D4.1: Interim Report on the Resilience-based stress-testing framework for AWR supply systems and technologies

Dionysios Nikolopoulos, Sotirios Moustakas, Archontia Lykou, Georgios Moraitis & Christos Makropoulos (NTUA)

Introductory Table

Project Ref. No.	HORIZON-CL6-2023-CLIMATE-01-2; GA No. 101136598
Project Title	Reliability and effectiveness of integrated alternative water resources management for regional climate change adaptation
Duration of the Project	2024-01-01 to 2027-12-31 (48 months)
WP/Task:	WP4 - Strategic Planning: options and pathways / Task 4.1. A resilience-based stress-testing framework for AWR supply systems and technologies
Document due Date:	2025-04-30 [M16]
Actual Date of Delivery	2025-04-29 [M16]
Leader of this Deliverable	NTUA
Dissemination Level	PU - Public
Document Status	Final

This project has received funding from the European Union's Horizon Europe research and innovation programme under grant agreement No. 101136598. This document reflects only the views of RECREATE consortium, neither the European Commission nor any associated parties are responsible for any use that may be made of the information it contains.

Deliverable Information Sheet

Version	Date	Author	Document history/approvals
0.1	2025-01-09	Dionysios Nikolopoulos, Sotirios Moustakas, Georgios Moraitis (NTUA)	Table of Content (Toc) created.
0.2	2025-02-07	Archontia Lykou, Sotirios Moustakas, Dionysios Nikolopoulos, Georgios Moraitis (NTUA)	CS3 Syros information was drafted.
0.3	2025-02-24	Anne Kleyböcker (KWB), Preben Thisgaard (KCR), Klaasjan Raat (KWR), Koen Zuurbier (PWN), Nikolaus Klamerth (ICRA)	CS1, CS2 and CS4 information included.
0.4	2025-03-24	Sotirios Moustakas, Dionysios Nikolopoulos, Georgios Moraitis (NTUA), Anne Kleyböcker (KWB), Preben Thisgaard (KCR), Klaasjan Raat (KWR), Koen Zuurbier (PWN), Nikolaus Klamerth (ICRA)	CS1, CS2, CS3 and CS4 KPI information updated.
1.0	2025-03-26	Dionysios Nikolopoulos, Sotirios Moustakas, Archontia Lykou (NTUA)	First complete draft for quality assurance.

1.1	2025-04-15	Dionysios Nikolopoulos, Sotirios Moustakas, Georgios Moraitis, Archontia Lykou (NTUA)	Document revision after quality review by Lydia Vamvakeridou-Lyroudia (KWR) and Wolfgang Gernjak (ICRA)
1.2	2025-04-22	Queralt Plana (EUT)	Quality control
1.3	2025-04-29	Dionysios Nikolopoulos (NTUA)	Final version

Executive Summary Section

This document (D4.1) serves as the interim report for T4.1 “A resilience-based stress-testing framework for AWR supply systems and technologies”. It links RECREATE and its Case Studies (CSs, which are North Holland, Kalundborg, Syros-South Aegean, and Costa Brava) to the concept of resilience as evolved from the engineering and socio-ecological system domains, with a methodological background for its application on modern water systems, that face significant stresses in the form of climatic and socioeconomic change, pertaining to water scarcity implications.

To this end, the methodological framework elaborates on the development of suitable Key Performance Indicators (KPIs) for multiple aspects and objectives of the systems, the formulation of standardized compound scenarios of multiple stressors, the modelling requirements and concepts for the water systems, the formulation of alternative configurations to compare with the baseline set-up, a stress testing approach for evaluation and presentation and communication of resilience results.

Pivotal in RECREATE is the exploration of adoption of Alternative Water Resources (AWR) to tackle water scarcity, and the methodological framework will be used to evaluate adaptation pathways that include such solutions (among other technical and non-technical interventions) in future alternative configurations of the systems. Therefore, this report conceptualizes the necessary links between tools that will be used to optimize the resilience of the future pathways and the assessment methodology as the practical implementation. Finally, the preliminary CS considerations in the contexts of KPIs and modelling configurations are presented.

Related Deliverables: This report will be updated in the final report, D4.2 (to be submitted in M36), where the finalized methodology development for resilient adaptation pathways and the implementation of the resilience assessment in the CSs will have been carried out.

EU added value/Contribution to EU policies: Outlines a comprehensive framework for assessing resilience of water systems in EU regions against uncertainty by implementing AWR technologies and pathways, related to Critical Entities Resilience.

Table of Contents

List of Abbreviations

ABM	Agent Based Modelling
ASR	Aquifer Storage Recharge
AWR	Alternative Water Resources
CAPEX	Capital Expenditures
CI	Critical Infrastructures
CS	Case Study
GDP	Gross Domestic Product
GW	Groundwater
KNMI	Koninklijk Nederlands Meteorologisch Instituut
KPI	Key Performance Indicator
LCOW	Levelized Cost of Water
MAR	Managed Aquifer Recharge
OPEX	Operating Expense
OWA	Overall Water Availability Indicator
PU	Public
QCRA	Quantitative Chemical Risk Assessment
QMRA	Quantitative Microbial Risk Assessment
RCP	Representative Concentration Pathways
RWH	Rainwater Harvesting
SD	System Dynamics
SDM	System Dynamic Modelling

SES	Socio-Ecological Systems
SSP	Shared Socioeconomic Pathways
TCO	Total Costs of Ownership
UWAB	Urban Water Agent Behaviour
UWOT	Urban Water Optioneering Tool
WP	Work Package
WT	Water Tool
WUEF	Water Use Efficiency Factor
WWTP	Waste Water Treatment Plan

List of Figures

1. Introduction

1.1 Aim and scope of this document

The RECREATE project aims to improve the resilience of water supplies and protect the status of natural water resources by facilitating the assessment and inclusion of Alternative Water Resources (AWR) in water management planning for water scarce regions, and to increase awareness and acceptance and trust in the fundamental role of AWR in climate change adaptation. This deliverable is part of WP4 *“Strategic Planning: options and pathways”* activities. Within the objectives of WP4 are to support strategic, long-term planning, aiming to transform water systems and services, by embedding supply systems and technologies for AWR at the appropriate phase of the water system ‘lifecycle’. To achieve this, WP4 has set the below objectives:

i. To stress test systems within a resilience assessment framework accounting for multiple uncertainties;
ii. To investigate and operationalise the emerging concept of dynamic intervention design to develop pathways for such transformations building on knowledge from WP1 and adding to the functionalities of RECREATE_WT (WP3);
iii. To provide a serious game to further support stakeholders’ engagement with the pathways; and
iv. To coordinate ‘beta testing’ and improvement activities for (i)-(iii) through the CS.

This report, D4.1 *“Interim Report on the Resilience-based stress-testing framework for AWR supply systems and technologies”*, is mostly related to the first above-mentioned objective, yet it sets the baseline for the rest of the objectives and WP4 activities and establishes synergies with other tasks and WPs of the project. Specifically, D4.1 defines the resilience stress testing framework and paves the way towards the development of adaptive pathways for AWR supply systems and technologies (Task 4.2) by ensuring the delivery of measurable outputs and the definition of CS relevant KPIs that can be used for assessing the resilience and communication/visualisation purposes. It also takes into account the climate change scenarios and outputs of T1.1 “Evaluating climate change impacts on water supplies and demands” and the AWR and upgrades of existing infrastructure examined in T1.5 *“Identifying synergies between existing infrastructure and upgrades required for water reuse”.* Further, it defines how any modelling chain can be adopted within the resilience framework and validates the process with the CS modelling approaches established under T1.5. Stress-testing scenarios of interest and KPIs are co-developed with relevant stakeholders as part of T4.4 *“Beta testing with ‘ground truth’”* and as part of CoP activities of WP2, while the results of stress-testing can be eventually accessible via the RECREATE_WT of WP3. Alignment with WP5 activities e.g. to incorporate the CS perspective and be aligned with the CS progress is ensured at all stages. D4.1 is the first report of the resilience-based stress-testing framework for AWR supply systems and technologies which will be updated and finalized in M36 in Deliverable D4.2 *“Final Report on the Resilience-based stress-testing framework for AWR supply systems and technologies”.*

1.2 Structure

D4.1 is structured as follows:

- Chapter 1 is an introductory chapter describing the aim, scope, and structure of the report.
- Chapter 2 defines the concept of resilience as adopted within RECREATE project and the system properties of relevance for WP4 work.
- Chapter 3 refers to the process of stress-testing for resilience assessment and elaborates on the operationalisation of the resilience definition to the CSs by making refences to the

system performance, KPIs categories and metrics that can be used for the quantification of resilience, disturbance, stressors, design horizons and scenarios and describes how the results of the resilience framework can be visualised and communicated.

- Chapter 4 focuses on the AWR adaptive pathways that would help increase the resilience of the system by defining how those are conceptualised and assessed via a modelling chain.
- Chapter 5 sets the base on the implementation of the resilience framework within the context of case studies by providing a brief description about each case study, elaborating on the modelling configuration, scenarios and modelling approaches and reporting on the early selection of KPIs.
- Chapter 6 sets out the early considerations and plan for future work (including how WP4 work will feed the project's RECREATE_WT) and makes reference to the next steps.

2. The concept of resilience

2.1 Literature review

The term 'resilience' has been in heavy use across a diverse set of domains for very long, in academia, practise and policy alike (Brown 2015; Bueno et al. 2021; Lawson et al. 2020; Meerow et al. 2016; Xu and Marinova 2013). An indicator of the prevalence of the term can be demonstrated in Figure 1; the sheer number of publications in various fields depict how the term evolved as a multi-disciplinary term (Juan-García et al. 2017), and can be regarded as a both a boundary object and a bringing concept between domains, fostering interdisciplinarity and transdisciplinarity (Baggio et al. 2015; Davoudi et al. 2012; Deppisch and Hasibovic 2013). Despite the profound popularity of the term, there is no consensus on a singular definition, with various frameworks, methodologies and propositions for resilience estimations and assessment arising. Scholars have shown that this interpretive flexibility contributed to the adoption of the term in policy discourse, and even in policy mandates such as the Critical Entities Resilience Directive (Directive (EU) 2022/2557 2022). The latter becomes very important for EU Critical Infrastructure (CI) sectors that includes the water, energy, telecommunications, transportation, and others, thus, in extension for the RECREATE project as well. As such, before delving into various interpretations of resilience, including the one which will be used in the project hereafter, it is paramount to clearly recognize why resilience is a sought-after trait in water CIs.

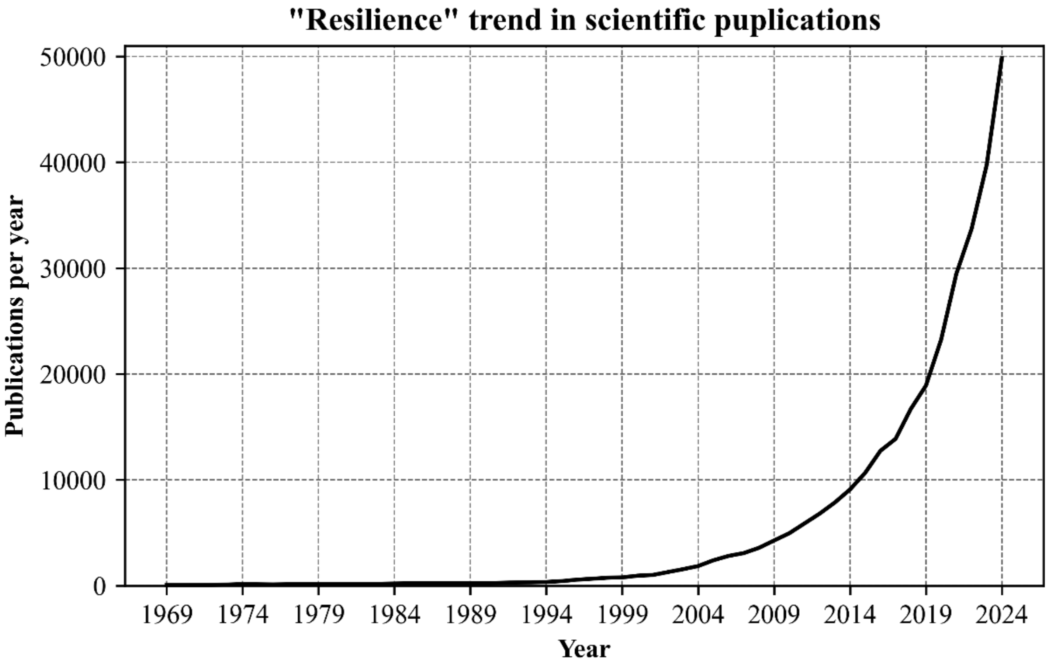

Figure 1: The Indexed scientific publications per year (315,138 up to 04/12/2024) in the Scopus database, relevant with resilience in various domains.

