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Developing water wise cities:

A Resilience Assessment method applied to Oasen's water system

KWR Watercycle Research Institute

BTO

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2. Executive Summary

Strategic asset management and long-term infrastructure planning for urban water systems is currently increasingly challenged by a series of conflicting trends and processes. These include demand issues due to urbanization and increasing expectations of the services provided, water supply issues in terms of quantity and quality, especially in view of large-scale hydro-climatic changes and delivery issues as aging infrastructure becomes less reliable, and new investment is limited. These issues impact the reliability and climate-proofing of cities, as aging infrastructure, often designed with a single "extrapolated" future in mind, restrict the flexibility and adaptability of the entire socio-technical urban system in view of more dynamic futures. For this purpose, the idea of resilience has been gradually embraced by the water sector as the way of moving away from the ever-more elusive objective of 'fail-safe' infrastructure design towards a more realistic 'safe-to-fail' approach, and thus dominates policy discourse in future 'proofing' systems. The new aim is to design systems able to perform under significant long-term uncertainties, essentially being more "resilient". However, the term itself as well as the framework to operationalize its analysis are not well defined; both are actually at their infancy.

This work follows on the articulation of such a new methodology to assess urban water systems' resilience and its operationalization through a toolbox developed in our previous research that allows application of the methodology for different water systems. As a result, it forms an extension of the Water Wise Concepts project, in which we developed the assessment methodology by defining resilience as "*the degree to which an urban water system continues to perform under progressively increasing disturbance*". Using this definition, we are able to quantify the elusive 'resilience' system's attribute by computing its component terms: notably performance as a function of disturbance. Performance is measured here through reliability, which is defined for the purposes of our work as "the ability of the system to consistently deliver its objectives, considered over a timespan". This extension of the term 'reliability' allows us to account for a wide scope of "failure modes", beyond the typical use of the term in literature. Disturbance is applied to the system under analysis via the use of different "world views" i.e. scenarios incorporating a wide range of socioeconomic and hydroclimatic parameters that inflict pressure to the system. Different scenarios vary in the magnitude of pressure as well as the rate at which this pressure builds up on the system under the specified design horizon, ranging from very mild to extreme future world views. This ensemble of scenarios allows the assessment of performance under very different conditions. Performance is affected by both the installed technologies and the way they are connected (design concept) i.e. by the system's configuration. The resilience assessment framework analyses different configurations of the system under the same pressures to identify the best future performer.

When developing this framework, we initially demonstrated it in a semi-hypothetical case study termed Watercity (Makropoulos *et al*, 2016). In this work we further develop our methodology, and apply it in a real-world case, as a further proof of concept: that of the **Oasen water system**. Alternative configurations of the Oasen system are developed, in consultation with Oasen and then stress tested against progressively worse scenarios in the form of complete world views. Results are presented and discussed.

Three progressively more distributed configurations were examined here: a 'business as usual' **centralised** configuration which represents the system as it is today; a 'next step' **decentralised** system configuration with a number of smaller treatment plants substituting major centralised ones and RO technology being adopted throughout; and a 'further ahead' **distributed** configuration, with a large number of much smaller RO-based treatment units providing water services at the very local level. The analysis does provide insights on, for example, trade-offs between resilience and robustness as well as between centralized and decentralized systems.

Although a detailed technical assessment of the Oasen water system is outside the scope of this work, whose value is mostly on method development and 'reality' testing, there are insights to be gained by the work on the case study *per se*: we conclude, for example, that the "Next Step" decentralized, RO-based solution has significant advantages compared to the other two configurations, for all but the most extreme scenarios used. Interestingly, this intermediate solution is also proven to outperform the further ahead configuration in some of the most abrupt, wild card scenarios investigated.

Having said this, the purpose of the method is not to reach strategic decisions on its own right, but to provide strategic decision makers with the understanding of the performance of alternative options under long term uncertainty. The final choice of systems depends on the desired trade-off between resilience and efficiency (incl. costs) and as such falls firmly within the remit of Water Company Management Boards.

It is suggested that after this real-world proof-of-concept application of the resilience assessment method, the process is mature enough to be applied to other water infrastructure systems and hence support more informed long-term infrastructure planning under large-scale uncertainty.

3. Strategic Planning for Water Infrastructure under uncertainty – a short introduction

3.1. Planning for the long term: a shifting landscape for infrastructure design and operation

Infrastructure planning and management (operational, tactical and strategic) is about being concerned with the longer term. That is because, infrastructure we build today need to provide the service they were designed to deliver for several decades, and that means that they will, inevitably, be subjected to unknown (and possibly unknowable) future pressures. The real extent of this challenge doesn't come into full view, until the actual rates of infrastructure renewal are examined more closely. It is, for example, indicative that, in some cases, with the current rate of infrastructure renewal, the average sewer has to last about 700 years (Gee, 2004). To reduce this unrealistic expectation, levels of investment required by the water sector are very high indeed. In 2002, the US estimated that annual costs for investment needed, between 2000 and 2019, were between $11.6 and $20.1 billion for drinking water systems and between $13 and $20.9 billion for wastewater systems (CBO, 2002). These levels of investment however, never actually materialized (Baird, 2010).

As such, water services are currently, and for the foreseeable future, facing significant challenges in the form of internal and external *pressures* (Figure 1). These pressures affect:

a) the **supply side** (in terms of both quantity and quality) due to hydro-climatic changes and resulting uncertainty.
b) the **demand side** with demographic and socio-economic trends changing demand levels and patterns while levels of service and related customer expectations increase (Brown *et al*. 2009, Rygaard *et al.* 2011) and
c) the **infrastructure in between,** as infrastructure itself gets older and less reliable in a context of limited new investment (see discussion above).

CLIMATE IS CHANGING A LOT AND FASTER THAN WE WOULD HAVE LIKED | DEMOGRAPHICS ARE ALSO SHIFTING THROUGH (ALSO) MIGRATION | AND THE ECONOMY IS STILL IN TOO MUCH FLUX

Supply patterns are affected (both in terms of quantity and quality) | **Demand patterns** that used to change slowly are now changing faster – also affected by geopolitical shifts | The sector lags behind in **investment** needed for infrastructure – and is affected more and more by related sectors (e.g. energy)

Figure 1: The 'New Normal'? A shifting landscape for urban water management (and everything else)

Although these pressures, and the uncertainty that is associated with their future evolution, is not new *per se*, it is currently being suggested[1] that the rate and magnitude of change across all three areas of interest to long term planning for water services (Figure 1) are such, that dwarf past uncertainties and seriously challenge even the most sophisticated forecasting models. Even more ominously perhaps, the current era of higher levels of uncertainty is becoming known as 'the new normal', implying that this level of uncertainty to everything from climate to geopolitics and from technology to population shifts, is here to stay.

A recent article published by the International Water Association (IWA) suggests that "*For water utilities the new normal can be equated to unexpected and unplanned losses in revenue and increasing costs. The financial sustainability and strength of a utility will be constantly challenged by rapidly changing conditions and environment. This includes managing growing demand for water and sanitation, driven by urbanisation and population growth, at a time of growing water scarcity and less predictable hydrological patterns due to climate change*" (Ramphal, 2018). The recent example of Cape Town's water scarcity is a case in point, and it is instructive that Authorities in South Africa are also taking a 'New Normal' view point to the evolution of the pressures in their system[2].

Of course, 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 cannot be 'controlled' by a water company), 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 behavior change). These three interconnected systems (termed external, internal and transactional respectively within this work) can be seen in Figure 2.

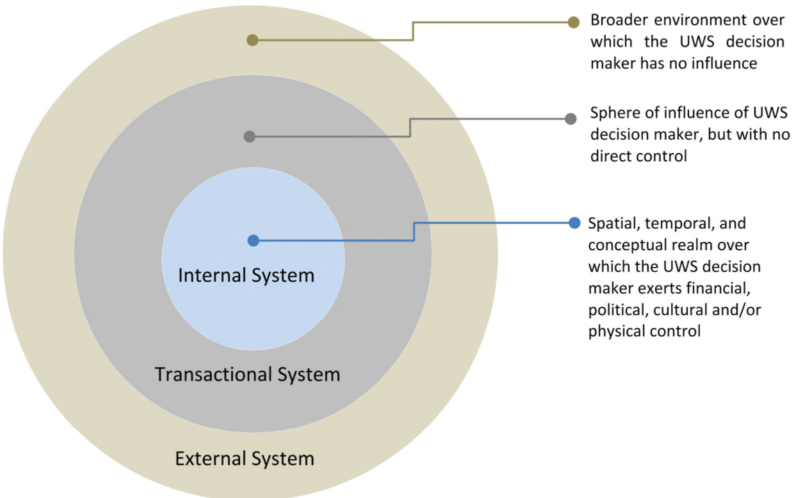

Figure 2: Interconnected systems and UWS decision maker influence

[1] http://www.iwa-network.org/advance-the-new-normal-exploring-water-energy-waste-partnerships/
[2] https://www.capetown.gov.za/Media-and-news/Advancing%20water%20resilience%20getting%20to%20an%20additional%20500%20million%20litres%20of%20new%20water%20a%20day

Although the specific aims of the water industry are (and will probably remain for the foreseeable future) centered around customer satisfaction, costs minimization, optimization 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. Performance of individual technologies and specialized (sub)systems, under 'normal' variability, captured for example in classic stochastic models, is more or less understood. However, in this study we argue that it is far less clear how *overall urban water system performance* is affected by a deployment of *portfolios of different technologies*, operating under (sets of) significantly different, uncertain *futures*. Here we report on the development of a method to address this challenge, present a toolbox that allows for the implementation of the method to water systems and demonstrate both, as a proof of concept, in a real-world case study: the Oasen water system in the Netherlands.

Clearly, the levels of uncertainty and related instability vary a lot from country to country and arguably the Netherlands, which act as a testbed to showcase the method developed in this report, is among the most stable countries within this shifting landscape. This stability however, in the case of the Netherlands, is more a result of a pro-active stance to emerging risks than anything else, and the interest of the Dutch Water Sector in Resilience, despite the relatively calm waters in which the country finds itself at this point, is a testament to exactly this proactive, forward-looking stance of the Sector and the Country as a whole.

3.2. Designing infrastructure for the 'new normal'

Three important innovations of the work presented in this report, differentiate it from other approaches to asset planning and infrastructure design:

1. A focus on novel, integrative, whole system modelling, that provides the evidence base to support long term decision choices regarding alternative water system configurations, based on their performance, under higher order uncertainty, at the overall system level. This is achieved through the further development and customization of a powerful source-to-tap water system model called UWOT (Makropoulos *et al*. (2008), Rozos and Makropoulos, (2012, 2013)). UWOT was used as the main model for the simulation of the entire water system and the assessment of its performance in terms of quantity (and quality) objective(s). UWOT is a bottom up, micro-component based, urban water cycle model, which simulates the demand, supply, wastewater and drainage at a range of time steps and multiple network scales. It should be noted here that the method developed is not depended on the use of this specific (or indeed any other) model. Other whole system models, or even specialized sub-system models (e.g. EPANET or Infoworks for the water distribution subsystem) can, in principle, be used within the same methodological framework, although an important contribution of the work and toolbox is the ability to model a complete water system, from the source, through supply and treatment to distribution and then on to sewerage, wastewater treatment and recipient water body. This in turn allows for the articulation and modelling of scenarios and pressures affecting different element of the water system, from source to tap, as well as the inclusion of diverse technological options (incl. for example, different degrees of centralization for treatment plants, reuse and recycling at multiple scales, rainwater harvesting, demand management etc.).

2. A powerful and versatile approach adopted to take long term uncertainties into account and examine what effects they have to the system(s) under study, through the creation of alternative 'world view' scenarios used in the modelling framework. The approach allows water companies to understand how their system is likely to behave when faced with a range of changing conditions (climatic trends, asset deterioration, behavioral patterns etc.) as well as accidents/incidents and/or extreme (black swan) events (Taleb, 2007) in the physical, social or economic spheres. The approach is based on the articulation of sets of scenarios, from mild to severe (see Chapter 6 for the scenarios developed for the case study of the Oasen system) with which to 'stress test' alternative water system configurations. It is important to note that these scenarios are not the only ones that can be conceived, nor necessarily the absolutely worst scenarios that can affect a particular case. They are internally plausible multi-faceted scenarios co-developed with water system owners, that examine a range of eventualities, without taking a view on the probability of each scenario occurring. Different scenarios can be co-developed with utilities and be adapted to the method. The important thing is that the same, internally consistent scenarios are applied to each of the alternative water systems under consideration.
3. A novel way of thinking about the desired properties of a water infrastructure system ("water system" henceforth in this report) that is subject to significant long-term uncertainties is proposed based on the two elements discussed above (whole system models and sets of long term scenarios). This is a central tenet of the report and the basis for the methodology developed, operationalized and demonstrated herein: the need for a methodological shift in long term strategic planning away from classic responses to long term uncertainty, which favor overdesigning systems to be 'full proof'. We argue, in accordance with current thinking among urban water scholars preoccupied with long term system performance, that this approach is as expensive as it is futile (Butler et al. 2017). This work proposes a new methodology based on the concept of *resilience* and operationalizes it through a toolbox that allows its application to different water systems. A discussion on both the operational definition of resilience in this work and the proposed methodology is included in following chapters of this report. The methodology was first developed by the authors in Makropoulos *et al*, (2016) and applied to a semi-hypothetical case. Here we expand both the method and the toolbox and apply it to a real-world case study.

3.3. Structure of the report

The remainder of this report is structured as follows:

In **Chapter 4** we introduce and explain the concept of Resilience and propose a specific method for its operationalization (based on Makropoulos *et al*, 2016), which stress tests the system under a range of scenarios and produces what will be termed herein 'resilience profiles'. It also briefly presents a toolbox developed for the production of resilience profiles for different water systems.

In **Chapter 5** we focus on the use of multiple tools from the toolbox in combination, explaining how we deal with one of the most subjective elements of the methodology: that of translating scenario parameters into model inputs.

Chapter 6 introduces the case study: the Oasen water system, and presents its main characteristics and quantities, as provided by the Oasen Water Company. It also presents the three alternative system configurations that were subjected to the resilience assessment. The chapter then presents and explains two sets of scenarios: (i) simple scenarios developed at the beginning of the modelling work, to explore the behavior of the model build within the UWOT modelling environment (these were termed *benchmark* scenarios – see section 6.3); (ii) the actual seven (7) scenarios developed for the resilience assessment of the three configurations of the Oasen system. Finally, the chapter introduces one Oasen-specific scenario of saline intrusion that was applied across the board and describes an additional set of four abrupt, short-duration scenarios, termed 'wildcards' that were developed for the case and superimposed on each long-term scenario at an arbitrary time (here, year 13 for consistency).

Chapter 7 presents the results from the resilience assessment for Oasen, initially for each individual configuration and then as a comparison between the three configurations under study.

In **Chapter 8** we present conclusions, both for the resilience assessment method itself, which was the primary aim of this work, and also for Oasen, based on the results obtained. A discussion on the potential use of the method and further developments is also included in this chapter.

The report also contains four (4) appendices:

In **Appendix A**, we summarise CAPEX calculations for the alternative system configurations under study. These are initial estimates, and their aim is to provide an order of magnitude for the investments required to gain the resilience improvements discussed in the report.

Appendix B presents the way in which UWOT has been upgraded to handle water quality. Water Quality is not what the model was initially developed for, and this development is novel in this study.

In **Appendix C** we present early ideas on a new metric (that of efficiency) that could be part of the resilience assessment methodology in the future. The efficiency metric was not used in this study, but these ideas were developed as part of the project, and as such are included here for completeness.

Finally, **Appendix D** looks at the link between this work, and UWOT in particular and other KWR tools, that could form part of a more extensive toolbox around the idea of Resilience, albeit not necessarily for the application of this specific method. In particular it looks at links between UWOT and the City Blueprint Tool. Both tools are part of the Watershare[3] Toolkit.

[3] https://www.watershare.eu

4. Introducing Resilience: From an elusive concept to an operational method

4.1. What is resilience anyway?

The increasingly volatile environment, within which water service providers need to operate, challenges our ability to forecast long term trends with sufficient accuracy beyond a window of a few years and suggests that the classic response to long term uncertainty, that of overdesigning systems to be 'full proof', against all eventualities, should be revisited (Butler et al. 2017). For this purpose, the idea of *resilience* is currently being discussed across the water sector as a way of moving from the ever-more elusive objective of 'fail-safe' infrastructure design towards a more realistic 'safe-to-fail' approach.

Resilience has recently been dominating the policy discourse in 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 stand points 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, Pizzol 2015). However, some common ground between recent attempts to develop formal definitions of resilience does emerge. Resilience, for example, is defined as a property of the system as a whole, rather than as a property of an individual element or unit and it is also suggested that resilience is a key property for the sustainability of the system. Following this (limited) common ground different definitions are mostly variations of two central themes (Pizzol 2015):

- "The amount of disturbance that a system can withstand without changing self-organized 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) also argues that there are three main ideas that literature returns to when resilience is discussed: 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, loosely, connected with redundancy or overdesign). It is also generally acknowledged that 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".

Resilience is also linked to sustainability, understood here as the "capacity of systems to maintain their functions in a context of continuous change" (Pizzol (2015) but also in Gallopín (2006) and Folke et al. (2003)). In fact, considered like this, resilience could be thought of as a central attribute or prerequisite of a sustainable system. In many ways, differences between these two terms could be understood as varying in the boundaries of the system in question and the number and scale of interactions of relevance.

Building on these aspects to define resilience as a design objective for water infrastructure, a key design choice comes at the crossroads between "remaining functional under disturbance" and "being able to return to a stable state after a disturbance". Here we adopt the lineage of the term as originally defined by Holling (1973) to be "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 to still retain essentially the 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*".

4.2. Quantifying Resilience – a discussion on Metrics

To be able to operationalise in practice this definition for the benefit of long term infrastructure planning however, we need to be able to define and compute its component terms: notably *performance* as a function of *disturbance*.

Performance is measured here through *reliability*, which is defined for the purposes of our work as "the ability of the system to consistently deliver its *objectives, considered over a timespan"*. This extension of the term 'reliability' allows us to account for a wide scope of "failure modes", beyond the typical use of the term in literature (see for example Mays 1989) and across the internal, external and transactional systems, depicted in Figure 2. Therefore, through this extended definition we are able to quantify the effects of different pressures on the water system and map those onto the resilience assessment process. As an example, Figure 3 presents failure modes that would affect the delivery of water i.e. reduce reliability against the water quantity objective of Table 1.

Table 1: Dutch Water Sector objectives (RIVM 2004 and DW directive)

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.

Water supply security	Ability to minimize risk (risk assessment)

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), defined "cml". However, one can also define reliability, focusing on either the frequency of disruptions or the volume of water not delivered or indeed some other undesirable water quantity aspect each providing different insights into the water system's performance (Atkinson *et al.* 2014).

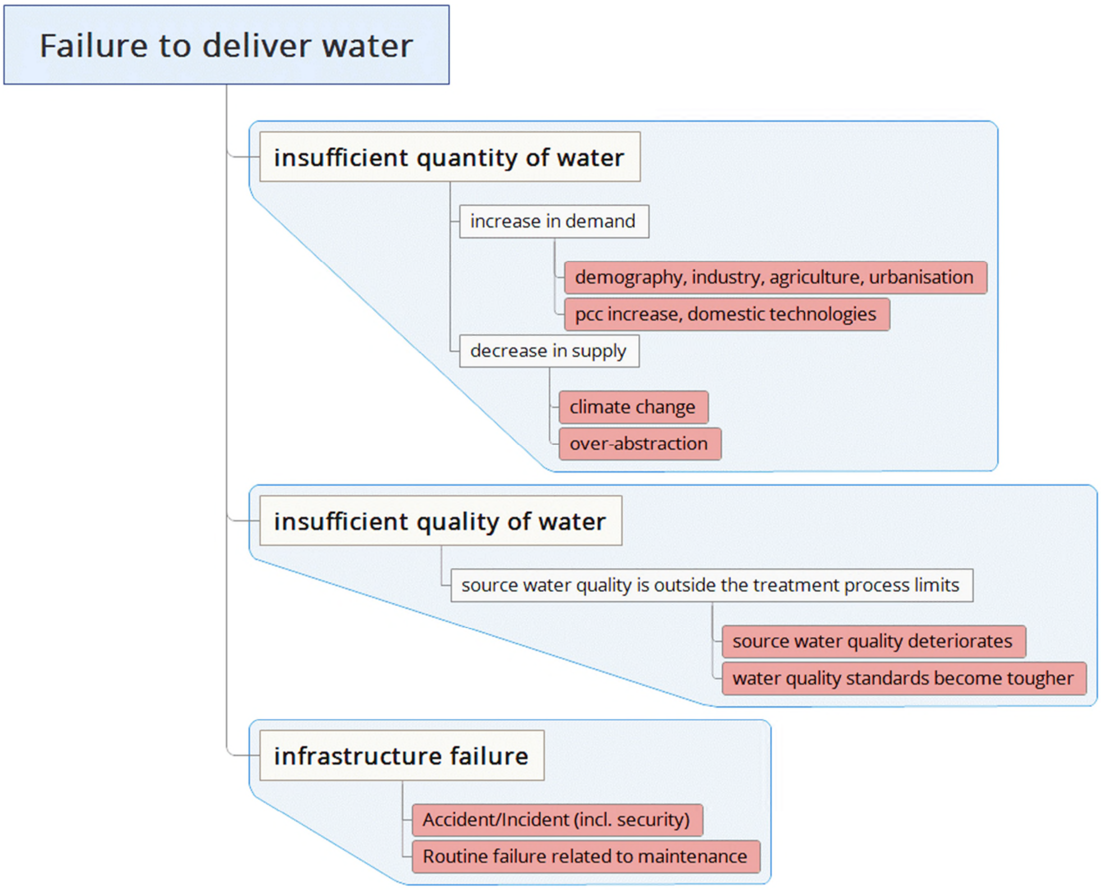

Figure 3: Different failure modes of water services for the water quantity objective

In this work, we use the following reliability metrics in order to quantify performance in terms of water quantity and explore links to resilience.

- The coverage reliability metric, which can also be termed *Volumetric Reliability* (R_V), is expressed as:

$$R_v = 1 - (\sum \text{deficit}/\sum \text{demand})$$

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.

- Costumer minutes lost, typically expressed per month or year, but hereafter modified for direct comparison to coverage as:

$$cml = (eqc\ with\ deficit * duration\ of\ failure\ in\ min)/all\ eqc$$

where, eqc is equivalent consumers.

Although other scholars have proposed that water quantity reliability metrics such as volume not delivered (Eq. 1) could be in fact considered measures of resilience *per se* (e.g. Butler, *et al.* (2014)) we suggest that from an Ockham's Razor view-point it would be preferable to keep all the variations of metrics related to water quantity provision (volume and frequency) as part of reliability, and keep the term resilience closer to its original definition (see above).

Before we proceed with linking our (extended – see above) working definition of reliability to the concept of resilience we introduce one more related term, which can be quantified using the proposed approach: Robustness.

4.3. What is Robustness?

Robustness is a term often interlinked with performance and resilience (Jeuland and Whittington 2014, Herman *et al.* 2015). It is a fundamentally desired trait of a system in the sense that a resilient system can absorb stresses by being robust (Redman 2014). 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. Thus, hereafter robustness is defined as 'the extent to which a system can keep performing within design specifications under increasing stress'. This is 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. In this analogy, the palm tree sways heavily to the wind whereas the sycamore stands still even in strong winds. However, the sycamore tree can be uprooted in the strongest winds, but the palm tree still stands. As such a robust system is also resilient, but the opposite does not necessarily hold: a system can be very resilient without being very robust.

4.4. Introducing the Resilience Profile Graph

With these definitions in mind we attempt to visualize what a change in the relevant behavior (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 4, termed hereafter in our work the *resilience profile graph*. The graph is, essentially, a stress-strain diagram, with the behavior of the system under increasing disturbance communicated through the area under the curve. Each point of the graph is a calculation of 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. To scale resilience and robustness to maximum of 1 (or 100%), we propose that the area under the curve is divided by the area of a "completely robust" system. The area under the curve of the completely robust system is equal to $1.00\ \times \#\ of\ scenarios\ analyzed$.

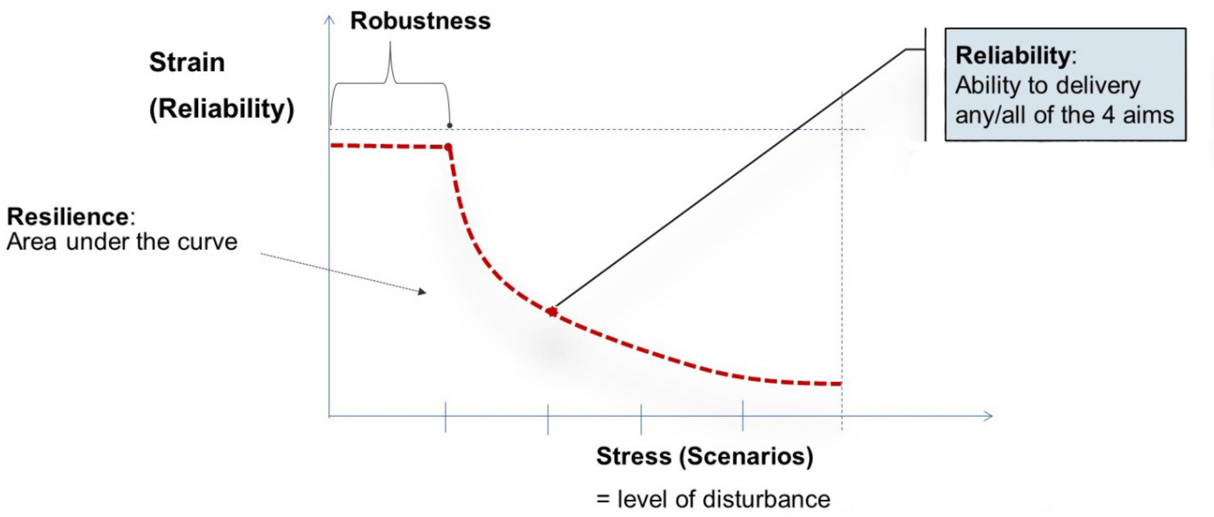

Figure 4: Resilience profile graph

A graphical summary of the proposed terminology, arising from the proposed definition of resilience can be seen in Figure 5.

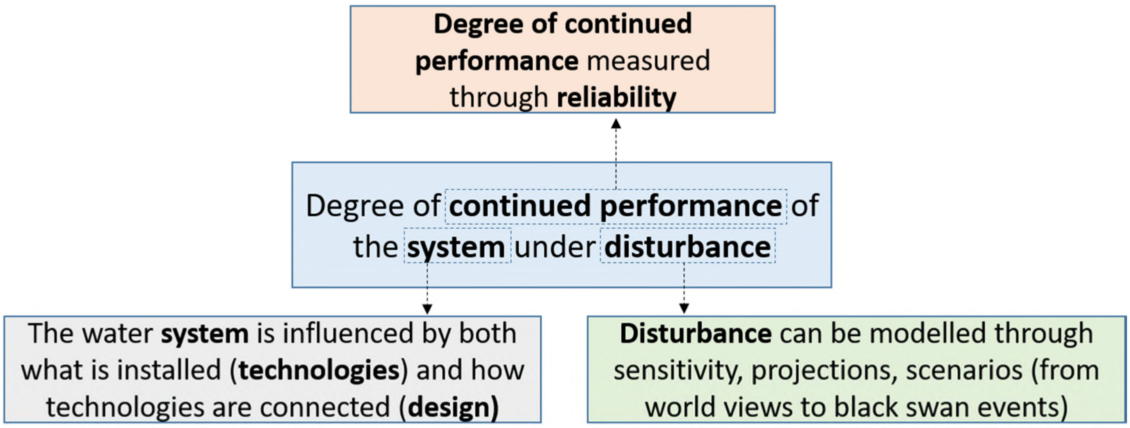

Figure 5: A graphical summary of the proposed methodology.

4.5. Overview of the Methodological framework

To produce such resilience profile graphs for a given water system we propose the following methodological steps (first developed in an earlier BTO Report by the same team – see Makropoulos *et al*, 2016):

1. Select an urban water system to test and identify its current (benchmark) state.
2. Setup alternative cases for the same water system, where different design philosophies and interventions to support them, including technical and non-technical measures are applied. These alternative configurations are termed in these work *levels of ambition* (see for example Makropoulos and Butler 2010)**.**
3. Build one or several models for each case and set of interventions (in this work we will demonstrate this with the UWOT model (Makropoulos *et al.* (2008), Rozos and Makropoulos, (2012, 2013), and Rozos *et al.* (2013), section 4.6.2).
4. Develop a set of scenarios following a vector of increased disturbance (section 4.6.1) and present a narrative for some of the external variables which are expected to influence the internal system through two "pathways":

   a. Either directly affecting some variable of the internal system (e.g. Climate scenario affecting rainfall which affects resource availability in the simulation).
   b. Affecting some variable of the transactional space (Figure A.1) which then influences an internal system variable (e.g. socio-economic climate [external] affecting customer behaviour [transactional] leading to adoption of water efficient appliances [internal]).
5. Subject each model to the *same scenarios* to allow for the performance of the system to be evaluated.
6. Plot *a resilience profile graph* of the system for every alternative intervention configuration
7. Explore a number of pertinent questions, including for example:
   a. Testing different interventions to see which ones and in which combinations improve the system's resilience
   b. Testing the same interventions under different scenarios, including possibly wildcards (see section 6.8).
   c. Identifying scenario parameters that are most severe for specific water systems and identifying threshold values of those parameters after which they cause significant loss of performance to the water system – to trigger responses.

This method provides a new (realistic) design objective for water infrastructure planning, in that water systems are required to perform 'as designed' within their design specifications (e.g. for the return period of design events) but also 'well enough' under significant long-term uncertainties, despite, inevitable, loss of reliability. As such, it introduces a more resilience-oriented approach to infrastructure design.

4.6. Software Tools

In the following sections, two software tools developed and customized to allow these steps to be implemented are briefly presented. The focus of the tools is to calculate the resilience profile graph (Figure 4) of a given urban water system by: (a) developing the x-axis (**Scenario Planner**) b) calculate the reliability of a given system in the y-axis (**UWOT**). A third tool is also under development, the **Water Technology Library**. This last tool is a knowledge base where different components of the water infrastructure system with their properties are housed to allow the end user to select and model different interventions within each water system configuration.

4.6.1. 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 materialized 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. As expected complexity and uncertainty are key aspects of this approach and different type of scenarios can help in evaluating water systems as visualized in Figure 6.

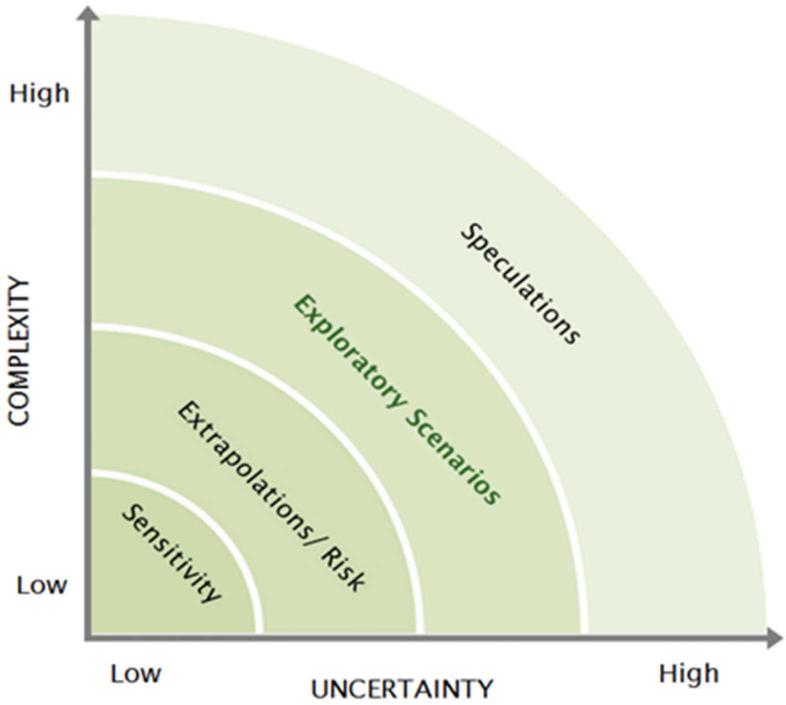

Figure 6: Different types of scenarios useful for future system exploration (adapted from Zurek and Henrichs (2007))

The central idea is to simulate the complexity of the real world to test various options under controlled conditions (see for example, Agudelo-Vera *et al*., 2016). However, as the systems we are considering are open-ended and complex, there are implications for how we define the categories and parameters in order to describe a future scenario. The ultimate goal here is to perceive various real-world entities as parameters appertained to a specific category. For critical realists, an entity is made real by its 'causal efficacy'; that is, its influence on human behaviour. An entity can be 'materially', 'ideally', 'artefactually', and/or 'socially' real (Fleetwood 2005). We simplify these categories by clustering the 'ideal' and the 'social' under the Sociocultural realm and the 'material' under the Biophysical realm with the 'artefactual' under the interpenetrating Socio-biophysical realm. Other categorisations of water control, such as technical-physical, organisational-managerial, and socioeconomic-regulatory (Mollinga 2008), can also be logically clustered under our categories. The three most basic categories of real structure and mechanisms are thus taken to be: Sociocultural; Biophysical, and Socio-biophysical. 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 uses 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 the simulations for this study are presented in Figure 7 - Figure 9. 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 seen 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 testing the resilience of an UWS the 'rate' of change is considered to have greater impact 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 10, Type 1 and Type 2 scenarios are characterized by equal 'Magnitudes' of change but in the Type 2 scenario more than 30% of the parameters changed abruptly compared to 10% for Type 1. Type 1 scenarios involve the least severe types of change with Type 7 including the most severe.

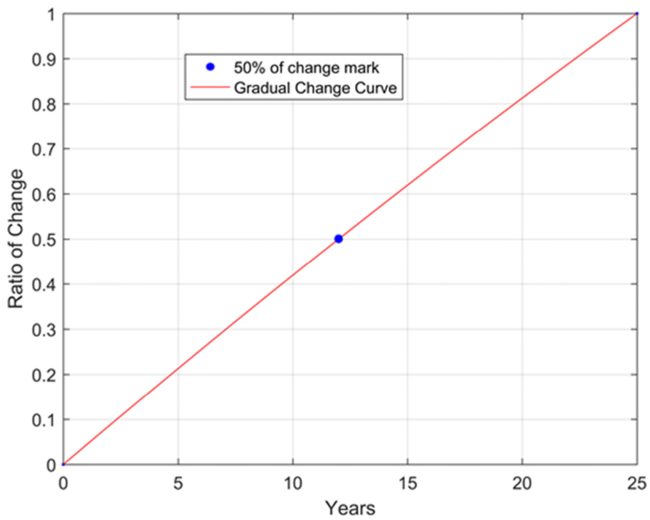

Figure 7: Gradual rate of change

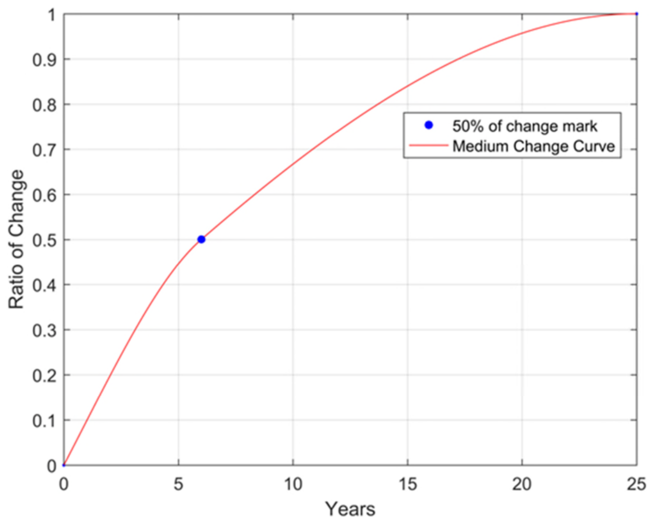

Figure 8: Medium rate of change

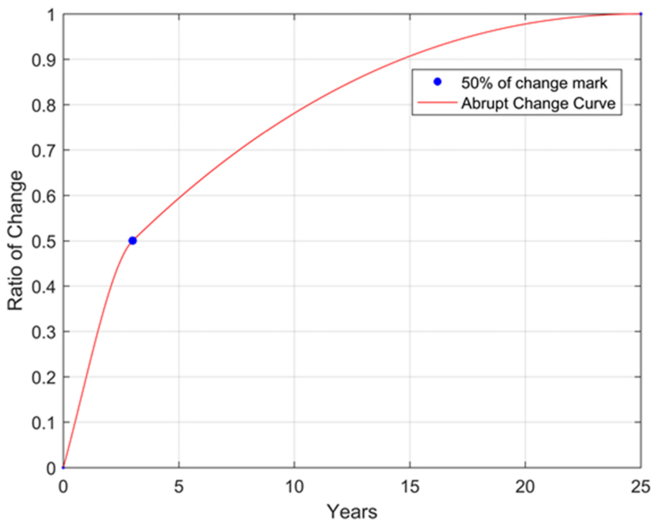

Figure 9: Abrupt rate of change

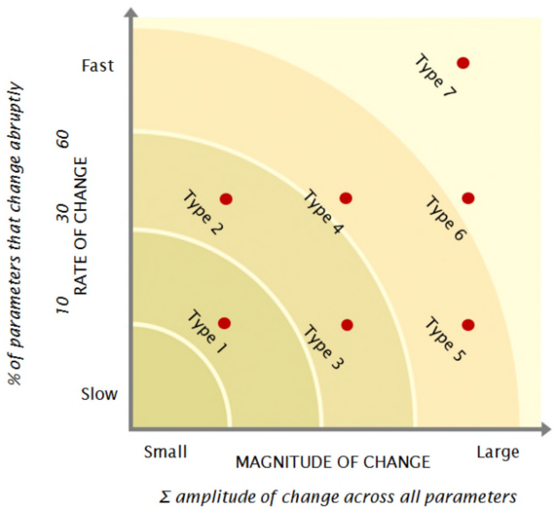

Figure 10: Types of future scenarios regarding rate and magnitude of parameters' change.

The construction of these scenarios, which need to be developed for all practical applications in collaboration with the UWS decision makers themselves, is facilitated by a custom-built tool called *Scenario Planner* developed in this project. The tool 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 form a specific scenario and (c) enforces an internal consistency check between parameter values to help the user avoid non-sensical scenarios. The interface of the Scenario Planner tool can be seen in Figure 11. Further presentation of this tool, which is still under development, is beyond the scope of the report, as the aim here is to showcase the general method rather than the specific tools used to implement it.

