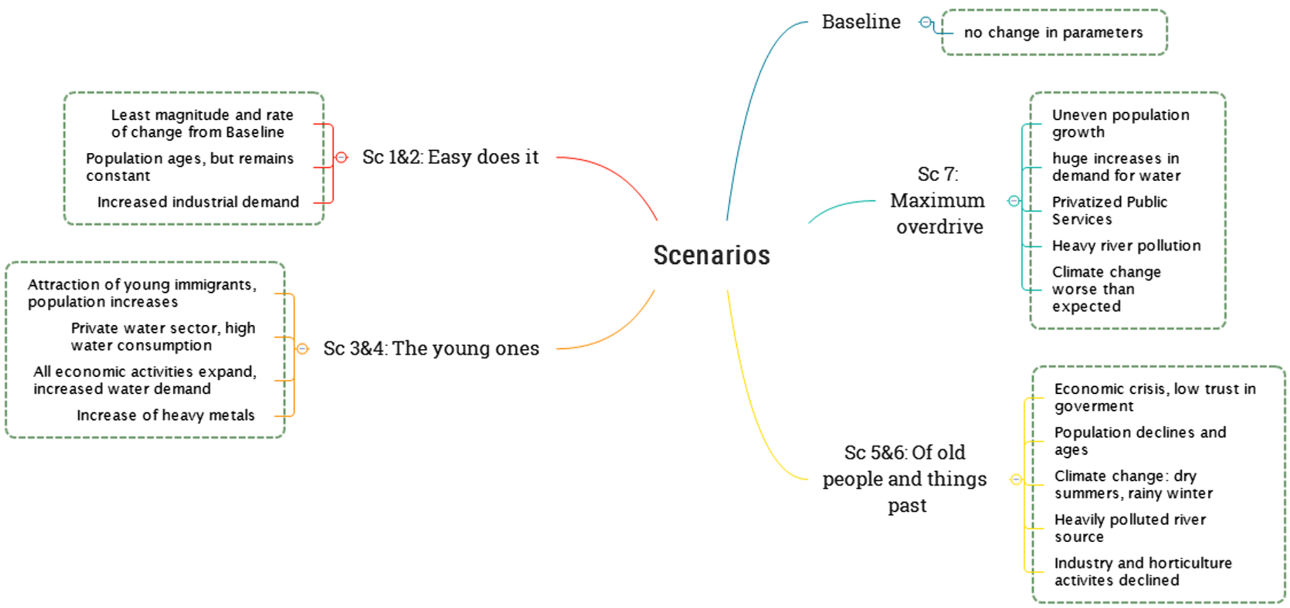

Figure 11. A summary of the main narratives/key differences of the scenarios used in the simulations. Each scenario was given a short name, indicative of the main assumption of the narrative (e.g. 'Easy does it' are scenarios of relatively mild changes across the board, while scenarios termed 'Of old people and things past' contain narratives dominated by aging populations, deteriorating infrastructure, and declining industry – see also the supplemental data for this article, which can be accessed at https://doi.org/10.1080/1573062X.2018.1457166).