The traditional notion of designing water systems (common in virtually all engineering works) is to provision them for specific eventualities related to their purpose, e.g. design a levee for the flood with a return period of 50 years, sizing a water distribution network accounting for the population of the system after 50 years, plan the capacity of a water supply reservoir for meeting a specific future demand with 99% annual reliability etc. Then, some (typically large) safety factors would be incorporated in the design (Stakhiv 2011), to account for uncertainty and this over-engineered system would be considered "fail-safe" for the planning horizon – typically 25 to 50 years for most water infrastructure. However, practice has demonstrated that failures occur at engineering works, and the "fail-safe" notion is as futile as it is expensive, while also being misleading to decision-makers and public alike.

Often, these failures can be attributed to one of the major challenges of water systems in most of the developed world, ageing infrastructure; Most of the water systems serving current communities are typically already reaching their planned lifetime or even surpassing it at large in the case of early industrialized countries, as most urban infrastructure was built between the 1930's to 1980's (Fletcher et al. 2017; Stakhiv 2011). Replacement rates of components in water systems is globally heavily lagging behind their ageing (Cashman and Ashley 2008; Selvakumar and Tafuri 2012) due to budget constraints and high associated costs (Hukka and Katko 2015; Savic 2005), and as such gradually global water infrastructure gets older and less reliable (for example, capacity is reduced, leaks are introduced etc.). Also, workforce is ageing, and the original engineers and specialists with immense knowledge of the design and operations of systems are exiting the industry with not guaranteed replacement (Clark et al. 2011). The prolonged lifetime of systems means that these will face conditions that drastically deviate from the original planning phase.

But, most importantly, disruptions and failures of water systems (and to other CIs as well) are often attributed to extreme phenomena or unprecedented before events, or even compound hazards – some caused by the interconnectivity of CI at many levels and the cascading effects that stem from failure elsewhere. There are a lot of uncertain global stressors that adversely affect water systems either directly (e.g., the hydroclimatic changes) or indirectly (e.g. the effects on wastewater systems efficiency due to increased pharmaceutical/drug use during the COVID-19 pandemic, the energy crisis caused by the ongoing Russo-Ukrainian war) and some transpire chronically (e.g. a long drought) or abruptly (e.g., a cyber-physical attack on the SCADA of a water system) (Butler et al. 2017; Dawson et al. 2010; Juan-García et al. 2017). The indication from the recent policy discourse in the water sector, is that these stressors are fast becoming the "*New Normal*" (Ramphal 2018) and in the foreseeable future the sector should be prepared to make decisions within a context of deep uncertainty (Hallegatte et al. 2012), i.e., with uncertainties that cannot be estimated with collecting information about previous instances and uncertainties not statistical in nature (Lempert et al. 2004; Walker et al. 2013).

The stationarity concept, i.e., the assumption of variables (e.g., precipitation, temperature etc.) fluctuating within an envelope of macroscopically steady statistical parameters, which has been fundamental for the development of traditional water systems, is undermined by the volatile ever-changing global environment, with significant climatic and socioeconomic change. For example, the historically observed data for climatic variables, used and updated for decades, may no longer be adequate to meaningfully plan for climate variability and extremes (Cosgrove and Loucks 2015). Under climate change, water availability will be challenged, as will be the provision for flood protection. But water availability is also diminishing due to increased pollution and contamination issues, strongly correlated with the increasing population and economic growth (Boretti and Rosa 2019).

Besides the challenges in availability, water demand is another perplexing issue, as the trends of population growth, urbanization and socioeconomic development have forced global water demand in the last century to increase more than 600% (Wada et al. 2016) with signs to continue increasing, and water consumption patterns have experienced major shifts due to changing demographics, immigration waves, and involuntary displacement due to armed conflicts, famines, natural disasters and economic reasons, a trend that may increase in the volatile future (WWAP 2019).

Under these premises, the aspirations to develop "fail-safe" water systems under the deep uncertainty of the future world across so many dimensions are rendered unrealistic, and a new way of system thinking is required (Pahl-Wostl et al. 2011). The consensus among contemporary academics is that water system design philosophy should be geared towards systems that anticipate uncertainties, are prepared against them, adapt to adversity by learning, and are generally "safe-to-fail" (Butler et al. 2017; Holling 1996; Makropoulos et al. 2018), without catastrophic impacts and complete loss of services during disruptions. Pivotal to this philosophy is the concept of system resilience. The resilience theory and concepts are all about coping with the unexpected and continuing to perform under uncertainty.

Resilience has its engineering roots in the material science domain (e.g., Mallet 1856, 1862; Merriman 1885; Thurston 1874; Tredgold 1818), with definitions like "the quality of being able to store strain energy and deflect elastically under a load without breaking or being deformed" (Gordon 1978), which taken in a metaphorical sense still resembles interpretations in other fields. However, resilience permeated through systems thinking with the seminal work of Holling (1973), in the context of ecological systems in phase space returning to an equilibrium state, after a perturbation, which is identified as the starting point for system resilience (Francis and Bekera 2014). Holling defined resilience as "a measure of the persistence of systems and of their ability to absorb change and disturbance and still maintain the same relationships between populations or state variables", suggesting also that as a property is more important than population count at any moment for the ecological viability of a population. It is also contrasted with the stability trait, suggesting that very stable ecological systems, i.e., exhibiting very low variability in population densities over time may not persist severe shocks. Also, the same work illustrated the existence of multiple stability domains (or basins of attraction) after a perturbation, contrary to the more static understanding of the domain at the time, which called for inherent stable ecological systems that return to the original single stability domain after removing human perturbation.

Shortly, these ideas for ecological systems were applied in the context of water resources systems (Fiering and Holling 1974) and in water systems planning (Fiering 1976). There it was suggested that in engineering resource systems, imposing stability by specific strict standards that need to be met, such as design objectives met with close to perfect probabilities could end up restraining the system with high mis-allocated costs due to the possibility of system exposure to unknown threats, for which no probability of occurrence can be assigned. Nonetheless, ecological resilience for a while continued to focus on single stable state assumptions for systems, due to the difficulty in demonstrating multiple stable states in the real world (Folke 2006). For this reason, resilience was interpreted and readily measured in various works as the "return speed" to the single equilibrium point following a perturbation event (O'Neil et al. 1994; Pimm 1984, 1991; Tilman and Downing 1994). Early resilience conceptualization in the water sector followed this principle, and in the important work of Hashimoto et al. (1982), where resilience describes the speed of transition from a failure state back to a satisfactory state – calculated probabilistically, as the inverse of the average time periods a failure state is expected to last.

Holling (Holling 1996; Holling and Meffe 1996) proposed that the metric of return speed to equilibrium should be termed "engineering resilience" to differentiate from "ecological resilience" due to the difference in the scope and objectives of implementation with regards to the "stability" concept. Therefore, engineering resilience focuses on "maintaining efficiency of function" and stability near the assumed or designed global equilibrium and used primarily by engineers in designing single-objective ‘fail-safe’ systems. On the contrary, ecological resilience focuses on “maintaining existence of function”, acknowledging the fact that disturbances can force systems to flip between different equilibrium states, commonly used by biologists and ecologists who search for ‘safe-to-fail’ systems. During the same time, ecological resilience evolved from the 1973 definition to account for the emergence of different stability domains after perturbation as the “ability to adapt to change by exploiting instabilities” (Walker et al. 1981) and not just absorb disturbances. A subsequent evolution of resilience refers to “the capacity of a system to absorb disturbance and reorganize while undergoing change so as to still retain essentially the same function, structure, identity, and feedbacks” (Walker et al. 2004). In the same work it is also recognized that the interpretation of ‘engineering resilience’ cannot account for all failure modes (permanent or temporary) for systems and the retaining of functions at these modes, because of the possibility of multiple stable states after disturbances and perturbations (i.e., the system cannot fully recover). This definition is used commonly in the literature, in many domains besides ecology, albeit sometimes with small variations in wording, e.g.: (Falkenmark and Rockström 2010; Folke et al. 2004; Liao 2012; Schlüter and Pahl-Wostl 2007; Westley et al. 2011).

The ecological definition permeated a variety of fields where there is interaction between human/societal and natural/ecological systems in what is called socio-ecological systems (SES) (Gallopín 1991). In SESs, the ‘adaptive cycle’ is another very important aspect of resilience and reflects the learning aspect of the system behaviour (Carpenter et al. 2001; Folke et al. 2004; Gunderson 2000; Gunderson et al. 1995; Gunderson and Holling 2002; Nelson et al. 2007; Walker et al. 2004). In that sense, in many works that refer to resilience essentially within the context of the aforementioned definition, add explicitly the ability to learn and build adaptive capacity in the interpretation of SES resilience, e.g. Adger (2006); Carpenter et al. (2001); Wong and Brown (2009).

Water systems are not different than SESs, and resilience thinking has been identified as necessary in order to move forward in water governance and policy in the light of the deep uncertainties that unfold (Bakker and Morinville 2013; Dunn et al. 2017; Johannessen and Wamsler 2017; Lawson et al. 2020; Salinas Rodriguez et al. 2014), and as the conventional urban water management and design approach (focusing on system’s reliability, compartmentalization of supply, sewage and drainage services, large scale centralized works) is increasingly deemed unsustainable and unsuited to it (Wong and Brown 2009). However, resilience interpretations in the water sector vary significantly, with different authors proposing different definitions, accustomed to their diverse set of perspectives (Butler et al. 2014, 2017; Lawson et al. 2020; Mugume et al. 2015; Rodina 2019; Shin et al. 2018). Generally, definitions can be classified into three main categories (Rodina 2019), following the evolution of resilience in the other fields as aforementioned, i.e. engineering resilience, ecological resilience, and socio-ecological resilience. Shin et al. (2018) explain the reasons why there is not yet a single resilience definition and measurements in the water sector: generally, approaches have been inconsistent and theoretically deficient, not transferable for different types of water infrastructures, dependent on parameter estimation assumptions, computationally expensive for complex real-world cases or provided insufficient information for enhancing the decision-making process. However, common ground exists between recent attempts to develop formal definitions of resilience: It is generally agreed, that resilience is a property of the system as a whole, and not a property of an individual element or unit and resilience is a key property for the sustainability of a system. There is also agreement on several characteristics that endow resilience in water systems, such as interconnectivity, flexibility, adaptability, decentralized design and robustness (Rodina 2019) – traits that are the same in other engineering systems in general and discussed in the following section.