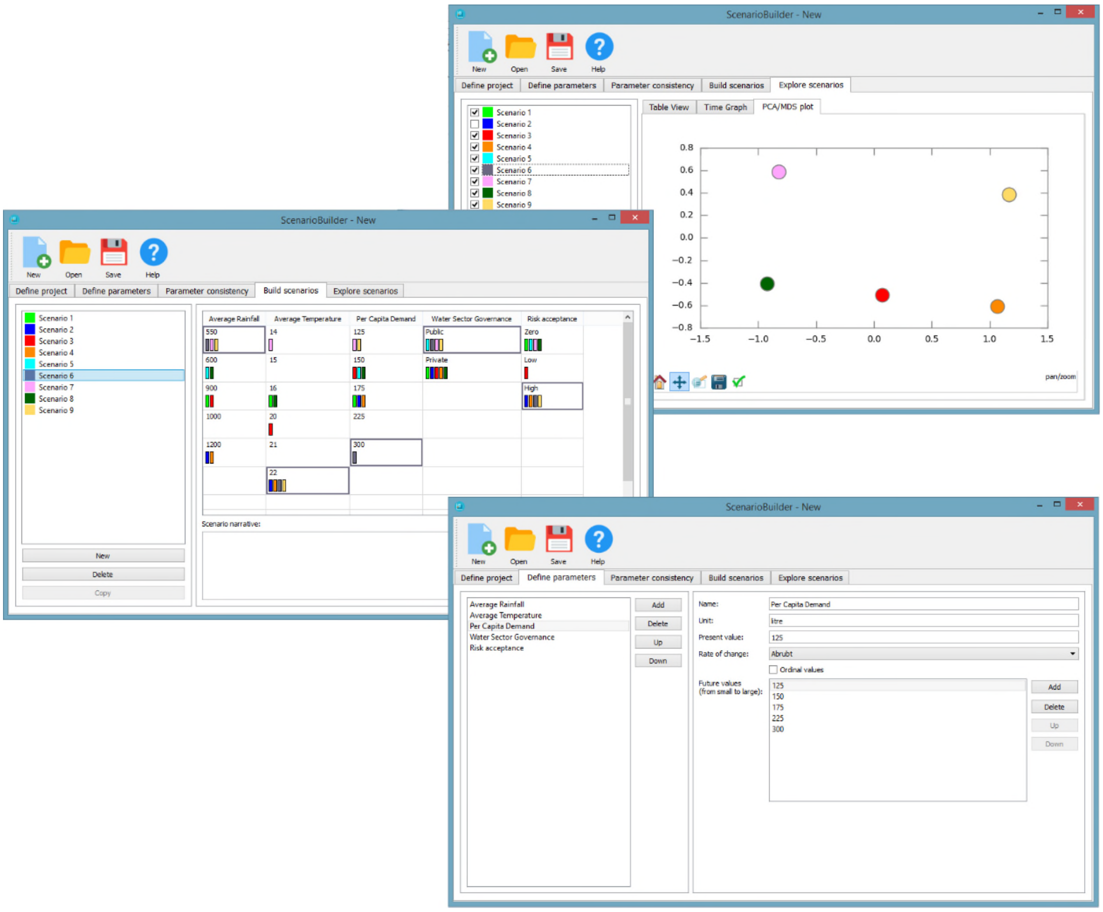

Figure 11: The user interface of the Scenario Planner tool.

4.6.2. 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 (and quality) objective(s) with compliance with the aforementioned methodology. UWOT is a bottom up, micro-component based, urban water cycle model, which simulates the demand at arbitrary time step and multiple network scales (from the household (Figure 12) to the hydrosystem (Figure 13). Unlike typical urban water models, which employ dual approach (simulate outgoing flows directly and assume incoming flows equal to demand), UWOT adopts a simulation methodology that is based on a single consistent approach for every urban water cycle flow. As every urban water flow is caused by a (deterministic) demand (need for potable water, need to drain storm water, need to dispose 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 *et al.* (2013).

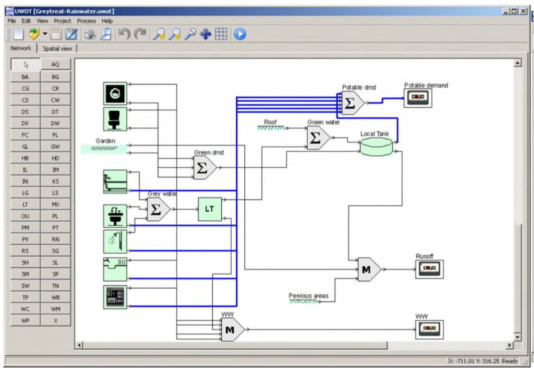

Figure 12: A UWOT representation of a household. Blue line indicates appliances requiring potable water.

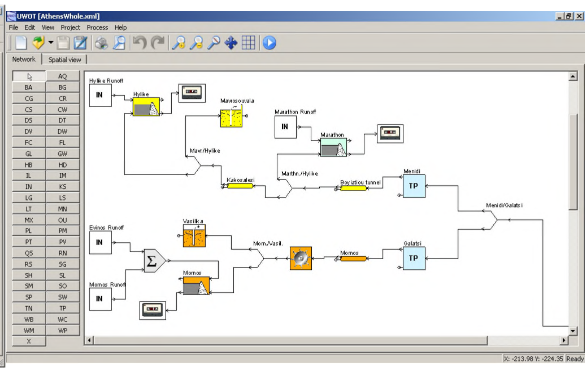

Figure 13: A UWOT representation of an external hydro-system (from the water sources to the water treatment plants (TPs).

4.6.3. Water Technology Library

The Water Technology Library is a knowledge base, in the form of a database, currently under development. The goal of the tool is to store bundles and relative technologies. It consists of a graphical user interface (GUI) front-end connected to an SQLite database backend. Data for various components can be imported to the tool and are available for retrieval.

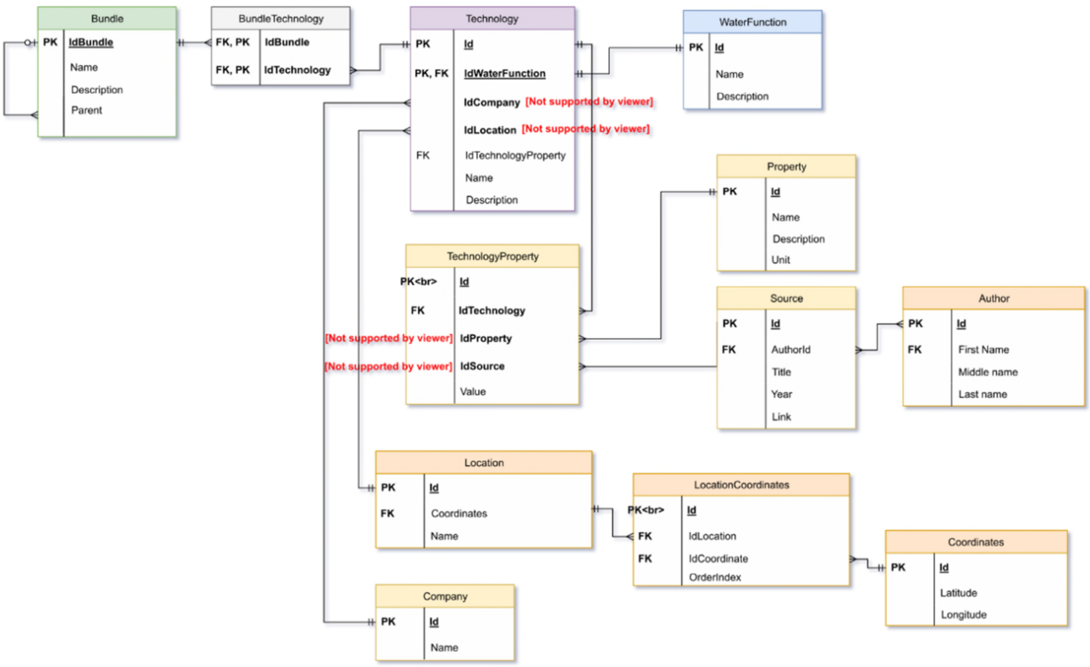

Figure 14: Design of the relational database which forms the backend of the Water Technology Library.

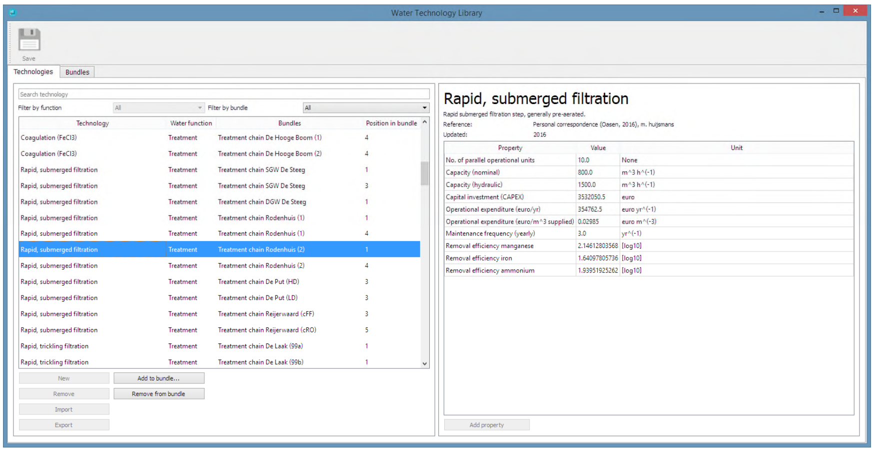

Figure 15: Main screen of the Water Technology Library, with the technology 'rapid, submerged filtration' selected.

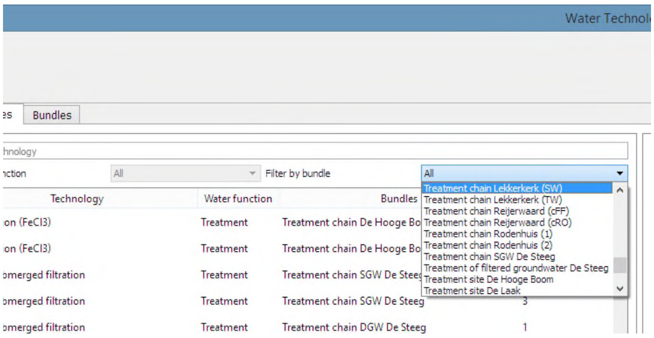

Figure 16: Selection dropdown menu to select a chain of technologies (here: a treatment chain).

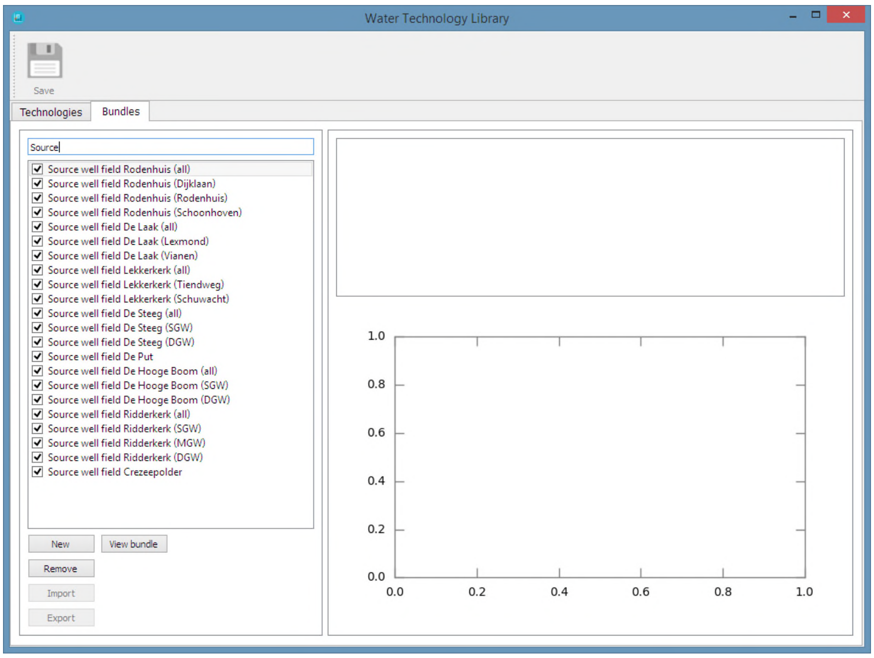

Figure 17: Bundles tab screen, where one searches a technology bundle, views, adds or removes a bundle from the list. The idea on the right, lower plane is to plot a selection of (scaled) bundle properties, like e.g. CAPEX or water production and losses. The right upper plane is reserved for selecting the specific properties to plot.

5. Using the tools in combination: from Scenario Planner variables to UWOT model inputs

5.1. Overview

In this project, effort was made to automate, to the extent possible, the link between scenario planner variables and UWOT model inputs. This entailed methodological and tool customisation work beyond what was originally available at the end of the previous phase of this work (Makropoulos *et al*., 2016) In what follows, we highlight the most important aspects of this automation with examples from our case study.

5.2. List of parameters and rough interpretation

While forming the methodology and the supporting toolbox in our previous work, we developed a comprehensive list of variables that could underpin several world views and allow us to construct rich, in narrative options, scenarios. These variables are:

- **Population**: Used to form population timeseries of Supply Areas (SA). It is the major driver of total water demand and waste production.
- **Number of households:** Used to form household timeseries of Supply Areas. It is a major component in many calculations as well as a factor that adjusts per capita water usage to include housekeeping activities etc.
- **Age distribution**: A factor that adjusts per capita water demand to account for different age group behaviours. Identifies percentage of people over 65 years old (usually retired and with different water needs).
- **Ethnic composition:** A factor that adjusts per capita water demand to account for different ethnic group behaviours. Identifies percentage of non-western people.
- **Knowledge development:** A factor that affects component failures and maintenance through directly affecting their duration. It is related to problem solving, action readiness and awareness.
- **Public finances:** A factor that affects component maintenance and duration of critical failures. Related to availability of resources for maintenance/repairs.
- **Electricity price for heavy users:** Affects energy costs. Used to measure the relative efficiency of each configuration.
- **Water sector governance:** this parameter affects component maintenance, quality of water services, basic probability of breakdowns, basic maintenance of components.
- **Risk acceptance:** A parameter that has direct impact on failure probabilities. It is linked with water sector governance.
- **Trust in government:** A factor that reflects water customers appreciation of services provided by public utility companies, and thus indirectly gives insight into the quality of services.
- **Trust in corporations:** A factor that reflects how water consumers view private utility companies. It indirectly gives insight into quality of services.

- **Dominant ideology:** A factor that describes the general socioeconomic scene.
- **Temperature:** A global variable that affects water consumption especially for agricultural uses.
- **Average rainfall and distribution:** A global variable that affects ground water recharge, river flow, storm runoff etc.
- **Phosphorus emission:** An index related to emissions on river water from agricultural uses.
- **Industry water demand:** Used to form timeseries of industrial water demand and industrial waste production.
- **Horticultural water demand:** Used to form timeseries of horticultural water demand
- **Domestic water use (behavioural):** A major driver of per capita demand. Used as the higher threshold for per capita demand.
- **Domestic water use (technological):** A major driver of per capita demand. Used as the lower threshold for per capita demand as it represents available technologies that preserve water.
- **Environmental values:** A major driver of per capita demand. Determines incentives for water preservation and energy saving.
- **Quality Standards Drinking water:** A legislative factor that determines acceptable water quality in view of meeting specific standards.

5.3. Automating the process: developing a Scenario Translator

The bridge between specifications in the scenarios given in both arithmetic and natural language (linguistic variables) form and UWOT simulation is the "scenario translator". This is a new development, expanding and automating the work undertaken during the 1st phase of the project (Makropoulos *et al.*, 2016) and as such will be discussed briefly next.

The translator is a script written in MATLAB. A scenario table in excel acts as input, in the format presented in Table 2, for a hypothetical Scenario X. This is imported as a MATLAB table, containing the following fields for each parameter: *variable type, initial and final values, rate of change and magnitude of change*. Each parameter is utilized as a variable. Part of the resulting MATLAB scenario table can be seen, as an example, in Figure 18.

Table 2: Partial extract of the scenario translator input table, illustrating its format.

	Scenario X		
Parameter	**Absolute (final) value**	**Magnitude**	**Rate**
Population	291420	1.17	abrupt
Number of households	140789	1.41	abrupt
Ethnic composition [%]	33.24	1.56	abrupt
Knowledge development [% GDP]	0.67	1.17	gradual
Electricity price heavy users [€/kWh]	5.95	1.15	medium
Public Finances [% GDP]	36.00	0.77	abrupt

<table>
<tr><td>Temperature (°C)</td><td>12.40</td><td>1.22</td><td>gradual</td></tr>
<tr><td>Average rainfall (winter) [mm]</td><td>452.13</td><td>1.05</td><td>gradual</td></tr>
<tr><td>Risk acceptance</td><td>zero tolerance</td><td rowspan="8">Magnitude is not defined for non – arithmetic parameters. The number of states changed is used instead.</td><td>medium</td></tr>
<tr><td>Trust in corporations</td><td>medium</td><td>medium</td></tr>
<tr><td>Trust in government</td><td>medium</td><td>medium</td></tr>
<tr><td>Knowledge about water sector</td><td>low</td><td>medium</td></tr>
<tr><td>Quality Standards Drinking Water</td><td>EU</td><td>gradual</td></tr>
<tr><td>E. coli (CFU 100ml-1)</td><td>low</td><td>gradual</td></tr>
<tr><td>Virussen/protozoa bacterien OR</td><td>low</td><td>gradual</td></tr>
<tr><td>Chloride (mg litre-1)</td><td>low</td><td>gradual</td></tr>
</table>

	Pop	NHouse	AgeD	Ethnic
VarType	'numeric'	'numeric'	'numeric'	'numeric'
InitialValues	[250000]	[100000]	[17.3000]	[21.3000]
EndValues	[2.9142e+05]	[1.4079e+05]	[17.3000]	[33.2400]
RateOfChange	'abrupt'	'abrupt'	'gradual'	'abrupt'
Magnitude	[1.1657]	[1.4079]	[1]	[1.5606]

Figure 18: Part of the imported MATLAB table.

The terms 'gradual', 'medium' and 'abrupt' have a pre-specified meaning as follows over the timespan of 25 years:

- **Gradual** rate of change means that 50% of change happens over 12 years.
- **Medium** rate means that 50% of change happens over 6 years.
- **Abrupt** rate means that 50% of change happens over 3 years.

This information is incorporated into the scenario translator as curve fitting objects for each category. An example of the fitted curves can be visualized in Figure 7 - Figure 9. Essentially, the attribute 'rate of change' is translated as a function R(t), able to return the ratio of change R of the specific timestep t in [0,1]. For arithmetic parameters this signifies the fraction of the change's magnitude that adds up to the parameters value. A yearly timeseries is constructed and later disaggregated down to the simulation timestep (which, in this case, is 1 day).

For linguistic variables the following process is followed: single-state (e.g. medium to high) changes happen at the 50% mark and two-state changes (e.g. high to low) happen at the 33% and 66% mark respectively. Again, a yearly timeseries is constructed and later disaggregated down to the daily simulation step.

To standardize linguistic (natural language) variables to categories [low medium high], a possible "states table" is constructed that holds the reference values for possible states for the linguistic parameters. The table can be considered as an internal vocabulary for the linguistic variables. The parameters are all standardized to 3 states [S1, S2, S3] ranging from the lowest (S1) to highest (S3) category. The ranking order is important for the construction of the internal vocabulary. Part of the 'states table' can be seen in Figure 19.

StatesT =

	WatGov	RiskAc	TrustCo	TrustGov	EnvirVal	KnowWater	DomIdeo	QualStand
S1	'public'	'zero tolerance'	'low'	'low'	'low'	'low'	'progressive'	'NL'
S2	'public-private'	'low tolerance'	'medium'	'medium'	'medium'	'medium'	'conservative'	'EU'
S3	'private'	'risk acceptance'	'high'	'high'	'high'	'high'	'liberal'	'WHO'

Figure 19: Part of the States table

A function then reads the scenario's initial & final parameter values and the respective year's value of 'change matrix' calculated from the curve fit, identifies the reference to the States Table and applies the transition. The sequence of actions undertaken by the function is visualized in Figure 20.

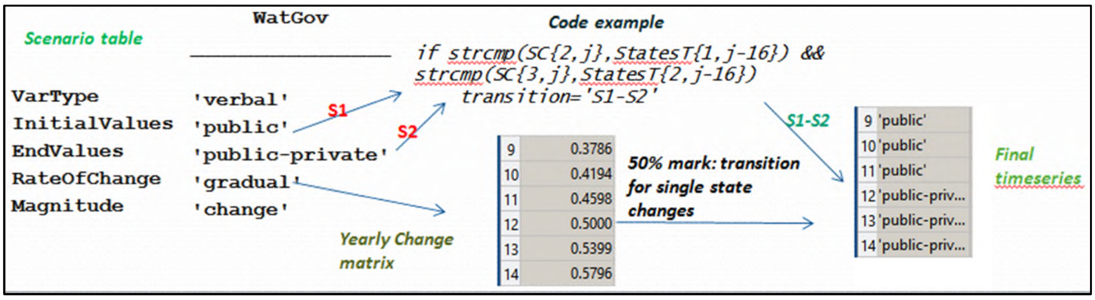

Figure 20: Process of constructing the yearly timeseries for a verbal parameter

The Scenario Translator's final output is the disaggregated timeseries[4] that are then used as input to UWOT.

5.4. Taking a closer look at some of the more challenging variables

While several parameters are self-explanatory and can be directly incorporated into UWOT modeling (like per capita demand and population) or can simply act as "multipliers" for demand (like age distribution and ethnic composition), some are less straightforward to estimate and contain more assumptions on how different parameters relate to each other and what UWOT models. These will be explained in more detail next.

5.4.1. Simulating failures in infrastructure components

Every component of the system to be modelled, is initially assigned a 'regular' component degradation timeseries that is affected by a number of parameters to form the actual, scenario-depended, timeseries of component degradation over time and also simulate incidents/accidents/faults. Component degradation timeseries typically have the form of a bathtub (as seen in Figure 21) where capacity is reduced slightly at the start of the simulation until initial problems after installation are ironed out and as the simulation progresses capacity is reduced naturally due to infrastructure aging. This timeseries accounts

[4] Clearly, when good estimates exist for the future development of any scenario parameter (e.g. population) these can be used 'off the shelf' rather than be recreated through the generic process described above.

for a standard, well-maintained infrastructure component. A function reads as input specified characteristics of the timeseries namely initial and final % of loss of performance, lifespan of the component, and time needed to reach full capacity. The lifespan, for reasons of simplicity, is the same for every component but the loss of performance can vary.

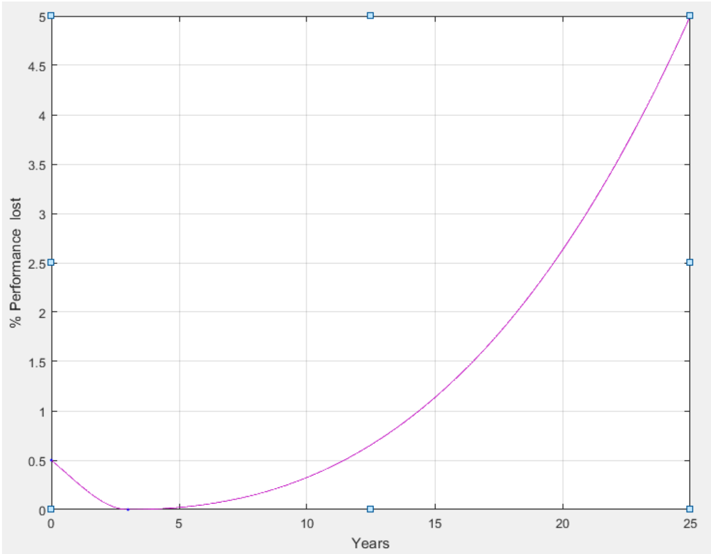

Figure 21: Typical normal component degradation (performance loss %) over time

It is assumed that component maintenance is influenced by water sector governance. When the water sector is fully private it is assumed that the effect is slightly worse maintenance, due to a desire for more profit and cost-cutting by the private sector. Trust in the respective type of water sector governance by the citizens (customers) can be interpreted as the level of provided services, indirectly indicating good or bad management. These two parameters can form a parametric rule that alters a multiplier affecting regular component degradation. A set of such rules is visualized below in Figure 22. Clearly, the opposite can also be true (a corrupted public-sector vs efficient and ethical private management).

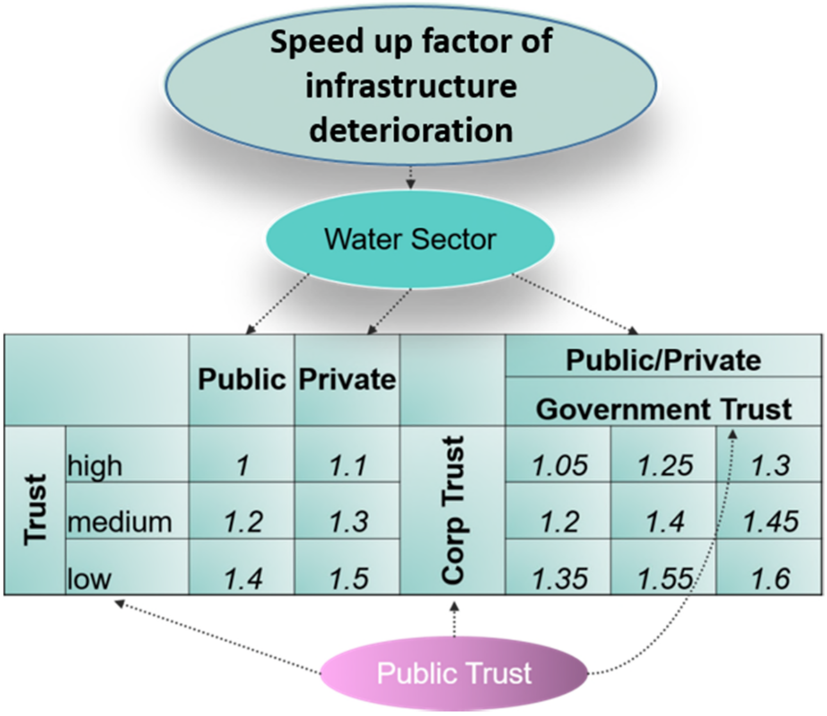

Figure 22: Rules for determining component degradation over time from political factors

Accidents that disrupt operations of a component are simulated in a similar way. A baseline, low probability, of disruptions is initially set, regardless of the scenario, e.g. 1/2000 days. The probability changes according to parameters 'water sector governance' and 'risk acceptance'. The probability of disruptions is increased as risk acceptance increases and rises as the transition from public to private governance progresses. A set of multipliers applied to the base probability are depicted in Figure 23.

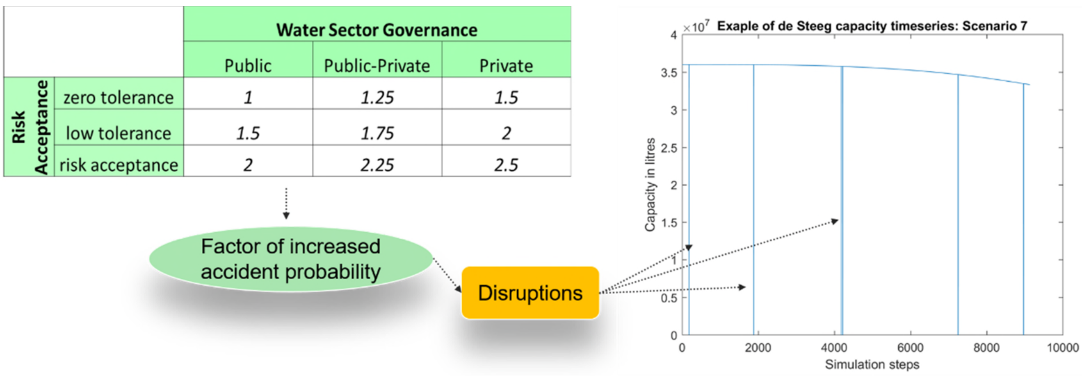

Figure 23: Rules defining daily probability of disruptions in UWOT components.

In the case of an operational disruption (accident/breakdown etc.) the duration of the fault is also an important aspect of the problem, as it directly affects reliability metrics (including customer minutes lost). Fault duration is determined by two variables interrelated through a Fuzzy Inference System (FIS). The input variables to the FIS are 'knowledge development' (higher knowledge development can be interpreted to lead to better solutions) and 'public finances' (higher public finances are interpreted as having more resources available for repairs). The FIS's output is the duration of operational disruption in days. The 'knowledge development' variable has three membership functions (low/medium/high) and the 'public finances' variable four membership functions, (very low/low/medium/high). The output 'duration' variable has three membership functions (short/medium/long), with actual values ranging from 1 to 7 days. This mapping, between membership functions and actual numerical values can of course be tailored to the case at hand. In other words, what is defined as 'long' duration will be different in different countries and that can be taken into account in the method.

A visual representation of the rules can be seen in Figure 24.

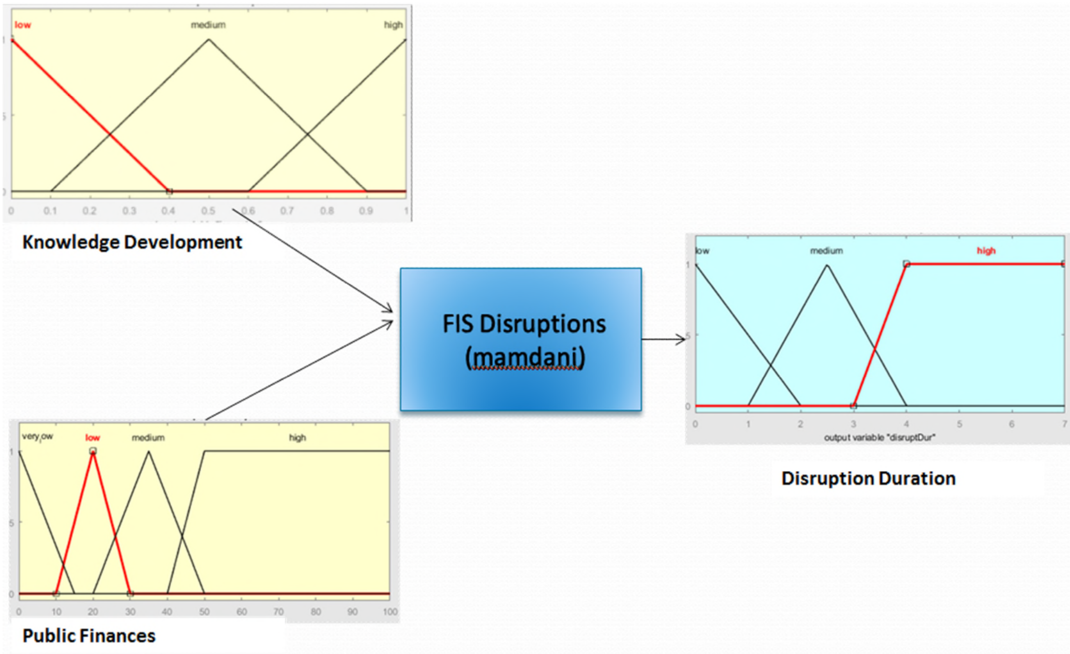

Figure 24: Visual representation of the FIS calculating duration of disruptions.

Both component degradation due to age and ineffective maintenance are described by the same timeseries that essentially presents current component capacity, which in UWOT terms translates to a threshold in a 'divergence' component. For accidents, the current step's value of the capacity timeseries is reduced to the capacity that is lost during the accident, which usually is half given redundant designs in case of WTPs and WWTPs. Of course, this can vary for every plant, and the scenario editor can easily account for more custom information, when available. An example of capacity timeseries with accidents over the simulation period is depicted in Figure 25.

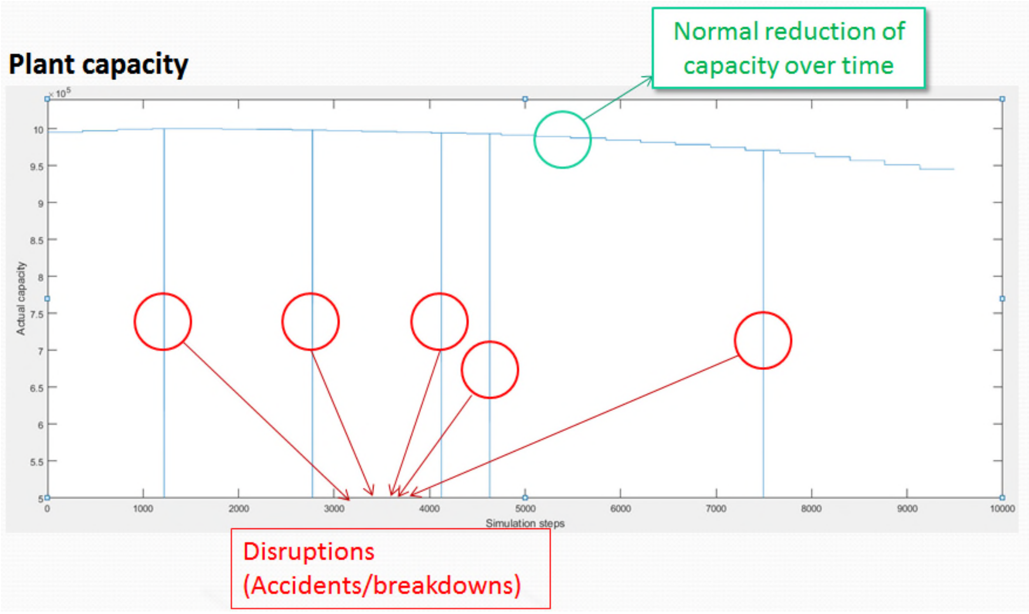

Figure 25: Plant capacity due to ineffective maintenance during a simulation period.

An indicative example from applying this logic to component failure in our case study (Oasen – to be discussed in following Chapters) is the calculation of the failure timeseries for transport pipes. Here we use historical data from Oasen area, where the annual failure rate of each km is 0.05 failure/km/year. Assuming that the daily event of 'no failure' per km is $(1-p)$ where p is the daily probability of failing, and in a year the event 'no failure' has a probability of 0.95 per km, then $(1-p)^{365} = 0.95$ and $p = 0.00014$ or 0.014% daily probability of failure per km. The probability is altered by 'maintenance' practices, similarly to other water cycle components as discussed above. Mean duration of failure to repair time is assumed to be equal to 3 hours. Each Supply Area has its own pipe network density (measured in connections per km) and thus network size grows with growing Supply Area (measured in number of households). For every SA we construct a random binary (either one for failure or zero for normal operation) timeseries that calculates the probability of failure of every km for every simulation step. This timeseries is multiplied by the daily demand. When a failure occurs, a UWOT logger component counts volume not delivered by pipe failure in a particular SA. An example is shown in Figure 26.

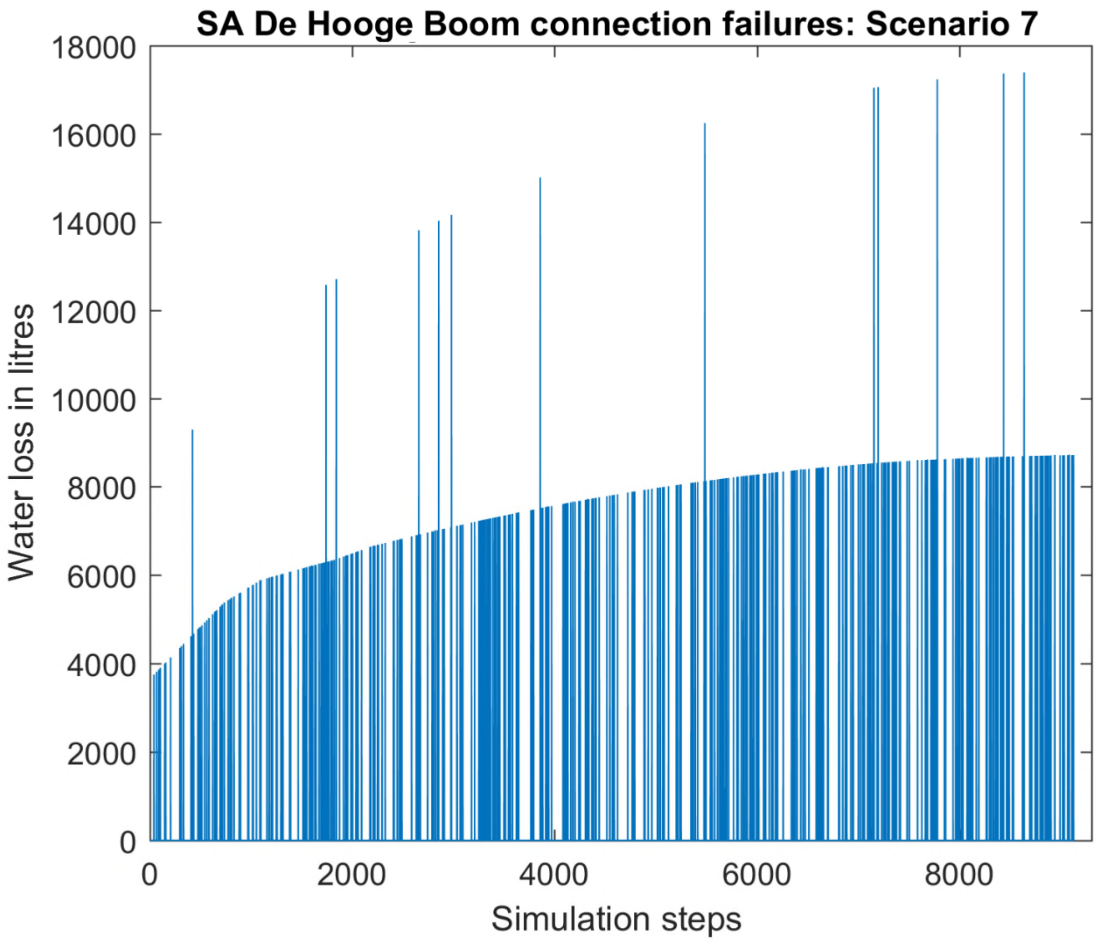

Figure 26: Example of pipe failures (depicted is volume of failure) in a simulation of 25 years.

5.4.2. Calculating basic per capita demand (basic PCD)

Basic per capita water demand is formed as timeseries. Three parameters affect the actual value in each time step. As Figure 27 illustrates, *behavioral domestic use sets the upper threshold* of basic per capita water demand, as it describes the need to consume water. *Technological water use* sets the lower threshold, due to the adoption of new technologies like dual flush toilets[5]. The linguistic variable '*environmental values*' enforces a simple parametric rule of an incentive to conserve water, that defines the final value of basic per capita demand within the limits imposed between the behavioral 'water demand needs' and the technology 'demand reduction' potential.

[5] Behavioral domestic use sets the **upper** threshold of basic per capita water demand, as it describes the 'theoretical' need to consume water. Technological water use sets the **lower** threshold, capturing the impact on (reducing) demand of the adoption of new technologies like dual flush toilets.

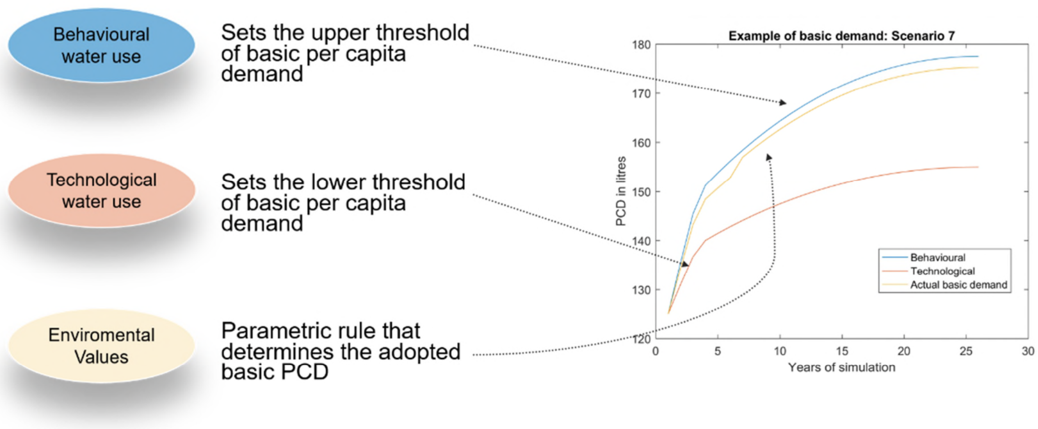

Figure 27: Definition of basic per capita demand (PCD).

The parametric rule employed is the following:

$$
\begin{aligned}
&basic\ water\ demand \\
&\qquad = behavioural\ use - (behavioural\ use - technological\ use) \\
&\qquad * \left\{ \begin{array}{ll} 0.1 & if\ enviromental\ value\ is\ \text{"}low\text{"} \\ 0.25 & if\ enviromental\ value\ is\ \text{"}mediuom\text{"} \\ 0.5 & if\ enviromental\ value\ \text{"}is\ high\text{"} \end{array} \right\}
\end{aligned}
$$

5.4.3. Transforming Basic to Actual per capita demand (actual PCD)

Basic per capita demand is then influenced by other socioeconomic factors to become the *actual per capita demand* taking into account also additional trends and pressures. Simple demographic rules alter the value based on a "sensitivity to change" value. For a given percentage deviation from the original starting values of the parameters, a fixed percent deviation from basic per capita change occurs. As shown in Figure 28 for every +1% deviation in people per household (defined as *population / number of households*) a -1% change occurs in PCD, for every +1% deviation in age distribution a +0.25% change in PCD occurs and for every +1% in ethnic composition +0.50% change in PCD is assumed.