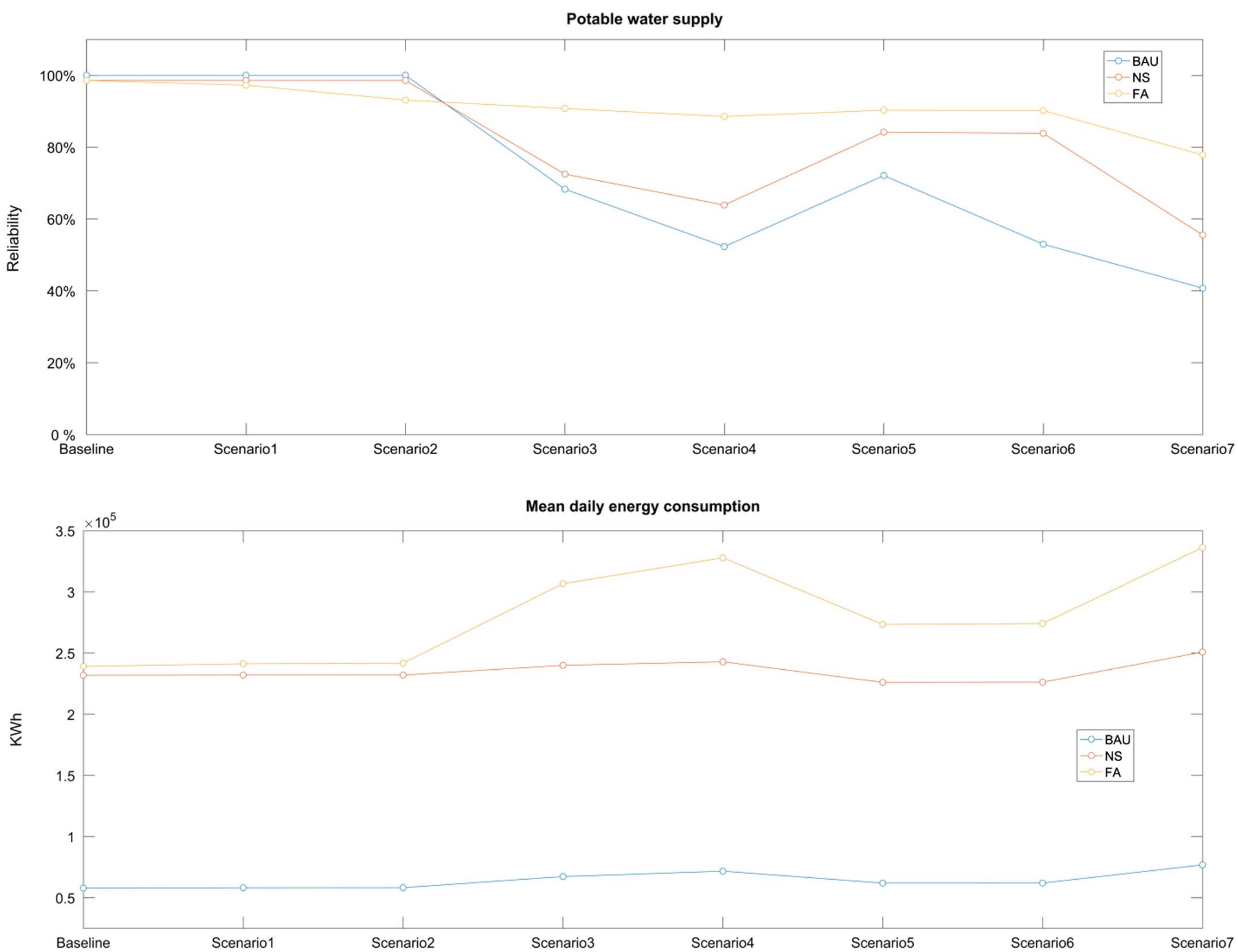

Figure 12. Top: simulation results of the volumetric reliability metric (Equation 1). Bottom: simulation results of mean daily energy consumption.

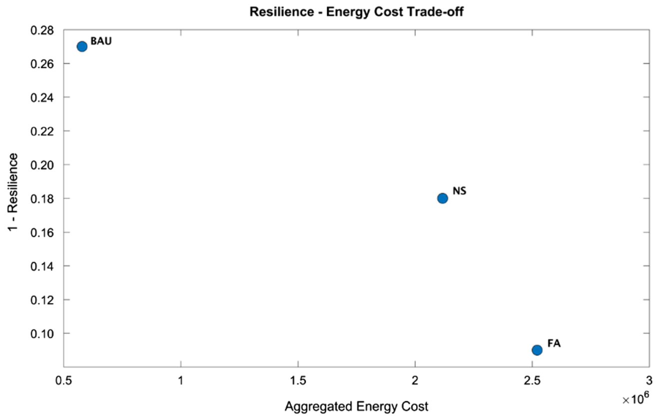

Figure 13. Trade-off between resilience and energy costs.

higher number of (small) component failures. However, from scenario 3 onwards, FA exhibits much higher reliability and as such is more resilient overall than the other two configurations. Following our definitions, it can be said that a distributed infrastructure configuration is more resilient but less robust than the more traditional, more centralised configurations. Although this is, of course, a case specific example, it does align well with the intuitive understanding that a centralised system will perform 'as designed' until the centralised infrastructure fails, but then it will fail spectacularly (more robust, less resilient) while distributed systems may exhibit more small failures throughout their life, but none catastrophic (less robust, more resilient). This result is interesting from the method perspective as it illustrates that the proposed approach (and the definitions on which it has been built) is able to provide such insights, for example on the trade-off between robustness and resilience, and inform comparisons between centralised and distributed options, which are central to much of the ongoing debate in the water sector (Makropoulos and Butler 2010; Marlow et al. 2013).

Comparison of the energy consumption in the three scenarios is also displayed in Figure 12 (bottom). Configuration FA is slightly more energy intensive than the NS configuration (note that the specific energy of FA water treatment is 3.23 kW h/m^3 against 3.43 kW h/m^3 of NS, but NS potable demand is 70% of FA potable demand). On the other hand, BAU is characterised by much lower energy consumption.