2.2 System properties that enhance resilience

There are various referenced traits in the large body of resilience literature that contribute towards a resilient water system. Some traits refer strictly to the 'technical' side, while others refer to the 'organizational' or the 'socio-ecological' sides. The (non-exhaustive) list includes:

- Robustness: describes an entity's ability to withstand a given level of stress without any degradation or loss of function (Bruneau et al. 2003; Carlson and Doyle 2002; Homayounfar et al. 2018; Krueger et al. 2019)
- Buffering capacity: having capacity in excess of what is necessary, which can be used in emergency conditions (Butler et al. 2014; Wildavsky 1988), e.g., provisioning larger tank capacities in the network.
- Safe failure (or soft failure): The ability to absorb sudden shocks or the cumulative effects of slow-onset stress in ways that avoid catastrophic failure, even when outside of design specifications (Tyler and Moench 2012) or managing failure in interdependent systems to avoid cascading effects (Little 2002).
- Agility/rapidity: the capacity of a system for rapid mobilization of resources necessary for recovery to return to an acceptable level of functioning, contain losses and/or avoid cascading effects and avoid future disruption (Bruneau et al. 2003; Harrald 2006; Liao 2012; Sharifi and Yamagata 2016). Note that recovery, in some resilience frameworks, can be communicated with a graph where the system bounces back at a stable operating condition (e.g., in Poulin and Kane 2021).
- Redundancy: The availability of multiple substitutable components with similar or overlapping functions give a reserve capacity to the system, providing an "insurance" (Liao 2012) that the whole system will not fail when a single component fails (Godschalk 2003; Sharifi and Yamagata 2016; Wardekker et al. 2010), e.g., the presence of redundant water quality sensors in a WDN's contamination warning system or redundant pumps in pumping stations as a reserve. A similar concept in the literature is modularity which besides substitutable components may also refer to the existence of multiple options in a system to deliver its service (Tyler and Moench 2012).
- Flexibility: Capacity of a system to be reconfigured in the face of uncertainties and having different options to adapt to short term changes (Liao 2012; Sharifi and Yamagata 2016).
- Diversity: Describes the degree of multiple distinct functions that can be simultaneously used in the system (Liao 2012; Wardekker et al. 2010), which enhances resilience and aids with perturbations, as there is greater functionality in the system. For example, a water system having total reliance on a single specific type of water source, e.g., surface water from a reservoir, may make the system susceptible to failure as climate changes. On the contrary, having the capability to also use alternative sources such as seawater desalination in an emergency, makes the system less vulnerable to prolonged drought conditions. Diversity is also related to multifunctionality, i.e., components of the system that provide a diverse set of functions, such as floodplain parks (Ahern 2011). Another related trait is 'omnivory' (Butler et al. 2014; Wardekker et al. 2010; Wildavsky 1988), referring to multiple ways of meeting needs resource-wise.
- Independence/autonomy: The self-reliance capability of various components to operate/function without external input, assistance or oversight enhances resilience and levels of a availability in a system, when other components are hampered (Godschalk 2003; Sharifi and Yamagata 2016). The autonomy trait can refer to systems as a whole that do not rely on other infrastructure for functioning. This is contrasting with other characteristics in the

literature, like *interdependence* and *interconnectedness*, which, depending on the context, can affect resilience positively or negatively (Sharifi and Yamagata 2016). For example, having the ability to receive support from other systems in case of failures is beneficial; but in interconnected critical infrastructures interconnectivity may be detrimental due to cascading effects from one disrupted sector to the other (Chang et al. 2007; McDaniels et al. 2007; Perrow 1999), e.g., a blackout in an energy production system affecting the pumps of a water supply system and the telecommunications sector.

- Cohesion: the existence of unifying relationships and linkages between system variables and elements (Fiksel 2003). Cohesion also applies to social systems denoting the strength of social connections and the sense of community.
- Resourcefulness: Refers to the abundance of resources (material aspect) available to the system for preparation against, response to and recovery from perturbations, also including the capacity of operators, decision-makers planners and other system stakeholders to plan, anticipate and act (human aspect) (Bruneau et al. 2003; Cutter et al. 2008; Sharifi and Yamagata 2016).
- Coordination capacity: A system that possesses good coordination between all relevant managerial stakeholders can recover faster from perturbations, as actions can be better planned and organized (Tyler and Moench 2012).
- Foresight capacity: Resilience is all about tackling future uncertainty; therefore, systems where future conditions can be evaluated before they manifest, and different scenarios are analysed in preparation, are more resilient (Sharifi and Yamagata 2016). Related terms in the literature are preparedness (Cutter et al. 2008) and anticipation (Fiksel et al. 2015).
- Collaboration: the existence of multiple opportunities and incentives for broad stakeholder participation to solve problems (Godschalk 2003; Sharifi and Yamagata 2016)
- Adaptability: the flexibility of a system to change in response to new pressures (Fiksel 2003), also entailing the capacity to learn from disruptions and perturbations (Carpenter et al. 2001; Folke et al. 2004; Gunderson 2000; Gunderson et al. 1995; Gunderson and Holling 2002; Nelson et al. 2007; Walker et al. 2004) and applying the knowledge to undergo change and reduce vulnerabilities in the future (Sharifi and Yamagata 2016)
- Self-organization: In self-organized systems macro-scale patterns, relations and relations emerge from independent interactions between smaller scale processes (Krasny and Tidball 2009). Self-organization capability is often associated with resilient systems (e.g., Adger et al. (2005); Carpenter et al. (2001); Liao (2012); Tompkins and Adger (2004)), due to the fact that actions and functions are distributed among different actors (as for example citizen participation in social systems) and not centralized (in true self-organized systems, typically there is absence of centralized control (Heylighen 2001)), thus response and adaptation to events can be faster (Liao 2012). Also, self-organized systems exhibit increased social and institutional memory, i.e., collective experience to deal with change (Folke et al. 2005). In social self-organization capable systems there is the capability of independent response to disruptions by local communities, cross-scale partnerships for management (Folke et al. 2005), and both horizontal and vertical institutional connections that foster better informed and more efficient decision making (Berkes 2007; Cutter et al. 2008). A relevant term is *flatness* (Wildavsky 1988), which refers to bottom-up systems, with less hierarchical and rigid command chains, which are more flexible and resilient. In technical systems, the mechanically analogous scheme for self-organization and flatness are distributed/decentralized/localized designs and management philosophy (versus traditional large-scale centralized systems) with a multitude of studies that show that this increases resilience e.g., (Ahern 2011; Bouziotas et

al. 2019, 2023; Chen et al. 2016; Farrelly and Brown 2011; Nikolopoulos et al. 2019; Panteli and Mancarella 2015; Sharifi and Yamagata 2016; Sovacool and Mukherjee 2011; Zahediasl et al. 2021).

- Creativity/innovation capacity: The property of a system to use disruptions as opportunities for positive gain. This requires the system to possess and innovation capacity and exert it (Sharifi and Yamagata 2016). Innovation strengthens resilience, because it reinforces the transformational capability of the system (Folke et al. 2010). The notion of positive gain (or even flourish) when a system is subjected to adversity can also be found in the literature as the concept of 'antifragility' (Babovic et al. 2018; Munoz et al. 2022; Taleb 2012).
- Efficiency: Depending on the context (e.g., for energy systems, economical systems, organizational resilience or in the industrial ecology field), there are scholars (e.g., Fiksel 2003; Godschalk 2003; Mafabi et al. 2012; Rose 2007) who find efficiency to be an important trait of resilient systems. However, there are other important yet counteracting traits that enhance resilience, like redundancy and flexibility; generally building redundancy and flexibility in a system hampers efficiency (at least in economic or resource-usage terms), thus resilient systems are not always the most efficient (Meerow and Newell 2015), while hyper-efficient systems (e.g., employing hyper-coherence (Redman 2014) between functions and components) with the most optimal (but not robust) decisions could actually possess less resilience (Walker and Salt 2006).
- Equity/fairness: applicable in communities and social systems, equity and fairness are important aspects and principles of resilience, coming up regularly in socio-ecological systems, community resilience and in the climate resilience discourse (e.g., (Cote and Nightingale 2012; Gunderson and Holling 2002; Nelson et al. 2007; Tompkins and Adger 2004; Vale 2014; Wilkinson 2012). As Nelson et al. (2007) note, in decision making there should be equity in both the process and the outcome, referring to the fairness of institutions, their representativeness, views on collective and individual good and in the distribution of vulnerabilities across a population. As such, social cohesiveness increases, which leads to a community's larger capacity for absorbing and recovering from shocks (Sharifi and Yamagata 2016). Affordability, accessibility and acceptability of technologies, solutions and interventions to transition to a more resilient system, are also related themes to be taken into account assessing equity.

The aforementioned traits can be incorporated into the design and management of water systems either as developed qualities of the system itself, like for example robustness, redundancy or diversity, or qualities of the surrounding socio-technical environment like resourcefulness, and foresight capacity. Technical (including AWR solutions) and non-technical interventions in the adaptation pathways generated within RECREATE contribute towards one or more of the aforementioned qualities in the CS they are implemented. These qualities can be evaluated by metrics or key performance indicators (KPIs), which can vary a lot from system to system (see for example a recent discussion in Bruckler et al. (2024). In RECREATE, for each CS we will introduce a suitable range of such metrics in order to undertake the resilience assessment procedure.

3. Stress-testing for resilience assessment

3.1 Operationalizing a resilience definition for RECREATE CSs

Although all water systems have similar objectives, albeit weighted differently in each case, including customer satisfaction, costs minimization, drinking water and effluent quality, environmental protection as well as asset management and cyber-physical security, system design philosophy and technology greatly affects performance and behaviour under different, uncertain conditions over a longer horizon (Nikolopoulos 2024).

In their works, Makropoulos et al. (2018) and Nikolopoulos et al. (2022) argued performance of individual technologies and specialized components of systems is typically well understood, but it is less clear how the overall water system performance is affected by a deployment of a portfolio of such different technologies, within a given design strategy for a set of alternative futures that incorporate uncertainties. Behaviour under both chronically transpiring stressors, e.g., climate change, and acute abrupt conditions that occur during a short timeframe should be studied in order to assess real world performance of a water system design. But the wider the system boundaries are, and the longer the design horizon is, the more important and challenging it is to formally conceptualize the difference between design alternatives (Makropoulos 2017). Therefore, a systematic methodology that is internally consistent is required for assessing different aspects (which can be measured with a multitude of measures) of the overall urban water system's performance under *deep* uncertainty, so that the nuances of various design options can be better understood and evaluated by water utilities during the strategic planning phase. The objective of course of this exercise, is to assess *resilience* i.e., following the evolution of interpretations presented in the previous section, assess behaviour when faced with perturbations and change, and adapting to them.

This assessment in the literature followed two main themes as explored by different scholars in the water sector, namely a) the return time or speed of a water system to normal operation after a disturbance, e.g., definitions found in the work of Hashimoto et al. (1982) and Kjeldsen and Rosbjerg (2004), pertaining to the 'engineering' resilience theme, and b) the ability or capacity of a water system to maintain a level of function coping or adapting to disturbance, or the amount of disturbance the system can absorb before significantly changing its form, structure, or (self-organized) procedures, e.g., definitions found in the work of Mugume et al. (2015), Amarasinghe et al. (2016), Butler et al. (2017) and Todini (2000), which are related to 'ecological' or 'SES' resilience.

As water systems are socio-ecological systems where people, technical systems and the environment come together and interact, an interpretation following the second theme becomes more useful. Butler et al. (2014) and Mugume et al. (2015) suggest that continuity and efficiency of the system during and under failure are the key properties for engineering systems, as these have been designed for a specific critical objective that should be met at least partially. In some instances, an otherwise 'resilient' water system that can recover very rapidly from a disruption, but has complete downtime and total service failure is not preferable to a system where a lesser part continues to serve (e.g., an emergency reserve) and takes longer to recover, due to its critical function (Nikolopoulos 2024). As such it is more beneficial to utilize a SES theme of resilience to water systems, in order to explore their integrity to a regime of uncertainty.

Following this rationale, in RECREATE we will follow the definition of resilience as elaborated in Makropoulos et al. (2018), where the term is interpreted as "the degree to which an urban water system continues to perform under progressively increasing disturbance". To be able to operationalize this definition in different contexts in RECREATE the component-terms need to be defined and then computed through modelling and simulation. The most import is performance as a function of disturbance.

3.1.1 Performance

For performance, we could use different suitable metrics or Key Performance Indicators (KPIs) describing specific objectives of interest each system has to meet (although across similar dimensions, as described in section 3.4). Each KPI can be used as a 'reliability metric' in the general sense, which describes "the ability of the system to consistently deliver the objective considered over a specified timespan". With the quantification of the reliability metric, it is possible to map the impact any stressor/disturbance/perturbation has on the resilience of a system. It is important to include CS leaders along with the relevant stakeholders in the identification process of KPIs, to co-create them in an equitable and fair manner, and not underrepresent an aspect of the system's performance.

3.1.2 KPI categories

The resilience indicators that will be used in the frame of this work are separated into three categories:

- Society

These indicators aim at expressing the effect of climatic scenarios, socioeconomic scenarios and interventions studied in the frame of this work (e.g. rainwater harvesting) to the availability and provision of sufficient water of good quality (with the required quality level depending, of course, on the intended use of water) for covering the water demands of societies. The water demands can refer to a variety of uses, including, for example, the domestic water demands, municipal water demands, demands by services/infrastructures (e.g. hospitals), agricultural irrigation demands, and industrial water demands. Indicators can be formulated per water demand and/or by aggregating them.