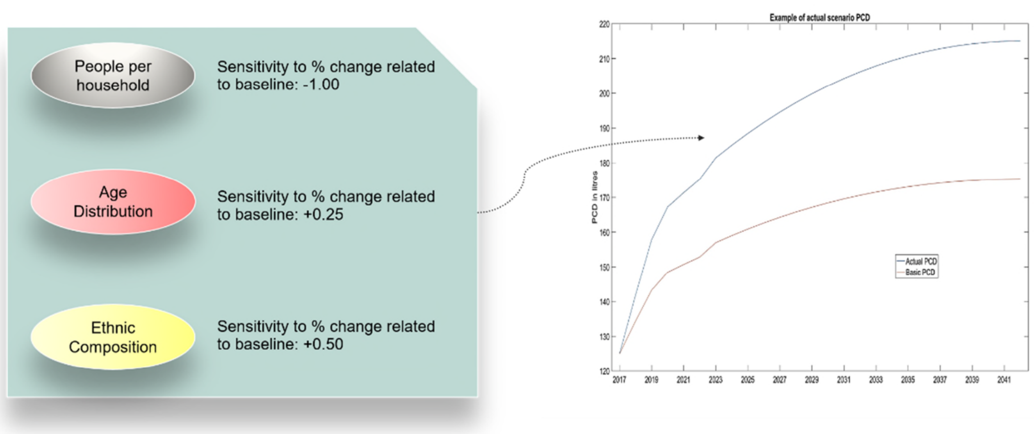

Figure 28: Actual per capita demand transformation

6. Modelling Oasen

6.1. The Oasen case study

Oasen is a public drinking water company and its shareholders are the municipalities in the eastern part of the Province South Holland. The history of Oasen begins in Gouda, 1883 where the first 165 houses connected to the pipeline network. Today, the HQ of Oasen are still in Gouda, but Oasen has expanded and currently supplies drinking water to 750,000 people and 7,500 companies. With seven drinking water purification plants, nine pump stations and a water tower, Oasen delivers 48 hm^3 liters of drinking water to customers each year.

In this case study, a simplified topology of a selection of Oasen's hydro system is developed to allow us to apply the resilience assessment methodology in a real-world system. Despite being downscaled, the model retains extensive detail of the actual water system and all major system and component attributes are included. Oasen provided the relevant data for the model, working in close collaboration with the authors to ensure its integrity.

6.2. Setting up the topology of Oasen's current system and initial proof of concept modelling

A simplified topology of Oasen's current system (termed hereafter the **Business As Usual** (BAU) configuration) was first developed to serve as a baseline, as well as a proof of concept for the subsequent modelling work. The BAU configuration model includes the following Supply Areas (SAs) and Water Treatment Plants (WTPs):

- **Supply areas**: Alblasserdam, Hazerwoude, Rodenhuis, Lekkerkerk, De Hooge Boom, Den Hoorn
- **Water Treatment plants**: De Steeg, Lekkerkerk, Rodenhuis, de Hooge Boom

It was agreed with Oasen **not to include** in the model the following SAs and WTPs:

- **Supply areas**: Elzengors, Reijerwaard, De Laak
- **Water Treatment plants**: De Laak, Reijerwaard, De Put

A map of the area and the simplified topology of the drinking water system is shown in Figure 29.

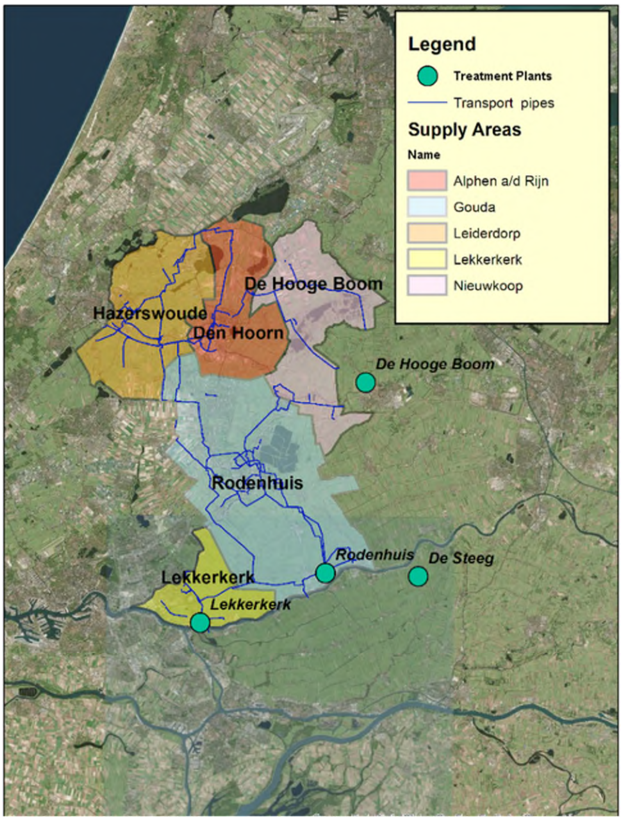

Figure 29: Map of the Oasen area

A schematic of the modelled supply areas and the treatment plants that service them, is depicted in Figure 30. This schematic acted as the basis for model parameterization. WTPs are connected to serve supply areas. Distribution networks between neighboring supply areas are interconnected to counter possible failures.

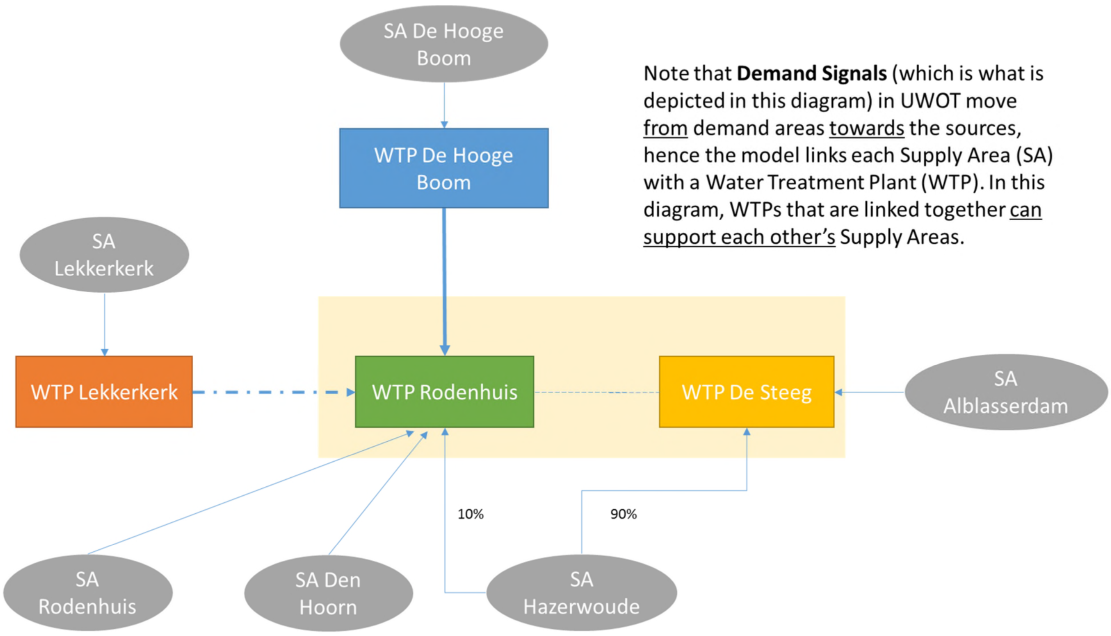

Figure 30: Simplified topology scheme of the Oasen area

The major SAs and supply elements of the BAU topology are summarized in Table 3 and 4 respectively. The topology, as delineated in UWOT is shown in Figure 31. From left to right, demand signals originating from each of the six SAs (input components) are conveyed through the water supply network (aqueduct components), processed though WTPs (Treatment components) and end up on water sources (groundwater and reservoir components). Logger components log signal activity in order to evaluate performance, i.e. passing of a demand signals to upstream[6] components or failures due to any of the failure mechanisms simulated place (pipe bursting, WTP accidents, water scarcity etc.),

Table 3: Major supply Areas of the simplified topology

Supply Area	Yearly Demand [hm^3]	Equivalent households	Equivalent Population
Rodenhuis	10.4	97326	223850
Hazerswoude	4.1	38126	87690
Lekkerkerk	2.5	23729	54577
Den Hoorn	4.2	39427	90682
De Hooge Boom	2.3	21906	50384
Alblasserdam	1.5	13787	31710
Total	24.98	538893	234300

Table 4: Major supply elements of the simplified topology

Treatment Plant	Treatment chains and Capacity	Net Production [hm^3/y]	Water Sources
Rodenhuis	2 chains of maximum production capacity 1500 m^3/h each (total 3000 m^3/h)	12.1	river bank filtrate and collected shallow groundwater
De Steeg	2 treatment chains: collected shallow groundwater with maximum production capacity 1500 m^3/h and deep groundwater with maximum capacity 1800 m^3/h (total 3300 m^3/h)	9.1 (production here will be higher as De Laak TP which serves the same SAs is not included)	shallow groundwater and deep groundwater
De Hooge Boom	2 treatment chains of maximum production capacity 154 m^3/h each (total 308 m^3/h)	2.3	river bank filtrate and collected shallow groundwater
Lekkerkerk	2 treatment chains: river	2.8 (restricted	river bank filtrate

[6] Note that in UWOT the demand signal 'moves' back from a SA to a water source.

	bank filtrate with maximum production capacity 240 m^3/h and deep collected groundwater with capacity 300 m^3/h (total 540 m^3/h)	by abstraction limit)	and deep collected groundwater
Total Production	**7.148 m^3/h (or 62.6 hm^3/y if sustained)**		

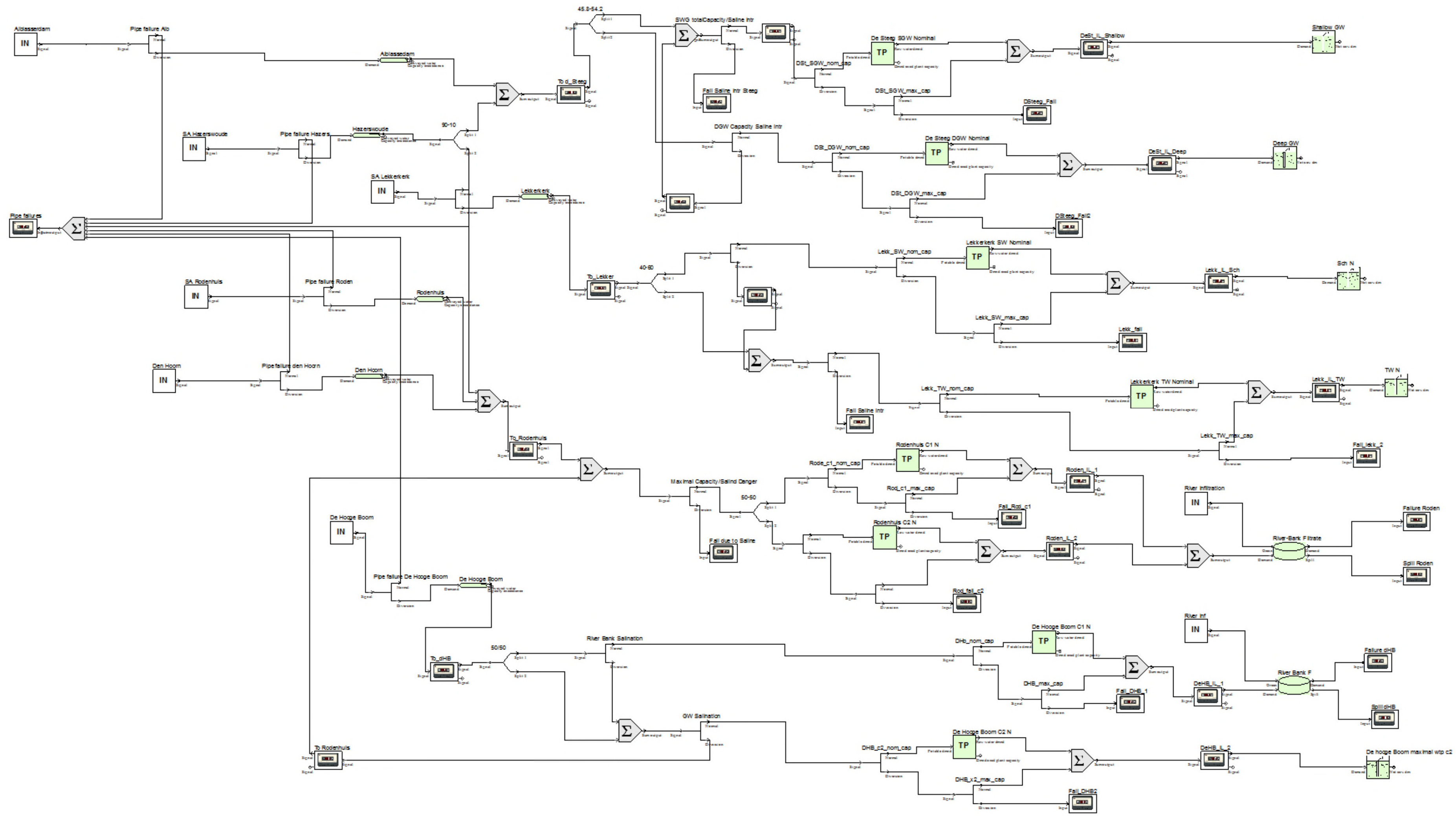

Figure 31: Complete UWOT topology for the BAU Oasen system

6.3. Benchmark Scenarios

To validate the model developed, we subjected it to a number of **benchmark 'test' scenarios**. These scenarios explore a future setting of increased demand (due to increased population), reduction in water supply (in the Oasen-specific form of saline intrusion) and aging infrastructure. These scenarios are tested in both standalone and combined fashion in order to evaluate the performance of the model and identify (and make certain we are able to simulate) specific characteristics of the Oasen system. This preliminary analysis along with Oasen's comments provided useful insights on how to create the scenarios and narratives of the complete resilience assessment performed next.

6.3.1. Increased Demand scenario

In this scenario, population doubles within 25 years (highly unlikely scenario, but useful as an extreme system benchmark), per capita demand fluctuates very slightly without a trend during the same period. The scenario is used for a preliminary analysis of the water supply service, effectively testing the capacity limits of individual WTPs. Key points of the scenario are:

- Population increases with a logistic model, a very common paradigm in future projections and water supply analysis
- Carrying capacity *K* is set to double the initial population of each SA, a rather high boundary
- The maximum daily rate of growth r_{max} is set to 0.05%. This is a very high rate, demonstrating an abrupt population change, as we seek to test the system's performance under extreme stress.
- Daily fluctuation percentage follows a normal distribution with m=0, s=1. *NR* notation in the equations below, stands for "random number" and is generated by a random number generation routine.
- Daily Demand D_i (with D_1 equal to yearly average) is given by the non-linear formula:

$$D_i = D_{i-1} * (1 + r_{max} * \frac{K - D_{i-1}}{K} + \frac{NR}{1000})$$

The daily demand for each of the 6 SAs is shown in Figure 32. The non-linear daily demand model gives a more "realistic" demand variation over time, including for example fluctuations (like peak factors etc.), but the formula is kept simple. These timeseries are used as UWOT inputs.

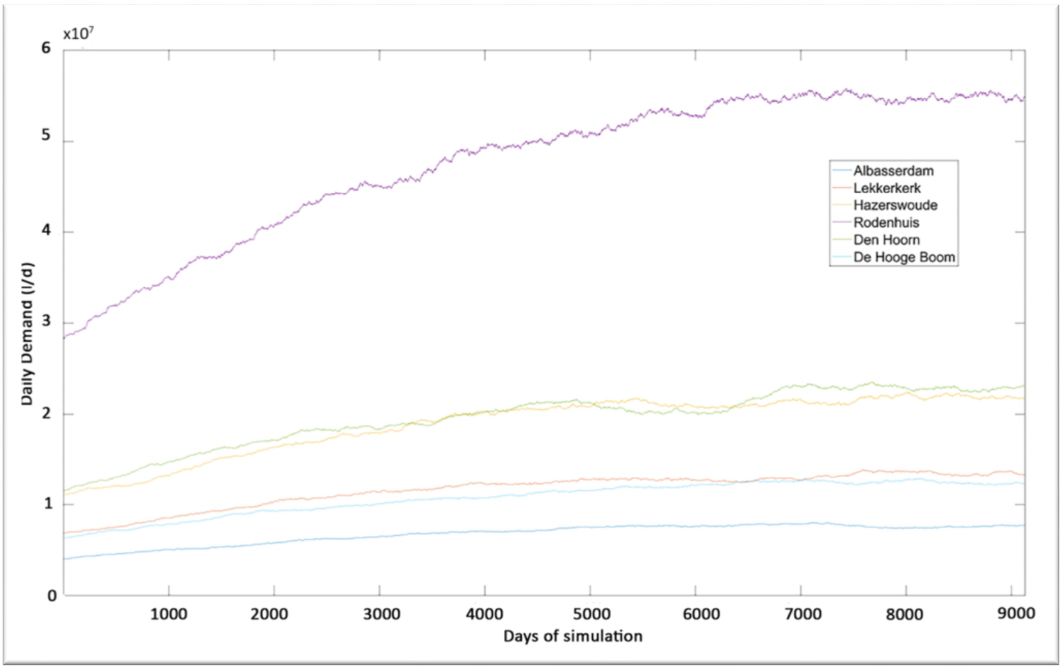

Figure 32: Daily demand ($\times10^7$ l/d) of each SA over a 25 years horizon for increased demand scenario

Table 5: SA initial and maximum daily demand

SA	Initial daily demand ($*10^6$ l/d)	Maximum daily demand ($*10^6$ l/d)
Alblasserdam	4.03	8.06
Lekkerkerk	6.93	13.89
Hazerswoude	11.14	22.44
Rodenhuis	28.43	55.83
Den Hoorn	11.52	23.56
De Hooge Boom	6.40	12.89

We then simplified the real-world connectivity between SAs and WTP attributes in the UWOT model as follows:

- Connectivity is simplified, with the removal of interconnectivity (by transport pipes), in order to asses each SA's characteristics separately and identify weak links.
- The capacity attribute of each WTP component is set equal to the lower *nominal* capacity of the treatment stages involved, instead of the maximum capacity. Two divergence components in UWOT act as thresholds: the first allows the signal with a value up to nominal capacity to pass to the WTP while the second diverts demand signals over the maximum capacity to failure loggers. This scheme allows us to spot WTPs working over nominal (normal) limits.

Figure 33 depicts this simplification.

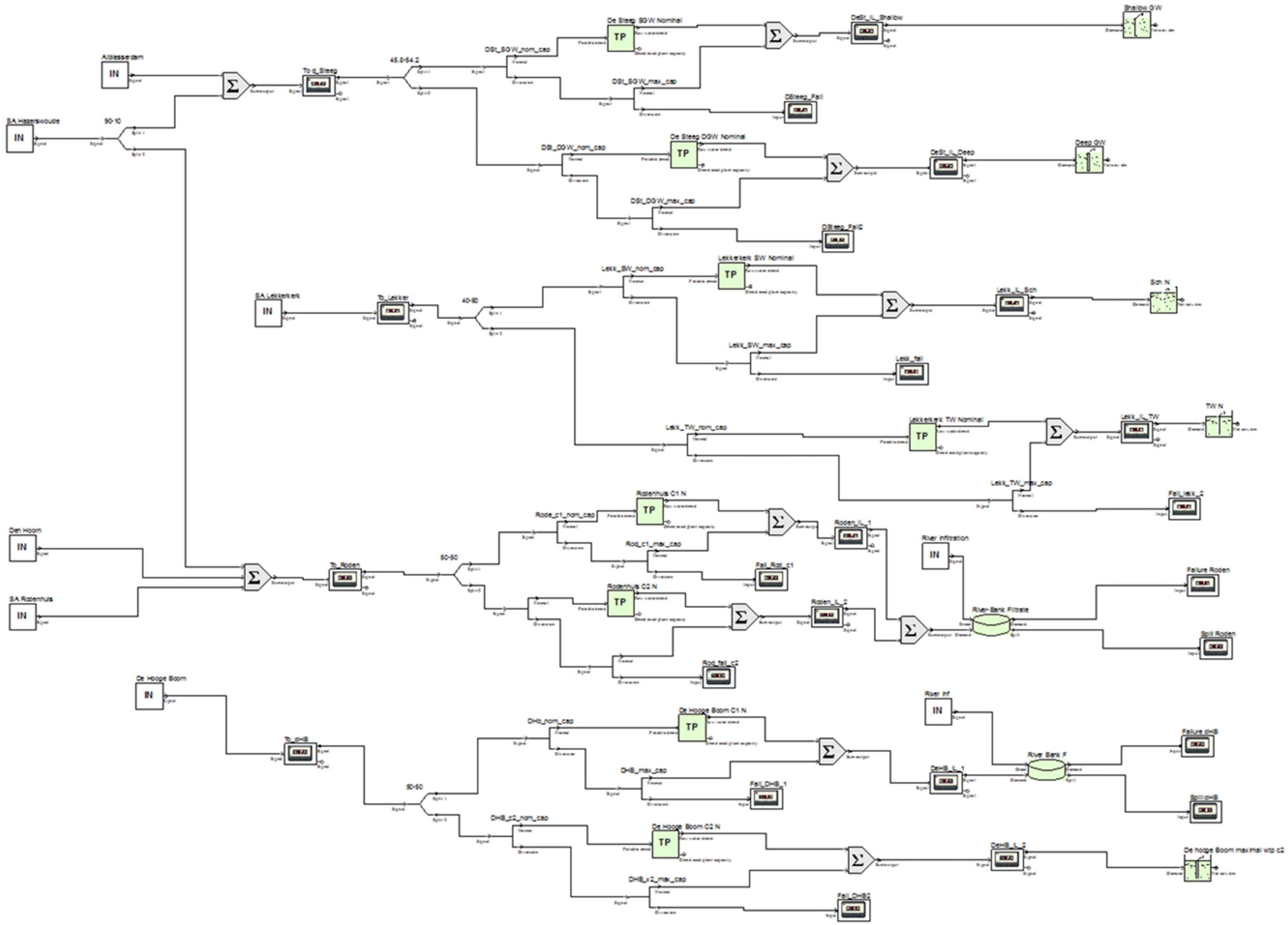

Figure 33: Simplified UWOT topology for increased demand scenario. Note the removal of interconnectivity (signal branches) compared to Figure 30

Figure 34 shows the total daily demand from all SAs (Alblasserdam, Lekkerkerk, Rodenhuis, De Hooge Boom, Den Hoorn, Hazerwoude) against the combined nominal and maximum capacity of all WTPs (De Steeg, Lekkerkerk, Rodenhuis, De Hooge Boom). It is clear from the simulation results that doubling the population stresses the WTPs well beyond their combined nominal capacity, but there is enough headroom to manage water supply (albeit only through the interconnectivity of SAs).

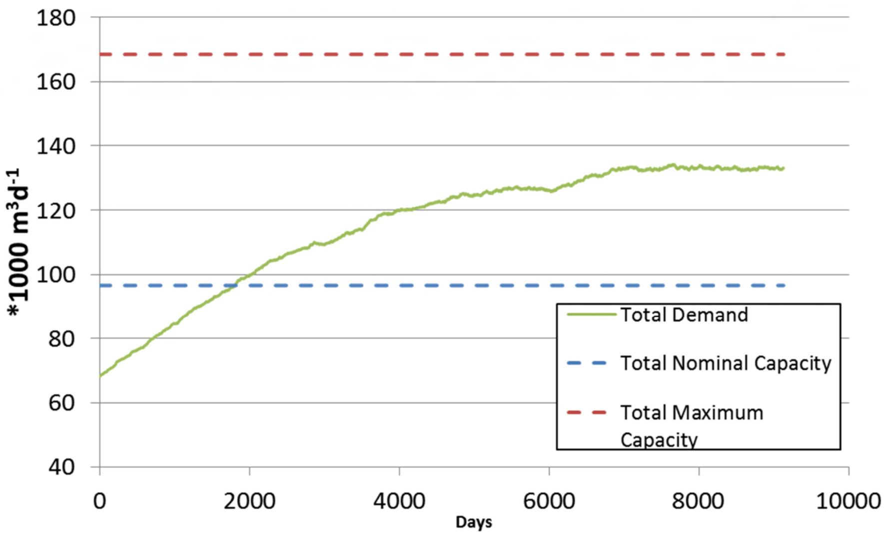

Figure 34: Daily total demand vs nominal and maximum combined WTP capacity for all 6 SAs

By also accounting for other minor failure mechanics (normal pipe failures, maximum borehole capacities) the minimum annual coverage of the system throughout the UWOT simulation is 83% as shown in Figure 35, which should be considered a solid performance outcome. In a UWOT topology that retains the real-world interconnectivity, coverage remains exceptional, mainly due to the large headroom (i.e the available overcapacity) of *De Steeg* WTP, as seen in Figure 36. However, this dependency on the reserved capacity of a single WTP may also be considered a vulnerability of the system.

Furthermore, as seen in the following Figures, WTPs Rodenhuis and De Hooge Boom operate above the nominal capacity of some procedures in the treatment chain. This may not currently affect operations but could become a bottleneck if demand increases. The fact that the system as a whole operates above nominal capacity even with roughly +50% demand should have an effect on plant maintenance, water quality etc., thus providing insight for the development of failure mechanisms in the complete resilience assessment (i.e. mechanisms related to maintenance).

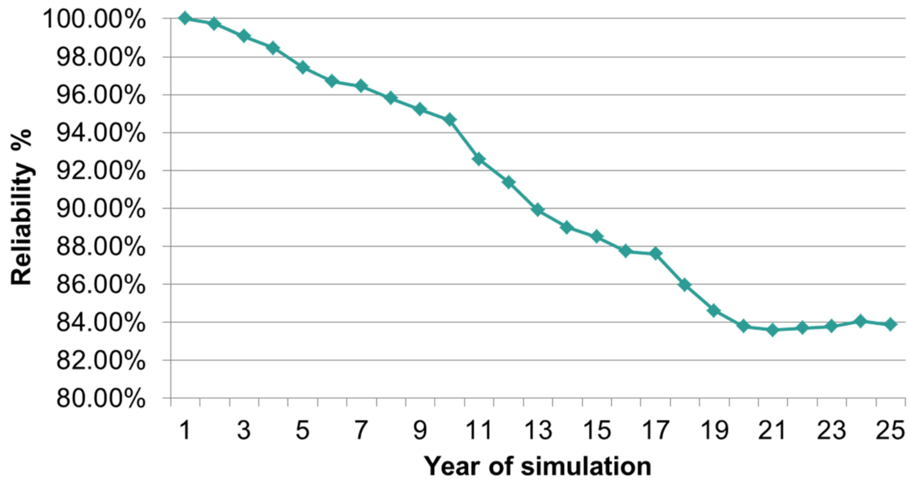

Figure 35: Annual coverage results of the scenario in terms of coverage reliability

The performance of each WTP is summarized in Figure 36 to Figure 39. Key points of note from the results are as follows:

- De Steeg, Figure 36: The plant is characterized by significant headroom and even when demand is doubled it is not particularly stressed. This excess capacity is very important for the overall system performance as it can reliably supply water to most other SAs apart from Alblasserdam and Hazerswoude.
- De Hooge Boom, Figure 37: The plant reaches its maximum capacity very early in the simulation (at circa 500 days); therefore, reliability is low and unsatisfactory as the minimum annual coverage drops to 55%.
- Rodenhuis, Figure 38: Nominal capacity is surpassed from the start, due to the fact that some elements of the treatment chains have lower capacities. Maximum plant capacity is also surpassed relatively early in this extreme scenario, after circa 400 days. Annual coverage drops to 85% as Rodenhuis is not adequate to cover the double demand of its respective SA, Rodenhuis, which is the biggest of the six.
- Lekkerkerk, Figure 39: Nominal capacity is quickly surpassed, stressing the maximum limit of the WTP. Here demand exceeds the maximum groundwater well capacity after circa 2000 days, thus the supply of Lekkerkerk is unreliable and coverage is lower than satisfactory (annual coverage rapidly drops to 73.6%). Note that maximum groundwater well capacity is set equal to daily permitted abstraction and not the physical maximum capacity of the pumps.

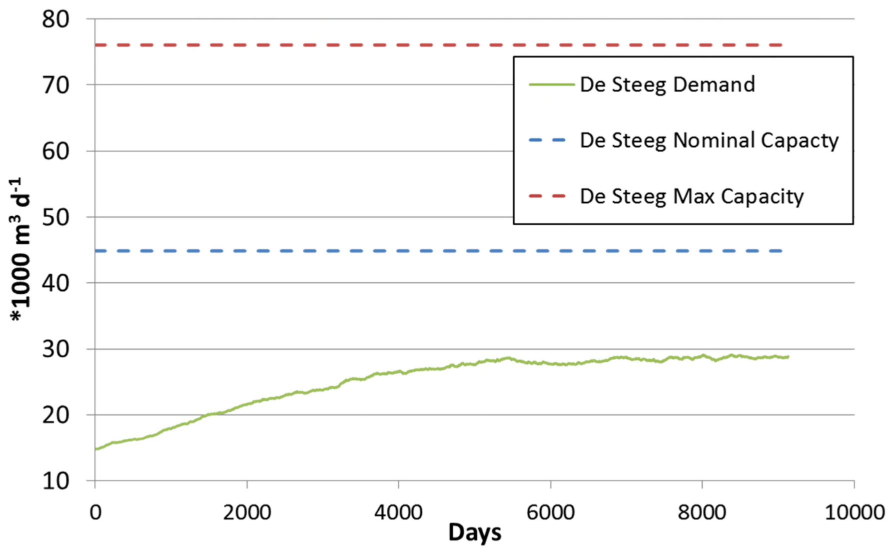

Figure 36: De Steeg WTP function under increased demand scenario, no performance loss.

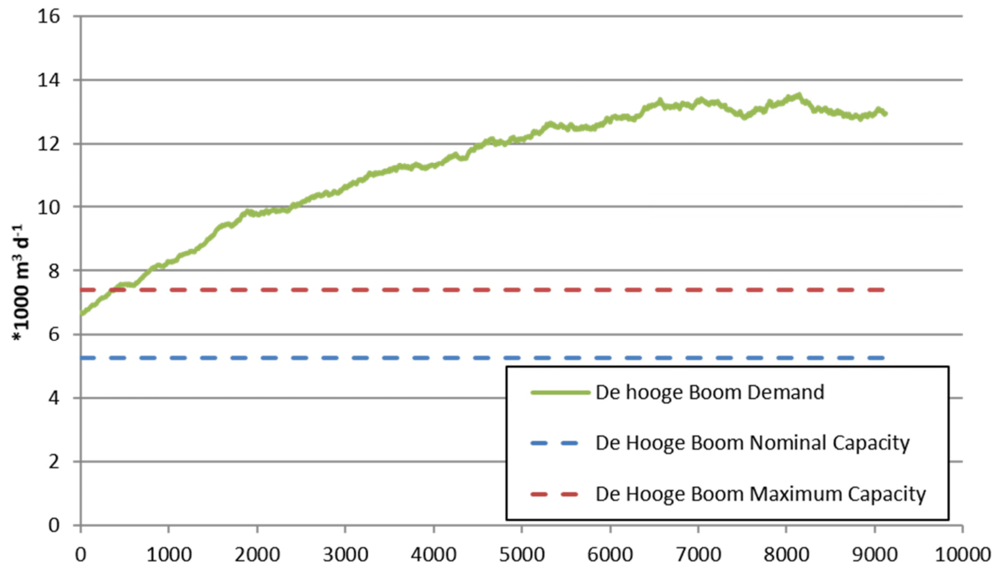

Figure 37: De Hooge Boom WTP function under increased demand scenario

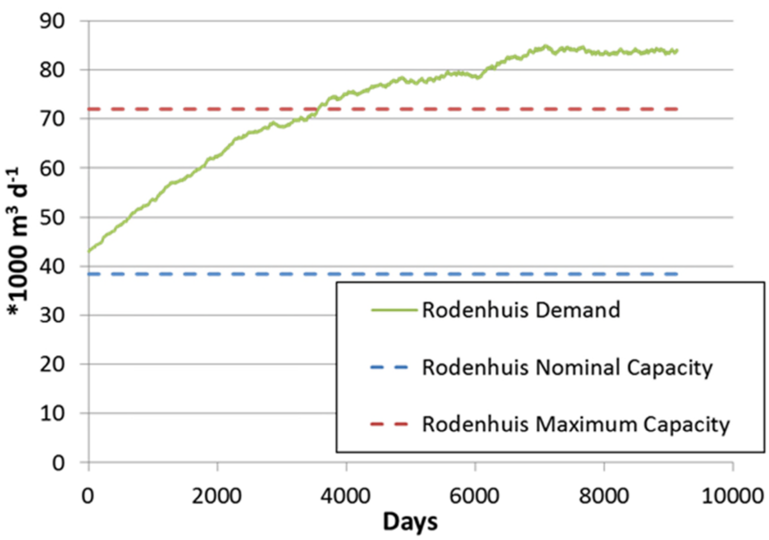

Figure 38: Rodenhuis WTP function under increased demand scenario

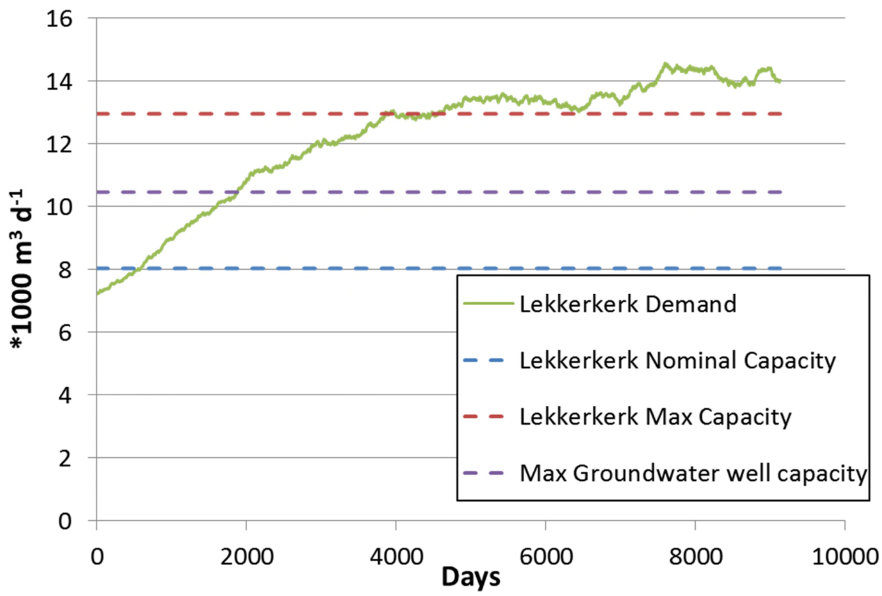

Figure 39: Lekkerkerk WTP function under increased demand scenario

6.3.2. Modelling saline intrusion

A hazard to Oasen is saline intrusion, specifically saline intrusion from the sea towards the river Rhine, affecting the most seaward WTP's of the Company. An example saline lens expansion is shown in Figure 40. Note that the figure is provided for illustrative purposes only and does not portray the mechanics of the specific saline intrusion scenario of relevance to Oasen.

In order to avoid overly-complex models that are suitable for a targeted groundwater study, we implemented a cellular automata (CA) approach to model saline lens expansion. We constructed scenarios with a single parameter termed *velocity factor* which effectively determines the rate of saline intrusion. The model is 2-dimensional as there is little point in simulating a 3rd (depth) dimension with mean groundwater level already below sea. The tool is simple and parsimonious and therefore suitable for the level of assessment undertaken in this study.

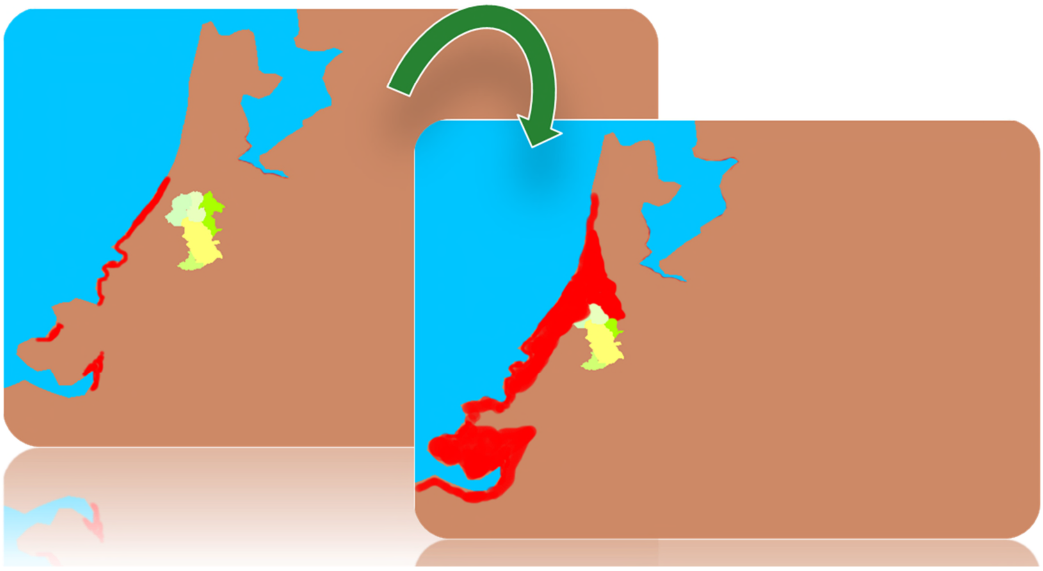

Figure 40: Mock-up example of salinity lens expansion over 25 years

The area is divided into binary cells with a coarse resolution of 200 x 200 m. Cells adjacent to the sea are assigned a value of "1" meaning that they have high salinity, all other cells are assigned a value of "0". We use a Moore neighborhood[7] with a radius of 4 cells. The sum of cells value in the neighborhood multiplied by the velocity factor determines the probability that the central cell will be also changed to value of "1" if it is "0" (i.e. change from low salinity to high salinity). In each iteration with an annual step, every cells' neighborhood is checked for cells with high salinity, a random number from a uniform distribution is generated and if the probability of the central cell is lower than the generated number it changes state from "0" to "1". Other transitions are not allowed. The output of the model at each annual iteration is the annual saline lens. The lens affects the wellfields of the Oasen area (15 wellfields in total, designated by number in Figure 41) when their position is overrun by the (modelled) saline lens. In this set of simulations, it was assumed that 1 year after saline intrusion is first detected in a wellfield, the wellfield becomes inoperative. This (crude) assumption helps us simulate the progressive increase in salinity by a simple mechanism (instead of only simulate spatial expansion). In these types of scenarios, we also retained the original interconnectivity of the system.