Finally, Figure 13 shows the trade-off between energy costs (which could also be thought of as an element of efficiency – see earlier discussion) and resilience. In this graph, 1-Resilience is plotted to allow 'best' solutions (in terms of both energy and resilience) to be closer to the beginning of the axes to assist visual interpretation of the results. From the figure, it becomes apparent that, to be able to improve resilience, both NS and FA configurations increase the amount of energy spent. What is interesting to note, however, is that improving resilience from the BAU to the NS configuration appears to be muchmore resource (energy) intensive, than to improve resilience by the same amount from the NS to the FA configuration. In other words, taking the second step in system modification (i.e. moving from NS to FA) can be implemented with a smaller energy cost while being rewarded with the same increase in resilience as the (much more expensive first step) from BAU to NS. Although this is, again, a case specific result, it does support the claim that the approach is sensitive to such insights and hence potentially valuable in strategic decision making, where these trade-offs are debated inside water company boardrooms.

Further experimentation with these (or other similar) configurations could focus on sensitivity analysis of key system elements (identifying for example critical points/decisions that would shift the resilience profiles for each configuration), look into better representations of the mapping between some of the more socio-economic drivers of the scenarios and model variables, as well as looking at different ways to incorporate water quality drivers, which have currently been bundled into a common metric.

6. Conclusions

This paper has presented a methodological framework aiming to help the water industry evaluate the long-term performance of different strategic interventions in the urban water system in a structured, evidence-based way, built around the concept of resilience. A set of tools used to operationalise the framework was briefly presented and a proof-of-concept analysis was undertaken using a semi-hypothetical, but realistic, case study. The results were examined to see if the types of pertinent questions posed in the process of strategic water systems planning could be supported using the proposed method. It is argued that the analysis does provide insights on, for example, trade-offs between resilience and robustness, between centralised and decentralised systems, as well as between resilience and efficiency (here presented in the limited guise of energy costs). The authors are currently applying the method to a real-world water system in The Netherlands, comparing between several options for system re-configuration proposed by the system operators. The method has the advantage of accounting for several stresses that can affect a UWS alone or in combination and therefore present a much more comprehensive overview of long-term system performance under uncertainty, without assigning specific probabilities to individual futures. As such it is suggested that the methodology could inform strategic planning under large-scale uncertainty and provide evidence-based support for investment decisions concerning future system configurations.

Clearly, the method is far from perfect: two obvious shortcomings are the need to translate several qualitative scenario parameters to (necessarily restricted) model inputs and as such introduce subjective bias into model results. This issue is always present when looking at complete socio-technical systems and has been addressed, to some extent, through the development of an enhanced toolkit for a more explicit representation of the complete system, as reported in Makropoulos (2017). However, as in all modelling work, internalising some system elements ultimately only pushes (subjective) assumptions to other system boundaries. The second shortcoming relates to the fact that, despite the best intentions and an active imagination, scenario planners always fall short of reality, which never ceases to amaze us. This quest to account for unknown-unknowns will be the holy grail for future studies, requirements engineering, and evidence-based decision making in the foreseeable future (Pawson, Wong, and Owen 2011) and efforts to account for this in a 'brute force' manner by testing 'all possible values' of certain parameters have to face the open-ended, highly complex, and interconnected nature of the socio-political and even physical landscapes, making them beneficial in only a small subset of pertinent questions. We would argue that, ultimately, the constraint is not in the inability to imagine (by definition) unknowable futures, which could improve with the advent of new ways of experimenting, such as serious games (Savic, Morley, and Khoury 2016), but in the willingness of the water sector to be prepared to think outside the box and prepare for unknowns. The proposed framework is flexible enough to account for any type of scenario developed, in collaboration with stakeholders, from the incremental to the most daring.

The framework will continue to be developed and demonstrated further by applying it to real-world case studies and complementing it with a robust set of supporting models and tools while also evaluating different aspects of the system including water quality and different types of events, such as the inclusion of 'wild card' extreme, one-off events in long-term scenarios. We also provided UWOT model files used in this work, through an open, online repository (Makropoulos and Nikolopoulos 2018), to allow interested readers to reproduce and/or improve upon our results and to use WaterCity as a testbed for additional research into water systems resilience. It is envisaged that this type of study will help fill (part of) the gap between policy rhetoric, specific water technology development, and strategic infrastructure planning, building on systems thinking and hydroinformatics for a more resilient water sector.

Disclosure statement

No potential conflict of interest was reported by the authors.

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