- Economy

The indicators falling under this category aim at expressing the effect of the different scenarios and interventions related to the availability of sufficient, good quality water on relevant economic variables. For example, such variables are the (unit) cost of the supplied water and the cost of interventions.

- Environment

The environmental indicators aim at providing information on the ecosystems' status with respect to the available water and/or water quality. The status of an ecosystem can be expressed by comparing the quantity and/or quality of water under a certain scenario/intervention with their corresponding values for ensuring the proper functioning of the ecosystem.

In the frame of a case study, a large number of indicators can be used. However, a smaller selection of indicators per case study (e.g. 1 or 2 indicators per category) can be eventually used in the frame of resilience assessment. The KPIs that will be used for resilience assessment are denoted as Primary KPIs, while the rest as Secondary KPIs.

3.1.3 Disturbance

Disturbance is modelled through the formulation of scenarios of stressors over a specified timespan, which can be of two types:

a) Univariate (i.e., including a single stressor or 'hazard' that affects the system)

b) Compound (i.e., including multiple stressors or 'hazards' that affect the system combined in a narrative)

We argue that in RECREATE CSs, the most interesting 'disturbance' is attributable to compound scenarios, that transcribe over a long horizon; In that context, various stressors from the climatic and socioeconomic realms will have the necessary space to unfold, intertwine and combine, leading also to acute disruption events, while changes in the systems e.g. due to ageing or the effects of (systematic or lacking) maintenance can also be evaluated, creating a scenario-scape that encompasses high uncertainty. Nonetheless, the methodology we utilize can readily accommodate cases with univariate stressor narratives, e.g. for testing limits of system to a particular stressor.

3.1.4 Stressors, design horizon and scenario modelling

The compound scenarios essentially are driven by narratives and consist of a set of changing parameters through the specified timespan. The aim is to provide a complete future world view for each scenario. As with KPI selection for performance evaluation, scenarios are better formulated considering the choice of stakeholders and expert opinion from CSs, regarding their magnitude of change and potential impacts, according to the examined CS. Scenarios can vary between mild to extreme cases, but nonetheless should stress the system under study outside of the normal expected conditions – for which the system was originally planned and designed for. In the case of RECREATE CSs, scenarios should include climatic variables and other socio-economic drivers; a large body of work already exists that formulates such scenarios for important variables, like the Shared Socioeconomic Pathways (SSPs) (O'Neill et al. 2017; Riahi et al. 2017), which eases the burden and complexity of formulating scenarios, as well as reducing subjectivity and bias, allowing a level of standardization between assessments for different regions, of scenario formulation. The SSP narratives describe a set of alternative plausible trajectories of societal development, which are based on hypotheses about which societal elements are the most important determinants of challenges to climate change mitigation and adaptation. According to each of the five SSP narratives, a plethora of climate change 'Representative Concentration Pathways' (RCPs) scenarios can be combined, describing different levels of greenhouse gases and other radiative forcings that produce different conditions for global circulation models that generate future climate projections (based on the application of models, to be further discussed in subsequent sections). From SSP narratives global circulation models produce climate projections (typically up to 2100) for several variables of interest, including temperature, precipitation and evapotranspiration which can be used in the modelling of scenarios in the RECREATE CSs. Other parameters of the socioeconomic context can be deduced from the narratives, such as population, urbanization, GDP, and others.

For RECREATE CSs, we propose the timespan of the design horizon to be 2100, and utilize the CMIP6 (Eyring et al. 2016) projections for the climatic variables up to 2100. Another possible route is to use the older EURO-CORDEX (Jacob et al. 2014) set of projections (stemming from CMIP5) for applications where improved downscaling is necessary (as the CMIP6 projections have coarser spatial resolution) and update them when new EURO-CORDEX datasets become available. The SSP1-2.6, SSP2-4.5 and SSP5-8.5 scenarios from CMIP6 are roughly comparable in the evolution of the variables with RCP-2.6, RCP-4.5 and RCP-8.5 from the EURO-CORDEX, so the procedure will be standardized across the CSs. This procedure will be homogenised with the outputs of T1.1, *"Evaluating climate change impacts on water supplies and demands"*. Socioeconomic projections should be structured according to the generic narratives of socioeconomic development of the SSPs but tailored to the specific circumstances and characteristics of the region. Data sources which have performed modelling for variables can be considered, including the IIASA datasets[1].

All different variables of each scenario to be evaluated for a water system should be in the form of timeseries, even if not changing, creating an ensemble bundle. Timeseries is used here with an expanded sense, as for some variables there could be the modelling need of changes both in the spatial and temporal dimensions, instead of an aggregate measure of the region changing temporarily.

3.1.5 Different system configurations/topologies incorporating AWR technologies

The first system configuration to be explored under the scenarios that are created, is the current 'as-is' infrastructure, in order to establish the baseline for comparison across the CSs. Current state, elements, form, structure, socio-economic metabolism features, and objectives are clearly identified. Then, a number of alternative configurations are formed which follow the adaptation pathways for each CS (see following section as this can involve a feedback loop), that include different design philosophies and interventions, technical and non-technical measures (see for example Makropoulos and Butler (2010) and Nikolopoulos et al. (2019)). In RECREATE, pivotal in the design of the alternative configurations are AWR solutions that aid in water scarcity problems. These solutions and the upgrades on existing infrastructure that will inform the configurations are examined under collaboration with T1.5 *"Identifying synergies between existing infrastructure and upgrades required for water reuse"*. Each different system configuration also presents a different system topology that should be modelled and simulated to generate results.

3.1.6 System modelling

Each developed configuration is used to develop one or several models using suitable simulation software, that are able in tandem to replicate in a holistic manner the behaviour of the system and evaluate performance as reliability to deliver on objectives measured through the selected KPIs, when exposed to the formulated scenarios of disturbance. A number of different models can be used for this purpose, as the resilience assessment methodology is model-agnostic. The **Urban Water Optioneering Tool (UWOT)** is a bottom up, micro-component based urban water metabolism model, which simulates the demand, supply, wastewater and drainage at temporal and network scale (from simple household to a complete hydrosystem) as flows, including a plethora of water technologies to evaluate as options for designing a system, and is suitable for many of the modelling requirements for the CSs (more information about UWOT in the publications of Makropoulos et al. (2008), Rozos and Makropoulos (2012, 2013), and Rozos et al. (2013)).

Other general purpose tools to couple in the modelling process to capture system behaviour are **System Dynamics Models (SDM)** (which can be created, for instance, using the Vensim software by Ventana Systems, Inc. (Ventana Systems, 2025) and **Agent-Based Models (ABM)** (e.g., using the Mesa modelling framework in Python). In Section 5, the modelling configuration of the CSs will be described along with the specific software considerations at the current state in each – which will be updated in the final report D4.2.

[1] https://iiasa.ac.at/models-tools-data

In many cases a combination of the aforementioned models can be applied, e.g. SDM being used as input to UWOT or SDM in combination with ABM (as for example in Chen et al. (2025).

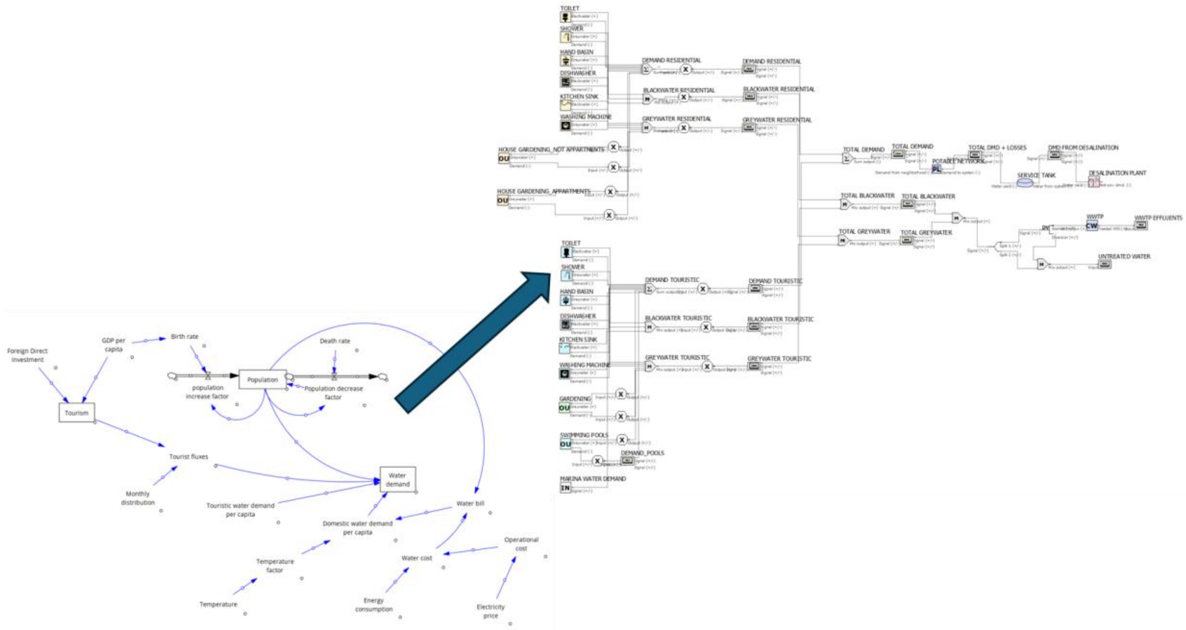

Figure 2: A schematic with a SDM coupled with UWOT for the Syros CS in a modelling chain to capture complex interactions between the sociotechnical environment and urban water system processes.

3.2 Assessing resilience & communication/visualization

The identification of KPIs, the formulation of scenarios and the development of models for the baseline and the alternative configurations of the systems under study constitute the basic ingredients for the stress-testing procedure to assess resilience in RECREATE. Every model will be subjected to the ensemble of scenarios in simulation and the results of the KPIs will be gathered. For each KPI, we can plot a resilience profile graph, as a graphical expression of performance in the form of a 'stress-strain diagram', such as the schematic example on Figure 3 with two hypothetical system configurations, where configuration 1 is more resilient than configuration 2, as expressed by the area under their KPI curves for the scenarios explored.

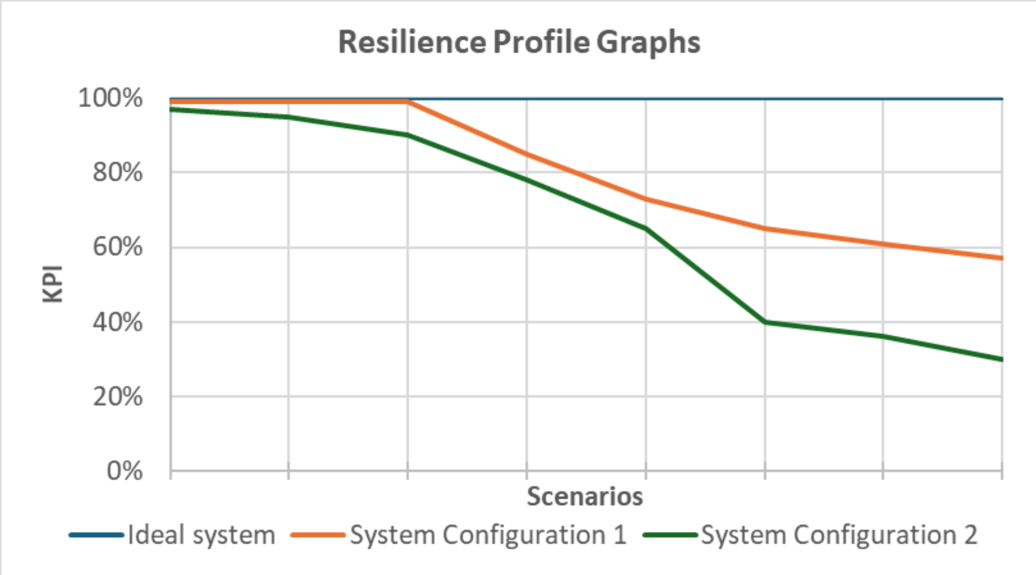

Figure 3: Schematic example of Resilience profile graphs for two different hypothetical system configurations compared to the ideal perfectly robust and resilience system across all scenarios

Each point of the graph is a calculation of a KPI of a given objective being met (y-axis), under the conditions specified by a particular stress scenario (x-axis) calculated by simulation. Area under each curve, is the resilience of the system. The x-axis of the graph is presented as a series of progressively more extreme disturbances in the form of compound scenarios in the general case and is therefore by definition an ordinal scale instead of a nominal. The same principal applies with univariate scenarios, and then the x-axis can be nominal. The disturbances in the graph cover conditions that can be both within design standards and well beyond design standards. The robustness trait can also be evaluated with this diagram, as it is the graphical extent for which there is invariance in performance against disturbance. To scale resilience and robustness to maximum of 1 for a standardized metric, the area under the curve is divided by the area of the ideal system, whereas robustness is divided with the number of points in the resilience profile diagram (i.e., the number of scenarios analysed). Essentially, using this scaling method, the area of the curve transforms into the average of the curve points in the y-axis, therefore the actual mean value of the or reliability metric against the scenarios. This fact allows for easy numerical and conceptual comparison between the three fundamental properties of the system's behaviour under the scenarios, namely reliability in the form of a KPI, robustness, resilience. Similar graphs have been used in evaluating resilience in a comparative fashion in other studies as well, e.g. Butler et al. (2017), Diao et al. (2016), Mugume et al. (2015), Wang et al. (2019). Note also that this graph is not the same as a resilience framework that uses an 'engineering' definition of resilience, where behaviour during a disturbance is assessed and recovery to a stable and accepted operation level is depicted.