[7] http://mathworld.wolfram.com/MooreNeighborhood.html

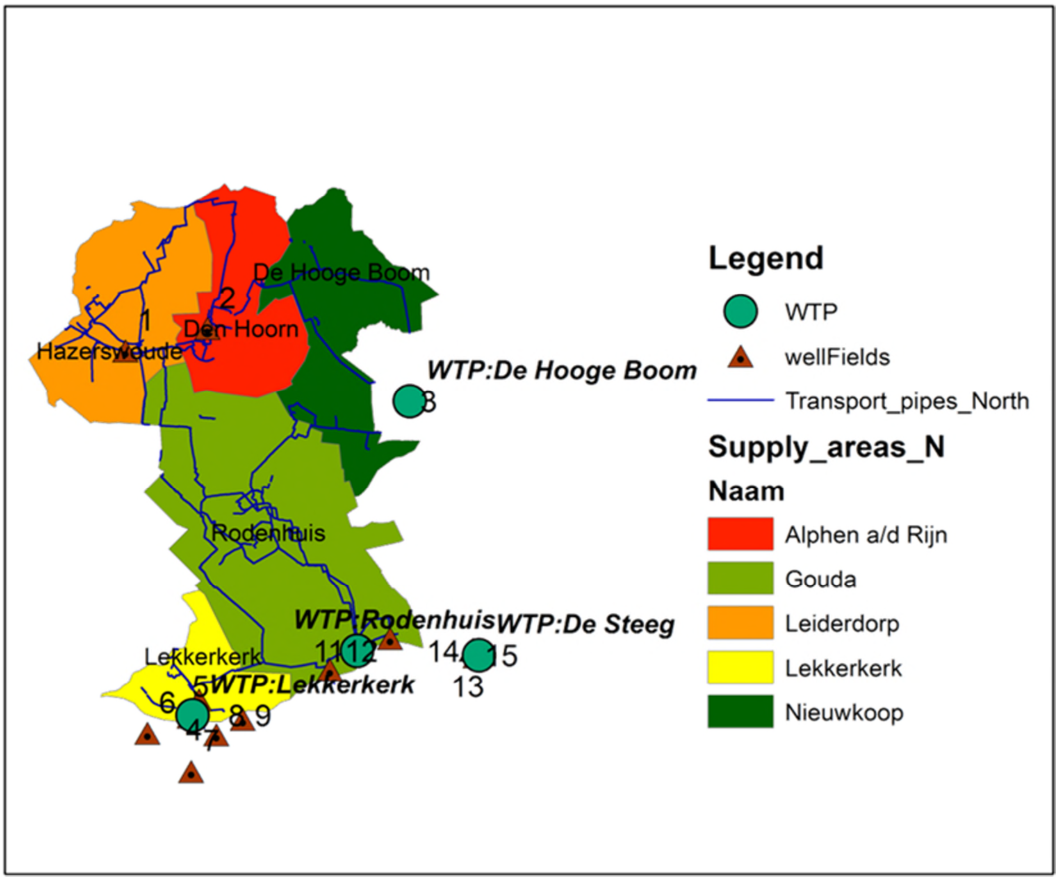

Figure 41: Position of wellfields and WTPs

6.3.3. Mild saline intrusion scenario

In this scenario the saline intrusion lens is expanding with a mild rate (by setting a low velocity factor in the CA model), and in a time span of 25 years affects only the northern wellfields of Oasen (these are linked to De Hooge Boom WTP) as depicted in the Figure 42 which is exported from the simple 2D CA model. De Hooge Boom actually uses two treatment chains with different sources, one with river bank filtration and one with groundwater wells. The hypothesis is that the recharge from the river can keep the salinity lens at a large enough distance from the river bank filtration units so they are not as severely affected. However, mixing with fresh water from another source must take place for production. The groundwater abstraction wells are abandoned when the salinity lens reaches them. When salinity is high, the De Hooge Boom SA is covered by the interconnected Rodenhuis WTP. This is achieved in UWOT by diverting the demand signal from De Hooge Boom to Rodenhuis WTP. Figure 43 shows the UWOT topology design that allows this level of connectivity and functionality. For each group of De Hooge Boom wellfields, a divergence component checks the lost "capacity" due to salinity and diverts demand to Rodenhuis WTP.

It should be noted that in this scenario demand does not change over time for simplicity while pipe failure is simulated for basic demand as this is an attribute of the component (same as in the case of increased demand scenario).

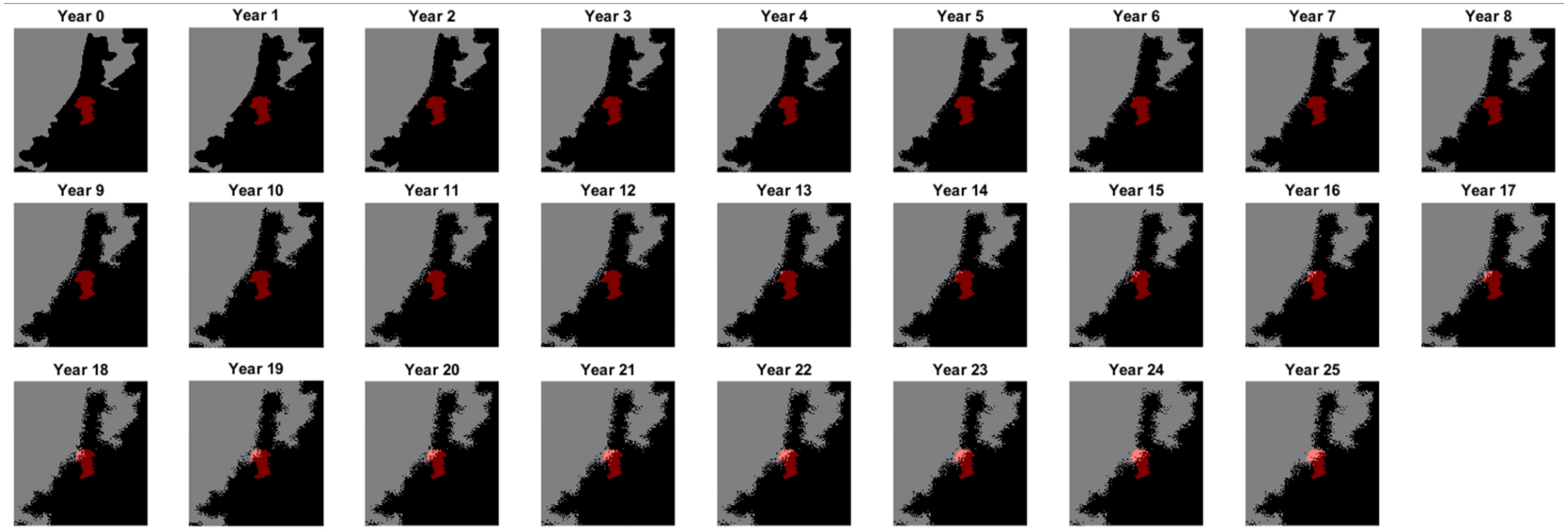

Figure 42: Mild saline intrusion scenario progression: Grey is area with high salinity (and sea in the 1st year), Red is the Oasen area and light red is Oasen area with high salinity.

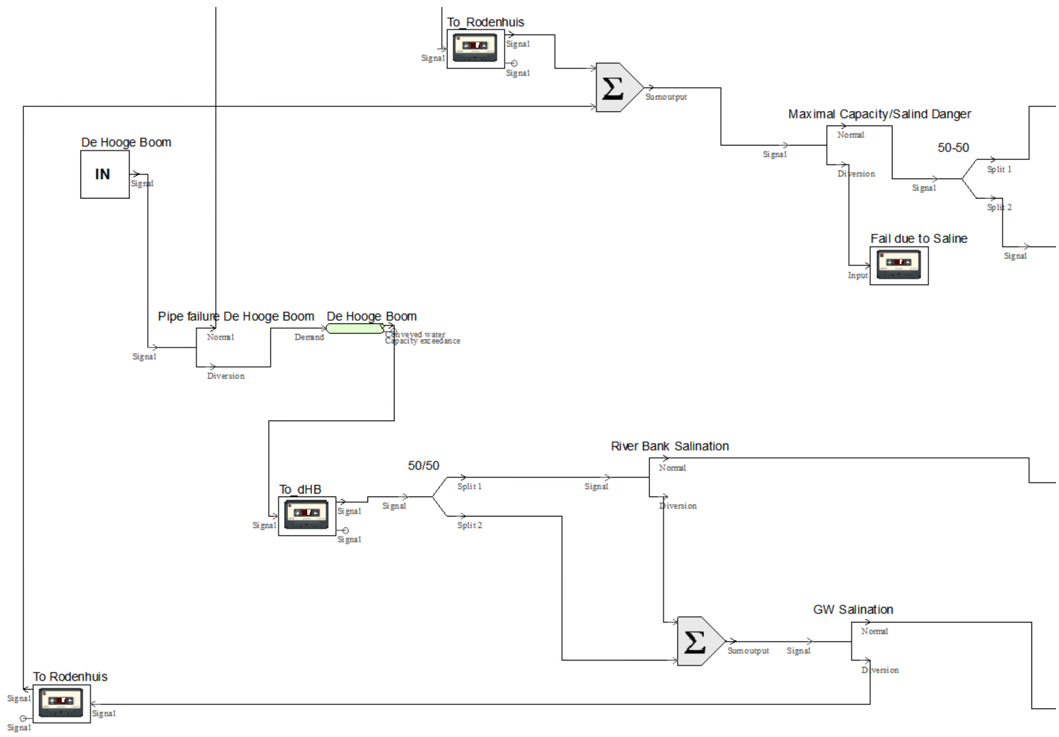

Figure 43: UWOT connectivity scheme of De Hooge Boom WTP in order to counter salinity problems. Demand signal is transferred to Rodenhuis WTP

Results from the simulation in the form of average annual coverage are shown in Figure 44. Mild saline intrusion does not affect operations much, since only the northern wellfields of Oasen are affected, and WTP Rodenhuis has enough capacity headroom to provide water for De Hooge Boom SA. Annual results are essentially the same as in the baseline scenario with basic pipe network failure probability, exhibiting high reliability.

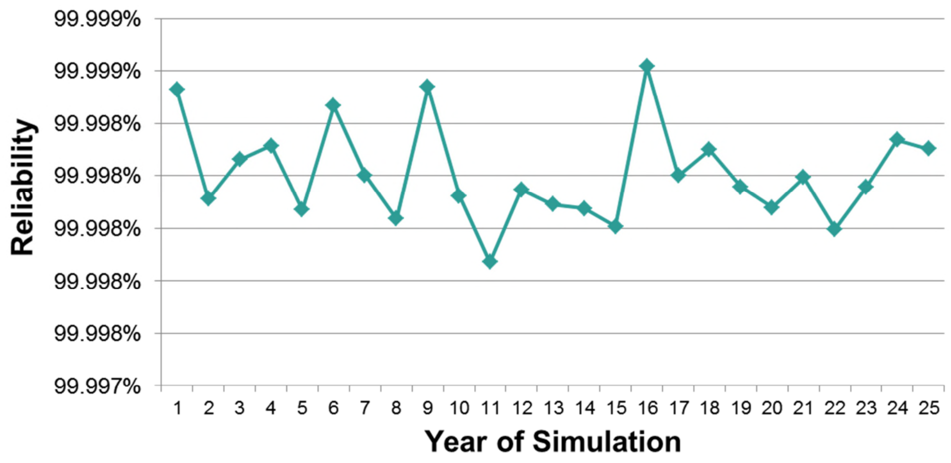

Figure 44: Annual coverage results of total Oasen water system for the mild saline intrusion scenario are exceptional with nearly 100% reliability

6.3.4. Extreme saline intrusion scenario

In this scenario, the saline intrusion lens is expanding with a very high rate (by setting the velocity factor at a high value, circa double that of the mild scenario), and in a time span of

25 years affects all wellfields of Oasen as depicted in Figure 46 exported from the CA model. In this scenario, saline intrusion does not affect the system while only the northern wellfields of Oasen are affected, but when the saline lens reaches the southern wellfields reliability collapses rapidly, as all wellfields are shortly and almost simultaneously affected (due to relative proximity and centralization). Annual results suddenly suffer, exposing the vulnerabilities of the current Oasen system to saline intrusion and reliance on centralized assets.

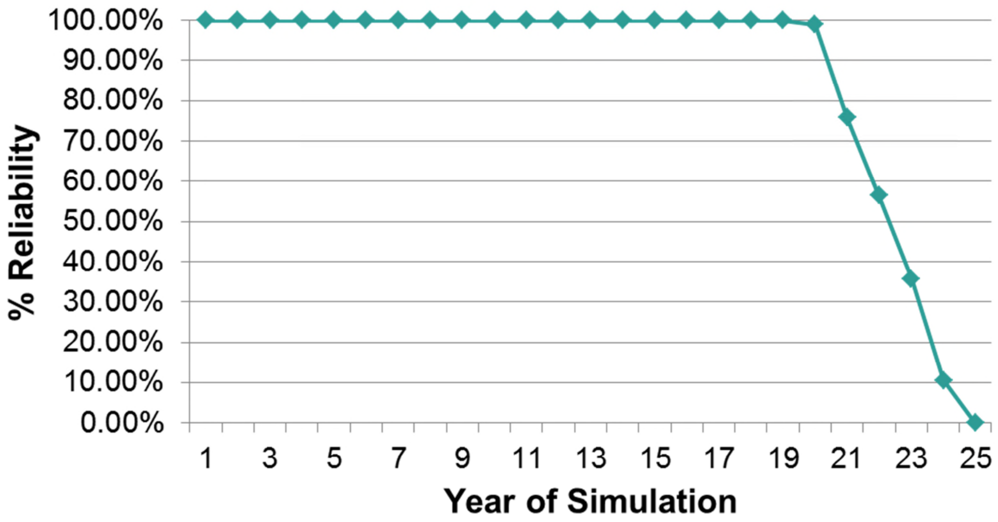

Figure 45: Annual coverage results of total Oasen water system for the rapid saline intrusion scenario are problematic with a steep decrease of reliability to almost 0%.

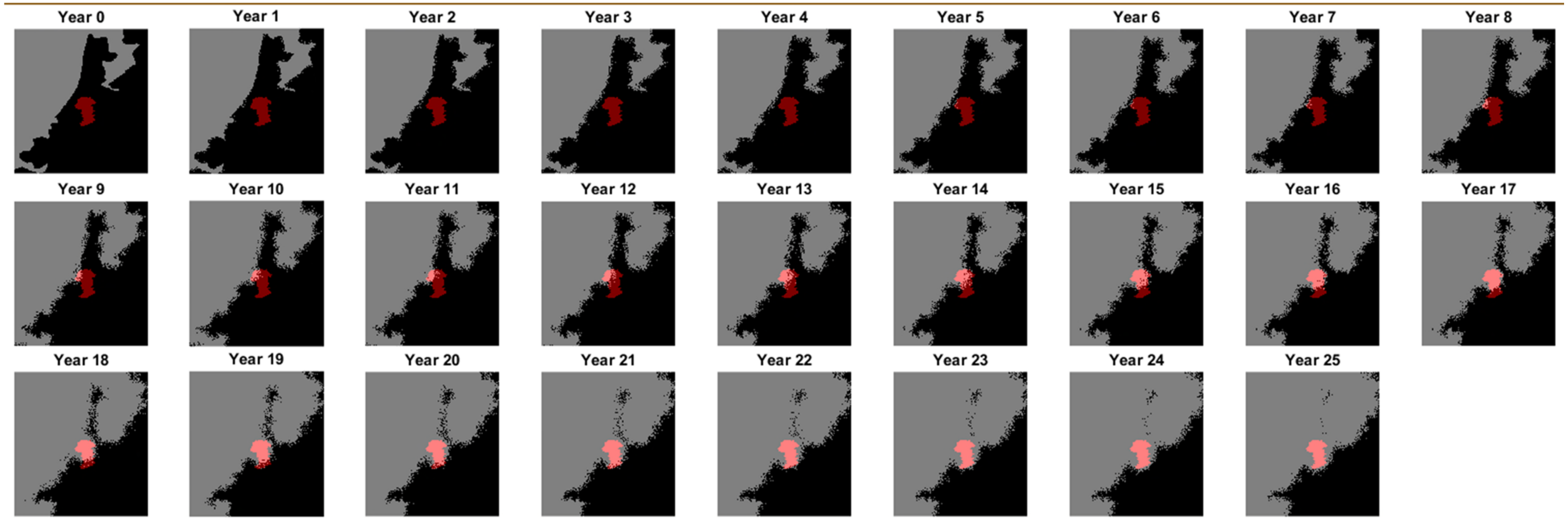

Figure 46: Rapid saline intrusion scenario progression: Grey is area with high salinity (and sea in the 1st year), Red is Oasen area and light red is Oasen area with high salinity. In year 25 all of Oasen area is affected

6.3.5. Combined pressures scenario

This was the most extreme benchmark for the Oasen water supply system in this preliminary proof of concept phase of the work. Multiple failure mechanisms are introduced and high pressures are combined to stress the system. In particular:

- Demand follows the *increased demand scenario* (section 6.3.1) where population doubles over 25 years, but per capita demand remains 127 L/d and people per household ratio remains unchanged).
- The pipe network length linearly follows the population expansion (as does the number of households i.e. connections). Pipe daily failure probability is the basic 0.00014/km, mean duration of failure is 3h (see section 5.4).
- Infrastructure ages. Natural degradation of components through a global natural degradation mechanism (i.e. the same for all major components) which is incorporated in pipe network, WTPs and wellfields. The rate of degradation is mild. This roughly translates to 5% capacity loss/failure probability increase over a timespan of 25 years. Maintenance of components is thorough so no additional wear-out of components or frequent accidental disruptions occur (see section 5.4).
- Saline intrusion follows the characteristics of the *rapid saline intrusion scenario* (section 6.3.4).
- The UWOT topology employed is the original with interconnectivity between SAs (similar to that used in the *saline intrusion scenarios*), visualized in Figure 31.

As expected, results indicate that this scenario is extremely stressful for Oasen. Even though all Supply Areas are interconnected to counter mild capacity loss due to aging infrastructure and source water scarcity due to saline intrusion in the north, demand increases rapidly. As can be seen during the period between 1 and 17 years in Figure 47, reliability drops with a rate that increases over time due to the increased demand. During the period between 17 and 22 years, several wellfields are abandoned due to saline intrusion lens reaching the southern area of Oasen, where most of the sources are located. Thus, the performance drop is steeper still. The water system appears to be very vulnerable to the combination of these pressures, becoming totally unable to provide water during the last three years of the simulation.

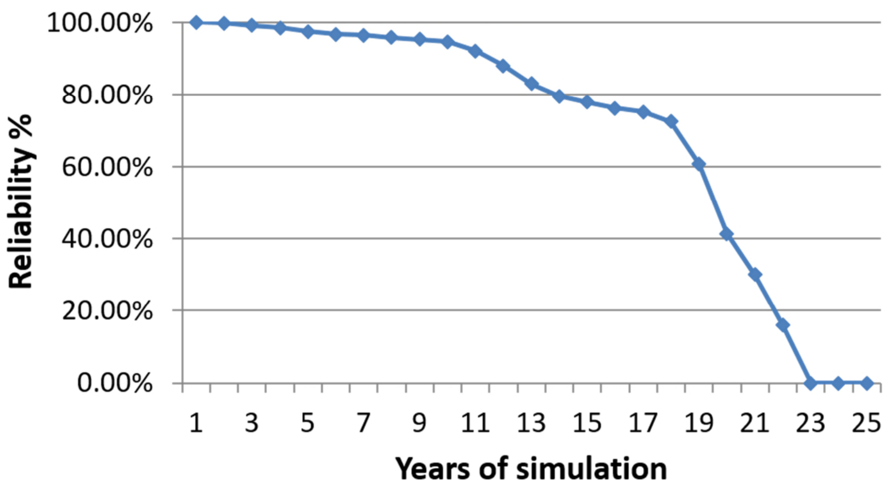

Figure 47: Annual coverage reliability metric in the combined pressures scenario

6.4. Undertaking a complete Resilience Assessment for the Oasen case

After the preliminary test scenarios, we embarked, together with Oasen, upon the creation of future water system topologies and scenario development, modelling and stress testing of the Oasen water supply system to produce resilience profiles. The resilience assessment undertaken made use of the full extent of the methodological framework developed throughout our research and it is the first time it is being applied in a real-world system.

- Three different topologies of the Oasen water supply system, termed *configurations* were developed:
  - **Configuration #1**: Business as Usual (BAU): The current relatively **centralised** topology of Oasen "as is".
  - **Configuration #2**: Next Step (NS): This topology explores **decentralised** options that can be implemented in a short/medium time horizon e.g. in 5-10 years.
  - **Configuration #3**: Further ahead (FA): This topology explores much more **distributed** disruptive options that typically need a longer timespan to be implemented e.g. 20 years.
- Seven different future world views termed *scenarios*, representing the increasing pressure to Oasen's water system defined using the same set of parameters from the hydroclimatic and socioeconomic realms:
  - Type 1&2: "Easy does it"
  - Type 3&4: "The Young Ones"
  - Type 5&6: "Of old people and things passed"
  - Type 7: "Maximum Overdrive"

We tested every configuration with all available scenarios, comprised of the same set of parameters, but with different rate of change and magnitude of change, as described in section 4. For the saline intrusion mechanics, we generated a single CA output (section 6.3.2) and used it in all cases, to ensure consistent behavior. Failures of different assets were generated as discussed in section 5.4.1. While, to some extent, results are affected by random number generated failures, it is suggested that the long timespan (25 years) in daily simulation steps (9.131 steps total) guarantees to some extent that, on average, every configuration faces a similar number of failures.

6.5. Configurations explained

The different configurations have the following characteristics and infrastructural elements:

BAU infrastructural elements: The system stays "as is":

- **Conventional treatment technology** plants:
  - Rodenhuis WTP: Maximum Production Capacity of 3000 m^3/h
  - De Steeg WTP: Maximum Production Capacity of 3300 m^3/h
  - Lekkerkerk WTP: Maximum Production Capacity of 540 m^3/h
  - De Hooge Boom WTP: Maximum Production Capacity of 308 m^3/h
- Interconnection between Supply Areas:
  - Circa 280 km of transport pipes
- Source options
  - River bank filtration
  - Shallow/Deep wellfields
- CAPEX: typical est. € 203,095,600 (see Appendix A)

- OPEX: typical of a similar sized conventional system
- Energy cost: 0.5 kWh/m^3

NS infrastructural elements: In this option the larger water treatment plants (10-16 hm^3/y)[8] are substituted by treatment units of 3-6 hm^3/y, which are still units with a proven track record. The new units use different sources and all new plants now use reverse osmosis (RO) as the primary purification technology, allowing them to operate even in high salinity.

- **Reverse Osmosis (RO) treatment technology** plants, more decentralized options with smaller plants:
  - Rodenhuis WTP 1: Maximum Production Capacity of 1000 m^3/h, re-allocated towards Gouda, next to the Hollandse IJssel, using surface water as main source
  - Rodenhuis 2 WTP: Maximum Production Capacity of 1000 m^3/h, re-allocated towards Polder Nieuwkoop, next to Nieuwkoop, using "seepage" water as main source
  - Rodenhuis 3 WTP: Maximum Production Capacity of 1000 m^3/h, stays at Bergambacht, using river bank filtrate as main source (same as current situation)
  - De Steeg 1 WTP: Maximum Production Capacity of 1800 m^3/h, remains in Lexmond using river bank filtrate as main source (same as current situation).
  - De Steeg 2 WTP: Maximum Production Capacity of 1500 m^3/h, re-allocated towards Sliedrecht, next to the Waal, using river water as main source.
  - Lekkerkerk WTP: Maximum Production Capacity of 540 m^3/h (same as current situation)
  - De Hooge Boom WTP: Maximum Production Capacity of 308 m^3/h (same as current situation)
- Interconnection between Supply Areas
  - Circa 350 km of transport pipes (due to more plants)
- Source options:
  - As BAU plus *brackish* water and *surface* water
- CAPEX: higher than BAU est. € 259,227,606 (Appendix A)
- OPEX: higher than BAU
- Energy cost: 2 kWh/m^3

FA infrastructural elements: In this option the existing water treatment plants (3-16 hm^3/y) are replaced by a series of approximately 100 small **RO-based purification units** of 70 m^3/h each. These units are located at the neighborhood level close to the customers and act as each other's back-up through a connecting network. The number of units per community is assumed proportional to the number of inhabitants. Rain water is also used as an *additional* source[9] at the domestic level.

- Maximum decentralization with 103 local units of 70 m^3/h
  - SA Rodenhuis: 43 plants
  - Hazerswoude SA: 16 plants
  - De Hooge Boom SA: 9 plants

[8] Note that a cubic hectometer is the volume of a cube of side length one hectometer (100 m) = 1 000 000 m^3

[9] It should be noted that rainwater is not used as drinking water. Domestic rainwater harvesting (RWH) is only a supplementary source alongside surface and ground water sources in FA scenario, not the main source. It is not feasible of course to cover the whole demand from rainwater but this was expected. Both topology and scenario results reflect this. It is important to note however, that domestic RWH reduces demand from other sources, thus making the FA configuration more resilient in high pressure scenarios. We made the basic assumption that rainwater can cover up to a maximum of 20% of daily usage (consistent for example with toilet flushing) and defined the topology accordingly.

- Albasserdam SA: 8 plants
- Lekkkerkerk SA: 10 plants
- Den Hoorn SA: 17 plants

- Domestic level Rain-water Harvesting
  - All households use the technology via the installation of a 2 m^3 tank per household
- Interconnection between Supply Areas
  - None, each SA is autonomous (no transport pipes between SAs)
- Source options:
  - Multiple sources, a wellfield for each local plant
- CAPEX: higher than NS est. € 260,186,956 (Appendix A)
- OPEX: much higher than NS
- Energy cost: 2 kWh/m^3

Figure 48 - Figure 50 depict the UWOT topology of configurations BAU, NS and FA respectively. BAU uses essentially the same topology already demonstrated in section 6.2, with the addition of more signal inputs to account for industrial and horticultural uses. Rodenhuis SA holds the industrial uses that utilize treated water (including the Cheese Industry) whereas horticultural activity takes place in De Hooge Boom SA and utilizes raw water from the two groups of abstraction wells found in the same area, also connected to De Hooge Boom WTP. The same distribution of uses is applied to the other configurations as well.

NS topology in UWOT is simpler than BAU despite the increased number of WTPs. This is because here we removed several signals 'divergences' as there is no need to check salinity thresholds because of the use of RO technology.

In order to simplify the FA topology, we undertook the following revisions of the UWOT model: a) we model the demand signal of a single household along with the rainwater harvesting tank, then amplify it to the Oasen scale via multiplication with the number of households and distribute it with splitter components for each SA according to its size b) we group together in a single 'super-component' the local WTPs of each SA e.g. the "Rodenhuis" TP has the characteristics of 43 local plants. Maintenance mechanisms still apply individually for every single local TP. We use a divergence component with a variable threshold in front of the TP super-component. The aggregated threshold of all local TPs changes according to total capacity. This results in a cleaner and more usable topology, without compromising in detail (i.e., the topology does not include a *X* number of TP components and a *X* number of divergence components to simulate every mechanism, but rather a super-component with the aggregated behavior comprised of a single TP and a single divergence UWOT components).

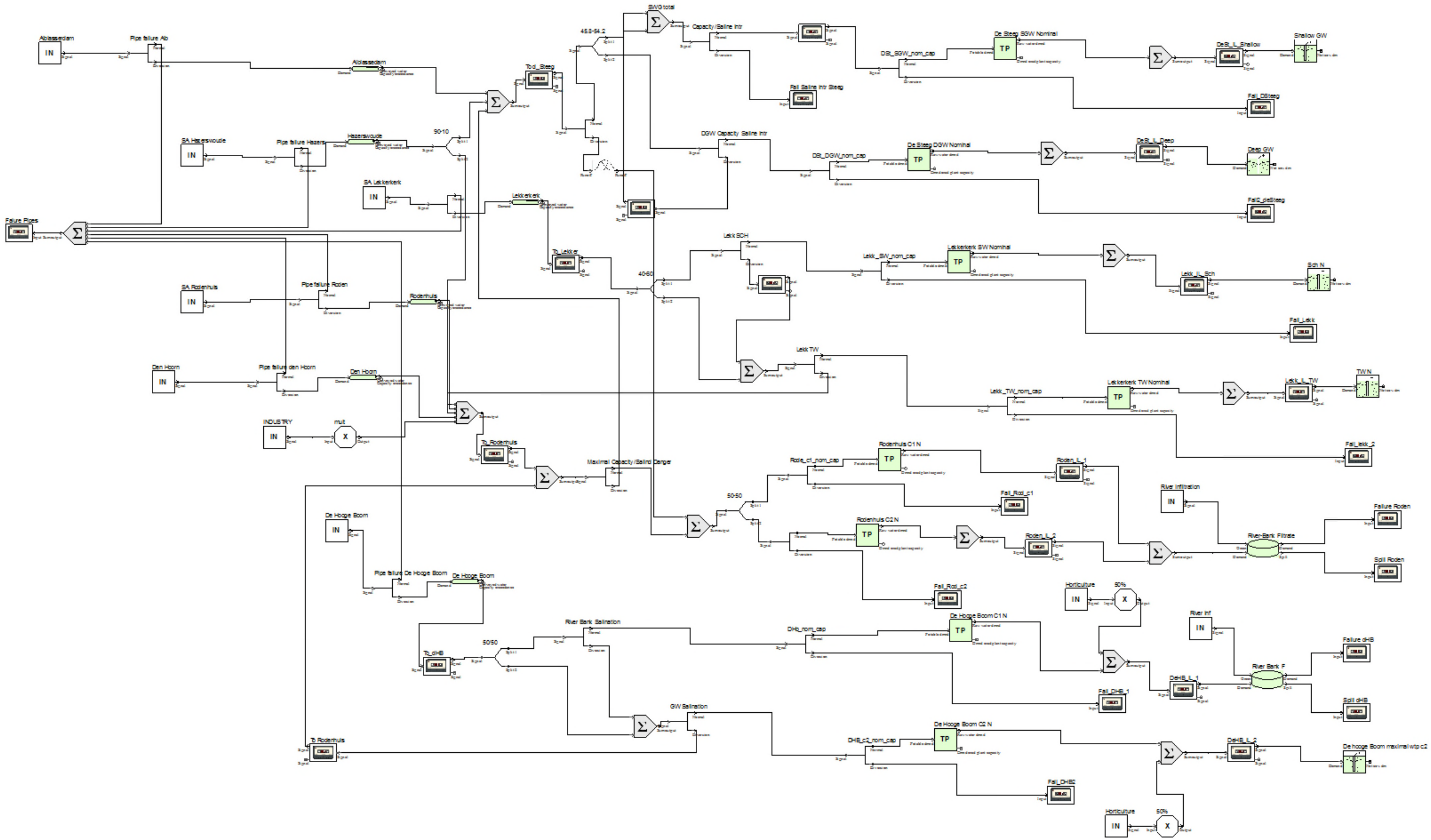

Figure 48: BAU configuration, UWOT topology

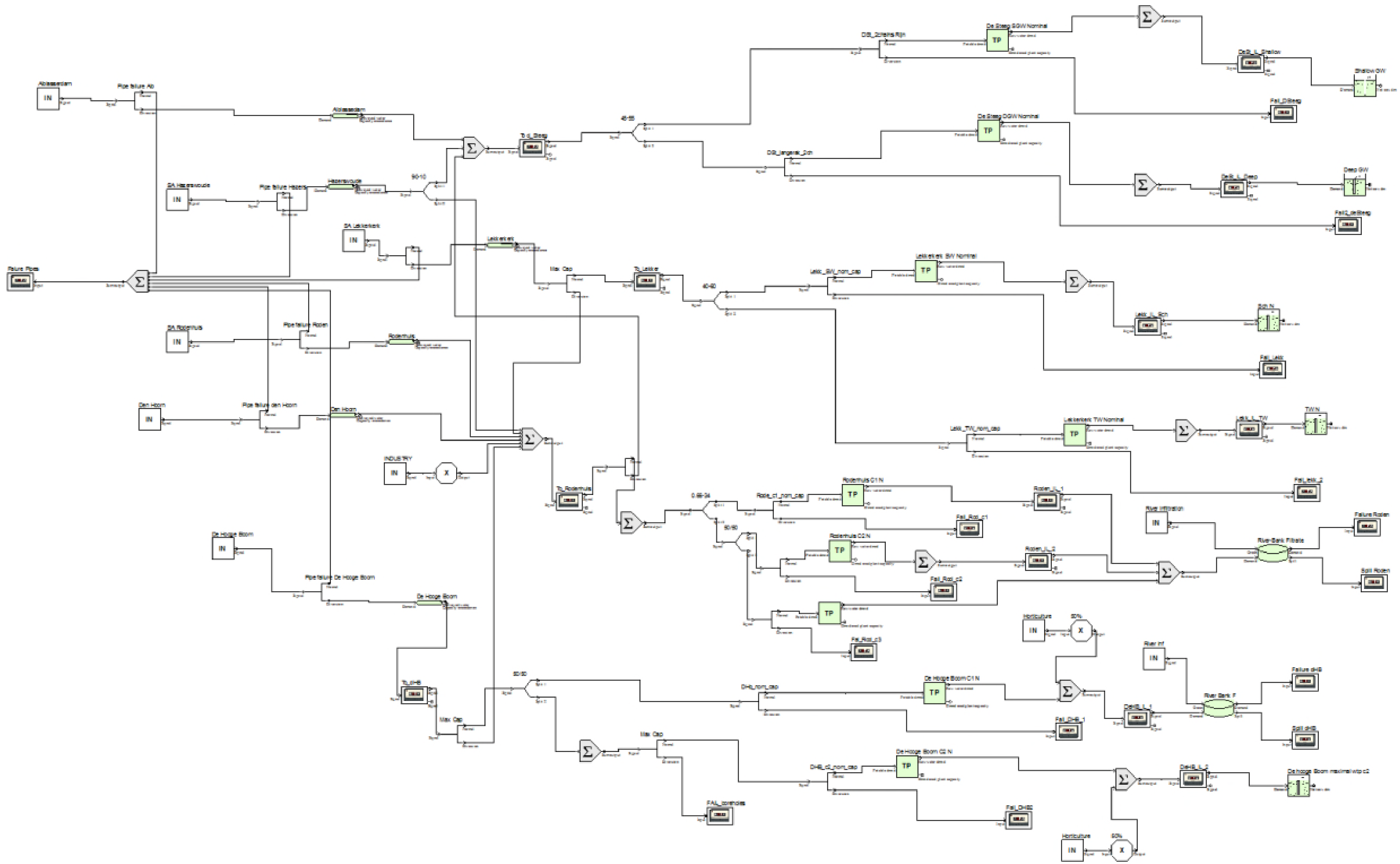

Figure 49: NS configuration, UWOT topology

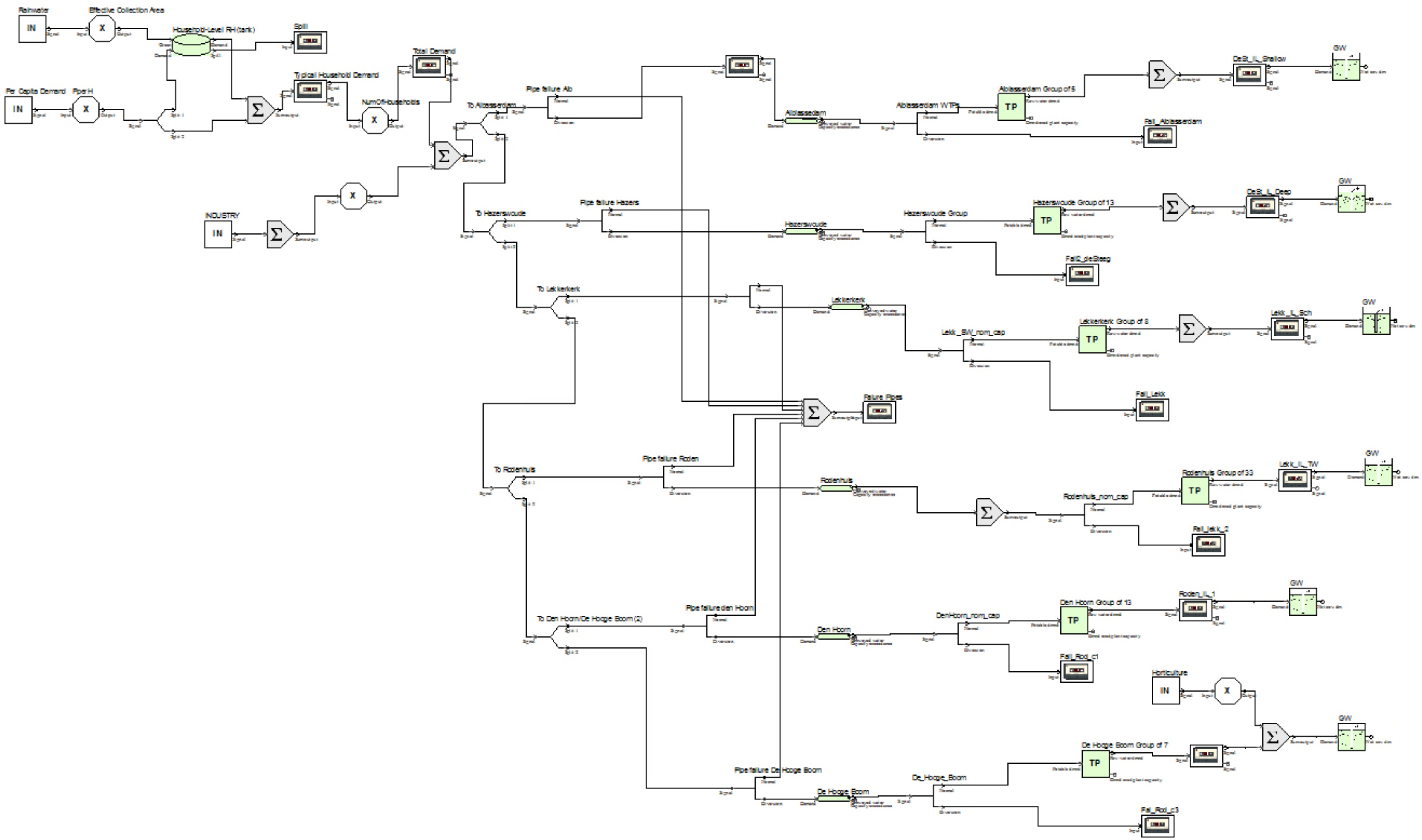

Figure 50: FA configuration, UWOT topology

6.6. Scenario-scape

The following seven scenarios that comprise the scenario scape have been developed with Oasen's insights and comments and include a variety of parameters of interest for their specific water system. The baseline parameter values are shown in Table 6. Magnitude of change in the scenarios explored refers to the factor that is applied to these values. For linguistic values single-state change or two-state change is denoted (see section 5.2 for details).

Table 6: Baseline values of parameters

Parameter	Baseline value
Population	538815
Number of households	227838
Age distribution (% above 65)	19.3
Ethnic composition (% non-western migrants)	8.9
Knowledge development (% GDP for scientific research)	0.57
Electricity price heavy users (€cents/kWh)	5.17
GDP (per capita) of area	39703
Public Finances (% GDP for public spending, national)	46.8
Temperature (degrees Celsius)	10.13
Average rainfall (winter)	211
Average rainfall (summer)	188
Cooling water demand industry/energy (km3/j)	14
Phosphorus emission to surface water	1.4
Horticultural water demand	1
Basic domestic water use (technology)l/p/d	125
Basic domestic water use (behavioral)l/p/d	125
Water Governance (Public, Public-Private, Private)	Public
Risk acceptance (zero tolerance, acceptance)	zero tolerance
Trust in corporations (low, medium high)	medium
Trust in government (low, medium high)	medium
Environmental values (low, medium high)	medium
Knowledge about water sector (low, medium high)	low
Dominant ideology (progressive, liberal, conservative)	liberal
Quality Standards Drinking Water (NL, WHO)	NL

6.6.1. Type 1 & 2 "Easy does it"

These scenarios exhibit the smallest magnitude and rate of change from the Baseline scenario. Type 2 differs from Type 1 in the rate of change of some parameters, however their magnitude is the same. The Oasen supply area stays roughly the same size, with no change in population and households. Aging occurs as expected with the population share of 65+ almost doubling. There is a modest increase in GDP. The Province of Zuid-Holland gradually allows its industry to expand, resulting in an increase in water demand. Due to a reduction in the usage of fertilizer there is a slight decrease in phosphorus emission to surface water. The political landscape is fairly stable with mostly liberal coalitions. Privatization of the water sector is off the table as trust in government to take care of utilities is high. Although there is a modest increase in industrial activity, to the expense of agriculture, peak contamination of surface water with pollutants remains limited.