For the cases where scenarios can have multiple realizations (such as utilizing a variety of climate models that generate projections for a specific SSP-RCP combination) and or stochastic variables, there does not exist a single performance curve describing the systems performance under the scenario. In that case the compound scenarios that form a different world views are considered "scenario types", and through multiple simulations for each one, a cloud of performance points (y-axis values) is generated at each x-axis point. For each scenario type, statistical properties, such as quantiles, can be calculated. Using the points from each scenario that correspond to a particular quantile, we can generate a curve that corresponds to a confidence interval (CI), encapsulating uncertainty in the resilience metric estimation per se.

The resilience aspect in different KPIs can be presented as scores in tabular form, or a multi-graph approach as presented for example in Nikolopoulos et al. (2022) and Nikolopoulos (2024). For illustration purposes of this paradigm, we include an example in resilience assessment undertaken in a different field. In Figure 4, the case of resilience of water quality sensors under cyber-physical attacks is analysed for a design problem with four alternative configurations, various scenarios with stochastic realizations and four alternative KPIs to evaluate resilience aspects. Even though not related with RECREATE, this serves as an example for understanding the visualization of the multi-graph approach, and also highlights the transferability of the methodology.

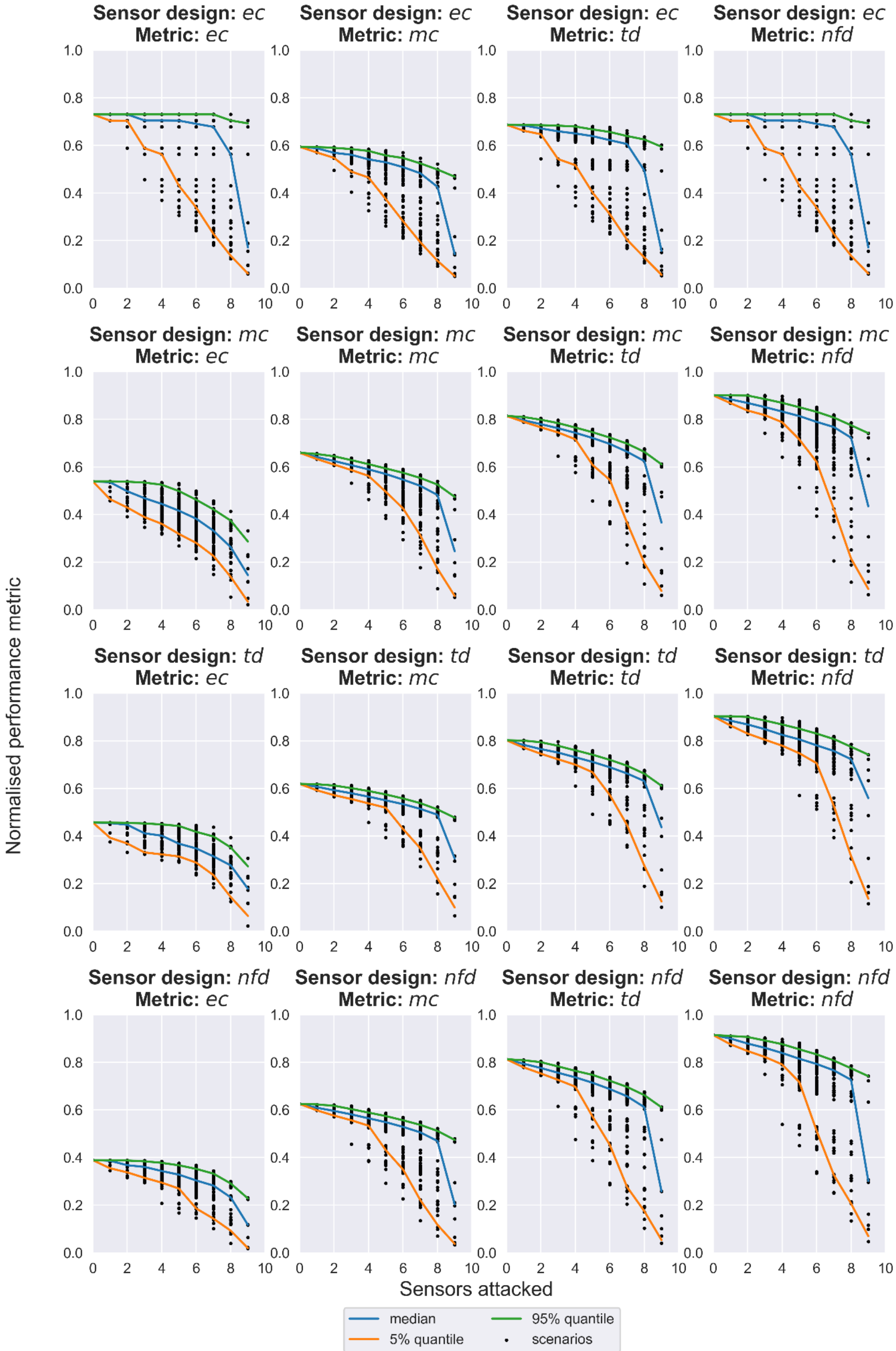

Figure 4: Example of resilience assessment of four altenative designs of water quality sensor placement under stochatic univariate scenarios of cyber-physical attacks, and four KPIs evaluated to demonstate how a multi-graph approach can be presented. Source: (Nikolopoulos et al. 2022).

4. Developing resilient AWR adaptation pathways

4.1 Conceptualization of the adaptation pathways delineation framework with regards to system resilience

An adaptation pathway is a set of AWR solutions, along with other technical and non-technical interventions, arranged as discrete decision points in time, which when implemented in a CS water system will increase the system's resilience as expressed with the selected KPIs (Figure 5). The generation of an adaptation pathway (the focus of work to be carried out in T4.2) is entangled with the resilience assessment methodology as the pathway delineation procedure is an optimization problem formulation, with one of the objectives being the maximization of the water system's resilience against climatic and socioeconomic change. The conceptualization is described below.

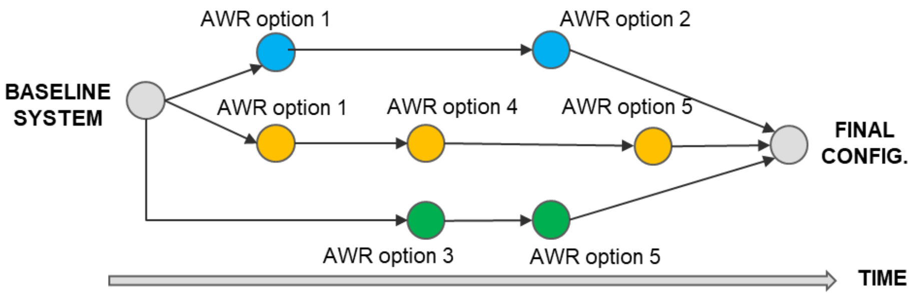

Figure 5: A schematic representation of adaptation pathways.

For each CS, a number of suitable interventions should be identified, forming the pool of available decisions. Discrete decisions can also correspond to the same intervention type, but differ in the application extent: that means differences in numerosity e.g., 2 or 3 new desalination plants or extent/scale of application, e.g., a campaign policy that runs for 1 or 2 years, tertiary treatment of 20% or 40% of wastewater produced. Each intervention/decision provides some benefits to the overall water system, generally enhancing some of the traits discussed in Section 2.2., and the effects on system performance should be well captured from the simulation models involved. At the same time, selecting interventions becomes a real non-trivial problem, because there are other factors that limit the feasibility of implementing all suitable interventions at the same time, including costs (CAPEX, OPEX), societal acceptance of solutions, technological readiness levels, implementation time needed, and possible negative effects of interventions as externalities (e.g. CO_2 emissions) among others. These factors should be clearly defined as characteristics of each intervention and/or be estimated if applicable in a CS from the simulation procedure. Besides resilience maximization across multiple KPIs, a number of more criteria emerges, that make the problem multi-objective (e.g., maximization of cost-effectiveness, maximization of feasibility, minimization of negative external impacts) that should produce a number of pareto-optimal non-dominated adaptation pathways (i.e., each pathway is better than all the others in at least one criterion).

The framework developed within T4.2 that will generate the dynamic adaptation pathways should operate in the following manner (subject to adjustment in work carried out in T4.2):

- Evaluate the forcing to adapt: the inputs of scenarios (climatic and socioeconomic time-varying variables/projections) produce a negative impact to performance of the water systems, which can be expressed by KPIs, and problematic behaviour from a point in time onwards can be identified by specific thresholds. The baseline performance at the various scenarios of the water system as is without interventions provides the benchmark. Evaluation is performed through the models developed for each CS, for each different scenario.

- Selection of interventions as a pathway solution: A routine will select a number of discrete interventions as decision points in time that correspond to the changes through time of the system. This part can happen progressively (one intervention after the other) or a complete selection from the pool as a solution, depending on the type of optimization procedure that will be developed in T4.2.
- Model modification: the model parameters of the CS water system should be altered based on the interventions selected at the specified point in time, for the timeframe of the simulation needed (specific intervals if progressively selecting interventions or the whole period if selecting all at once, depending on the type of optimization procedure to be developed).
- Model evaluation through simulation: utilize the simulation models to generate the KPIs for the modified model for the scenarios involved. The final intervention set for a model constitutes a candidate adaptation pathway, and as such, to link with the resilience assessment methodology, a new system 'configuration'.
- Performance evaluation: system's performance and resilience are evaluated and assessed against the baseline, calculating KPIs and the other criteria
- Repetition of the process to produce the pareto-optimal adaptation pathways: the multi-objective optimization procedure that will be formulated will be responsible for producing the final set of non-dominated adaptation pathways across the multiple KPIs and criteria selected.

4.2 Designing a modelling chain

Within T4.2 a complete modelling chain will be formulated, based on the concept presented in Section 4.1 (Figure 6). This modelling chain will include a scenario manager that handles input from scenarios, a stress-testing procedure for the CS water systems that leverages on the models developed for each one and uses the input from the scenario manager, a KPI and other criteria report manager, and an adaptation pathway delineation tool that utilizes optimization techniques to generate the set of adaptation pathways for different criteria.

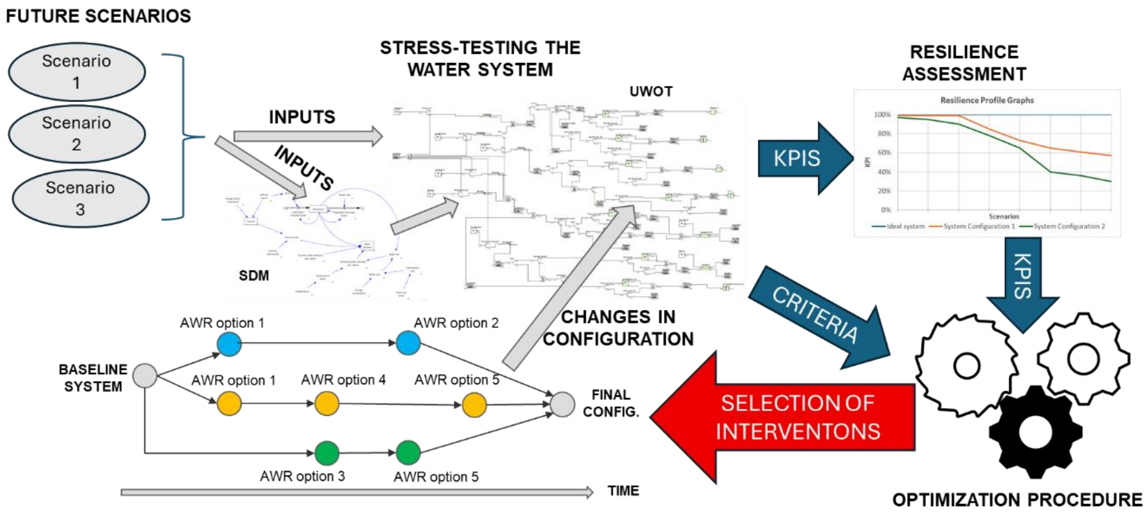

Figure 6: Conceptual modelling chain of the adaptation pathways generation modelling chain.

5. Resilience Framework within the context of case studies

In this section the preliminary considerations for the application of the RECREATE resilience framework are presented per CS. To this end, hereafter we analyse the brief descriptions of the scope and objectives, the current KPI selection (that might be updated in D4.2 based on the modelling work and the alignment with stakeholders as part of CoP and T4.4 activities), some early modelling configurations and scenarios of interest, as well as the planned interventions.

5.1 CS1 North Holland

5.1.1 Brief CS description – Challenges and planned interventions

PWN supplies water to more than 800,000 households, companies and institutions in the province of North Holland, that together use about 112 million cubic meters of drinking water annually. The current (drinking) water system was developed from the 1950s onwards, with surface water as the main water source. Part of this water is directly treated and distributed to the client, but the backbone of the drinking water supply are the dune infiltration (managed aquifer recharge, MAR) systems that are fed with pretreated surface water. After infiltration and recovery this water is distributed. The long transport pipelines from the raw water intake points to the dunes make the system vulnerable: the failure of a pipeline has major consequences. The water quality at the intake points is also under pressure, because of salinization at the intake point of the surface water during low flows of the river Rhine.

The demand for water is expected to increase in the coming decades due to population growth and increasing economic activity. At the same time, climate change is putting pressure on the supply of freshwater, especially during long dry periods and low flows of the Rhine. The prolonged droughts in 2018, 2019, 2020 and 2022 were clear warnings of what awaits us more often in the near future. In response, PWN wants to transform its current linear water system to a more robust and resilient circular system.

Key components in the foreseen water transition in North Holland are the use of alternative water resources, e.g. by incorporating brackish groundwater desalination, treated wastewater effluent reuse, and the creation of additional storage capacity, especially through nature-based solutions such as Aquifer Storage and Recovery (ASR). The question is how and where to add these different new components to the current (drinking) water system and how to integrate them with the natural existing water systems.

5.1.2 Modelling configurations and scenarios

The ambition until the end of the project is to have a framework in place to support PWN in making long-term investment planning to make the water system future-climate resilient (2050 and beyond), taking into account rising salinity levels in Lake IJssel and an increasing water demand due to population increase and a growing economy. Part of this framework is a SDM that will be developed for the PWN drinking water system, and that will subsequently be extended to include other elements of the North Holland regional water system, such as sewage water treatments plants and main surface waters.

SDM is a powerful tool to gain high-level insights in the functioning of complex systems, such as water systems. SDMs are flexible in their setup, and thus capable of integrated modelling of various systems that are generally modelled "stand alone" (e.g. surface water model, groundwater model, drinking water distribution model). While providing less detailed information than such stand-alone models, SDMs generally have a much shorter computing time, making them explicitly suited to quickly evaluate multiple scenarios for AWR management and to provide insights on how adaptations and interventions may propagate through the regional water system and its different subsystems.

The scenarios that will be evaluated will include compound risks / combinations of stresses, to provide a realistic insight in risks and challenges for (future) water supply in North Holland. Scenarios for chloride levels in Lake IJssel will be derived by coupling the national climate scenarios and national Delta Scenarios (SSP1, SSP2 and SSP5) to a local model from Lake IJssel. Water demand scenarios will be developed jointly with regional stakeholders, following the socio-economic approach of the national Delta Scenarios.

5.1.3 Preliminary design of modelling chain and inputs/outputs

The SDM will be setup using the Vensim simulation software by Ventana Systems, Inc. SDM North Holland v1.0 will describe the PWN drinking water system (Figure 7), and this version will subsequently be extended to include other elements of the North Holland regional water system. Physical data are needed to develop / setup the SDM and to develop climate and socio-scenario for evaluation (desktop scenario evaluations), but also serious gaming.

The following data is foreseen to be needed:

System components

- Drinking water system (network, production locations, buffers, dune system)
- Primary waterways (surface water)
- Wastewater treatment plants (WWTPs) (location, capacity)
- Industrial abstractions and discharges from/to surface water and discharges to the sewage system
- Demand areas

Inputs

- National climate scenarios (provided by KNMI) and national Delta Scenarios (provided by Deltares), including discharges of the river Rhine
- Current and predicted salinity levels of Lake IJssel at Andijk intake point, derived from national climate and Delta Scenarios
- Current and expected drinking water demand (daily patterns, distinguished between households and industry)
- Meteorological data (precipitation) (provided by KNMI)

Outputs

- PWN water supply to public and industries (daily basis)
- Flows of water between all different components of the anthropogenic water cycle (drinking water production, effluent treatment and discharge), surface water, and AWR (daily basis)

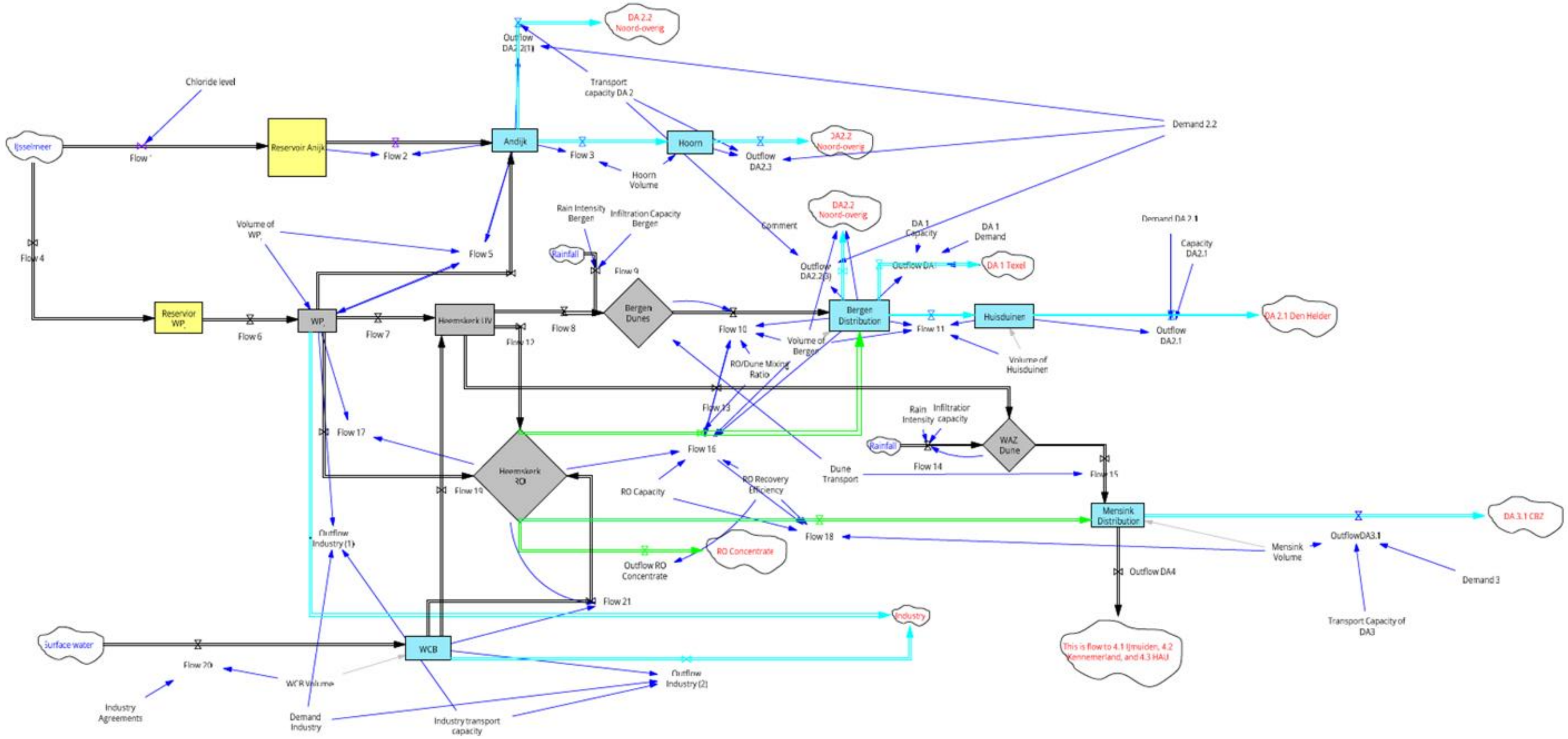

Figure 7: SDM North Holland version 0.1, PWN drinking water system.

5.1.4 KPIs

The key performance indicators for North Holland for the outcome of the modelling approaches and assessments are:

Society

- Operational buffer: percentage of operational drinking water buffer with respect to total supply. How long can water supply be maintained without usage of the main source Lake IJssel? (t)
- Relative use of surface water from Lake IJssel (%)
  - Intake surface water for drinking water
  - Intake surface water for regional water management (water authority)
- Relative usage of surface water from Lake IJssel (conventional source) for drinking water production (%)
  - Production of drinking water from Lake IJssel surface water (Mm3/yr)
  - Production of drinking water from AWR (Mm3/yr)
    i.e., wastewater reuse, brackish groundwater, water stored in times of surplus (ASR, climate buffer), and rainwater

Environment

- Environmental costs (Euro/m3)
  - Energy usage
  - Materials and resources
  - Waste streams

Economy

- Water production costs (Euro/m3)
  - Total Costs of Ownership (TCO)

5.2 CS2 Kalundborg

5.2.1 Brief CS description – Challenges and planned interventions

Kalundborg is a coastal, urban-industrial municipality located in north-west Zealand, Denmark, and is famous for the "Kalundborg Industrial Symbiosis". The Kalundborg Industrial Symbiosis Association was established in 1972 and links 19 private and public companies. The local industrial sector includes petrochemicals, light construction materials, food, pharmaceuticals, biotechnology, energy and bioenergy, as well as waste management and water companies and industries. Various water, energy and materials circular economy approaches are already being implemented, such as reuse of cooling water for steam production, reuse of gypsum from flue gas cleaning for plasterboard production, integrated heat management and transfer between industries and the district heating network, and heat recovery from process water for district heating.

A new industrial area is now being developed in the north-eastern part of Kalundborg. New companies will become part of the Kalundborg Industrial Symbiosis, which not only creates opportunities for the local economy, but also challenges to ensure fit-for-purpose infrastructure and sustainable use and reuse of resources, especially water. The use of water in this case will vary from company to company, but the overall aim is to optimise the use and reuse of water, provide fit-for-purpose qualities in line with the local water strategy and create a sustainable water management plan for the region.

Currently, the biotech sector uses groundwater and treated surface water sources (4-5 million m^3/a) and operates a large industrial wastewater treatment plant (2.3 million PE). Used water is treated in the industrial WWTP and the effluent is then sent to the municipal WWTP operated by KCR for further treatment. The industrial water accounts for up to 70% of the influent to the municipal WWTP. The WWTPs are interconnected and controlled by an innovative joint control system for an energy efficient operation (Schütz et al. 2024).