Table 7: Parameter values (magnitude and rate) of Scenarios 1&2

Parameter	Final Value	Magnitude of Change	Type 1 Rate	Type 2 Rate
Population	538815	1.00	n.a.	n.a.
Number of households	227838	1.00	n.a.	n.a.
Age distribution (% above 65)	29.92	1.55	gradual	medium
Ethnic composition (% non-western migrants)	8.90	1.00	n.a.	n.a.
Knowledge development (% GDP for scientific research)	0.57	1.00	n.a.	n.a.
Electricity price heavy users (€cents/kWh)	5.95	1.15	gradual	abrupt
GDP (per capita) of area	59554.50	1.50	gradual	gradual
Public Finances (% GDP for public spending, national)	46.80	1.00	n.a.	n.a.
Temperature (degrees Celsius)	11.14	1.10	gradual	gradual
Average rainfall (winter)	221.55	1.05	gradual	gradual
Average rainfall (summer)	197.40	1.05	gradual	gradual
Cooling water demand industry/energy (km3/j)	14.00	1.00	n.a.	n.a.
Phosphorus emission to surface water	1.23	0.88	gradual	medium
Horticultural water demand	1.00	1.00	n.a.	n.a.
Basic domestic water use (technology)l/p/d	125.00	1.00	n.a.	n.a.
Basic domestic water use (behavioral)l/p/d	125.00	1.00	n.a.	n.a.
Water Governance	Public	no	n.a.	n.a.

Risk acceptance	zero tolerance	no	n.a.	n.a.
Trust in corporations	medium	no	n.a.	n.a.
Trust in government	high	single state	gradual	gradual
Environmental values	medium	no	n.a.	n.a.
Knowledge about water sector	low	no	n.a.	n.a.
Dominant ideology	liberal	no	n.a.	n.a.
Quality Standards Drinking Water	NL	no	n.a.	n.a.

6.6.2. Type 3 & 4: The Young Ones

Faced with economic uncertainty and the outlook of an aging population the Dutch government together with the private sector formulates an ambitious plan to attract young immigrants from Asia and the Middle East to the country. This leads to a gradual increase in the Oasen area population. Water conservation is not a high priority with the younger generation and the partly privatized water sector was not very keen on pushing a change in behavior either. As a result of the economic expansion, both industrial and horticultural water demand gradually rises as well. To be able to serve this increasing demand at reasonable costs, quality standards are loosened. Due to an increase in industrial activity, the water sector has to deal with frequent increases in pollutants.

Table 8: Parameter values (magnitude and rate) of Scenarios 3&4

Parameter	Final Value	Magnitude of Change	Type 3 Rate	Type 4 Rate
Population	628086	1.17	gradual	abrupt
Number of households	320771	1.41	gradual	abrupt
Age distribution (% above 65)	24.13	1.25	gradual	gradual
Ethnic composition (% non-western migrants)	13.89	1.56	gradual	abrupt
Knowledge development (% GDP for scientific research)	0.67	1.17	gradual	gradual
Electricity price heavy users (€cents/kWh)	5.95	1.15	gradual	medium
GDP (per capita) of area	66752.40	1.68	gradual	abrupt
Public Finances (% GDP for public spending, national)	36.04	0.77	gradual	abrupt
Temperature (degrees Celsius)	11.14	1.10	gradual	gradual
Average rainfall (winter)	221.55	1.05	gradual	gradual
Average rainfall (summer)	197.40	1.05	gradual	gradual
Cooling water demand industry/energy (km3/j)	22.97	1.64	gradual	abrupt
Phosphorus emission to surface water	1.40	0.88	gradual	gradual
Horticultural water demand	1.60	1.60	abrupt	abrupt
Basic domestic water use (technology)l/p/d	155.00	1.24	gradual	gradual
Basic domestic water use (behavioral)l/p/d	177.50	1.42	gradual	medium

Water Governance	Public-Private	single-state	gradual	gradual
Risk acceptance	Risk acceptance	two-state	gradual	medium
Trust in corporations	medium	no	n.a.	n.a.
Trust in government	medium	no	n.a.	n.a.
Environmental values	medium	no	n.a.	n.a.
Knowledge about water sector	low	no	n.a.	n.a.
Dominant ideology	liberal	no	n.a.	n.a.
Quality Standards Drinking Water	WHO	two-state	gradual	gradual

6.6.3. Type 5 & 6: Of old people and things passed

The decades following the 2018 political crisis in the EU showed hardly any recovery. The brief periods of growth were quickly outdone by subsequent economic crises. The conservative governments of the 2020-2030 pushed an agenda of austerity and privatization. Trust in government hit an all-time low, with people looking to the private sector for solutions. The Oasen area was hit particularly hard. Population declined, with young families leaving for Amsterdam and Rotterdam exacerbating the already pressing burden of an aging population. Both industry and horticulture gradually left the area, leading to a decrease in water demand. Climate change leads to a series of exceptionally dry summers and huge peaks in rainfall in autumn and spring. Due to minimal regulations and oversight from authorities, the river Lek is frequently polluted with all sorts of chemical pollutants, worsened by the long periods of drought.

Table 9: Parameter values (magnitude and rate) of Scenarios 5&6

Parameter	Final Value	Magnitude of Change	Type 5 Rate	Type 6 Rate
Population	474157	0.88	gradual	gradual
Number of households	200497	0.88	gradual	gradual
Age distribution (% above 65)	44.58	2.31	gradual	medium
Ethnic composition (% non-western migrants)	6.68	0.75	gradual	medium
Knowledge development (% GDP for scientific research)	0.29	0.50	gradual	medium
Electricity price heavy users (€cents/kWh)	10.34	2.00	gradual	abrupt
GDP (per capita) of area	47267.22	1.19	gradual	abrupt
Public Finances (% GDP for public spending, national)	51.00	1.09	gradual	medium
Temperature (degrees Celsius)	12.36	1.22	gradual	medium
Average rainfall (winter)	240.54	1.14	gradual	gradual
Average rainfall (summer)	159.80	0.85	gradual	gradual
Cooling water demand industry/energy (km3/j)	7.00	0.50	gradual	abrupt
Phosphorus emission to surface water	1.13	0.81	gradual	medium
Horticultural water demand	0.50	0.50	gradual	medium
Basic domestic water use (technology)l/p/d	62.50	0.50	gradual	medium
Basic domestic water use (behavioral)l/p/d	87.50	0.70	gradual	medium
Water Governance	Private	two-state	gradual	medium

Risk acceptance	risk acceptance	two-state	gradual	medium
Trust in corporations	high	single-state	gradual	medium
Trust in government	low	single-state	gradual	medium
Environmental values	low	single-state	gradual	abrupt
Knowledge about water sector (low, medium high)	low	no	n.a.	n.a.
Dominant ideology	conservative	single-state	gradual	abrupt
Quality Standards Drinking Water	WHO	two-state	gradual	gradual

6.6.4. Type 7: Maximum Overdrive

Two decades of unprecedented growth have put huge strains on de Randstad. Being one of the winners in the catch-all competition between West-European cities, it has now to deal with the consequences: uneven population growth, huge increases in demand for water, food and energy and a relatively low tax-base. Most public services have been privatized and environmental regulations are minimal. The Lek River suffers from frequent peak concentrations of both chemical and biological pollutants. Drinking water quality norms have not been relaxed however, resulting in increasing pressure on the private water suppliers to reliably produce clean drinking water. The use of medicines has doubled due to aging and increase in chronic diseases. Climate change turns out much worse than expected with average rainfall in the winter increased by 50% and an average temperature increase of 4 degrees.

Table 10: Parameter values (magnitude and rate) of Scenario 7

Parameter	Final Value	Magnitude of Change	Type7 Rate
Population	711235	1.32	abrupt
Number of households	350870	1.54	abrupt
Age distribution (% above 65)	24.13	1.25	gradual
Ethnic composition (% non-western migrants)	22.78	2.56	abrupt
Knowledge development (% GDP for scientific research)	0.29	0.50	abrupt
Electricity price heavy users (€cents/kWh)	0.72	0.14	abrupt
GDP (per capita) of area	79406.00	2.00	abrupt
Public Finances (% GDP for public spending, national)	23.40	0.50	abrupt
Temperature (degrees Celsius)	14.18	1.40	abrupt
Average rainfall (winter)	316.50	1.50	abrupt
Average rainfall (summer)	94.00	0.50	abrupt
Cooling water demand industry/energy (km3/j)	56.00	4.00	abrupt
Phosphorus emission to surface water	1.67	1.19	abrupt
Horticultural water demand	4.00	4.00	abrupt
Basic domestic water use (technology)l/p/d	155.00	1.24	abrupt
Basic domestic water use	177.50	1.42	abrupt

(behavioral)l/p/d			
Water Governance	Private	two-state	abrupt
Risk acceptance	zero tolerance	no	n.a.
Trust in corporations	low	single-state	abrupt
Trust in government	low	single-state	abrupt
Environmental values	low	single-state	medium
Knowledge about water sector (low, medium high)	low	no	n.a.
Dominant ideology	liberal	no	gradual
Quality Standards Drinking Water	WHO	two-state	gradual

6.7. Saline Intrusion: an Oasen-specific scenario component

On top of the scenarios above that follow our previous work (Makropoulos, *et al.*, 2016), we added a rather severe saline intrusion scenario element across the board. The rate of saline intrusion could in principle be associated with scenario parameter values (especially climate change related variables) but for reasons of simplicity and comparability this was not further customized in this work.

6.8. Wildcard modelling

Wildcards are "black swan" events or sudden changes to the operation of the system that have unpredictable patterns and deviate from classical structural or operational failures in the sense of non-repeatability. To explore such events within the context of a resilience assessment, we decided not to embed them into the formal scenario space, as we did with other, more probability-driven variables (such as the probability of a pipe bursting for example), but rather to employ a standardized way of further stress testing all scenarios/configurations with such events. Specifically, wildcards were applied to every scenario at Year 13, which is the center of the time horizon under investigation. The benefit of (arbitrarily) stressing the system with a wildcard event in Year 13 across all scenarios is that by the middle of the simulation period, performance across configurations is typically not extremely different, but the effects of the scenarios are beginning to emerge, as per the rate of change attributes (even at gradual rate of change more than 50% of the change's magnitude for any scenario parameter has been already applied at Year 13 of 25). As such, the wildcard effect is different enough for various configurations and scenarios but is not overshadowed by extreme differences between scenarios e.g. SC7 +54% households in Year 25. We measure the impact the wildcard has over the specific period during which it is manifested, and finally we aggregate wildcard and scenario results (Figure 51).

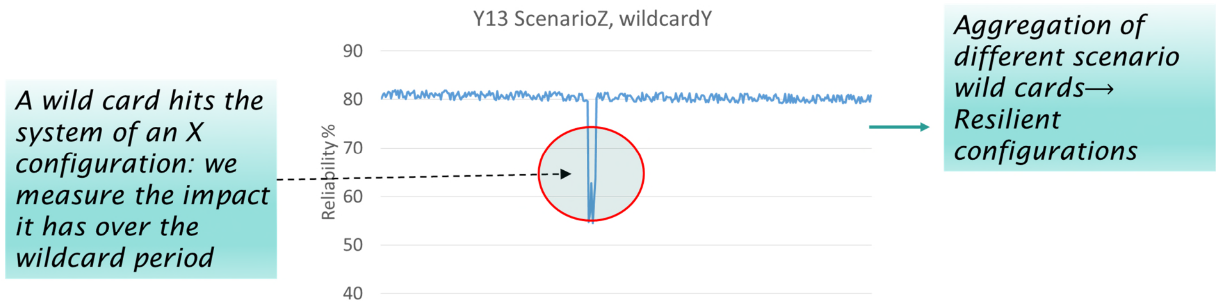

Figure 51: Schematic example of the effect a wildcard has on the system's performance

Four wildcards were developed as storylines and applied the case study:

Wildcard #1: Breach of Lekdijk

Narrative: "At Y13 during a storm, a dyke in the southern area is breached and the area close to the location of BAU's Rodenhuis WTP is flooded". Duration of wildcard is 7 days. Effect of the wildcard (model input):

- BAU configuration loses a major WTP (Rodenhuis) for 7 days until recovery, a heavy blow to system's reliability.
- NS configuration is built around decentralization and employs having two smaller units in the same area. One of them is located far from the dyke and in higher elevation, thus only one WTP is affected for 7 days.

- FA is completely decentralized with many smaller localized units laid out according to urban density. The area affected is not heavily urbanized (as shown in Figure 52), thus effects are minimal: only 2 out of the 43 interconnected smaller local WTPs are affected by the dyke breach.

Figure 52: View of the area affected

Wildcard #2: Summer with increased chloride and extreme drought

Narrative: "The summer of Y13 is characterized by an extreme drought, reducing rainfall by 75% and increasing chloride concentration in river water". Duration of this event is the 3 summer months of Year 13. Effects of the wildcard (model inputs):

- BAU configuration uses conventional technologies, and thus some of the bank-filtration units are abandoned (De Hooge Boom, Rodenhuis). De Steeg WTP is overburdened with the task of providing supply to nearly all areas, greatly reducing reliability.
- NS configuration uses RO technology. It is largely unaffected, and this can also be attributed to the interconnected SAs. When peak concentration occurs, water for mixing to areas affected can be transferred from Lekkerkerk and De Steeg that do not use bank-filtration units.
- FA uses RO technology, but the SAs are not interconnected. Also, the reduced rainfall greatly reduces the ability to cover demand through rainwater harvesting, thus the configurations reliability is mildly affected.

Wildcard #3: Hacking of critical infrastructure

Narrative: "On 13/06 of Y13 a hacker group exploits a backdoor in the SCADA of the most critical component of the system, gains control through a ransomware, shuts down the water supply and demands ransom." Duration of wildcard till crisis averted: 1 day.

- In the BAU configuration the De Steeg WTP is targeted. Reliability is drops as the demand is diverted to Rodenhuis WTP which has a small capacity headroom.
- In the NS configuration the two smaller De Steeg WTPs (which are assumed to be managed and controlled through the same centre) are targeted. Both shut down. Reliability is drops as the demand is diverted to the two Rodenhuis WTPs which have a small capacity headroom.

- In the FA configuration it is assumed that the largest WTP group is targeted, which is the Rodenhuis group in this case. The local WTPs are assumed to be controlled and monitored using a single SCADA system at the SA level. As such, all plants shut down. Different SAs are not interconnected in this configuration for back-up. Reliability suffers, as there is no way to cover demand other than (local) rainwater harvesting in the SA that is affected.

Wildcard #4: Extreme immigration due to climate change

Narrative: "Due to climate change people from southern Europe and the Middle East, immigrate *en masse* to northern Europe at Year 13. Oasen is particularly affected facing a population increase of 10%" This resembles a sensitivity test to all configurations, and a more "linear" behaviour is expected across this wildcard. Wildcard period is a whole year.

6.9. A final note on metrics: Oasen-specific metric modifications

For the specific purposes of modelling Oasen we made the assumption that the cml metric (see section 4.2) equals to:

cml = (# of people affected * duration of failure)/all people served

where # of people affected equals volume not delivered/per capita demand (pcd).

This interpretation was also cross-checked with Oasen representatives. We use the basic pcd at the start of the simulation to transform the daily demand to equivalent customers served (eqc) and the daily deficit to equivalent customers affected. We also assumed a duration of the failure resulting in said deficit. Here we have selected 1 day (1440 min) but this is a simplification, due to the coarser daily timestep of the study and could of course be refined in follow-up studies if needed.

7. Results and Discussion

7.1. BAU results

Initially we tested the BAU configuration against all scenarios (SC 1 to SC 7). Results are summarized Figure 53, using the coverage metric (see section 4.2). Results are annual averages and follow the progression of the scenario parameters based on the specific world views, across the 25 years of the simulated period. As seen from the graph, the BAU configuration is not very resilient as the simulation progresses. While reliability is reasonably high across all scenarios at Y1 of simulations, it collapses rapidly as pressures increase (SC3/4 and SC7). Even mild pressure scenarios (SC5/6) exhibit significant loss of reliability at the end of the simulation, something to be expected, as saline intrusion takes its toll against the wellfields affected. A significant "drop" of the resilience profile occurs in the last 3 years of the simulation.

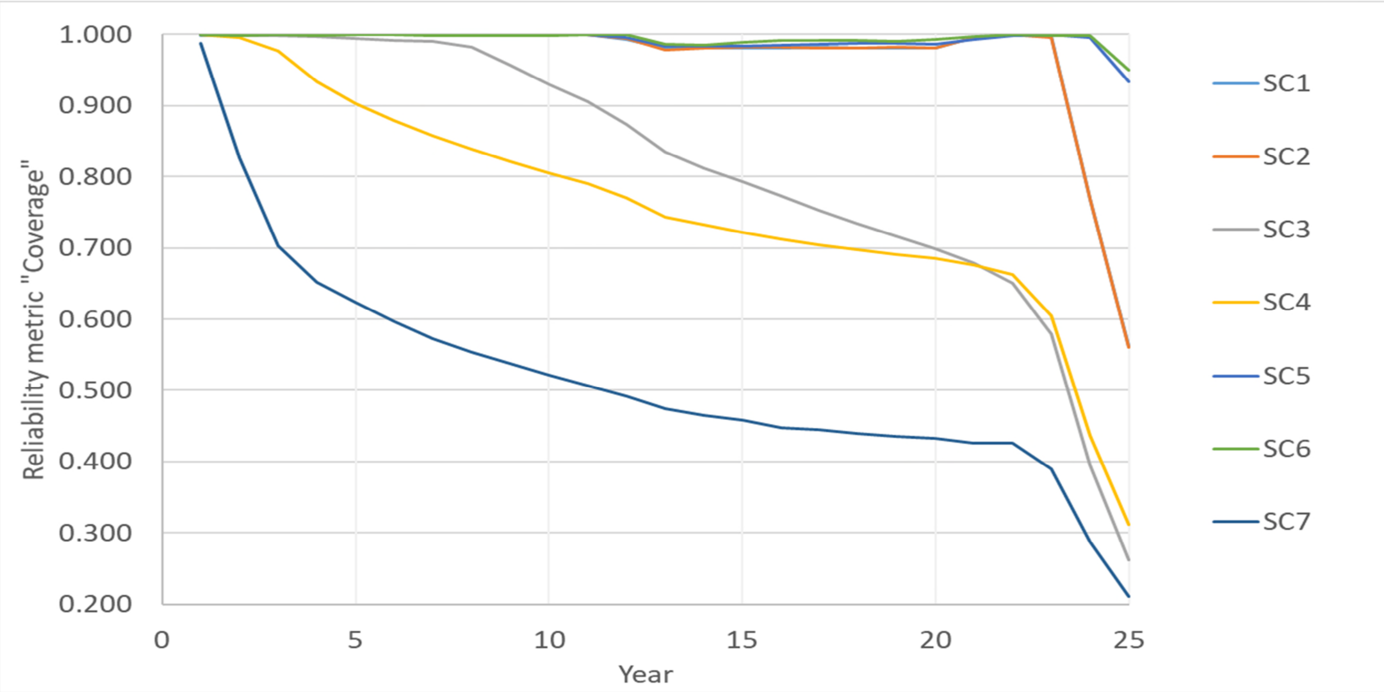

Figure 53: BAU annual coverage progression of different scenarios

Results from the cml metric in the form of average daily minutes lost are presented in Figure 54 to Figure 54 as average, maximum and minimum daily cml values respectively. Values are shown as bar charts of every scenario in six-year splits for convenience and better readability.

Maximum daily cml values are much higher than average daily values, owning to the random nature of disruptions occurring at the component level e.g. WTP failures. These disruptions generally have a low frequency but convey a large deficit. Thus, there exist high maximum daily values of cml even in scenarios/time-splits where the average daily cml values are very low. However, as pressure increases in stressful scenarios/time-splits the difference between average and maximum cml values is minimized because disruptions in operation become more frequent and are of bigger volume and the system struggles to maintain adequate operation. Results from the minimum daily cml values show that in the less stressful scenarios (SC 1/2/5/6) the system is able to perform at least tolerably, early in the simulation (i.e. up to year 13 cml range between 0 and 25) if no accidental disruptions occur.

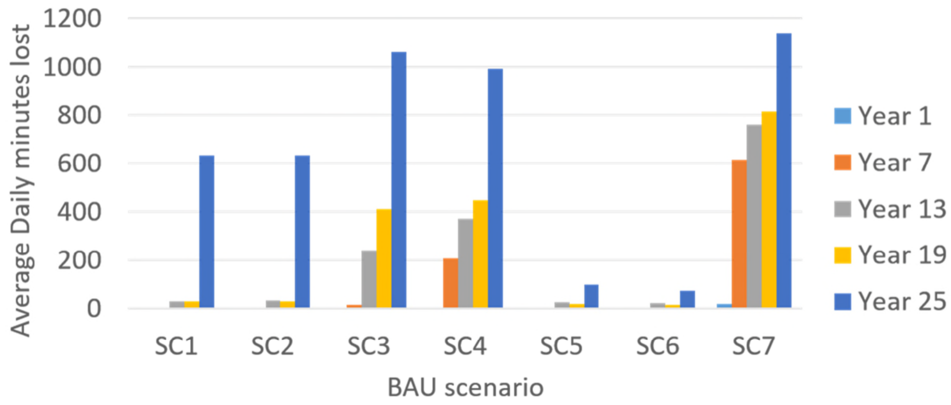

Figure 54: BAU daily average minutes lost grouped by scenario

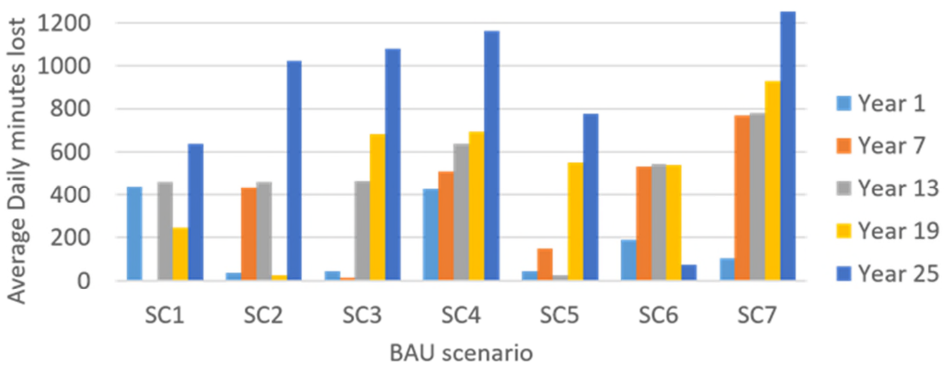

Figure 55: BAU daily maximum costumer minutes lost grouped by scenario

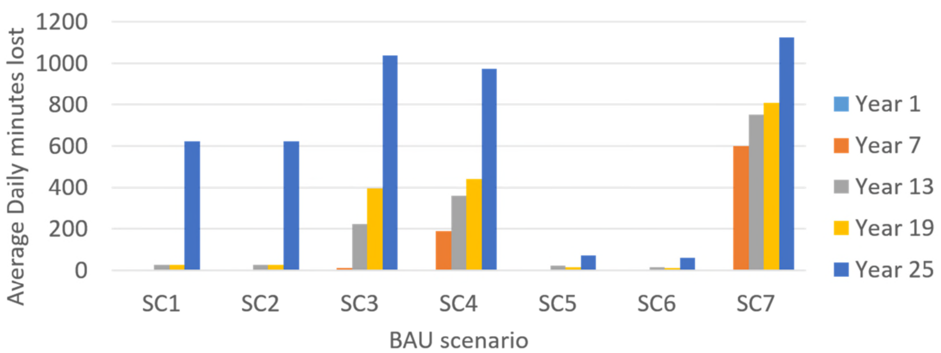

Figure 56: BAU daily minimum costumer minutes lost grouped by scenario

The yearly aggregated cml values are useful to convey information about total deficits. Actually, the cml metric is quite comparable to the "coverage" metric, if one converts it to **'customer minutes served'**. Figure 57 presents aggregated annual "customer minutes served" results, for three characteristic time splits, i.e. at years 7/13/25. Scenarios in this figure are **ordered by severity**. Results show that only in SC5/6 does the BAU configuration retain a (barely) acceptable level of service through the whole simulation. In terms of scenario severity, it can be noted that SC6 is the less stressful scenario in terms of water quantity and SC5 follows. The minimal difference between SC2 and SC1 in severity is attributed to the stochastic nature of failures (more small failures occur - randomly - in SC1 than expected) as the pressure is similar.

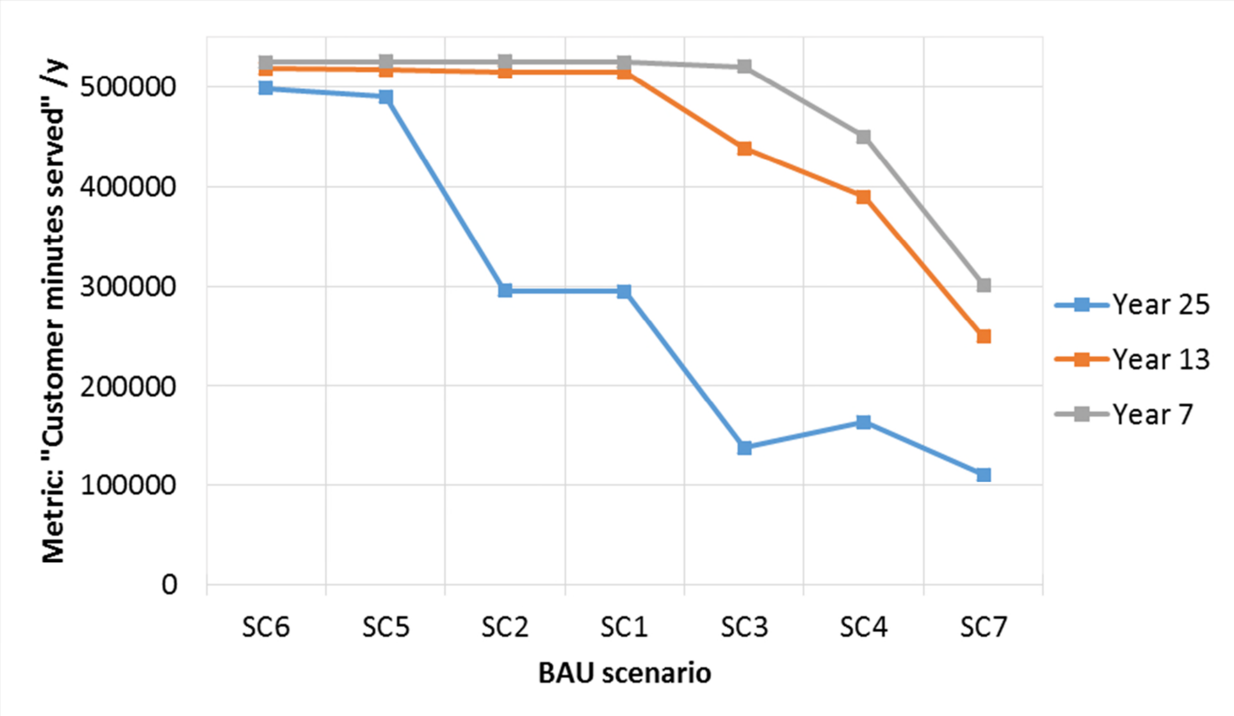

Figure 57: BAU annual customer minutes served in select time-splits, scenarios ordered by severity

7.2. NS results

After testing NS against all scenarios (SC 1 to SC 7) we summarize results of the coverage metric in Figure 58. The NS topology exhibits much better results in all scenarios and simulation years than BAU with coverage being very good (>99%) throughout the complete time horizon (i.e. up to Year 25) in the less stressful scenarios. It also retains better performance for a greater timespan in SC3/4 & SC7, although in SC7 performance collapses rapidly. The better performance is attributed to the greater redundancy (from the decentralization of the two larger WTPs) and the capability of the RO system to counter quality problems, especially saline intrusion which is the key weakness of BAU configuration.

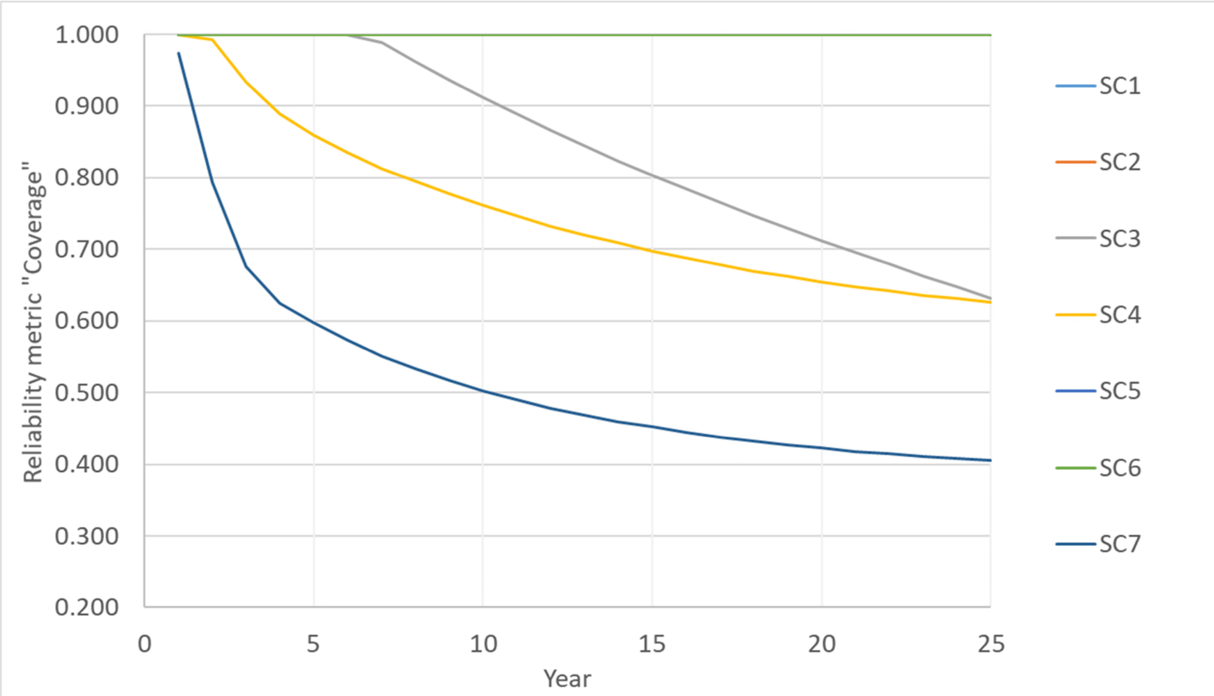

Figure 58: NS annual coverage progression of different scenarios

Results from the *daily average cml* (Figure 59) show a clear advantage against BAU, as in four of the scenarios cml is almost 0. However, the metric *maximum daily cml* (Figure 60) does show that as the pressure increases in later years, difference between average and maximum cml values is minimized as disruptions in operation become more frequent and result in bigger volumes of what cannot be delivered. We can deduct from the minimum daily cml values (Figure 61) that only high-pressure scenarios in later stages of the simulation are somewhat disruptive, which is unlike the situation in the BAU scenario. A sudden reduction in performance occurs in the most stressful scenarios SC3/4 - SC7, whereas in BAU performance degradation was more progressive. Results from total annual "customer minutes served" in characteristic time splits (Figure 62) show that performance is good and effectively the same in scenarios SC1/2/5/6.

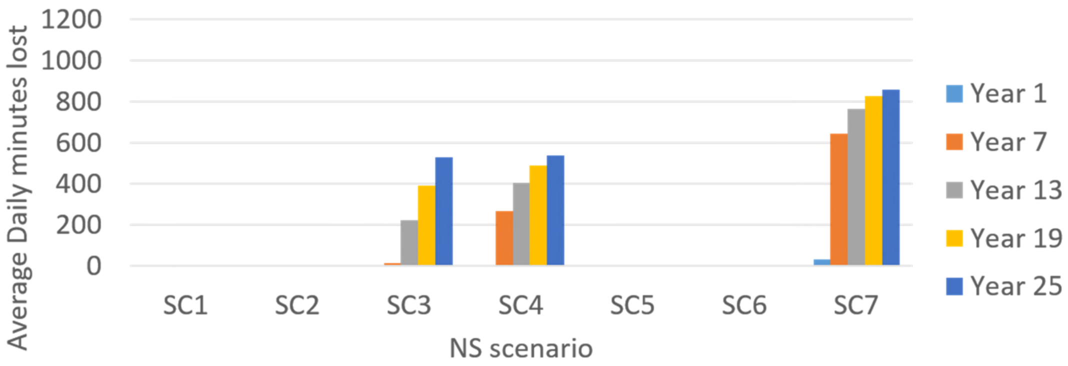

Figure 59: NS Bar chart of average daily cml grouped by scenario

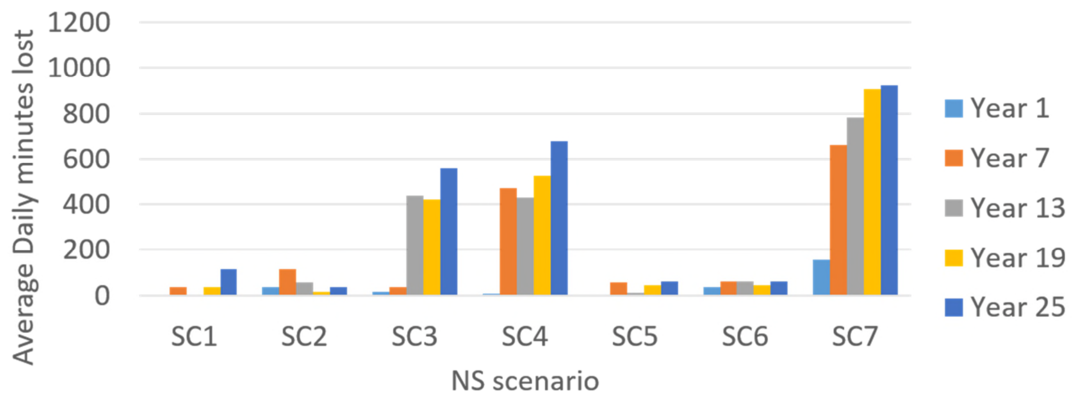

Figure 60: NS Bar chart of maximum daily cml grouped by scenario

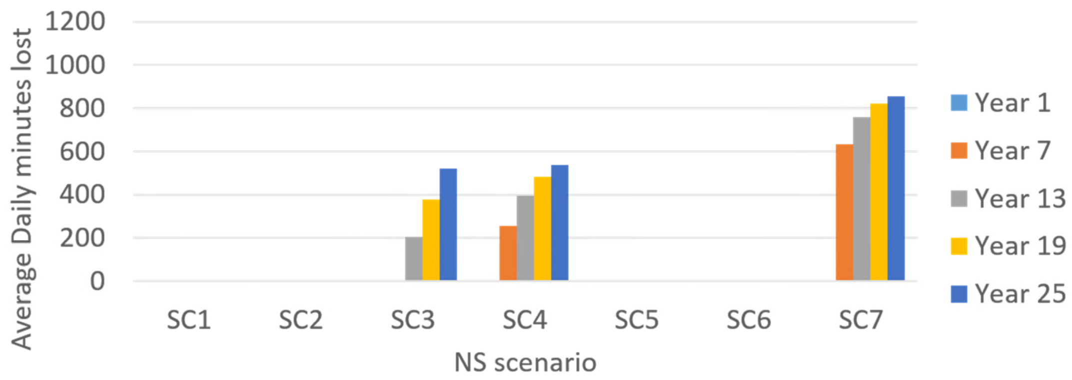

Figure 61: NS Bar chart of minimum daily cml grouped by scenario

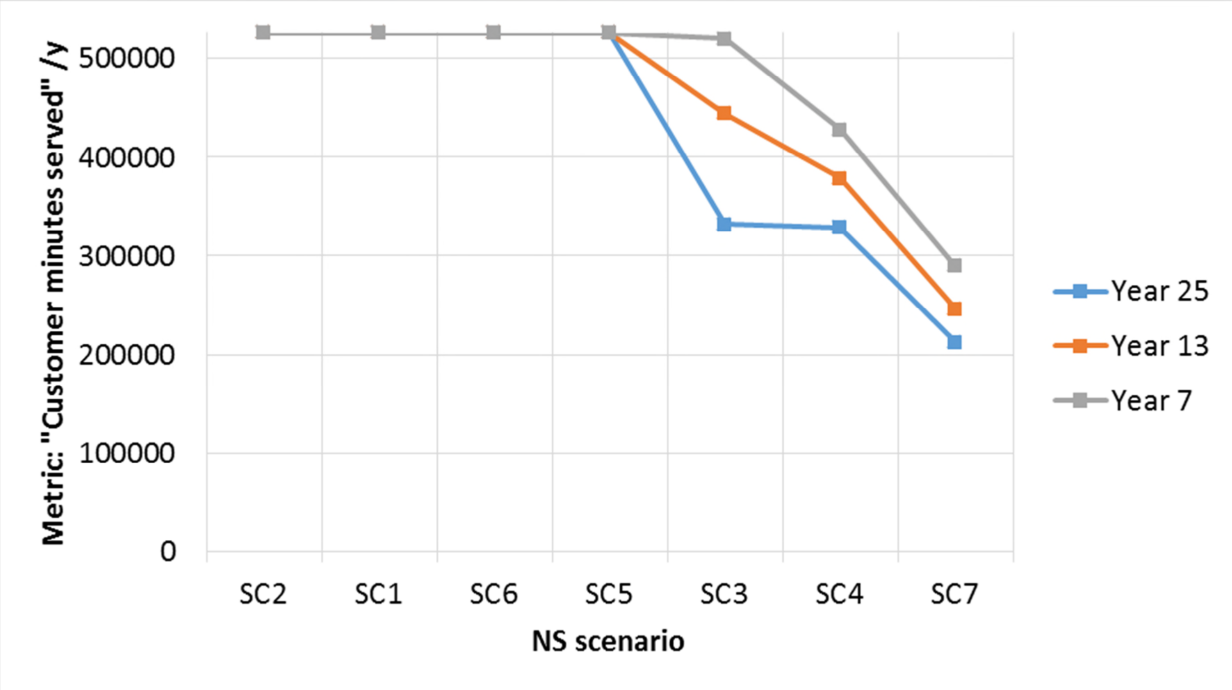

Figure 62: NS annual customer minutes served in select time-splits, scenarios ordered by severity

7.3. FA results

After testing the FA configuration against all scenarios, we summarize results of the coverage metric in Figure 63 (note that some scenarios yield identical performance and as such only 4 of the 7 lines are distinguishable).

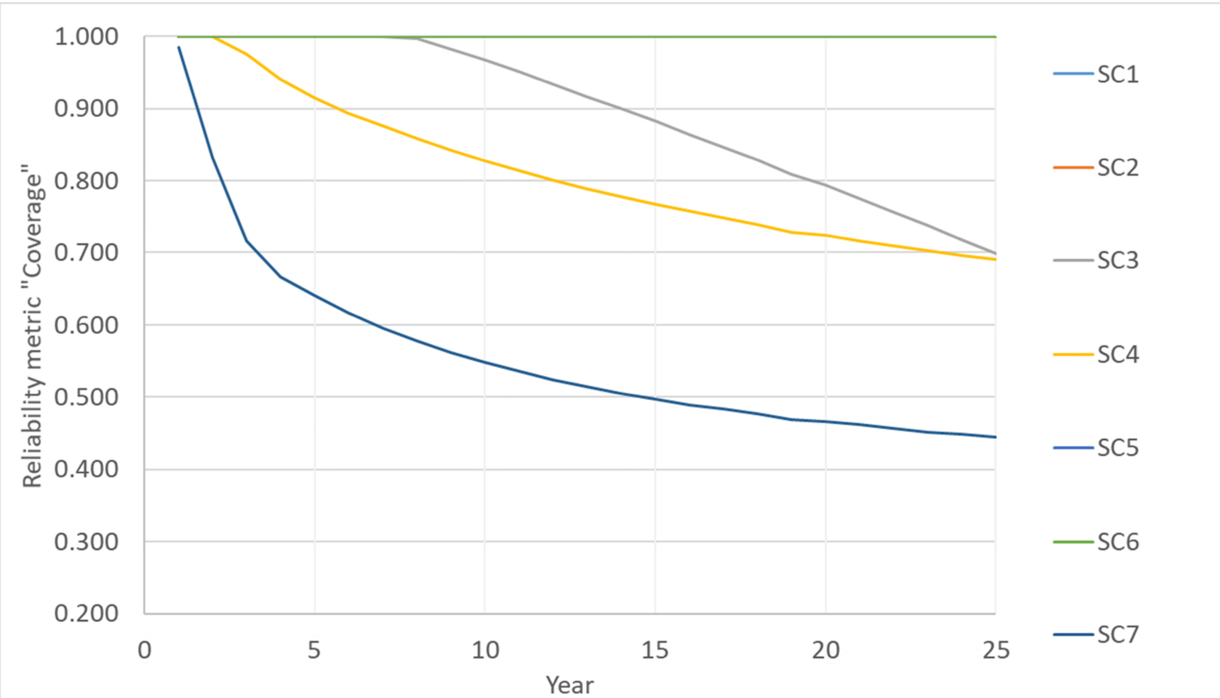

Figure 63: Annual coverage progression of different scenarios

The FA configuration yields good results, although in this particular topology, SAs are not interconnected like in NS and BAU. This becomes a drawback when significant failures occur. As can be seen by the progression of performance throughout the simulation period, the FA configuration continues to perform at least at some degree as the timespan progresses even in high pressure scenarios. Coverage is acceptable throughout the time horizon in the less stressful scenarios. This is partly attributed to the smaller actual demand due to water savings by rainwater harvesting systems and partly to greater redundancy from the decentralization of all WTPs (as anywhere from 8 to 43 plants serve a SA).