Challenges

- Rapid expansion of Kalundborg Industrial Symbiosis with increasing water demand.
- Surface water from lake Tissø may no longer be used for water supply in the near future, or only to a limited extent.
- Longer drought periods are expected in summer and more precipitation in winter.
- Groundwater abstraction is limited.
- EU Water Reuse Regulation 2020/741 is not yet applied in Denmark (use of treated wastewater for agricultural irrigation).
- Uncertainty about the price of fit-for-purpose quality and how to finance new distribution systems for fit-for-purpose water.

Planned interventions:

To meet the projected demand in the future (up to 20 million m^3/a, a 300-400% increase from today) and to make the industrial water supply more climate resilient, the use of several different water sources is envisaged, including reclaimed water and desalinated seawater, rainwater, and existing sources such as lake water and groundwater. Therefore, the use of alternative water resources will be modelled for different scenarios (see 5.2.2) and evaluated in order to propose an appropriate water management strategy for the future.

5.2.2 Modelling configurations and scenarios

For CS2, UWOT will be used to model the system. Therefore, the results of climate change impact modelling and groundwater modelling will be used to predict future water demand and availability. A distinction will be made between two cases, one in which the lake water is used as a water resource and one in which it is not, due to the challenge of possible prohibition. In both cases different scenarios will be investigated and compared.

In **case 1**, the currently used lake water can be included as a potential source in the future. Corresponding scenarios could look like the following examples:

- Scenario 0 (baseline): Groundwater and lake water are the only water sources for both the municipality and industry.
- Scenario 1: Groundwater + lake water + desalinated seawater
- Scenario 2: Groundwater + lake water + desalinated seawater + reclaimed water
- Scenario 3: Groundwater + lake water + desalinated seawater + reclaimed water + harvested rainwater
- Scenario 4: Groundwater + lake water + desalinated seawater + harvested rainwater

In **case 2**, the scenarios do not include the lake water, as it may no longer be possible to use the lake water in the near future. Examples of such scenarios would be:

- Scenario 1-0 (baseline): Groundwater is the only source of water for the municipality and industry.
- Scenario 1-1: Groundwater + desalinated seawater
- Scenario 1-2: Groundwater + desalinated seawater + reclaimed water
- Scenario 1-3: Groundwater + desalinated seawater + reclaimed water + harvested rainwater
- Scenario 1-4: Groundwater + desalinated seawater + harvested rainwater

5.2.3 Preliminary design of modelling chain and inputs/outputs

The aims of the modelling approaches, as explained in 5.2.2, are:

- Identify synergies between existing infrastructures and alternative water resources implementation (T1.5)
- Identify risks and perform evaluation of AWR supply systems and technologies deployment (T1.3)
- Stress-testing baseline and future configurations of the water systems under different climate and socio-economic scenarios (T1.1, T4.4, ST5.2.2)

The scenarios (see 5.2.2) will be evaluated using life-cycle and risk assessments (QMRA; QCRA) in order to determine the optimal technology configuration in terms of environmental impacts and economic viability and to derive important hints for the future water management strategy of Kalundborg.

5.2.4 KPIs

The key performance indicators for Kalundborg for the outcome of the modelling approaches and assessments are:

Environment

- Direct water availability footprint (freshwater use vs. use of AWR)
- Environmental impact (CO_2 footprint)

Economy

- Cost efficiency of different AWR scenarios (determined by assessing operational costs for energy consumption, personnel and chemicals)

Society

- Number of jobs in the industry counted as “full-time person equivalents"

5.3 C3 Syros-South-Aegean

5.3.1 Brief CS description – Challenges and planned interventions

Syros is a Greek island in the Cyclades (Aegean Sea) with an area of 83.6 km^2 and a population of 21124 people (2021 census). The island's drinking water supply network, sewer system and wastewater treatment plants (WWTPs) are managed by the Municipal Water Supply and Sewerage Company of Syros (DEYAS). The drinking water supply network largely relies on reverse osmosis seawater desalination plants, with a total supply of 1.7-2.2 hm^3/year (including the network losses), while groundwater can also contribute to a much lesser extent. For 2023, the desalination plants and the groundwater abstractions accounted for 96% and 4%, respectively, of the water supplied by DEYAS (data by DEYAS). The irrigation demands, on the other hand, are largely covered via groundwater abstractions. Currently, a relatively small quantity of wastewater that undergoes tertiary treatment is used for Managed Aquifer Recharge (MAR) and irrigation.

Increased heatwaves and droughts related to climate change scenarios would increase both the domestic and the irrigation water demand, putting pressure on the water supply system and the (ground)water resources. The water demand during the warm touristic period (summer) could increase substantially. An intensification of groundwater abstractions could result in salinization in the coastal aquifers. Apart from the climate scenarios, a further increase in the touristic fluxes (and, thus, the associated consumptions) driven by socioeconomic factors could further stress the water supply system.

The interventions related to AWR to be examined within the modelling work are:

- Extension of wastewater reuse for MAR and irrigation.
- Extension of Rainwater Harvesting (RWH) installations on the island to alleviate the pressure on the other water sources. Similar to other Greek islands, harvesting rainwater is not a new practice for Syros. Rainwater cisterns have been traditionally used in the island and some are still in use today.

Detailed information about Syros case study is available in Deliverable 5.1.

5.3.2 Modelling configurations and scenarios

The modelling investigations consider the current conditions as the baseline configuration. Subsequently, alternative 'future world views' will be applied to the baseline conditions along 3 axes:

- System configuration/topology

The system configurations will involve a different mixture of AWR interventions, as well as policy measures, and the extent to which interventions are applied. For instance, different configurations can vary between the fraction of available roofs/terraces to the total available that are used for RWH. This way, the RWH potential to provide spare capacity to the system under the current climatic and socioeconomic conditions will be investigated and assessed.

- Climatic scenarios

Those involve climatic model input variables (at regional or local scale when available), related to the trends captured under selected RCPs. This, at minimum, includes climatic variables such as precipitation and temperature, which are drivers of the model(s) and can influence the resilience of Syros under both the current and potential future system configurations (with the addition of AWR interventions). An example involves the examination of the effects of future RCP precipitation trends on the system resilience under different RWH application scales and the evaluation of the intervention.

- Socioeconomic scenarios

Those involve model input variables of socioeconomic nature (at regional or local scale when available), such as the size and educational level of the island population, the magnitude and seasonality of the touristic patterns, as well as relevant economic indicators (e.g. prosperity and purchase power). Those are directly related to the future paths selected and the underlying assumption of selected SSPs. An example involves the evolution of the system dynamics, and specifically the dimensions of water and energy demands on the island during tourist and off-tourist seasons, under the effect of permanent residents and tourist population changes.

More details about climate change scenarios and narratives will be documented in D1.1 *"Future water supply availability and demand based on different RCP scenarios"*. It is noted that the final configurations and scenarios that will be investigated will account (if applicable) for the feedback and inputs collected from stakeholders of the Syros CS (via CoP activities and dedicated meetings).

5.3.3 Preliminary design of modelling chain and inputs/outputs

A sophisticated modelling approach is under development for the case study of Syros involving three different models in order to:

- Identify synergies between existing infrastructures and alternative water resources implementation (T1.5)
- Identify vulnerabilities, risks and perform evaluation of AWR supply systems and technologies deployment (T4.1)
- Stress-testing baseline and future configurations of the water systems under different climate and socio-economic scenarios (T1.1, T4.1, ST5.2.3)
- Design and deliver pathways of deployment for AWR interventions at different phases and quantitatively assess the gains in water systems resilience (T4.2).

More specifically, as presented in Figure 8 and foreseen under T1.5:

  - UWOT is applied in Syros to consolidate current water and wastewater infrastructures at the CS level for simulating water fluxes. Different AWR interventions will also be simulated via this model.
  - SDM will be used for the estimation of water demand components (see e.g., the domestic and the seasonal rise of touristic water demands) at higher scales by considering the effects of external drivers such as macroeconomics indices, climatic conditions, electricity market fluctuations as well as internal drivers, such as the water supply system state and resources capacity.
  - ABM will be investigated as a sub-component of the modelling scheme to explore consumers' behaviours and how those can change due to external factors, such as raising awareness campaigns, different pricing policies, education and outreach programs which encourage water-efficient behaviours.

Primary input and output data of the three models, as well as primary data they exchange are depicted in Figure 9.

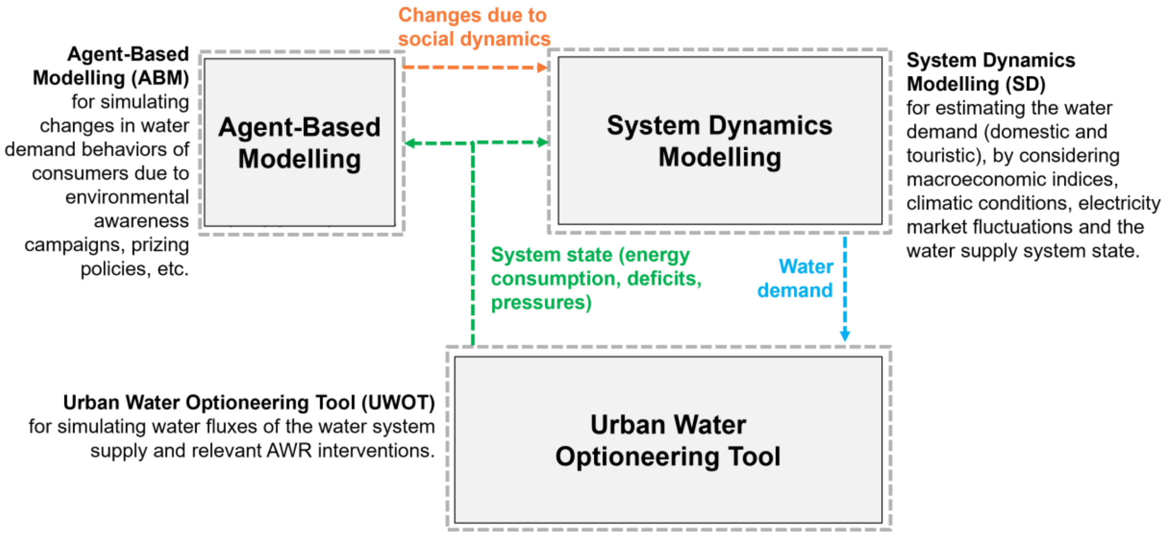

Figure 8: Modelling approach of Syros case study.

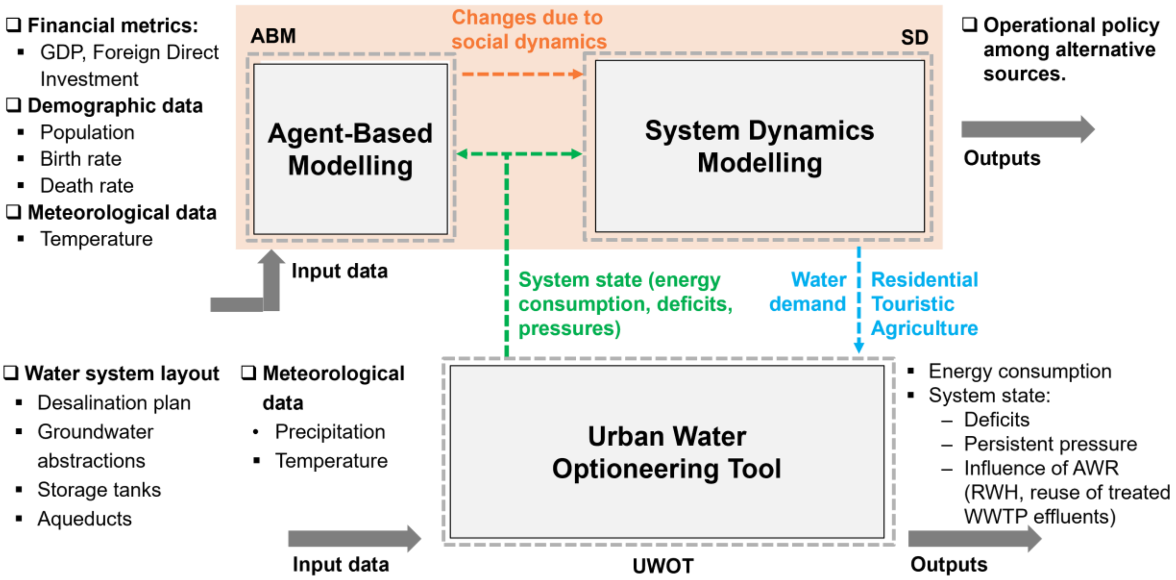

Figure 9: Primary input and output model data.