Results from the second metric, *daily average cml*, highlight good performance. The difference between average and maximum cml values is bigger than in the NS configuration, indicating a bigger headroom to tackle failures. This is attributed to the less disruptive failure of local plants (there are other local plants in the same SA to back them up and performance loss is smaller) and to some extent the demand reduction due to RWH. This is impressive considering that the very large number of plants in the FA configuration means an order of magnitude more failures and disruptions due to accidents, maintenance issues etc. This indicates that the other configurations hit maximum capacity of the system faster despite having interconnected SAs. This is a strong benefit of the decentralization concept. From the minimum daily cml values it can be seen that high-pressure scenarios even at later stages of the simulation are not as disruptive as in the other configurations, but nonetheless performance does decrease.

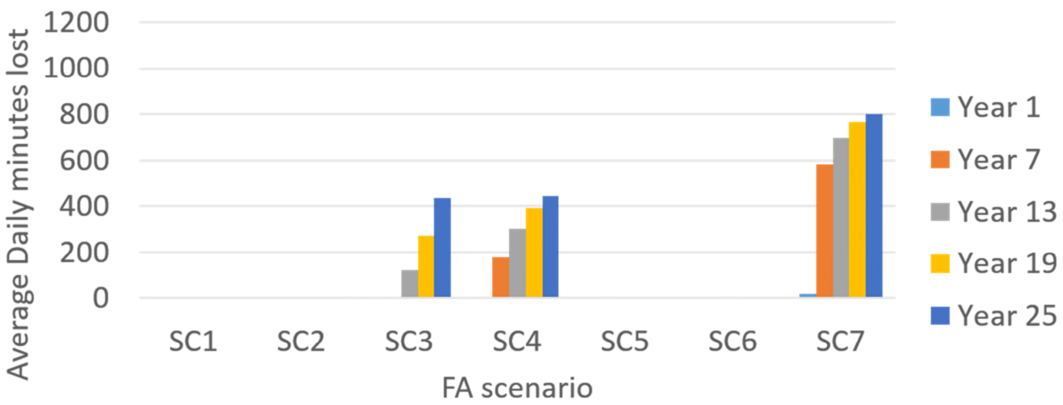

Figure 64: FA Bar chart of average daily cml grouped by scenario

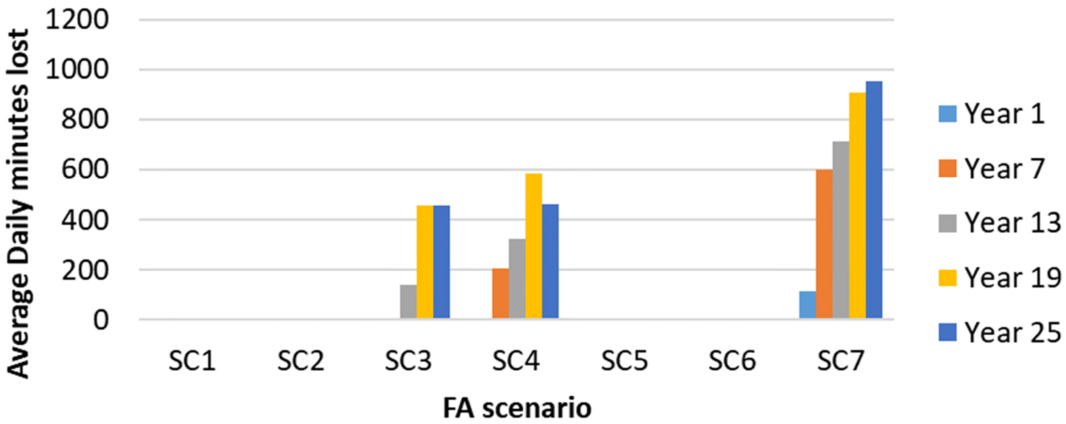

Figure 65: FA Bar chart of maximum daily cml grouped by scenario

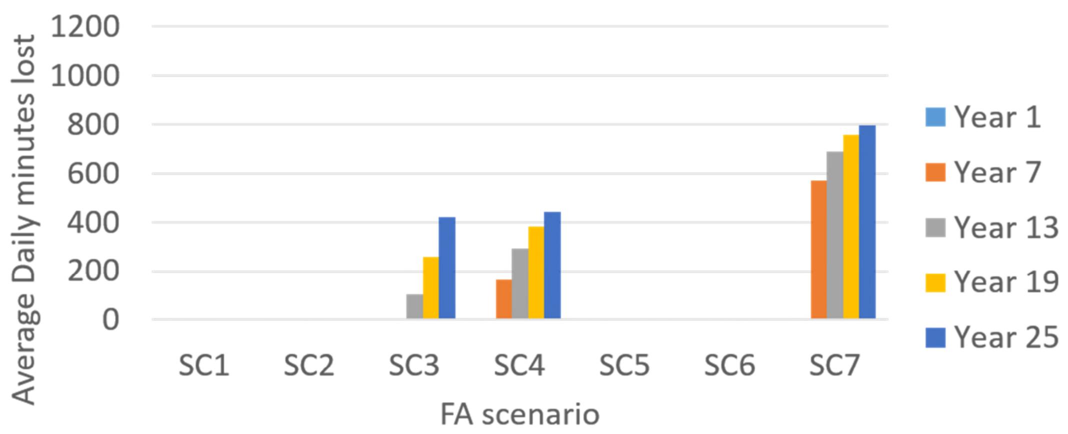

Figure 66: FA Bar chart of minimum daily cml grouped by scenario

It is evident that there is a sudden reduction in performance in the most stressful scenarios SC3/4 - SC7, whereas in BAU configuration performance degradation was more progressive, similarly to the NS configuration.

In Figure 67, scenarios are ordered by severity and the plot refers to "customer minutes served" in three characteristic time splits. The order from less stressful to extreme is SC5/2/1/6/3/4/7, which is somewhat different from the order in the NS configuration. The difference is attributed to the stochastic nature of failures and not the underlying mechanisms, as performance is effectively the same in scenarios SC1/2/5/6.

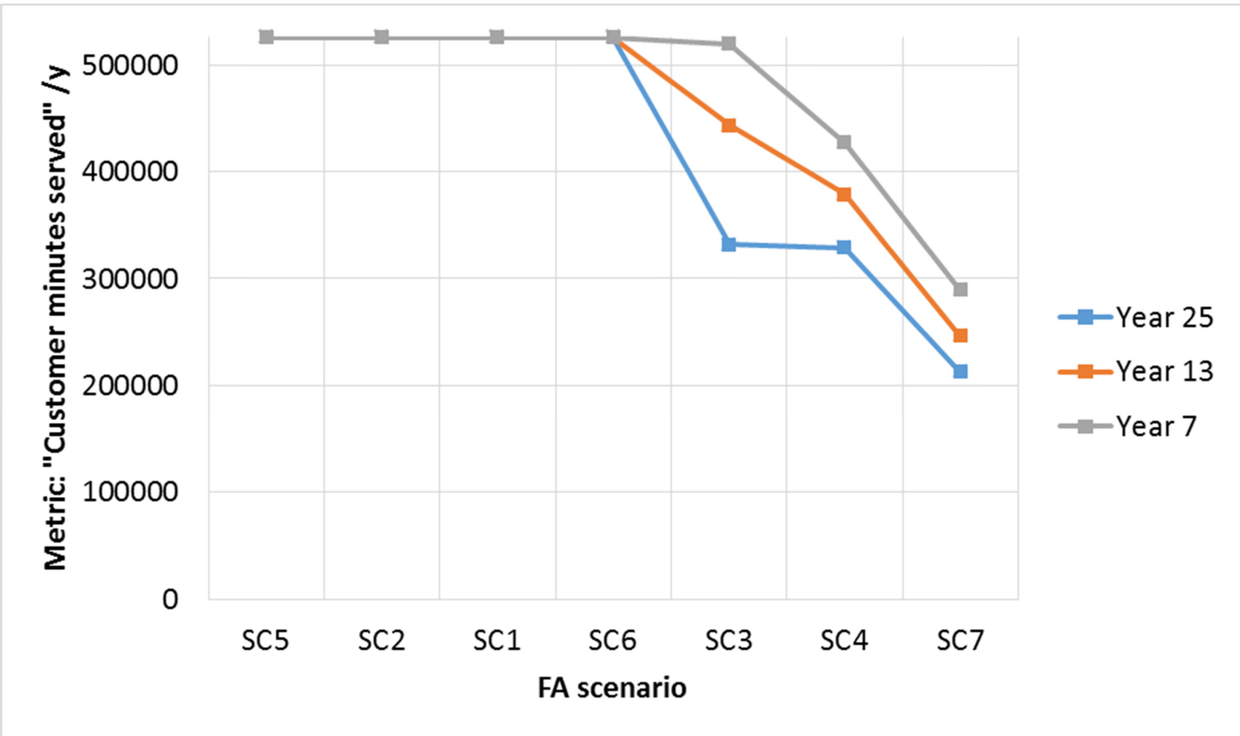

Figure 67: FA annual customer minutes served in select time-splits, scenarios ordered by severity

7.4. Comparison between BAU, NS and FA

Generally, FA is more resilient than both BAU and NS. Reliability is reasonably high across all scenarios for the first years of simulations and collapses with a slower rate as pressures increase (SC3/4 and SC7). Scenarios SC1/2 and SC5/6 result in no significant loss of reliability in terms of coverage and cml, in neither the NS nor the FA topology. FA is the configuration with the best overall scores across all Scenarios.

We compare results at the end of the simulation (Year 25, the worst year by definition) in Figure 68 and Figure 69. FA has comparable results to NS but has a respectable 4% to 7% coverage advantage or 50 to 100 cml advantage in the stressful scenarios SC3/4/7. However, one could argue that the greater cost of the configuration is not justified in a world view with less extreme changes in pressures.

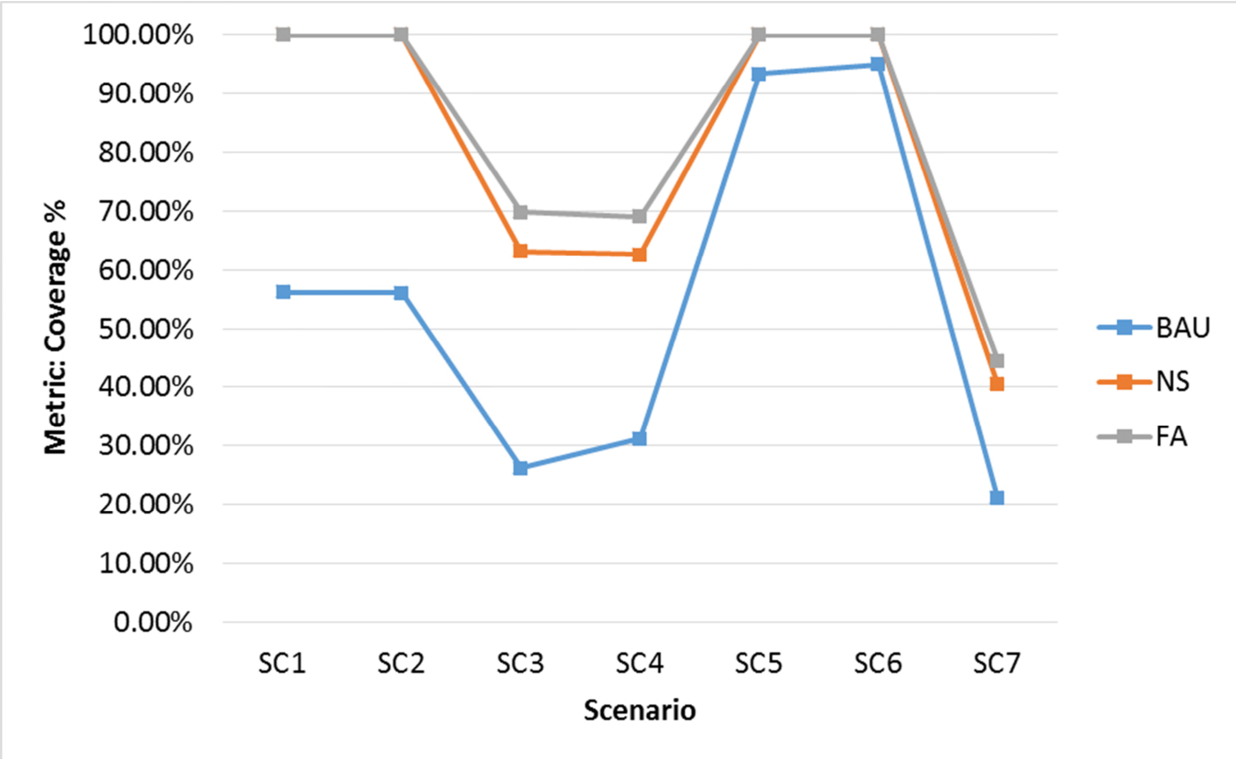

Figure 68: BAU, NS and FA comparisons at Year 25, coverage metric, results presented by scenario number

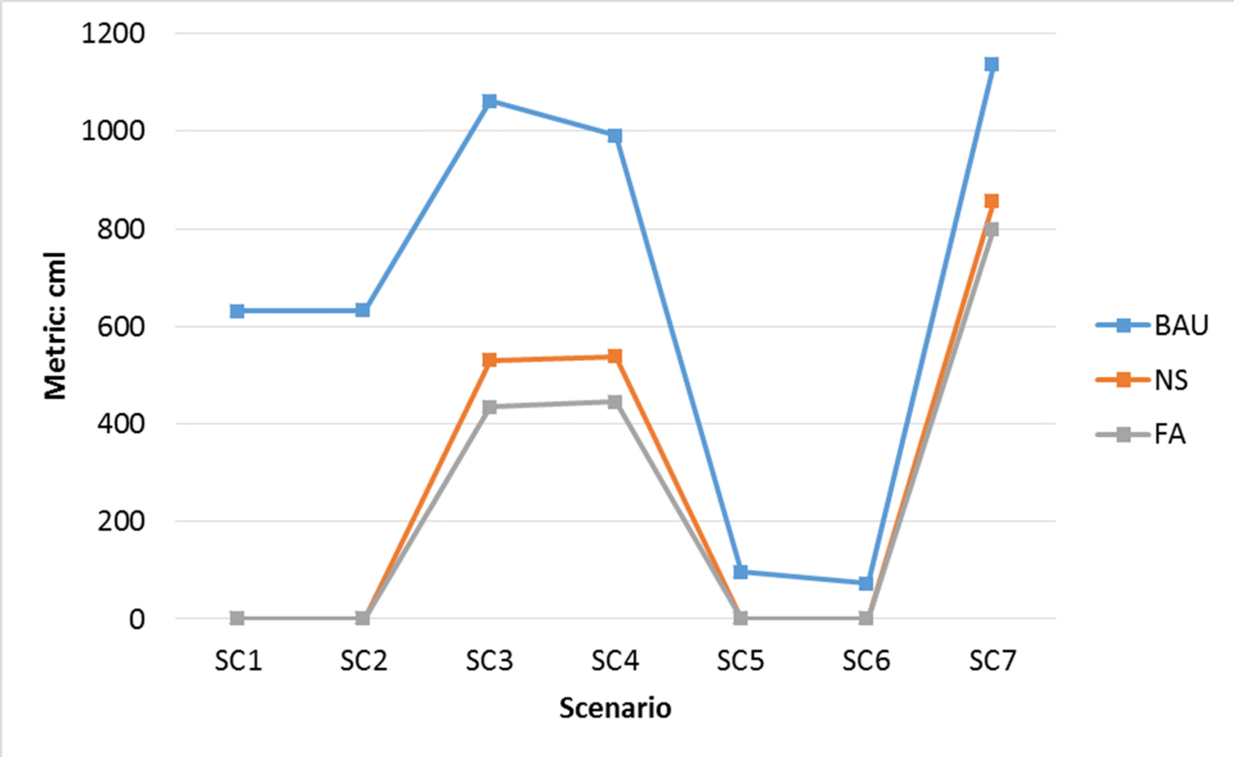

Figure 69: BAU, NS and FA comparisons at Year 25, cml metric, results presented by scenario number

In Figure 70 and Figure 71, a comparison of all three configurations is shown using average results across the whole simulation timespan (Years 1 to 25). These graphs constitute the complete **resilience profile graphs** (as discussion in section 4.4). Overall performance for FA is similar to NS in less stressful scenarios but FA configuration pulls ahead with a reliability capacity advantage in the more extreme scenarios.

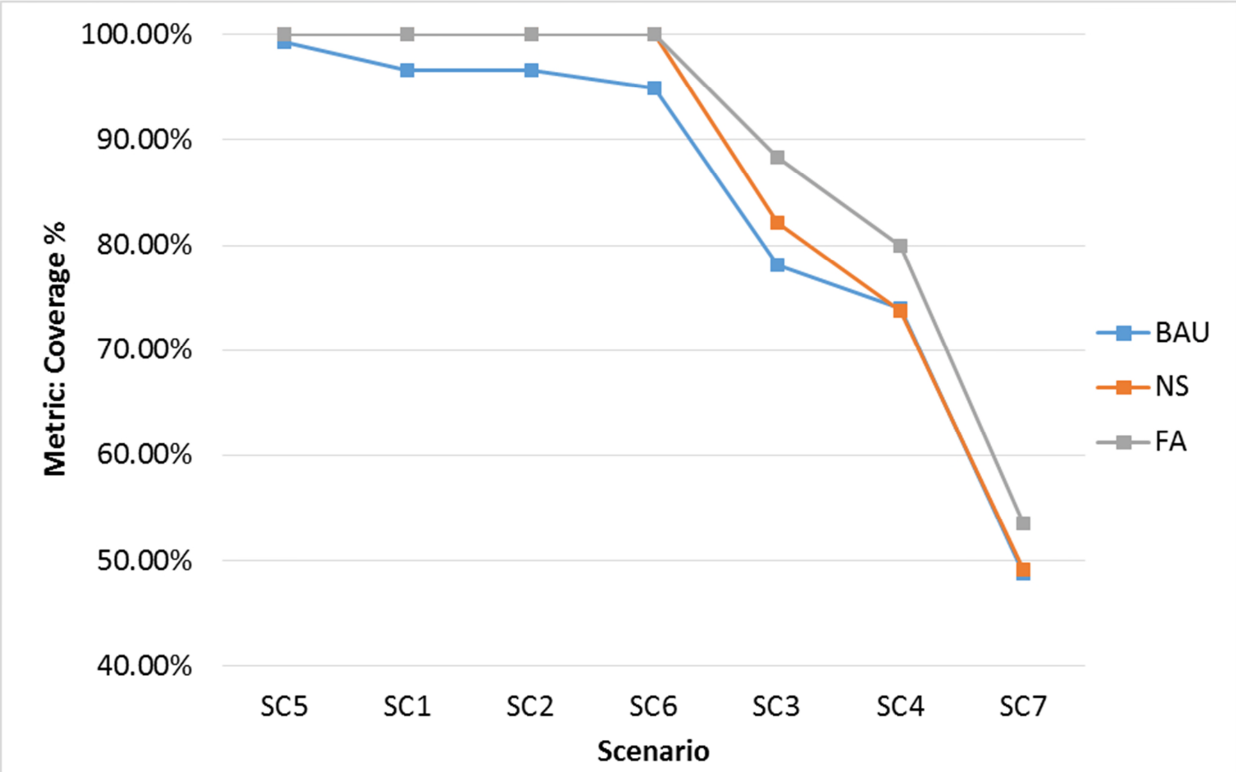

Figure 70: Comparison between BAU, NS and FA configurations average coverage metric, over the whole simulation period, ordered by severity.

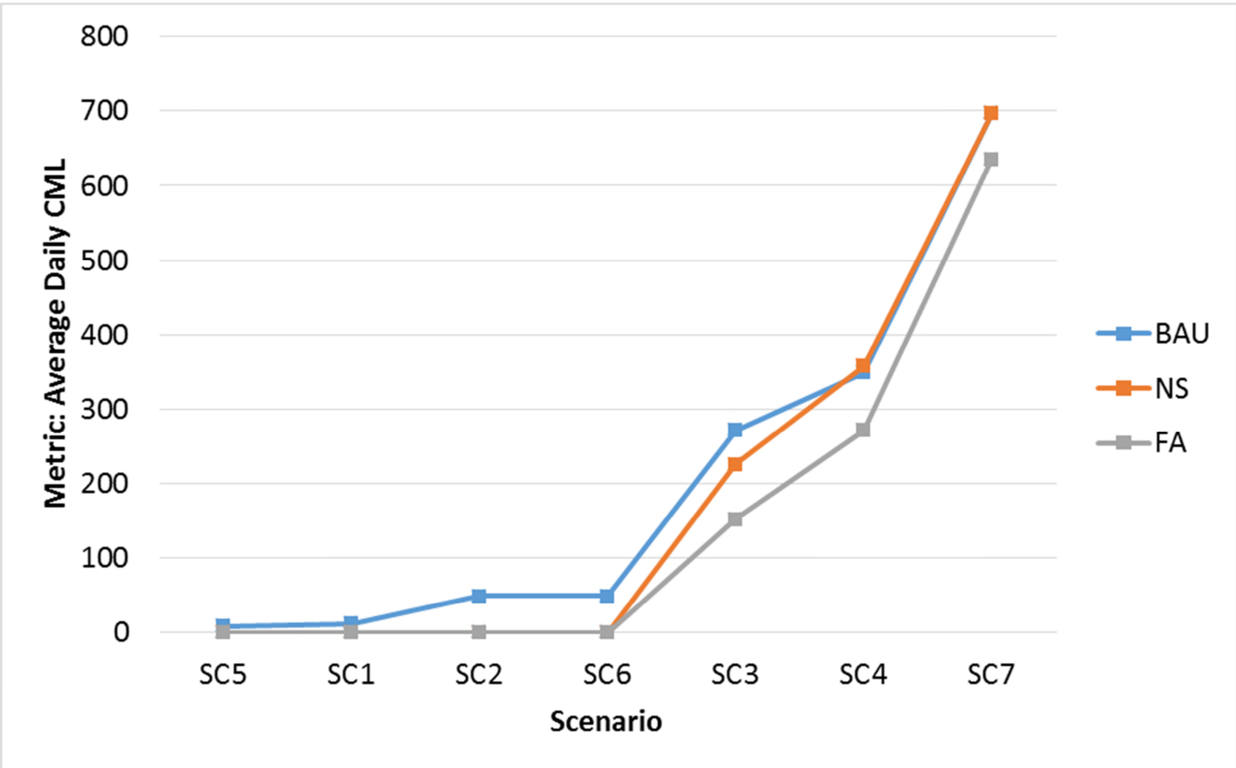

Figure 71: Comparison between BAU, NS and FA configurations average daily cml metric, over the whole simulation period, ordered by severity.

We will now investigate the behaviour of the three configurations under abrupt, highly disruptive scenarios, termed 'wildcards'.

7.5. Wildcard results

Wildcard #1: Breach of Lekdijk

Results are summarized in Table 11 for the wildcard period (7 winter days of Year 13) along with the normal scenario-based resilience assessment results of the same period. Clearly BAU is heavily affected and is the worst performer, while FA is the best performer as it appears to be unaffected by the event due to interconnectivity of the localized plants in the same SA.

Table 11: Wildcard #1 results.

Scenarios	Configurations					
	BAU		NS		FA	
	With Wildcard	Without Wildcard	With Wildcard	Without Wildcard	With Wildcard	Without Wildcard
SC1	43.880%	98.112%	99.999%	99.999%	99.999%	99.999%
SC2	43.994%	97.877%	99.998%	99.988%	99.999%	99.999%
SC3	35.264%	83.442%	76.018%	84.415%	91.632%	91.632%
SC4	31.189%	74.313%	64.760%	72.019%	78.848%	78.848%
SC5	53.269%	98.373%	99.999%	99.997%	99.999%	99.999%
SC6	44.510%	98.676%	99.999%	99.968%	99.999%	99.999%
SC7	22.133%	47.387%	46.585%	46.879%	51.434%	51.434%

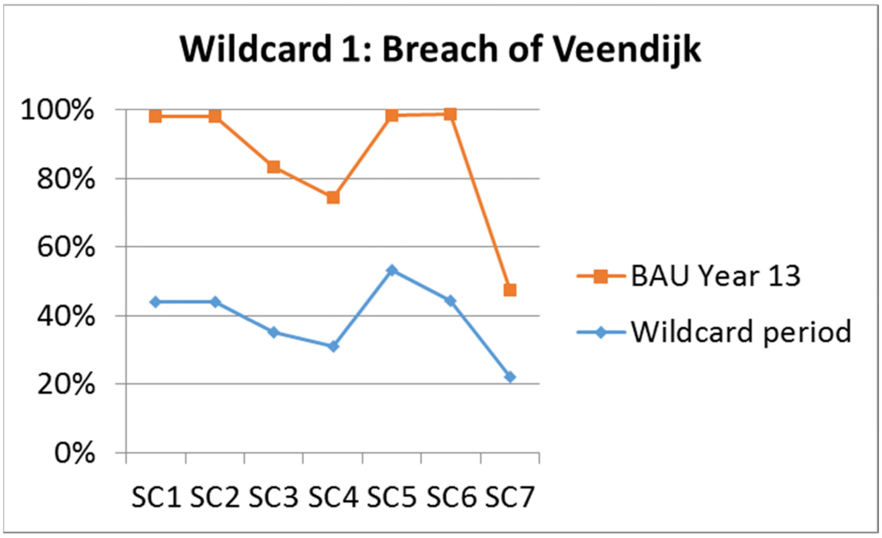

Figure 72: Wildcard #1 and Scenario-based BAU reliability for the same period

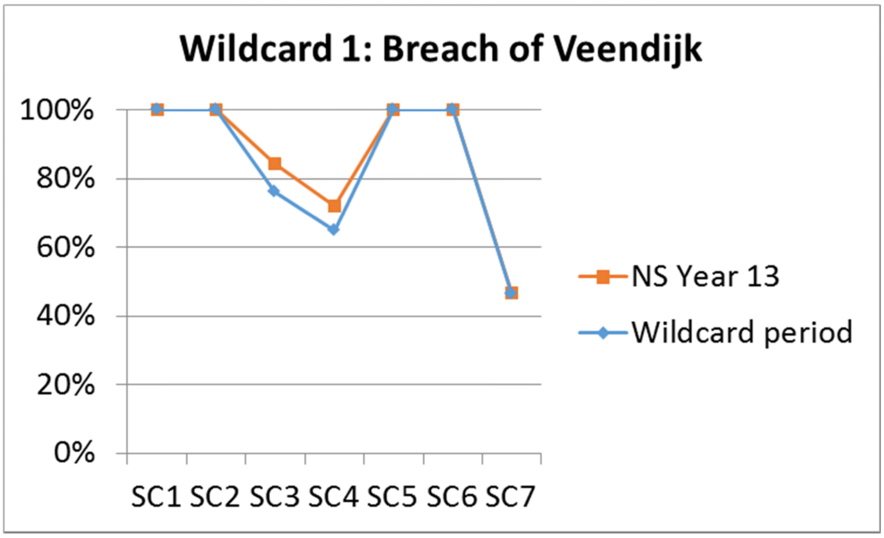

Figure 73: Wildcard #1 and Scenario-based NS reliability for the same period

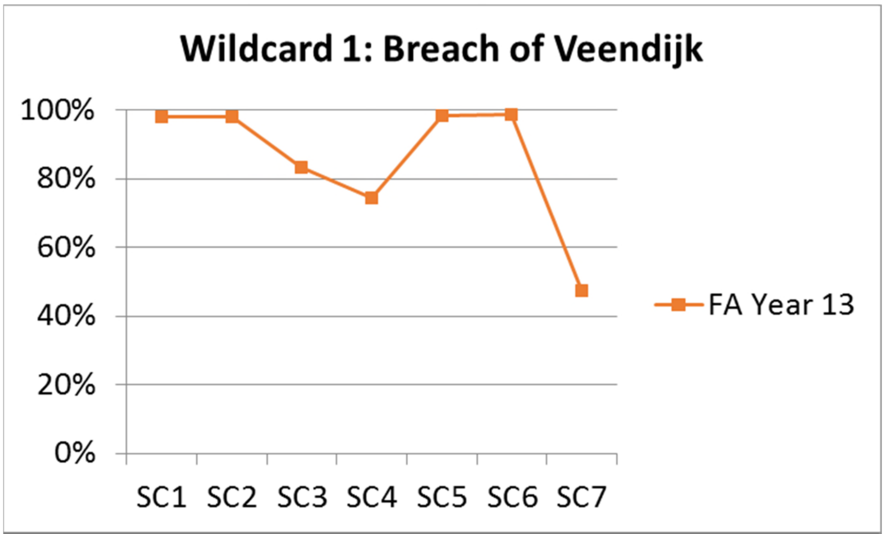

Figure 74: Wildcard #1 and Scenario-based FA reliability for the same period (wildcard doesn't affect performance)

Wildcard #2: Summer with increased chloride and extreme drought

Results are summarized in Table 12, for the wildcard period along with the normal scenario-based resilience assessment results of the same period. Clearly BAU is heavily affected, being the worst performer, with NS now coming up as the best performer.

Table 12: Wildcard #2 results.

Scenarios	Configurations					
	BAU		NS		FA	
	With Wildcard	Without Wildcard	With Wildcard	Without Wildcard	With Wildcard	Without Wildcard
SC1	43.88%	98.11%	100.00%	100.00%	99.99%	100.00%
SC2	43.71%	97.88%	99.99%	99.99%	99.99%	100.00%

SC3	35.21%	83.44%	84.41%	84.41%	87.88%	91.63%
SC4	31.16%	74.31%	72.02%	72.02%	73.97%	78.85%
SC5	53.30%	98.37%	100.00%	100.00%	99.99%	100.00%
SC6	61.08%	98.68%	99.97%	99.97%	99.99%	100.00%
SC7	22.11%	47.39%	46.88%	46.88%	47.08%	51.43%

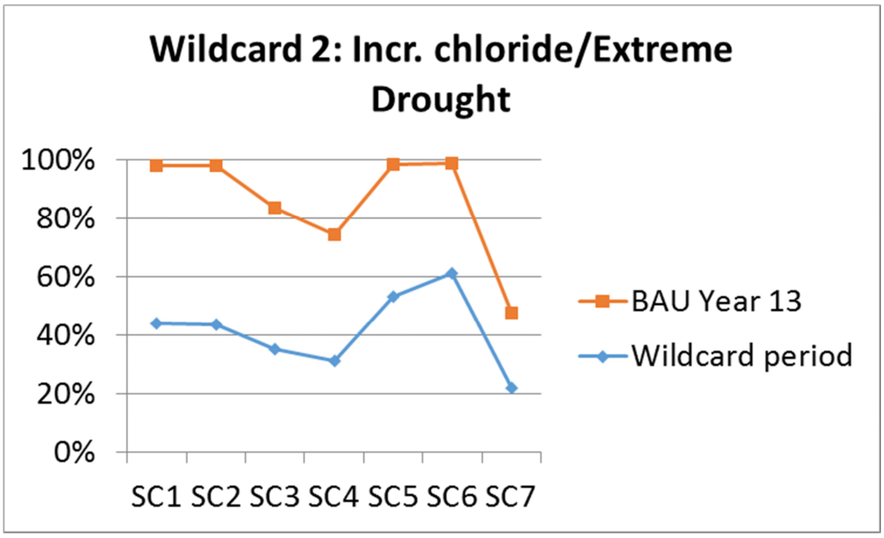

Figure 75: Wildcard #2 and Scenario-based BAU reliability for the same period

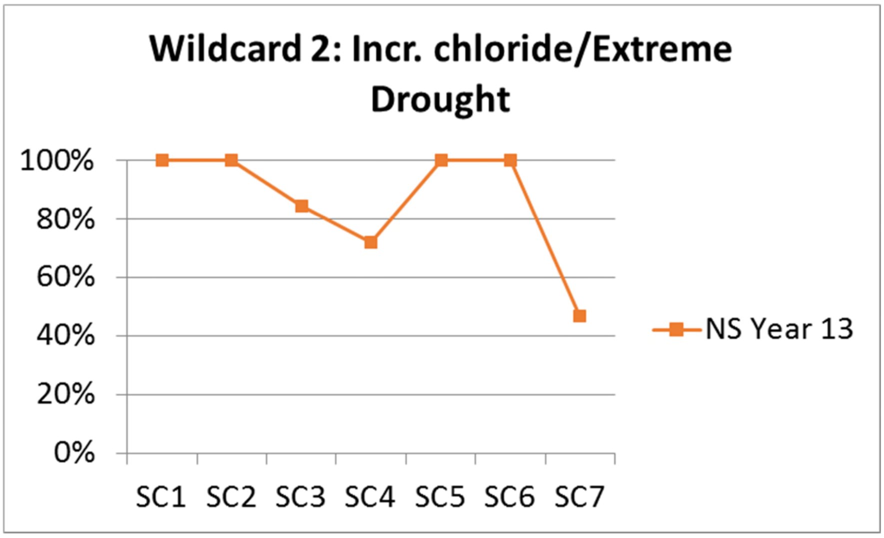

Figure 76: Wildcard #2 and Scenario-based NS reliability for the same period (NS is unaffected)

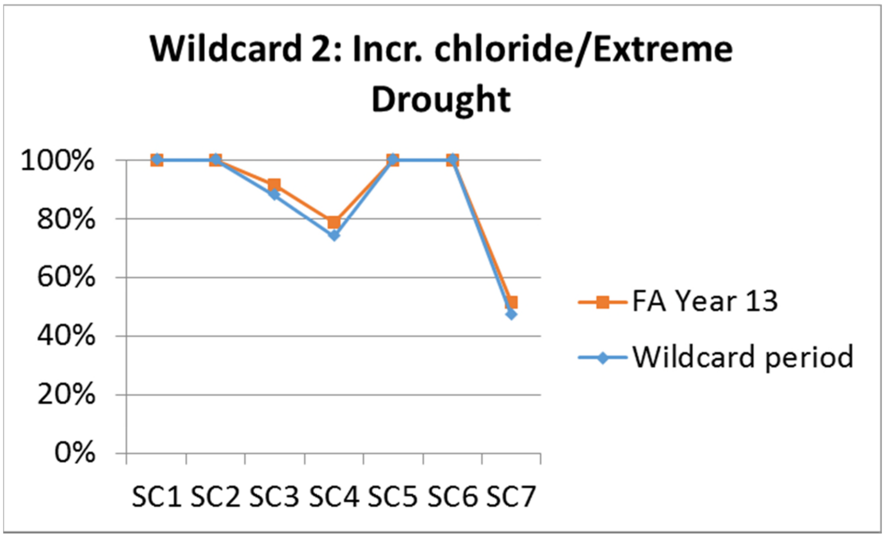

Figure 77: Wildcard #2 and Scenario-based FA reliability for the same period

Wildcard #3: Hacking of critical infrastructure

Results are summarized in Table 13 for the wildcard period along with the normal scenario-based reliability results of the same period. Surprisingly, there is no configuration that is clearly much better or worse than the others in all scenarios, albeit for different reasons. However, BAU is never the worst performer, and appears to be the best performer in SC1. Taking into account average performance, BAU appears to fair better across the board. NS's worse performance than BAU is explained through the headroom capacity lost as RO technology ages faster than conventional plants and at Y13 actual NS capacity is lower than BAU (the same is also true for FA, which also has no interconnectivity from other SA's).

Table 13: Wildcard #3 results.

Scenarios	**Configurations**					
	BAU		NS		FA	
	With Wildcard	Without Wildcard	With Wildcard	Without Wildcard	With Wildcard	Without Wildcard
SC1	92.06%	98.11%	76.49%	100.00%	62.58%	100.00%
SC2	74.82%	97.88%	76.34%	99.99%	62.58%	100.00%
SC3	55.02%	83.44%	35.21%	84.41%	63.76%	91.63%
SC4	47.02%	74.31%	46.57%	72.02%	50.98%	78.85%
SC5	95.67%	98.37%	97.30%	100.00%	62.66%	100.00%
SC6	98.92%	98.68%	100.00%	99.97%	62.83%	100.00%
SC7	31.16%	47.39%	30.76%	46.88%	33.97%	51.43%

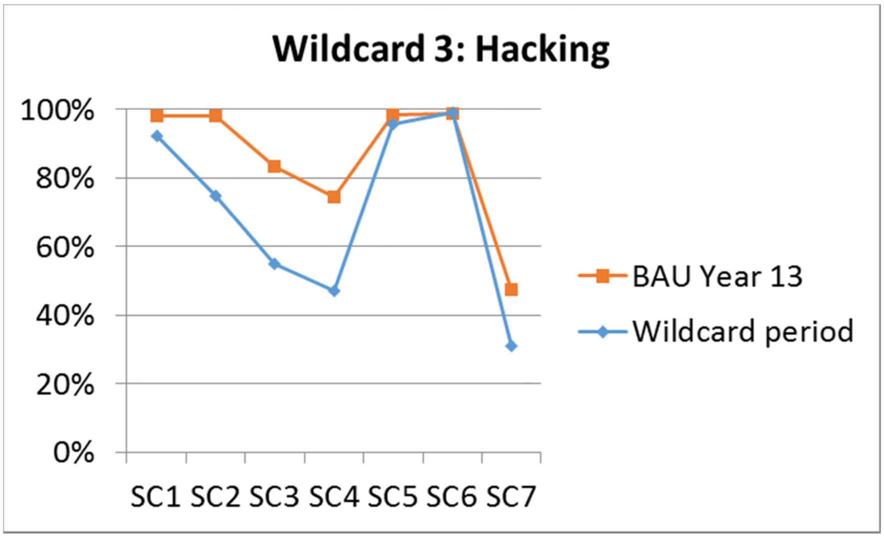

Figure 78: Wildcard #3 and Scenario-based BAU reliability for the same period

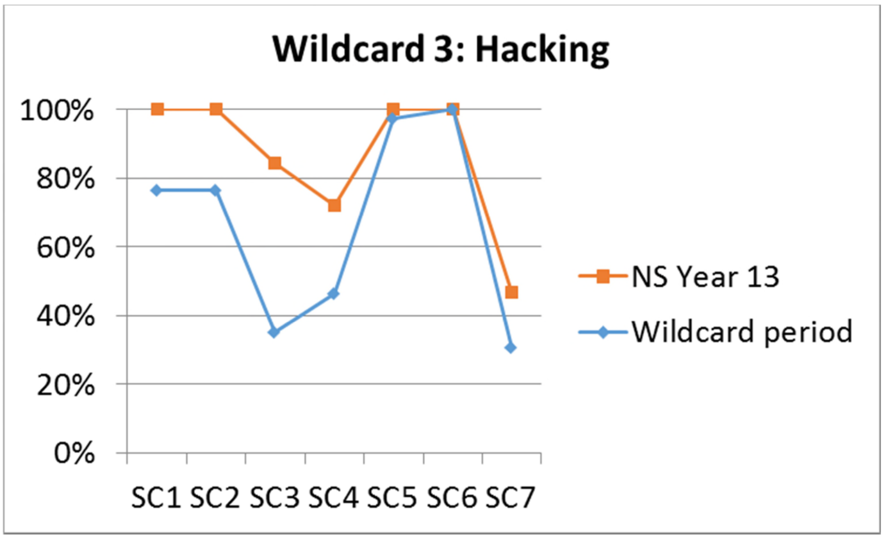

Figure 79: Wildcard #3 and Scenario-based NS reliability for the same period

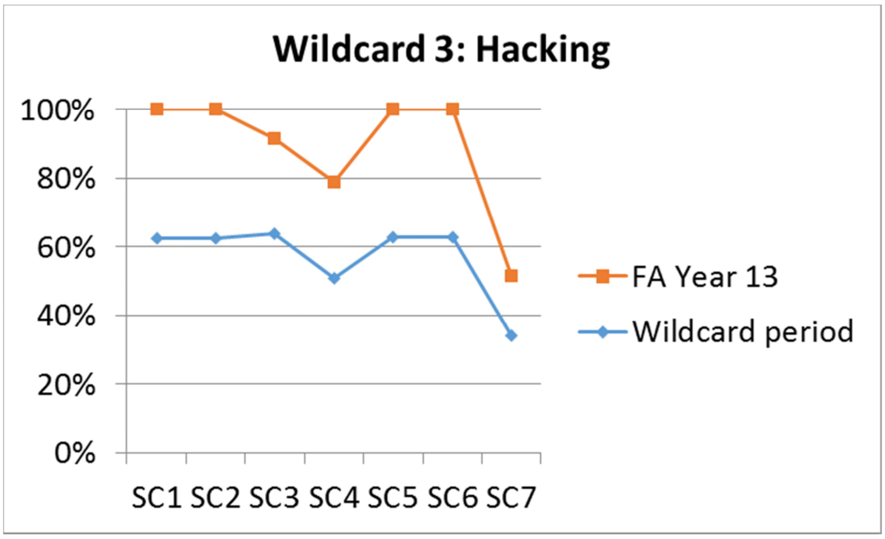

Figure 80: Wildcard #3 and Scenario-based FA reliability for the same period

Wildcard #4: Extreme immigration due to climate change

The best configuration in terms of managing this wildcard is proven to be the FA (in part due to rainwater harvesting reducing peak demands), the worst performing configuration against the tougher scenarios is NS (in part due to being more affected by variables linked to maintenance of the RO technology variables, which lower the capacity headroom in aging plants) as seen in Table 14. However, the average performance of BAU and NS is not that different (84.3% vs 84.2%).

Table 14: Wildcard #4 results.

	Configurations					
Scenario	BAU		NS		FA	
SC1	98.105%	98.112%	99.997%	99.999%	99.999%	99.999%
SC2	98.266%	97.877%	99.988%	99.988%	99.999%	99.999%
SC3	81.811%	83.442%	77.702%	84.415%	87.104%	91.632%
SC4	69.813%	74.313%	67.277%	72.019%	73.425%	78.848%
SC5	97.786%	98.373%	99.997%	99.997%	99.999%	99.999%
SC6	98.294%	98.676%	99.967%	99.968%	99.999%	99.999%
SC7	46.048%	47.387%	44.475%	46.879%	47.303%	51.434%

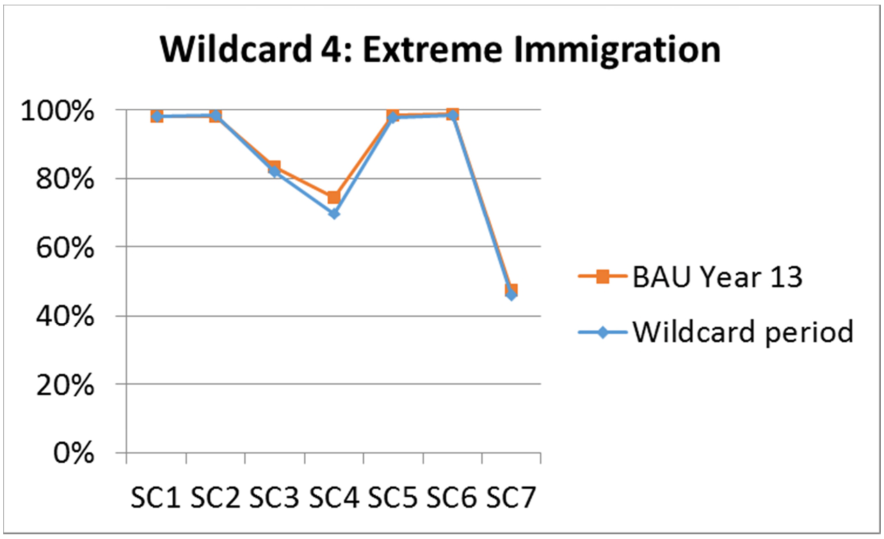

Figure 81: Wildcard #4 and Scenario-based BAU reliability for the same period

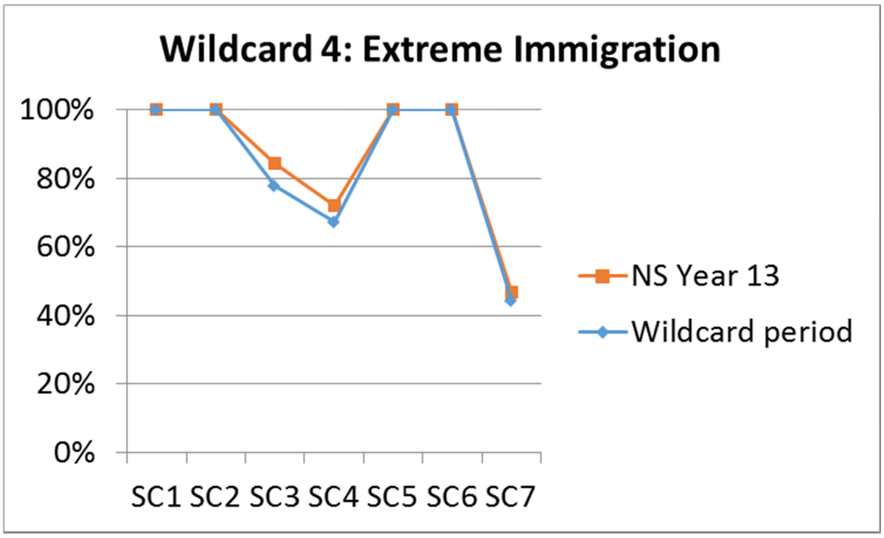

Figure 82: Wildcard #4 and Scenario-based NS reliability for the same period

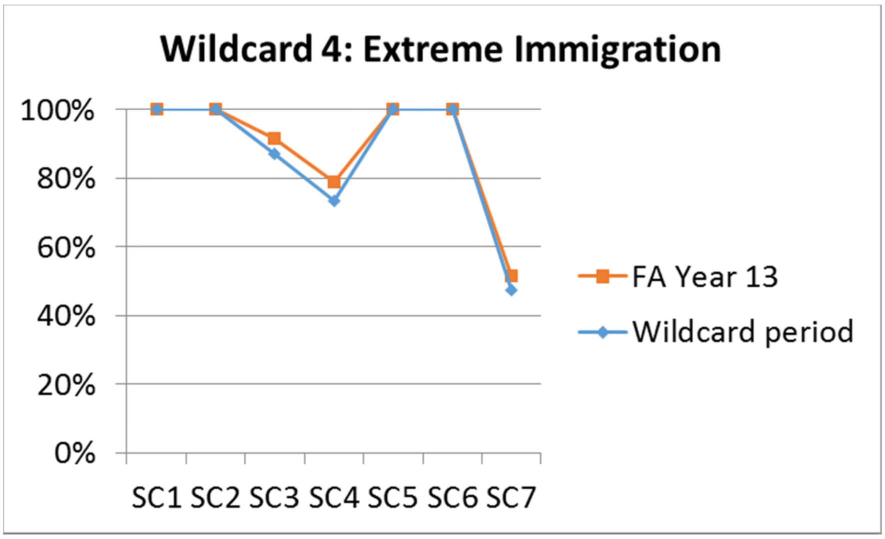

Figure 83: Wildcard #4 and Scenario-based FA reliability for the same period

7.6. Comparison of wildcard results

- BAU exhibits the worst performance against wildcards #1 "Breach of Lekdijk" and #2 "Summer with increased chloride and extreme drought", but behaves relatively well, on average, against wildcard #3 "Hacking of critical infrastructure" (76% vs 66% of the NS and 57% of the FA)
- NS is the best configuration against wildcard #2 "Summer with increased chloride and extreme drought" and is the worst performer (but by a very small margin) against wildcard #4 "Extreme Immigration".
- FA is the best configuration in wildcards #1 "Breach of Lekdijk" and #4 "Extreme Immigration". but performs badly on average scenarios in wildcard #3 "Hacking of critical infrastructure".

It has to be noted however, that these wildcards have very different timespans (a day, a week, a summer and a whole year) and also probability of occurring (although calculating this probability is not realistic/viable). This makes direct comparisons difficult and sometimes misleading. A question that poses itself when thinking about these outcomes, is: "Is it better to have a configuration that is very good against some risks but vulnerable against some others (like the FA) or a relatively average performer (like the NS)?"

8. Conclusions

8.1. Motivation for the work

The starting point of this work was the realization that strategic asset management and long-term infrastructure planning for urban water systems is increasingly challenged by higher order uncertainties, including demand issues due to urbanization, population shifts (also partly due to geopolitical 'turbulence') coupled with aging populations, and increasing expectations for services provided, water supply issues in terms of both quantity and quality, especially in view of large-scale hydro-climatic changes and delivery issues as aging infrastructure becomes less reliable, and new investment is limited. This increasingly volatile environment, within which water service providers need to operate, challenges our ability to forecast long term trends with sufficient accuracy beyond a window of a few years and suggests that the classic response to long term uncertainty, that of overdesigning systems to be 'full proof', against all eventualities, should be revisited (Butler et al. 2017). For this purpose, the idea of *resilience* is currently being discussed across the water sector as a way of moving from the ever-more elusive objective of 'fail-safe' infrastructure design towards a more realistic 'safe-to-fail' approach.

In this report, and its predecessor (Makropoulos et al., 2016) we argued that a new (realistic) aim for water service provision should be to build water systems able to perform 'as designed' within their design specifications (e.g. for the return period of design events) but also 'well enough' under significant long-term uncertainties, despite, inevitable, loss of reliability – in other words we argued for a more resilience-oriented approach to infrastructure design.

8.2. Developing resilience into an operational concept

However, we acknowledged that the term *resilience* itself, as well as a framework to operationalize its application, were not well defined enough to allow water companies to embark upon resilience assessments of their systems. This work follows on the articulation of such a new methodology to assess urban water systems' resilience and its operationalization through a toolbox developed in our previous research (Makropoulos et al., 2016). We provide an operational definition of resilience as "*the degree to which an urban water system continues to perform under progressively increasing disturbance*". Using this definition, we are able to quantify a system's resilience, by calculating its component terms: notably performance as a function of disturbance. Performance is measured here through *reliability*, which is defined for the purposes of our work as "the ability of the system to consistently deliver its objectives, considered over a timespan*"*. This extension of the term 'reliability' allows us to account for a wide scope of "failure modes", beyond the typical use of the term in literature. Disturbance is applied to the system under analysis via the use of different "world views" in the form of scenarios incorporating a wide range of socioeconomic and hydroclimatic parameters that inflict pressure to the system.

Different scenarios vary in the magnitude of pressure as well as the rate at which this pressure builds up on the system under a specified design horizon, ranging from very mild to extreme future world views. It should be noted here that **these scenarios do not represent 'forecasts' of future**, nor do we assign probabilities in their coming to pass – as this would negate the basic premise of our work: that of irreducibly high orders of uncertainty affecting the systems in the longer term. **As such the whole**

approach can be more aptly described as a 'stress test' where the probability of a given stress on, say a concrete element under pressure, is not a relevant parameter for the designer. The ensemble of scenarios applied on the system through modelling, allows for an evidence-based assessment of its performance under very different conditions. Performance is affected by both the installed technologies and the way they are connected (design concept) i.e. by the system's configuration. The resilience assessment framework analyses different configurations of the system under the same pressures to identify the best future performer.

8.3. From method development to real-world demonstration

In this work we further developed the methodology to operationalize the concept of resilience for the water sector. A set of tools developed for the application of the methodology were expanded, including a (now fully operational) Scenario Planner, a more automatic procedure for translating scenario variables to UWOT model inputs as well as a new CA based tool for (quick) saline intrusion scenario sketching. The ability of UWOT to take into account water quality was extended and its relationship to other resilience assessment tools, like the City Blueprint tool was explored (see *Appendix D*). Furthermore, the work explored the idea of efficiency and the trade-off between efficiency and resilience in urban water systems (*Appendix C*).

Importantly, the method and tools were tested in a real-world system, that of Oasen. This was to 'stress test' the method itself on a real-world system and allow the team to further develop both the method and tools to address the challenges of real world applications. As such, custom configurations and scenarios for the system were developed in collaboration with Oasen, and a resilience assessment of a significant part of their water system was undertaken. These scenarios included, for the first time, the idea of *wildcards*: extreme events whose probability of occurrence is unknowable, but whose impact may be critical to the system's performance.

The results were examined to see if the types of pertinent questions posed in the process of strategic water systems planning in general and Oasen in particular, could be supported using the proposed method and toolbox. The analysis provides insights into, for example, trade-offs between resilience and robustness, as well as between centralized and decentralized systems.

8.4. Insights for Oasen

Although the primary purpose of this study was to showcase the method (and to further develop it where needed) and not to provide a detailed technical analysis of the specific Oasen case, insights into the system's resilience are visible in the results. Results suggest, for example, that significant gains in resilience for Oasen, compared to their current system, can be achieved by moving towards the "Next Step" (move to a radically different purification concept (RO systems) coupled with moderate decentralization) configuration, while a more extreme decentralization configuration (such as the rather disruptive, "Further Ahead") does not really achieve significant performance enhancements in most of the scenarios examined. Interestingly, and perhaps counter-intuitively, from the analysis of wildcard scenarios, introduced into the method for the first time in this report, it appears that although both "Business As Usual" and "Further Ahead" come up as the best configurations in some wildcard events, they perform quite badly in others, while "Next Step" seems to be a relatively stable (average) performer overall, providing more confidence towards suggesting a "Next Step" type of configuration as the best way forward for Oasen. It should also be noted that domestic rainwater harvesting, as implemented in the Further Ahead system is not configuration–specific nor incompatible to a Next Step type of system and has been shown to enhance performance. This option of course requires private investments by customers and is not straightforward to implement. It could be viewed as an option in the transaction space of Figure 2, its value being that it can compensate, to some extent, the loss of interconnectivity in drastically distributed systems (here illustrated as part of the Further Ahead scenario).

Another type of insight coming from the study is the *sensitivity* of the current (and of the potential alternative) water system(s) of Oasen to certain scenario variables. As seen from the response of the configurations to the full set of scenarios created (e.g. Figure 70) it is scenarios 3, 4 and 7 which affect all system configurations the most, while the current system (BAU) is also affected to some extent even by scenarios 1, 2 (with the addition of the saline intrusion cross-cutting scenario) and 6. This suggests that both the current system but also the other system configurations, to a lesser extent, are vulnerable to significant increases in demand (driven, for example, by population increases through migration postulated in scenarios 3 and 4). This is, of course, a result of the dependence of Oasen on groundwater as a resource, the rates of renewal inherent in this resource (albeit with bank filtration) and, importantly, the strict constraints on abstraction imposed to the well field production by the authorities. The current system is especially vulnerable here due to its sensitivity to futures where saline intrusion and pollution generated from industrial zones upstream, affects the main groundwater resources.

Looking at wildcards the difference between configurations becomes even more pronounced: a breach of Lekdijk for example is a catastrophic event for the current system, while only marginally affecting the NS and not really affecting at all the FA configuration. The same is true of increased chloride and extreme drought scenarios due to the technologies involved, but perhaps more interestingly and less intuitively two other aspects of the NS and FA configurations come into view in the wildcard analysis: that of limited connectivity of the FA scenario and that of more rapid aging of the RO technologies in both NS and FA configurations. The former means that although no single event is able to impact significantly the ability of the company to deliver water services to most of its customers in these decentralized/distributed scenarios, there are more failures per unit time and there is less ability to supply water from other SAs when things go wrong. The latter is effectively decreasing, as a function of time, the headroom available as a backup supply, even within a given SA, when for any reason, some treatment plants are rendered non-operational. Both these aspects come into sharp relief in both the 'normal' and wildcard scenarios.

A final point worth making, also coming from the wildcard scenario analysis is that although very distributed solutions do allow for a spreading and minimization of (spatial) risks as seen in the resilience of the FA configuration, there are important ways in which even the most distributed configuration is centralized and thus vulnerable to other pressures: case in point is the cybersecurity scenario (wildcard #3, see for example Figure 80) where it is assumed that to be able to control the massively decentralized local treatment plants in the FA configuration, these are all controlled through a central SCADA system and thus more vulnerable to a cyber-attack than the more centralized BAU and decentralized (but not fully distributed) NS, as these allow for manual back-up controls on site, potentially by-passing, for a limited time at least, the affected central control. Such a manual override would not be possible in the FA configuration; hence it is this configuration that suffers the most from such a wildcard. It is suggested that this interplay between physical and cyber infrastructure (or *cyber-physical infrastructure*) and related, targeted stress testing should be the subject matter of a further, more targeted investigation.

What is important to note is that, although only a small set of questions and options was actually tested in this work for Oasen, the model is now built and operational and as such, additional targeted questions can now be answered at a fraction of the time and cost of this study. In that respect, a significant side benefit of the project for Oasen is that there now exists a 'digital twin' of the company's main infrastructure to be further queried and refined at will.

To further explore these and other insights and pertinent questions, additional work can further focus on the specific interventions and options identified, refining the UWOT model based on specific follow-up questions that will certainly arise, and, when necessary, also using more detailed models for different parts of the systems (e.g. a detailed, case-specific groundwater model, at local and regional scales would yield more accurate results on the key stress of saline intrusion).

It is also suggested that final decision making would certainly benefit from detailed cost benefit analysis with realistic assessments of CAPEX and OPEX of the configurations under study, an area where the water company itself has more in depth practical knowledge than researchers do. A first approach to costing some of the options is presented in *Appendix A*, but as this is based on several difference sources and expert judgement, its actual numbers need to be taken as indicative only.

Finally, it should be clear, that the scenarios examined here were not meant to be 'realistic', nor can their inclusion in this study be taken as an indication of their relevance to Oasen *per se*. As discussed in the sections presenting the Resilience Assessment Method, the stress-testing philosophy adopted to calculate the resilience metric, seeks to explicitly test the *limits* of a system's performance with ever more *extreme* scenarios. Within this context it must be clear that although significant improvements in resilience are possible if Oasen moved towards a 'Next Step' type of configuration, the existing BAU system is already impressively resilient.

8.5. Insights on the Resilience Assessment Method itself

Clearly, the method is far from perfect. Two obvious shortcomings are:

i. 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 toolbox for a more explicit representation of the complete system, as reported in Makropoulos (2017). However, as in all modelling work, internalizing some system elements ultimately only pushes (subjective) assumptions to other system boundaries.
ii. 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 seizes to amaze us. This quest for accounting for unknown-unknowns has been a holy grail of future studies, requirements engineering and evidence-based decision-making for some time (Pawson et al., 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 only in a small subset of pertinent questions.

Having said this, we would argue that ultimately, the constraint is not in the ability to imagine (by definition) unknowable futures, which could improve with the advent of new ways of experimenting, such as serious games (Savic, et al., 2016), but in the willingness of the water sector to be prepared to think outside the box and prepare for unknowns.

A proactive water company (such as Oasen) and a forward looking, resilient water sector (such as the Drinking Water Sector in the Netherlands) could also use this approach to identify key scenario variables that are more critical to the system's performance. Depending on whether these key scenario variables were part of the external, internal or transactional system (Figure 2) different strategies could lend themselves as suitable responses, including for example closer monitoring of trends in the external system (e.g. immigration policies, energy pricing or climatic shifts), collaboration with relevant sectors to modify drivers in the transactional system (e.g. saline intrusion in the Delta, working with farmers sharing water resources etc.) or direct action in the internal system scenario variables (e.g. demand management at household levels). Such a pro-active approach, based on the resilience assessment methodology could turn the problem on its head and focus attention to critical, albeit perhaps little noticed future scenario variables rather than trying to (only) forecast current trends. In a similar vein, the method could be run 'in reverse' and identify 'threshold' values for these scenario variables, or for water system variables, or indeed (and perhaps more interestingly) combinations of both, which, when surpassed, affect the system significantly. This would empower utilities (and the sector as a whole) to develop 'forward looking observatories' (in combination with scenario variables monitoring as above) as part of their resilience-enhancing strategies and potentially act as triggers for appropriate responses.

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 complexity of both the scenario scape and the water system (also potentially accounting for links with and cascading effect between associated infrastructure: wastewater, energy, flood protection etc.) that exist in all but the simplest situations, mean that this evidence-based, formal modelling and stress testing approach can yield results that are *not accessible through intuition alone*, of even the most experienced system operators.

It is further suggested that the idea of stress-testing could also be used, suitably modified, to examine more closely effects of wildcard events (such as intentional cyber-attacks, physical attacks and their combinations) on water infrastructure conceptualized as proper cyber-physical infrastructure. Although an initial attempt to look into this issue as one of the wildcards selected for the case study was undertaken in this work, yielding interesting results, more research is needed into the formal modelling, stress-testing and risk assessment of the combined cyber-physical water system. The need for such research is rising as the risk of cyberattacks is also rising with the rise of instrumentation, IoT and other ICT-related developments in the water sector.

8.6. Epilogue

We conclude that the resilience assessment methodology, developed and demonstrated in this work, is easy to implement on practically any water system, after suitable customisation, and is able to take into account a wide range of specific hazards/events/scenarios and infrastructure options. It can be used to (i) stress test alternative water system configurations and assess their ability to perform (or otherwise) under a whole range of stresses, in other words quantify their *resilience*; (ii) enrich an initial resilience assessment with follow-up *what if* or sensitivity-type questions, based on the same models, testing options, assumptions, variables and scenarios (iii) help identify the scenario parameters or combinations of parameters that are the most 'stressful' for a given system and inform a '*monitoring'* process within the water sector of these (physical, socio-economic or even political) parameters and (iv) be used to back-calculate *threshold values* of scenario parameters and their combinations that would be deemed 'tipping points' for water system resilience thus triggering appropriate *responses* (from political lobbying to new infrastructure commissioning) from the sector.

We suggest that following this real-world application, there is enough know-how to apply the method in a relatively short time[10] for any new water system. Important datasets that need to be available include water infrastructure layouts and functional descriptions, information on hydrology and available water resources as well as demand characteristics. Socio-economic data although desirable is not essential as they can be considered variables to be explored within the scenario scape.

We argue that, despite its limitations, the resilience assessment method, can serve as a 'birds eye view' screening and steering tool for strategic infrastructure planning under large scale uncertainty, at the company level. As such it can precede the commissioning of more detailed design studies of screened options, and additional (more detailed but also costlier) modelling of separate sub-system elements.

The framework will continue to be developed and demonstrated by applying it to other real-world case studies and complementing it with a robust set of supporting models and tools while also evaluating different aspects of and risks to the system, including, for example, *security of water systems, as cyber-physical infrastructure*. 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.

[10] An order of magnitude would be between 3 and 6 months depending on case complexity and data availability. For a system already modelled (like Oasen) follow up questions and investigations could be typically answered in much shorter timescales (1-2 months).

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Appendix A: CAPEX estimations

Scenario	Technology	Category	(Design) capacity or length of supply mains	Capacity units	CAPEX/ unit cap.	Counts (per capacity unit)	CAPEX	Main assumption	CAPEX VO WWC AREA
NS	Surface water intake (brackish/surface)	Raw water collection	1	m3/h	€ 874	TBD	TBD	Based on RHDHV-data	
BAU	River bank filtration (shallow/deep, averaged)	Raw water collection	1	m3/h	€ 1,639	TBD	TBD	Average based on Oasen data - see sheet 'CAPEX source water intake'. Ratio deep/shallow: 0.27	
BAU	Shallow well fields (averaged)	Raw water collection	1	m3/h	€ 1,551	TBD	TBD	Average based on Oasen data - see sheet 'CAPEX source water intake'	
BAU	Deep well fields (averaged)	Raw water collection	1	m3/h	€ 1,880	TBD	TBD	Average based on Oasen data - see sheet 'CAPEX source	

								water intake'	
BAU	ZS Rodenhuis	Treatment	3000	m3/h	€ 46,865,294	1	46,865,294		
BAU	ZS De Steeg	Treatment	3300	m3/h	€ 63,941,415	1	63,941,415		
BAU	ZS Lekkerkerk	Treatment	540	m3/h	€ 13,624,867	1	13,624,867		
BAU	ZS De Hooge Boom	Treatment	308	m3/h	€ 14,027,976	1	14,027,976		
BAU	Interconnection between Supply Areas (BAU)	Supply	280	km	€ 189,000	280	52,920,000	Transport pipes costs based on De kostenstandaard (RHDHV, 2017)	
BAU (TOTAL)									€ 203,095,600.08
NS	ZS Rodenhuis (surface water intake, RO)	Treatment	1000	m3/h	€ 23,571,549	1	23,571,549		
NS	ZS Rodenhuis (RB well fields, RO)	Treatment	1000	m3/h	€ 26,811,972	2	53,623,944	Polder Nieuwkoop and Bergambacht have the same treatment	
NS	ZS De Steeg	Treatment	1800	m3/h	€	1			

	(Langerak, RB well fields, RO)				38,044,694		38,044,694		
NS	ZS De Steeg (Alphen aan den Rijn - brackish (RB) well fields, RO)	Treatment	1500	m3/h	€ 41,192,975	1	41,192,975		
NS	ZS Lekkerkerk (RB well fields, RO)	Treatment	540	m3/h	€ 14,987,354	1	14,987,354		
NS	ZS De Hooge Boom (RB well fields, RO)	Treatment	308	m3/h	€ 15,430,774	1	15,430,774		
NS	Interconnection between Supply Areas (NS)	Supply	325	km	€ 189,000	325	61,425,000	Transport pipes - see De kostenstandaard (RHDHV, 2017)	
NS (TOTAL)									€ 259,227,606.09
FA	Decentralized plant, no supply mains	Treatment	70	m3/h	€ 2,162,951	103	222,783,989	without emergency electricity supply	
FA	Rain water harvesting for drinking water, hh level	Raw water collection and treatment	2	m3	€ 3,561	427808	1,523,241,057 (private, household investment)		

FA	Rain water harvesting for grey water, hh level	Treatment	0.016	m3/h	€ 608	427808	260,186,956		
FA	Supply mains, i.e. only (smaller) distribution pipes, no transport pipes	Supply	?	km	€ 153,000	103	TBD	?	
FA (TOTAL)									> € 222,784,000 public + 1B private

Appendix B: Water Quality

Quality indices and simulation in UWOT

UWOT is able to simulate signals that transmit quality alongside quantity. Currently, UWOT supports one quality index, though the simulation can be expanded to more using a simple workaround. The quality index needs to be a concentration value for each timestep, for the particular substance of interest. The UWOT and scenario translator process are explained in more detail below.

CDF distributions – baseline scenarios

A baseline scenario Cumulative Distribution Function (CDF) of concentration must be provided for every quality index, as shown in the following Figure 84a. The CDF data are converted to a *cfit* object in MATLAB by fitting a linear interpolating function between each set of points, as shown in Figure 84b. The *cfit* uses the fraction of time 'F' as an independent variable and concentration 'C' as a dependent variable.

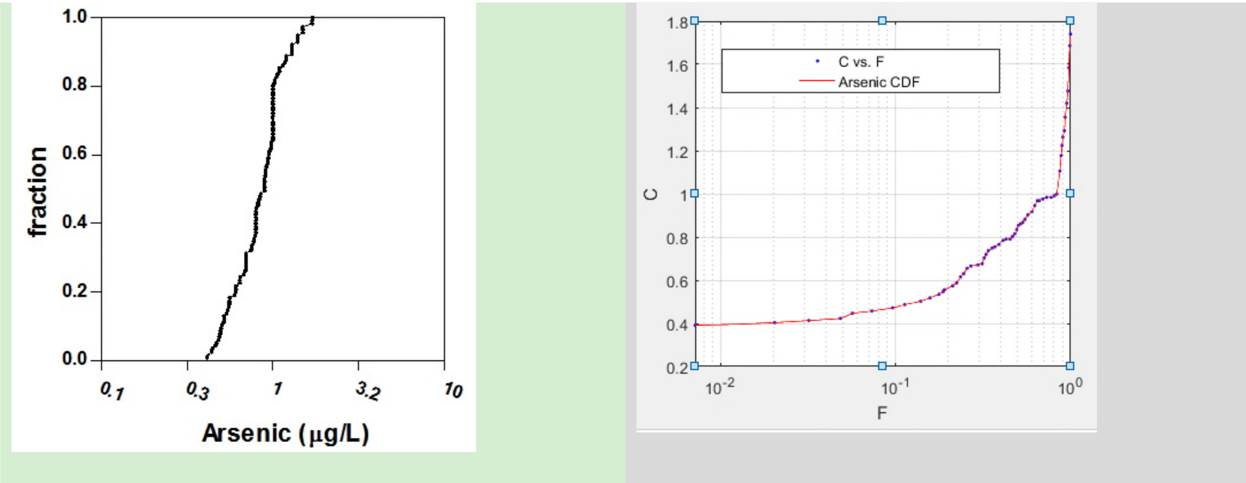

Figure 84a(left) and b(right): CDF chart of Arsenic concentration and curve fitting in MATLAB.

The *cfit* object acts as the generator of the respective quality parameter (concentration or N per L) by using a random number as the seed representing F. An example of a concentration timeseries over a specified simulation period can be seen in Figure 85.

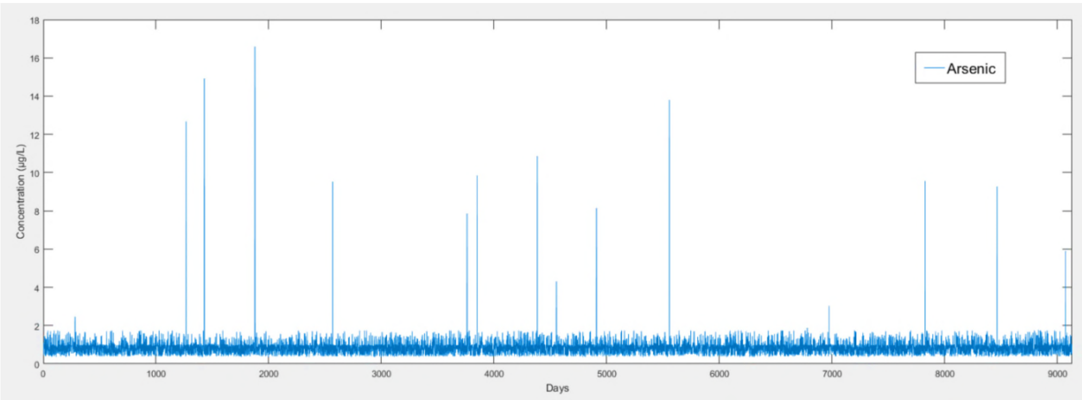

Figure 85: Simulation of Arsenic concentration over the span of 25 years.

Further scenarios

The quality parameters have three different states regarding their probability distribution: low, medium, high. These states change dynamically over time as specified by a rate of change that differs in every scenario. In order to simulate the change of the probability distribution an appropriate multiplier of the *cfit* output is assigned to each state. The multiplier could generally differ for each parameter but as a proof of concept the following values are applied: 1x –low, 2x-medium, 4x-high. An example is shown in Figure 86, where the parameter Arsenic changes with *gradual* rate of change from *low* to a *high* state within a span of 25 years.

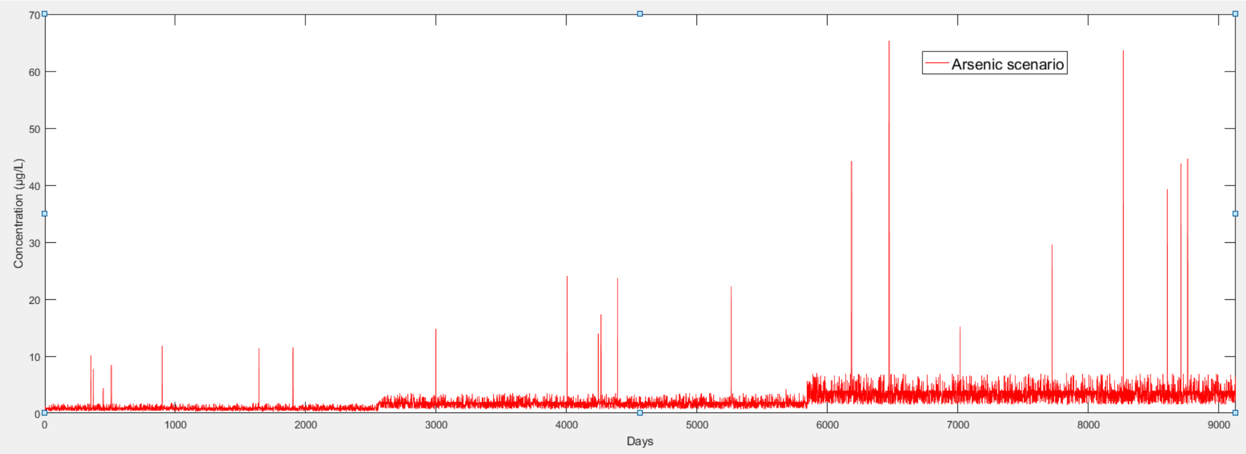

Figure 86: Simulation of Arsenic concentration with state of probability distribution changing gradually from low to high.

UWOT quality simulation

UWOT is currently is capable of applying only a single quality index to the signal path. Therefore, we developed, for the purposes of this work a workaround as follows:

1. Isolate the model part upstream of required quality checking.
2. Clone the source and demand signals, the quality splitter and quality filter components as well as any reservoir/tank that intervenes with the source and demand signals for each quality parameter.
3. Log the sum of quality splitter divergences.

The schematic of the process is depicted in Figure 87, where two different parameters are used as an example. The logged timeseries of cumulative quality related failures is transformed to a binary control variable as shown in Figure 88 where *0* means no failure logged and *1* any amount has logged as a failure. The control variable is multiplied by the demand signal and used as the threshold of a divergence component in the full simulation model without the quality splitters and filters as these are no longer needed. This, effectively, makes a switch that 'checks' all quality metrics. If a threshold different than *0* is met (i.e. the demand of that particular timestep) the whole amount is diverted to the quality failure logger, as can be seen in Figure 89 that depicts the schematic of the process.

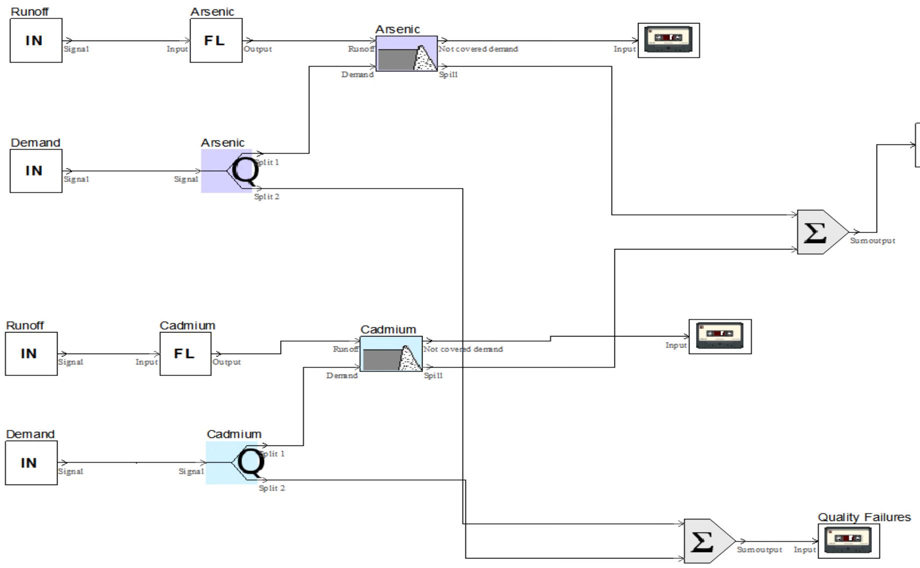

Figure 87: Example of quality simulation for two parameters (Arsenic and Cadmium) in UWOT and logging of quality failures.

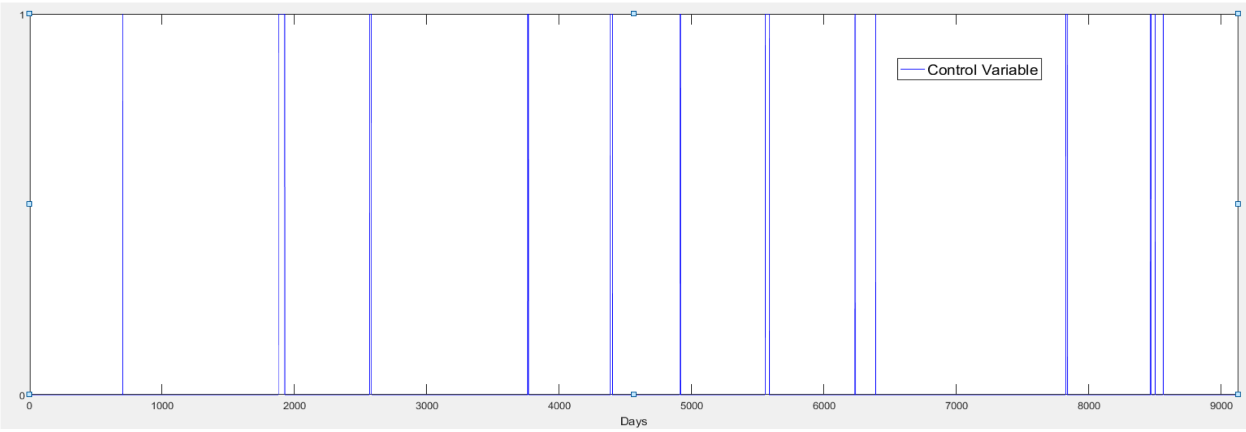

Figure 88: Example of control variable relating to suitable or not quality regarding the parameters of Figure 87.

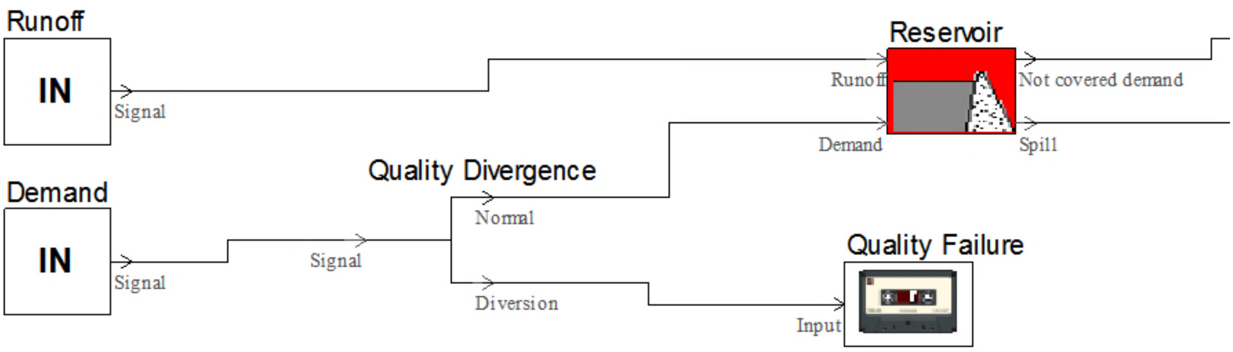

Figure 89: Example of the final schematic of quality failure simulation.

Appendix C: Efficiency – an exploration of alternative viewpoints for a comprehensive Resilience Assessment

Definition of the problem

The previous project (Makropoulos *et al*., 2016) defined a framework within which it is possible to discuss a system's resilience in a mathematical way (i.e., it allows to model a system's ability to remain functional with respect to an uncertain future). To preserve this mathematical approach, we here summarize the existing definitions before adding new elements to the model.

The current drinking water distribution system has a given **Configuration**. This Configuration can be changed by modifying the system. The current system is designed to meet current demands with respect to supply, quality, et cetera. In the future, demands or the context of the system could change according to various possible **Scenarios**, thereby subjecting the system to **Stress**. The level of functionality the system can maintain while in a certain configuration and while subjected to the Stress of a given Scenario is called the Configuration's **Reliability** (between 0% and 100%) for that Scenario. A Configuration's **Resilience** is defined as the unweighted average of the Configuration's Reliabilities within a pre-defined set of gauge Scenario's. A Configuration's Robustness is the fraction of the same set of Scenario's within which the Configuration is able to function with 100% Reliability. In this way, Resilience and Robustness provide relative measures for a Configuration's ability to cope with future Scenarios.

The framework should be expanded in such a way that it supports analysis of the trade-off between a Configuration's Resilience and its **Costs**. This includes the definition of a new index number, the **Efficiency**, which will be a measure for the amount of performance that can be bought per unit Cost by implementing a certain Configuration. Here, we focus of Efficiency defined as the Reliability per Euro. It is worth noting that measures of performance less abstract than Reliability could be used, such as liters of water delivered. Similarly, while we focus on monetary Costs here, different types of costs might be used, such as kg of CO_2 produced.

Overview of literature on Resilience, Costs and Efficiency

(Blue: specifically, about drinking water distribution systems) (*: about efficiency but not about Resilience)

The majority of current literature about the Resilience of infrastructure does not explicitly consider the relations between Resilience and Costs (Berche et al. 2009; Dorbritz 2011; Zobel 2011; Tamvakis en Xenedis 2012; Duijnhoven en Neef 2014; Zobel en Khansa 2014; Diao et al. 2016; Herrera et al. 2016). Establishing such relations is often mentioned as a worthwhile task for future research, however (Cutter et al. 2008; Snediker et al. 2008; Gay 2013; Tamvakis en Xenedis 2013; Willis en Loa 2015; Hosseini et al. 2016; Sharifi 2016; Sharifi en Yamagata 2016; Nan en Sansavini 2017).

The current literature typically associates the Efficiency of infrastructure with the minimization of one specific parameter, such as impact on the environment (Huang et al. 2013*; Stanchev en Ribarova

2016*) or water use (Kontokosta en Jain 2015*; Chu et al. 2015*; Topi et al. 2016*). A relation between Efficiency and Resilience has been researched for graph theory – with an Efficiency derived from path length (Netotea en Pongor 2006; Brede en de Vries 2009), for ecological networks – with and Efficiency related to path length and number of paths (Ulanowicz et al. 2009; Fath 2015) and – analogously to the ecological networks – for infrastructure (Li and Yang 2011; Chen en Chen 2016). This literature does not associate Efficiency with monetary Costs explicitly, although the various parameters might easily be monetized and path length can be considered a type cost in its own right. It should also be noted that a trade-off between Efficiency and Resilience is always found.

In the literature that does try to define a relation between Resilience and Costs, a number of approaches appear. In the first approach, the Resilience of a number of different Configurations is plotted versus their Costs, resulting in a Pareto chart (e.g., Todini 2000; Cimellaro et al. 2010; Matrosov et al. 2015; Wright et al. 2015; Zhang en Wang 2016). Here, Configuration Costs may have limited definitions, such as the number of additionally installed valves, but more complex definitions, involving combinations of investments, operational costs and damages, are considered as well.

A second approach involves the use of extensive cost-benifit analysis (Mechler et al. 2008; Arena et al. 2014; Proag en Proag 2014; Wei et al. 2014). The various costs related to a possible new Configuration are estimated as precisely as possible and are then compared to a similar appraisal of the current Configuration. The types of Costs considered include investments and operational costs, but special attention is paid to the differences in Costs during periods of Stress: a relative reduction in Costs due to Stress is seen as the benefit of higher Resilience, against which Costs must be weighed.

Finally, in line with the cost-benefit approach, several expressions for a system's Resilience have been developed that at least partly depend on the system's monetary Costs (Gay 2013; Proag 2014; Cook et al. 2016). Again, different types of Costs such as investments and repair costs are included.

Suggested Approach

Determining the total Costs involved with a given Configuration lies at the core of work package 2.4.2. At this point, however, finding a detailed and realistic list of costs is beyond the scope of the task. It is important to note, though, that the total Costs of a configuration consist of several components that may each depend on different factors. Here, we construct the total Costs from several abstract components that can be divided base on their dependencies. We do this qualitatively initially and then summarize and illustrate this with mathematical expressions and examples.

We divide the **Total Costs (C, in €)** of a given Configuration into three main components: **Investments (*I*, in €)**, the Costs required for realizing the Configuration; **Upkeep (*U*, in €·y^{-1})**, the operational Costs related to use and maintenance of the Configuration; **Losses (*L*, in €·y^{-1})**, the Costs incurred by a loss in Configuration functionality, i.e., by a loss in reliability. An important difference between *I* on the one hand and *U* and *L* on the other hand is that *I* typically represents a one-time expenditure during the Configuration's implementation while *U* and *L* are recurring costs. Consequently, *U* and *L* depend on the **Timescale (τ, in y)** over which Configuration Costs are compared. Since *U* and *L* may differ per Configuration, the comparison of Configuration Costs will depend on τ as well. As a result, Configurations that require high Investments but have low Upkeep and Losses will be disfavored by comparisons over short τ, but may, in the long term, perform better than Configurations with high Upkeep and Losses.

Apart from their dependency on τ, U and L may also vary with the Scenario. One reason to distinguish between U and L is the fact that they depend on the Scenarios in different ways. L represents the monetary losses involved with deficiencies in system functionality, such as the revenue missed when distribution lapses, or the fines incurred when environmental targets are not met. It is therefore directly related to the Reliability, which may by definition vary per Scenario. Conversely, U depends on the Stress induced by a Scenario, rather than on the Reliability that is a resultant of that Stress. To illustrate the difference, consider a water treatment plant that: meets 100% of demand while running at 50% capacity in Scenario A; also meets 100% of demand while running at 100% capacity in Scenario B; and meets 70% of demand while running at 100% capacity in Scenario C. When comparing the plant's performance in Scenarios A and B, we see that its Upkeep increases (the plant has to run at higher capacity, expending more energy and manpower) without a decrease in Reliability (demands are still met for 100%). When comparing Scenarios B and C, on the other hand, we see that Reliability dwindles, increasing L, whereas the plant runs at the same capacity and thus keeps the same U. It should be noted that it could be plausible for U to be even higher in Scenario C, as it might be more expensive to run at 100% capacity while subjected to higher Stress. Summarizing: U depends on the **Stress (σ_s, dimensionless)** induced by the Scenario; L depends on the **Reliability (r_s, dimensionless)** of the Configuration in the Scenario – which in turn depends on σ_s.

The above shows that the Costs of a Configuration may vary with the Scenario it is subjected to. The efficiency of the Configuration within that Scenario (**e_s, in €$^{-1}$**) may be expressed in terms of I, U, τ, r_s and σ_s:

$$e_S = \frac{r_S}{I+\tau\cdot U(\sigma_S)} \qquad (1)$$

Note that L is not included in (1) because of another difference between U and L: whereas I and U are Costs that are required for operation, L represents Costs that are a result of operation a Configuration, and is essentially a monetized version of r_s. Actual monetization of the Reliability will Depend heavily on significant assumptions, however, and is currently beyond the scope of the project.

Also note that equation (1) does not take into account the fact that r_s and σ_s may change over time during a Scenario. Rather, it is assumed that the Scenario is active and constant during the complete period τ. This is in line with the central project assumption that a Scenario represents a long-term world state (which is why a single value for the Reliability can be attributed to a Configuration within a given Scenario). To take into account possible variations with time (for instance to include the effects of the transition period between the status quo and the Scenario), time series of r_s and σ_s need to be defined for each Scenario. Consecutively, a method for transforming the r_s time series into a single effective value needs to be defined, for instance:

$$e_S = \frac{\frac{1}{\tau}\int_0^\tau r_S(t)\cdot dt}{I+\int_0^\tau U(\sigma_S(t))\cdot dt} \qquad (2)$$

To obtain a single Efficiency index number that may be attributed to a Configuration together with the Resilience index number, the Efficiencies specific to the different Scenarios need to be aggregated into the Total Efficiency (**e_{tot}, in €$^{-1}$**). One possible way to do this is to simply take the unweighted average over the e_s, much like the way the Resilience is obtained from the Reliability. One disadvantage of this approach is that unlikely, high-cost Scenarios may dominate e_{tot}. A possible solution would be to weigh the e_s from each Scenario with the corresponding likelihood that said Scenario occurs. However, attributing such a likelihood to a Scenario is far from trivial, would be based on heavy assumptions, and goes beyond the scope of this project. Still, for a decision maker, it might be a valuable additional tool to be able to attribute subjective beliefs of likelihood to Scenarios (***b**$_s$*, dimensionless). This would allow the decision maker to prioritize the Reliabilities in Scenarios that are perceived to be most important. The simplest expression for the Total Efficiency then is:

$$e_{tot} = \frac{\sum_s (b_s \cdot e_s)}{\sum_s (b_s)} \quad (3)$$

with:

e_{tot}	**[€$^{-1}$]**	**=**	**Total Efficiency of a Configuration**
e_s	[€$^{-1}$]	=	Efficiency of a Configuration for a given Scenario
I	[€]	=	Investments
U	[€·y^{-1}]	=	Upkeep
t	[y]	=	Time
τ	[y]	=	Time scale of the cost analysis
σ_s	[-]	=	Stress during a given Scenario
r_s	[-]	=	Reliability of a Configuration for a given Scenario
b_s	[-]	=	Belief in a given Scenario

Note that the dimensions of the various quantities may change when different measures for performance and cost are used instead of Reliability and Euros

Again, it should be noted that this approach assumes that Resilience and Costs are determined for a Scenario that has a duration of several tens of years, representing long term global trends rather than short, sudden, short-time **Incidents**. Incidents are taken into account insofar as they are assumed to be effects of Scenarios, for instance: the global trend of increasing traffic pressure (Scenario) leads to an increase in the frequency of pipe failures (Incidents). This corresponds to the approach in BTO 2016.049 with respect to the definition of Reliability based on quantitative targets. Summing over the Costs of all occurring incidents may provide the basis for a more detailed expression for *U*:

$$U(\sigma_s) = u_f + u_s(\sigma_s) + \sum_i \left[f_i(\sigma_s) \cdot \left(c_{f,i} + \tau_{r,i}(\sigma_s) \cdot \left[c_{t,i}(\sigma_s) + c_{r,i} \right] \right) \right] \quad (4)$$

With u_f fixed Costs, such as rent and overhead; u_s Stress dependent Costs, such as energy use; f_i the frequency of a given type of incident; $\tau_{r,i}$ the time required for recovery from a given type of incident; $c_{f,i}$, $c_{t,i}$ and $c_{r,i}$ the respective fixed repair costs (e.g., material costs), repair costs per unit time (e.g., man-hours) and costs for loss of functionality (e.g. lost revenue). Further description of the various Cost components may be based on the parameters that characterize the Scenario. For instance: economic developments may change material costs, or political developments may change the cost of man-hours. Properties of the Configuration may play a role as well. The Configuration for instance largely dictates the energy use and the nature of the incidents that can occur. The knowledge contained in work packages 2.2 and 2.3 should be used for this.

Illustrative Examples

Here, the approach described above is illustrated. Five hypothetical Configurations with different Reliability curves are exposed to 7-gauge Scenarios with increasing stresses (σ_1=1, σ_2=2, …, σ_7=7). The Configurations' Reliability profiles are shown in figure 1a. For each Configuration and Scenario, e_s is then determined according to equation (1) for a period of τ=50 years, in which U is defined as according to:

$$U(\sigma_s) = u_f + u_s \cdot \sigma_s \qquad (5)$$

This is a simplified version of equation (4), in which $u_s(\sigma_s)$ is expressed as a linear function of Scenario Stress, with u_f representing fixed costs and u_s representing a basic sensitivity to Scenario Stress. Each Configuration's Resilience, dummy estimations of I, u_f and u_s, and a short description of the rationale behind each example Configuration are given in the table below. The Table 15 and Figure 90 show that the profiles of Configurations 2 and 3 were designed result in the same Resilience. The same holds for Configurations 4 and 5. This emphasizes the fact that Configurations may show markedly different behavior despite having the same Resilience. Therefore, additional information, such as an accurate estimation of costs, may be useful to better support decisions.

Table 15: Summary of system profiles

#	Resilience	I	u_f	u_s	Summary
1	0.42	0	0.2	0.2	The base system. By definition, this requires no Investments. It has relatively low operational costs but is quite sensitive to stress.
2	0.57	2	0.2	0.2	System in which a small budget was used to neutralize the effects of a single disaster (high Stress, possibly low Belief) scenario
3	0.57	2	0.4	0.1	System in which a small budget was used to enhance Reliability in several Scenarios. It results in higher fixed costs, but lower stress sensitivity
4	0.75	4	0.8	0.4	System in which a high budget was used to make a system as robust as possible. This requires a large upkeep.
5	0.75	16	0.4	0.2	System that was completely redesigned with a huge budget to be equally reliable in every Scenario without much change in Upkeep

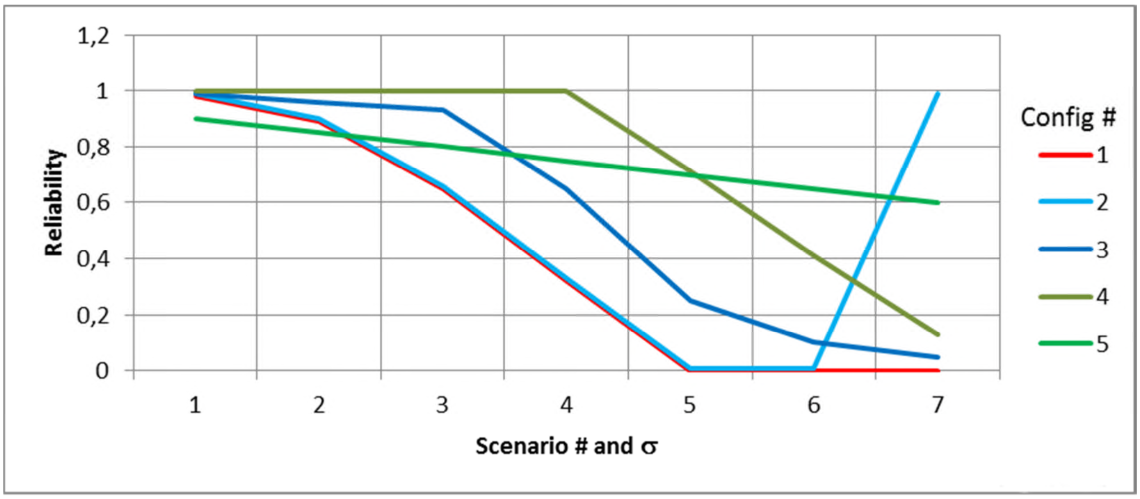

Figure 90: Profiles of resilience

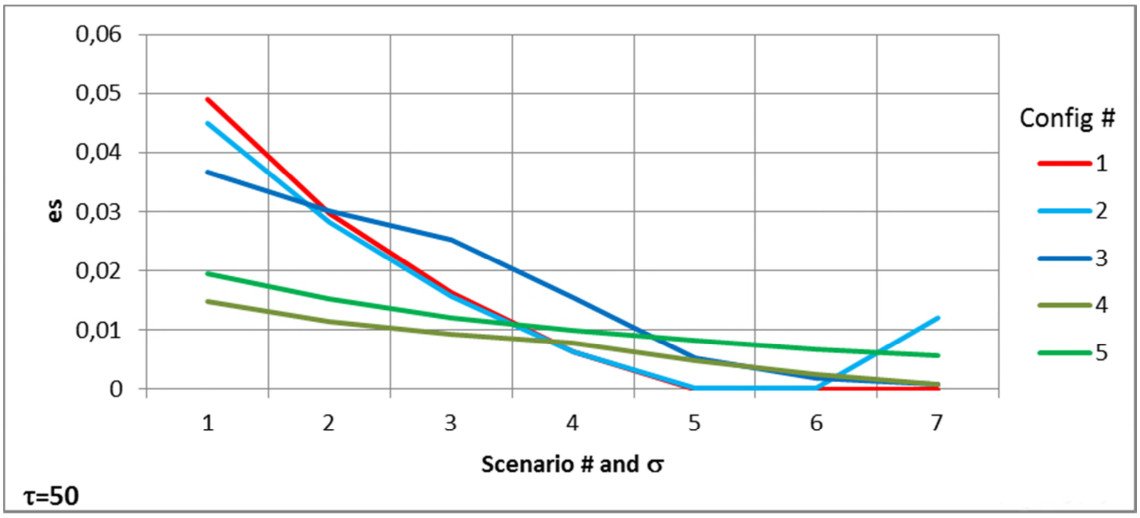

Figure 91: Profiles of efficiency

Figure 91 shows the resulting e_s profiles of the Configurations. It can be seen that, in different Scenarios, different Configurations are the most efficient. In the first Scenario, for instance, Configuration 1 has the same Reliability and Upkeep as Configuration 2, but its Investments are lower which makes it more efficient. Despite its high Resilience and relatively low Investments, Configuration 4 is never the most efficient due to its high Upkeep. Configuration 5, on the other hand, eventually becomes the most efficient despite the huge Investments required, thanks to its low upkeep. In Scenario 7, Configuration 2 becomes most efficient thanks to its specialized increase in Reliability in that Scenario.

Figure 92 and Figure 93 show the total Efficiency per Configuration (denoted with the labels) as determined from the Efficiency profiles in Figure 91 according to equation (3). In Figure 92, the beliefs per scenario were chosen to be equal, so that the total Efficiency is simply the unweighted average of the e_s in the different Scenarios. In Figure 93, the beliefs were chosen so that each Scenario is believed to be twice as unlikely as the next, i.e. $b_i = 2 \cdot b_{i+1}$. The beliefs denote relative differences in perceived likelihood, not mathematical, factual chances, meaning that Efficiency values should not be compared across charts. Comparing the trends in Figure 92 and Figure 93, it can be seen that Configuration 1 becomes more efficient when the likelihood of more stressful scenarios becomes lower. Also, depending on the choices for Scenario Beliefs, either Configuration 2 or 3 is the most efficient of the two. This demonstrates that taking account Scenario Belief may indeed lead to different decisions.

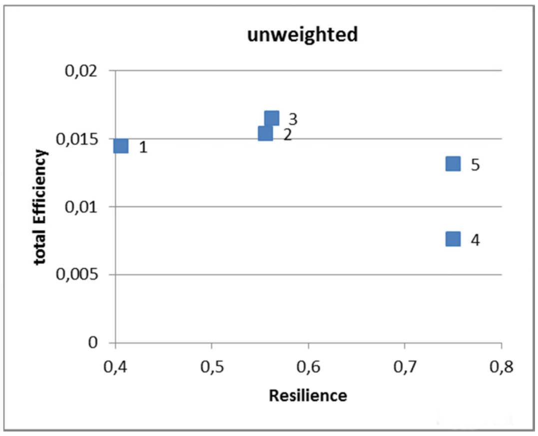

Figure 92: Scenarios with equal beliefs

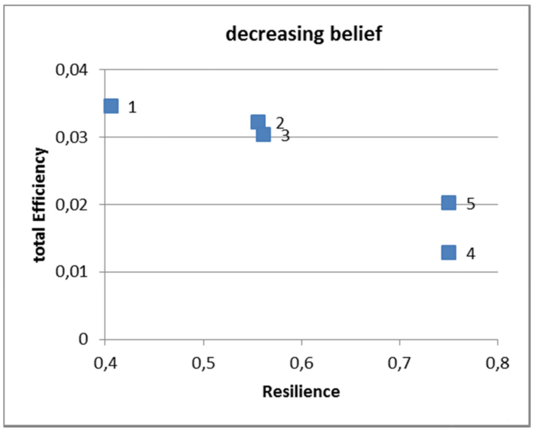

Figure 93: Taking into account Scenario belief

Although the examples presented here illustrate the value and use of an Efficiency index number, it should be stressed that these are only simplified examples. Especially the determination of *U* should be much more involved in order to arrive at accurate Cost estimations.

Appendix D: Completing the chain: Linking UWOT with City Blueprint

Introduction

KWR has traditionally put much effort into the creation of applied knowledge of various aspects of the water cycle. More recently, attention is given to integrative approaches regarding the resilience of urban water management. As a result, one of the five communities of practice within Watershare® (https://www.watershare.eu/) is about resilient urban water management. Here, the combined results of years of research regarding this topic is bundles into tools that ensure the continued application and improvements of developed knowledge.

Table 16: Building blocks for water resilience.

Tool	Goal	Operational	toolholder
City Blueprint	Baseline assessment urban water management	Yes	Kees van Leeuwen
City Blueprint Governance	Assessment of the governance capacity needed to address urban water challenges	No	Stef Koop
FutureMap	Assistance in strategic planning and goals setting	Yes	Andrew Segrave
Scenario Planner	Interactive tool to facilitate users in developing fit for purpose scenarios explore future developments	No	Henk-Jan van Alphen
UWOT	Long-term integrative modeling tool to assess the resilience of the urban water system	Yes	Christos Makropoulos

Two of the most active tools within the Watershare community are the City Blueprint and UWOT. Because the City Blueprint and UWOT both focus on urban water management but have a rather different time horizon, level of detail and time demand, they are very complementary to each other. The City Blueprint provides a first baseline assessment using broad indicators covering all components of the urban water cycle, whereas UWOT is a more in-depth, detailed analysis that includes scenario's and focusses on specific local conditions and questions of water quality, quantity, efficiency, costs and service provision to customers/civilians. The City Blueprint is a quick scan indicator assessment based on publicly available data in developed and developing countries all over the world where the information availability can be rather limited. Hence, the type of indicators is largely shaped by this limited data availability. UWOT on the other hand, is more focused on in-depth analyses and modeling of the urban water systems based on a larger data input and a more detailed and long-term scope. In order to provide cities with a coherent and logical user-package of Watershare tools, it is essential that the City Blueprint and UWOT are more connected and integrated. This needs to be done on both a conceptual level as well as a methodological level. Both approaches are within the Watershare community of Practice "*Resilient Urban Water Management*'' together with "*City Blueprint – Governance*", "*FutureMap*" and "*Scenario Planner*". In order to provide a broad conceptual overview, we firstly describe how the different Watershare tools are interconnected and complementary, and we discuss how the *Resilient Urban Water Management* tools provide an important step in helping cities and other stakeholders by showing its usefulness and cohesion with the other communities of practice within Watershare. Secondly, we provide a rationale to further connect the City Blueprint and UWOT tools on a more profound and methodological level.

Conceptual integration

A coherent Watershare user package for resilience profiling

Cities are centers of innovation, economic development as well as climate mitigation and adaptation. Rapid urbanization, climate change and inadequate investments lead to water and climate challenges that may overwhelm the resilience of many urban areas. The current water crisis is largely a crisis of information sharing and adequate governance because technology is often available and best practices are already applied in a few cases. In fact, cities, companies and other stakeholders can benefit a lot by sharing experiences, implementing knowledge and best practices. However, they need to develop a long-term strategy based on three generic steps:

1) knowing what their current water management baseline situation is;
2) tool users need to anticipate on long-term impacts, risks and uncertainties by setting long-term goals supported by interim targets;
3) tool users need to develop comprehensive plans and strategies to bring these goals and targets into practice. Integrated models that analyze different scenario's enable resilient planning that anticipates on long-term impacts, risks and uncertainties.

Within the Watershare Community of Practice "*Resilient Urban Water Management*", we have developed a set of interconnected tools that enable ''*Resilience profiling*'' which guides water managers in making strategic long-term decisions (Figure 89).

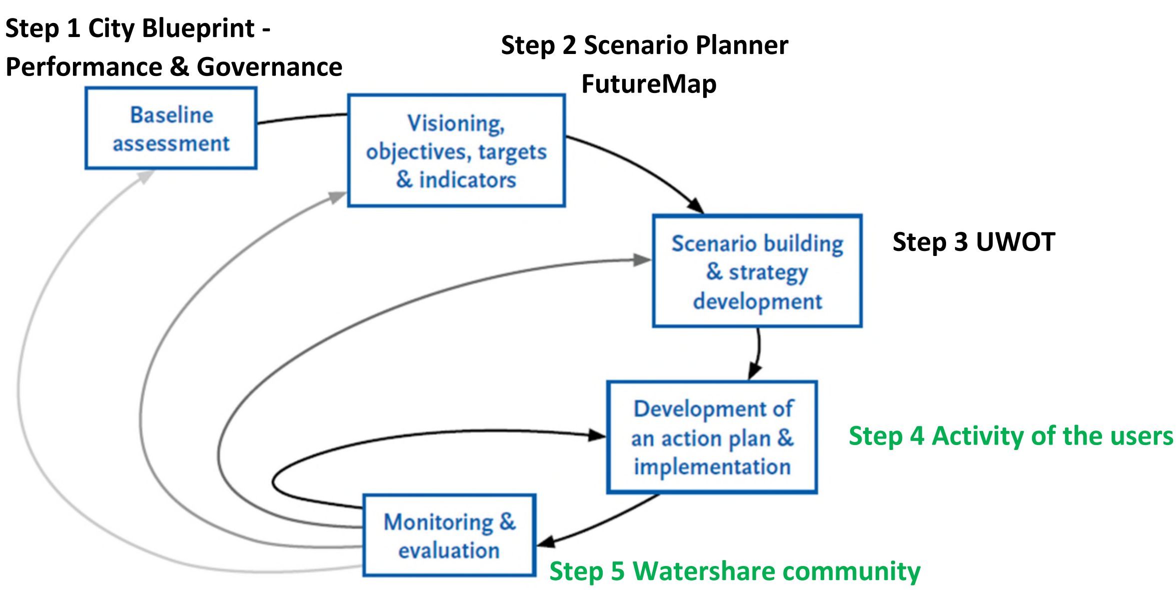

Figure 94: Overview of the process of resilience profiling. For the development of long-term action plans, cities are facilitated based on three steps: 1) a baseline water management assessment (City Blueprint

Approach); 2) setting objectives and targets (FutureMaps); 3) assessing the resilience profile under different scenarios, management choices and design philosophies (Resilience assessment). Monitoring and evaluations continuously optimizes this process.

For the first step, the City Blueprint Approach (CBA) is developed. The CBA consists of three indicator frameworks that assess the baseline situation: A) a framework that assesses the main social, environmental and financial trends and pressures that may affect local water management decisions; B) an urban water management performance framework and; C) a framework to identify most effective and efficient pathways to increase the governance capacity necessary to address existing urban water challenges. These water challenges are tightly interlinked with the experienced trends and pressures and the shortcomings in water management performances. For step 2, the *FutureMap* tool facilitates strategic decision-making by considering the time horizon that decision makers and managers apply. *Scenario Planner* is an interactive tool to build scenarios that most suited its purposes. For step 3, the UWOT tool is developed that assesses the city's resilience performances under scenarios of increasing pressure and different water system design philosophies. This set of tools provide essential insight in opportunities and necessities for improvement and which Watershare tools can contribute to these efforts.

The role of resilience profiling within the Watershare community

Community of Practice *Resilient Urban Water Management* provides a coherent set of tools that enables comprehensive resilience profiling which is necessary to identify key challenges and find optimal solutions within the Watershare community and beyond. The three steps provide important strategic insight with respect to the other four Watershare communities of practice:

I. Sub-surface water solutions
II. Emerging substances
III. Future-proof water infrastructure
IV. Resource recovery and upcycling

I. Sub-surface water solutions

The *City Blueprint* tool includes a basic indicator groundwater quality and includes indicators regarding the water scarcity, i.e. indicator 20 *drinking water consumption* and the trends and pressures provide basic insight into the water scarcity situation in the city and surroundings. The *City Blueprint – Governance* tool can provide insight into the specific conditions and pathways towards more governance capacity to address the water challenge of water scarcity. It provides a stakeholder analyses method and may assess the awareness and openness of the most relevant stakeholders in a city with respect to sub-service solutions. *FutureMap* is able to provide long-term horizon scanning to identify barriers or opportunities that will emerge in the near and further future to adopt sub-surface water solutions. In particular, the tool can assist in the time-planning and goals setting in order to formulate goals and objectives that are supported by the organization in question. *ScenarioPlanner* is able to build scenarios based on selected parameters and their rate of change. It therefore is an important base for *UWOT* to map the potential of sub-surface water solutions under ranging future scenarios such as increased water demand, changing rainfall patterns or design philosophies of the urban water system.

Members: National Technology University of Athens, Naturalis Biodiversity Centre, SvensktVatten & University of Bath.

Watershare tools:

1. WellGrapher – Provides insight into the effect of land use change on the quality of well water
2. Soil leach – Screening to identify sites that are potentially susceptible to the leaching of pollutants to groundwater
3. ASR Performance Assessor – Assesses the potential of Aquifer Storage Recovery
4. Soil sensing – assesses impacts of measure on the landscape and vegetation using factors like groundwater levels, soil acidity and soil nutrient fertility
5. Well clogging risk index – tool to estimate the risks of chemical well clogging
6. Groundwater monitoring – tool to get the most out of their groundwater data with minimal effort and costs

II. Emerging substances

The *City Blueprint* tool includes basic indicators of wastewater treatment and drinking water quality as well as stormwater separation that influences the exposure of emerging substances. The *City Blueprint –governance* tool can be applied to map the awareness and stakeholders' perception that determine the governance capacity to reduce potential health and environmental impacts of emerging substances in local, regional or national decision-making. The *FutureMap* may identify future trends and developments that can affect the magnitude or impact of emerging substances. Importantly, may provide a valuable task of time horizon that stakeholders consider in the management of these risks. These insights can be used to create the most suitable scenarios within the *Scenario Planner* tool which in turn can be used for an optimal resilience analyses within *UWOT* tool. *UWOT* includes water quality aspects and future scenarios in which for example an aging population use more medicine. Therefore, UWOT can provide long-term insight into the future trends and developments of emerging substances within the urban water system.

Members:

Waterschare tools: *JWRC Japan WEater Research Centre KOMPETENZZSENTRUM Wasser Berlin, KIST Korea Institute of Science and Technology, KWR Watercycle Research Institute, SvensktVatten, VITO, University of Bath, WLN Indonesia*

1. QRMA Treatment Calculator – Quantitative Microbial Risk Assessment of drinking water
2. Cyano Control Guidance – Guidance to control Cyano algae in surface water
3. eDNA - Monitoring aquatic biodiversity using eDNA
4. AbetES - Decision Support System with information on emerging substances
5. SewScan – Scanning biomarkers of endogenous human metabolism in sewage water

III. Future-proof water infrastructure

In most places there is a serious infrastructure investment deficit. Over 22.6 trillion US$ 950% of the total infrastructure expenditures) is needed to refurbish the water systems worldwide (UNEP 2013). Yearly expenditures on water infrastructure for developed countries are around 1% of the GDP. For developing countries this is about 3.5% with extremes up to 6% and more. The *City Blueprint* tool includes a category infrastructure where the leakage rate of water distribution networks is indicated. Also the average age of a sewer is taken as a proxy for the infrastructure maintenance state. Furthermore, the operation cost recovery ratio for drinking water and sanitation services are included as a proxy for the financial possibilities to maintain and improve water infrastructure. The *City Blueprint – Governance* assessment can provide valuable insight in the main barriers or enabling conditions that determine the governance capacity to make the water infrastructure more resilient. The *FutureMap* can provide important insights into the time horizon that stakeholders consider in their strategic decisions concerning the development or refurbishment of water infrastructure. It is essential to know what the time-horizon of expected returns on investment is desired and how this affects current strategic decisions. The *Scenario Planner* can facilitate water managers in developing suitable scenarios that can provide the relevant information for modeling purposes. *UWOT* provides long-term insight and strategic knowledge regarding the resilience of urban water infrastructure under different future scenarios and design philosophies.

Members: University of Bath, Water Research Commission, VITO, Victoria, National Technical University of Athens, KWR Watercycle Research Institute KOMPETENZZENTRUM Wasser Berlin JWRC Japan Water Research Center IO environmental solutions

Watershare tools:

1. Chlorine free - ten-step plan to attaining chlorine-free drinking water
2. Self-Cleaning Networks – provides design rules for self-cleaning pipe networks
3. Mains investment planning - calculates the investment requirements for the replacement of water mains
4. Network Flow Performance – generate a clear display of flow volume time series
5. NOMatter – select optimal choice for NOM (natural organic material) removal
6. Water-Use info – understanding water demand and water discharge of optimal networks and installations

IV. Resource recovery and upcycling

The *City Blueprint* tool assesses the resource and energy recovery of both wastewater and solid waste in its baseline assessment. The *City Blueprint – Governance* tool can provide important insights and identify potential pathways to increase the governance capacity to improve the resource recovery of waste products in wastewater or solid waste. *FutureMap* tool may provide a horizon scan of future trends and developments that affect the time-perspective of stakeholders and decision-makers to impede or enhance more resource recovery in their wastewater treatment. The *Scenario Planner* tool enables water managers to select multiple possible developments, changing parameters that could be relevant for the feasibility of resource recovery in different applications. UWOT is able to simulate recovery of water from wastewater directly and indirectly simulate other resources (incl. nutrients) as a function of wastewater flows. *Members*: *CTM Centre technologic, University of BATH, WLN Indonesia, Water Research commission KlST Korea Institute of Science and Technology, KWR Watercycle Research Institute, and Kompetenzzentrum Wasser Berlin*

Watershare tools:

1. Residual cycle - decision-making support tool that encompasses all relevant aspects of the reuse of residuals, primarily those from drinking water treatment processes

Integrating the City Blueprint and UWOT

There are clear connections between the City Blueprint and UWOT. Facets of basic water service delivery, water quality and other City Blueprint categories can be analyzed in more detailed and on a more dynamic level using UWOT. The City Blueprint tool consists of 7 broad categories each with three or four indicators (Table 17: Overview of the categories and indicators of the City Blueprint tool.). The average score of the indicators of a category make up the category score. The City Blueprint indicators have a comprehensive nature and often measure the result of management decisions whereas UWOT focusses on the long-term resilience profile of these pre-determined decisions. Therefore, many City Blueprint indicators can be considered as system boundaries of UWOT. For example, indicator 1 Secondary WWT is a direct performance indicator within the City Blueprint assessment while UWOT considers this treatment ratio as an input before the actual resilience assessment is performed. UWOT can provide indicators that are sensitive to changing social and climatic conditions which are also very related to the City Blueprint categories. This approach can provide the City Blueprint categories with a UWOT type dynamic resilience profile that behaves differently under different scenarios. This is the rationale we apply in order to integrate both methods in a clear, understandable and constructive way.

Table 17: Overview of the categories and indicators of the City Blueprint tool.

I Water quality	1. Secondary WWT 2. Tertiary WWT 3. Groundwater quality
II Solid waste treatment	4. Solid waste collected 5. Solid waste recycled 6. Solid waste energy recovered
III Basic water services	7. Access to drinking water 8. Access to sanitation 9. Drinking water quality
IV Wastewater treatment	10. Nutrient recovery 11. Energy recovery 12. Sewage sludge recycling 13. WWT energy efficiency
V Infrastructure	14. Stormwater separation 15. Average age sewer 16. Water system leakages 17. Operation cost recovery
VI Climate robustness	18. Green space 19. Climate adaptation 20. Drinking water consumption 21. Climate-robust buildings
VII Governance	22. Management and action plans 23. Public participation 24. Water efficiency measures 25. Attractiveness

For each City Blueprint category dynamic sub-indicators are selected to be assessed within the UWOT tool (table 2). Only dynamic indicators which change under different scenarios of increasing pressure a proposed and marked green. Furthermore, some dynamic indicators that are part of the City Blueprint are included as they are fit for application within the UWOT environment. The categories II *solid waste* treatment and VII *governance*, are largely beyond the scope of UWOT. For category II, we propose to remain the City Blueprint results as they are and include them in the results of the UWOT's analyses of the sub-indicators (Table 18: Proposed set of dynamic indicators for each category that can be assessed within UWOT and the scenario planner tool. For category II solid waste treatment and category VII governance, no dynamic sub-indicators are provided as this is beyond the scope of the UWOT analyses.). It is also opted to provide a best estimate of based on the scenario assumptions. For category VII, we can choose the same approach or score this category with sub-indicators that are direct results of the scenario assumptions that UWOT is processing. The average of the dynamic sub-indicators that are analyzed in UWOT provides a score for the City Blueprint categories. In this way, we can do a basic comparison between the City Blueprint results under different scenarios with the current City Blueprint results.

Table 18: Proposed set of dynamic indicators for each category that can be assessed within UWOT and the scenario planner tool. For category II solid waste treatment and category VII governance, no dynamic sub-indicators are provided as this is beyond the scope of the UWOT analyses.

I Water quality	1. BOD in surface water 2. Nitrogen concentration in groundwater 3. Chlorine concentration in groundwater
II Solid waste treatment	4. Solid waste collected 5. Solid waste recycled 6. Solid waste energy recovered
III Basic water services	7. Volume of drinking water not delivered 8. Sewage blockages 9. Parameters of drinking water quality
IV Wastewater treatment	10. Nutrient recovery 11. Energy recovery 12. Recovery of valuable metals 13. Sewage sludge recycling 14. WWT energy efficiency 15. WWT performance failure 16. Combined sewer overflows 17. WWT energy consumption 18. Drinking water leakages 19. Wastewater leakages 20. Operation cost recovery 21. Investment level 22. Cost efficiency distribution network 23. Cost efficiency sewer 24. Pipe failure
VI Climate robustness	25. Green space 26. Urban temperature increase 27. Infiltration capacity 28. Drinking water consumption 29. Independency of domestic water use 30. Share of rainwater use 31. Share of grey water use
VII Governance	32. Management and action plans 33. Public participation 34. Attractiveness

Final remarks

We conclude that resilience profiling of urban water systems is also about facilitating cities and other stakeholders with a clear set of tools and options. In order to truly facilitate cities, fit-for-purpose sets of tools and research projects need to be selected which are specific for each city or stakeholder. An example of such an application for Oasen has been described in this report. Links between tools are sometimes easy to make to exploit synergies. For example, the Scenario Planner is already linked to the UWOT environment and its integration has been improved during this work through the scenario translator scripting process. In this appendix, we also make a basic methodological connection between City Blueprint and UWOT (Figure 95) highlighting the potential integration and synergy between these two complementary tools.

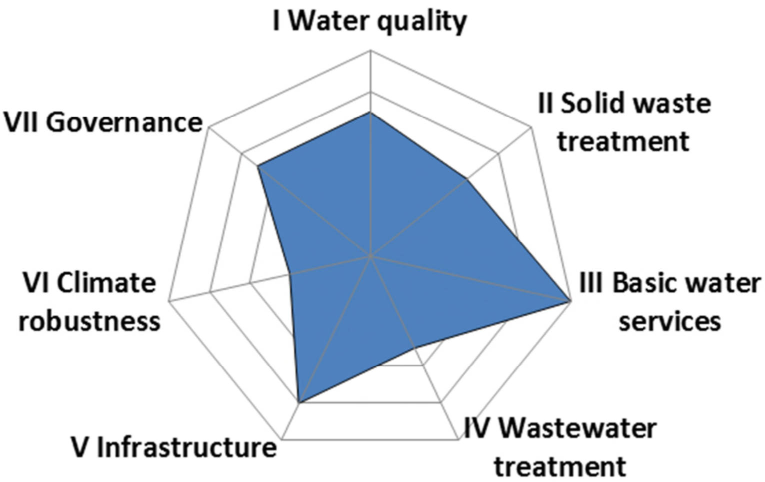

Figure 95: Envisioned output of the City Blueprint categories using the scores of sub-indicators assessed within the UWOT model.