5.3.4 KPIs

Some relevant indicators for the case study of Syros are listed below. Please note that the list is not exhaustive. The system resilience can be assessed based on (some of) those KPIs and/or aggregated forms of those.

Society

- The following indicator expresses the demand for desalinated water in relation to the production capacity of the desalination plants:

$$Desalination\ demand\ capacity\ index = \frac{Desalinated\ water\ demand}{Desalination\ plants'\ capacity}$$

The indicator will be calculated for different time scales (e.g. daily, monthly, seasonal, yearly). Values larger than 1 would denote that the water demand exceeds the desalination plants' capacity. For values smaller than 1, the smaller the value, the larger the spare capacity of the desalination plants.

- When the water demand for desalinated water exceeds the desalination plants' capacity, the deficiency can be quantified as:

$$Desalinated\ water\ demand\ deficiency = \frac{Desalinated\ water\ demand - \ Desalination\ plants'capacity}{Desalinated\ water\ demand}$$

When the demand is smaller than the desalination plants' capacity, the above indicator is set to zero (0).

- When the water demand exceeds the supply, the water supply system deficiency can also be expressed as in terms of its duration. This duration can be converted to a dimensionless quantity by dividing it with the total duration of a reference period (e.g. August, when the tourist fluxes currently reach their peak).
- Indicators that quantify the contribution of AWR interventions to the water consumption can be expressed via **RWH usage** and **MAR contribution**, presented below:

$$RWH\ usage = \frac{Collected\ rainwater\ used}{Total\ domestic\ water\ consumption}$$

$$MAR\ contribution = \frac{Managed\ aquifer\ recharge}{Groundwater\ abstractions}$$

Environment

- The trends in the quantitative status of the groundwater bodies can be expressed, for example, via the **Groundwater Exploitation Index**.
- The **change in groundwater depths** from is another useful indicator with respect to the quantitative status of groundwater:

$$GW\ depth\ change = GW\ depth - \ Baseline\ GW\ depth$$

- In terms of water quality, the main interest in the frame of this case study is groundwater. In that sense, the **chemical/ecological status of groundwater** could be examined. This is important with respect to MAR as it can gradually alter the quality of groundwater (at least, locally).

Economy

- Since the potable water demand in Syros is essentially covered via seawater desalination, the financial aspect of the supply is important. Based on the demand evolution over time (affected by both the socioeconomic and climatic conditions), as well as on the mix of water used to cover this demand (e.g. desalinated water, collected rainwater, reclaimed wastewater), the **operational cost (OPEX)** related to the water consumption can **change**. This can be expressed as:

$$OPEX\ change = \frac{Baseline\ OPEX - Potential\ future\ OPEX}{Baseline\ OPEX}$$

Positive indicator values suggest a decrease in operational costs in relation to the baseline costs.

- To decouple the operational cost from the population size, the **unit cost of water** (€/m^3) could be used instead of the total OPEX:

$$Unit\ OPEX\ change = \frac{Baseline\ m^3\ cost - Potential\ future\ m^3 cost}{Baseline\ m^3\ cost}$$

5.4 CS4 Cost Brava

5.4.1 Brief CS description – Challenges and planned interventions

The Costa Brava Region lies in northern-east Catalonia with an area of approximately 3072 km^2. The Case Study concentrates on the Muga catchment which has an area of approximately 853km^2. The land use in this catchment is divided into 58% mixed forest area, 37% agricultural land and 5% urban use.

The Muga river has a length of 64km and 1 large reservoir (Boadella Reservoir) and 17 smaller dams and interruptions. The Area's Drinking water treatment plants (DWTPs) and supply, wastewater management (WWTPs) and sewer system is managed by Concorci d'Aigües Costa Brava Girona (CACBGi) and urban water management entities like Fisersa (Figueres de Serveis SA, Empresa plurimunicipal de Figueres). The drinking water supply of the area is provided by the Boadella Reservoir, direct water abstraction from the river and wells, with a total supply of 12 hm3/a for domestic use and 5 hm3/a for industrial and other uses in the Alt Empordà Region (data provided by the Catalan Water Agency, ACA (from Catalan, Agència Catalana de l'Aigua) only covers the Alt Empordà region and not the Muga catchment). Additionally, a desalination plant in the Alt Empordà region and the construction of water reclamation plants in Figueres and Llançà will increase the available water in the region by 15 hm3/a. The recent droughts have left the reservoirs at perilous low levels and future heatwaves and very possible droughts related to climate change will put on more pressure on surface and groundwater resources. The coastal region of the Muga catchment has a high touristic influx during the summer months, which increases the water demand drastically. St. Pere de Pescador for example has a population of approximately 2000 people during winter, and a touristic influx of ca. 12000 people during summer. Further increases in tourism will pose additional challenges for the water supply in the future.

The alternative water resources (AWR) interventions to be examined within the modelling work are:

- Extension of wastewater reuse (indirect potable reuse) for MAR and irrigation.
- Extension and construction of Desalination plants on the Costa Brava to alleviate the pressure on the water supply network.

Detailed information about Costa Brava case study is available in Deliverable 5.1.

5.4.2 Modelling configurations and scenarios

The modelling investigations consider the current conditions as the baseline configuration under normal and drought conditions. Seasonal changes (population changes, water demand and tourism) will be applied to the baseline conditions. Additionally alternative climate scenarios and socioeconomic scenarios and changes will be applied to the baseline conditions to extrapolate for future scenarios.

- System baseline configuration:

As AWR are not the norm and part of the future water resources, baseline conditions will involve the state-of-the-art water abstraction, treatment and distribution as well as water policies in the case study area. The baseline for modelling will include the available water provided by the river Muga, the Boadella reservoir, groundwater abstraction and wells. Water demand will include the normal water demand by population as well as seasonal changes, especially during summer, when tourism will heavily influence the water demand. Differences will be observed in the different population hubs (Figueres with a stable population of ca. 50000 and very low tourism, Roses with a 100% change of population during summer and St. Pere de Pescador with an increase of 600% in population).

- Climate scenarios:

Three RCP climate scenarios with their input variables on a regional and downgraded local scale will be selected. The climate variables will include precipitation, temperature and evaporation, which are the drivers for the models. These drivers will influence the stress and resilience of the models under present and future system configurations. Future precipitation and evaporation trends will have a direct impact on available water resources and thus will show how AWR can soften water stress.

- Socioeconomic scenarios:

Those scenarios involve model input variables of socioeconomic nature like census data, tourism data, changes in agriculture (different crops need different amount of irrigation), educational level and knowledge about climate change and its consequences. Changes in directives on indirect potable reuse, the acceptance of the population in indirect water reuse, adaptation of treatment plants and installation of new desalination plants too will impact the models. Future water demands in this region will be highly affected by population changes, adaptation to drought restrictions, changes in policies and tourism during the year.

More details about the climate change scenarios and narratives will be documented in D1.1 “Future water supply availability and demand based on different RCP scenarios”. It is noted that the final configurations and scenarios that will be investigated will account (if applicable) for the feedback and inputs collected from stakeholders of the Costa Brava CS (via CoP activities and dedicated meetings).

5.4.3 Preliminary design of modelling chain and inputs/outputs

A modelling approach is under development for the case study of Costa Brava/ Muga catchment involving different approaches:

- Modelling the baseline by identifying water supply and demand through a steady state model where the main supply comes from the reservoir, river and wells and the main demand is attributed to the current socio-economic state (stable population, tourism, industry and agriculture).
- Identify water supply throughout the system and evaluate where risks and vulnerabilities lie to impose possible future AWR. Identify possible wastewater streams as future AWR sources for indirect potable reuse.
- Stress-testing baseline and future configurations of the water systems under different climate and socio-economic scenarios.
- Design and deliver pathways of deployment for AWR (desalination, WWTPs) interventions at different phases and quantitatively assess the gains in water systems resilience.

More specifically, as presented in Figure 10 and foreseen under T1.5:

  - UWOT applied to the Costa Brava (Muga catchment) consolidates the current water demand/supply using statistical data and current water and wastewater infrastructures for simulating water fluxes.

Modelling approach in the Costa Brava Case Study using UWOT

Urban Water Optioneering Tool (UWOT)

To simulate water fluxes of the water system supply and relevant AWR interventions Figure 10 shows the baseline model with a total water demand covered from the Boadella reservoir and groundwater wells, while produced wastewater is treated in a WWTP and the effluent is returned into the Muga river.

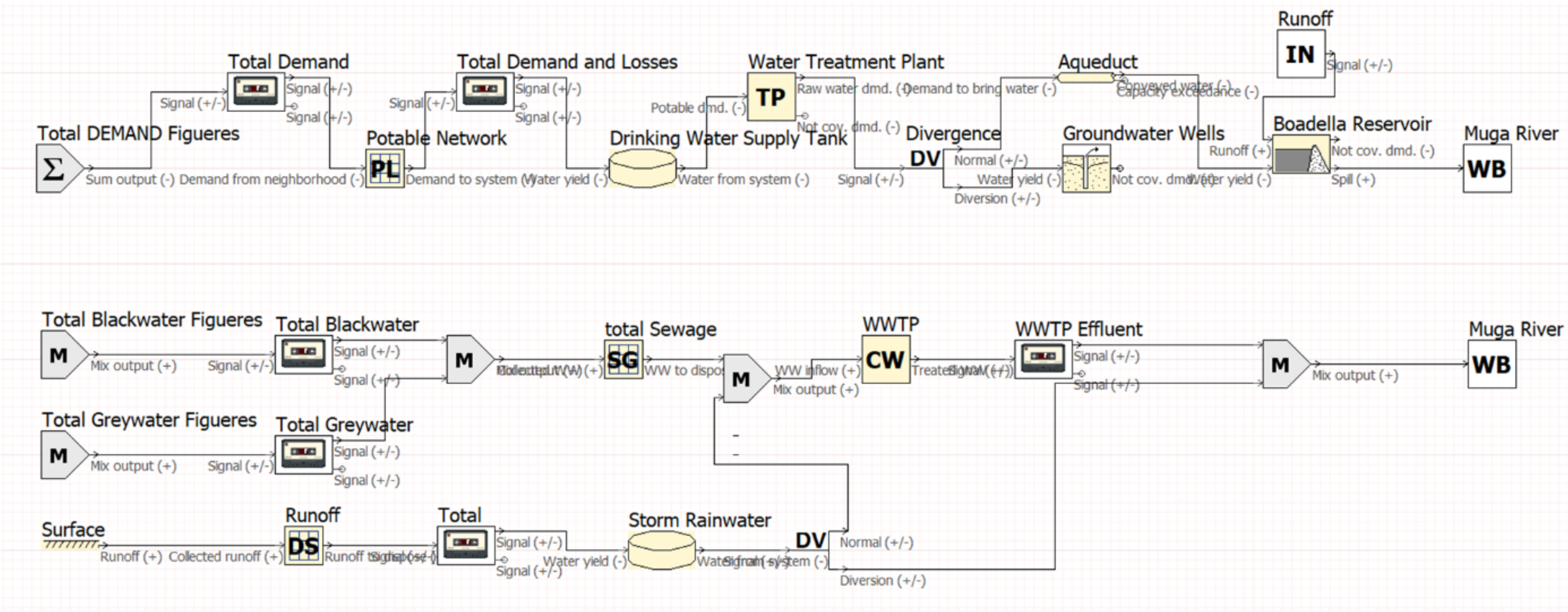

Figure 10: Baseline UWOT model for Costa Brava.

Figure 11 shows a relevant AWR intervention in the same location as Figure 10. Part of the AWR is the use of treated wastewater for groundwater recharge, another AWR intervention is the use of desalination plants, which directly feed into the drinking water supply.

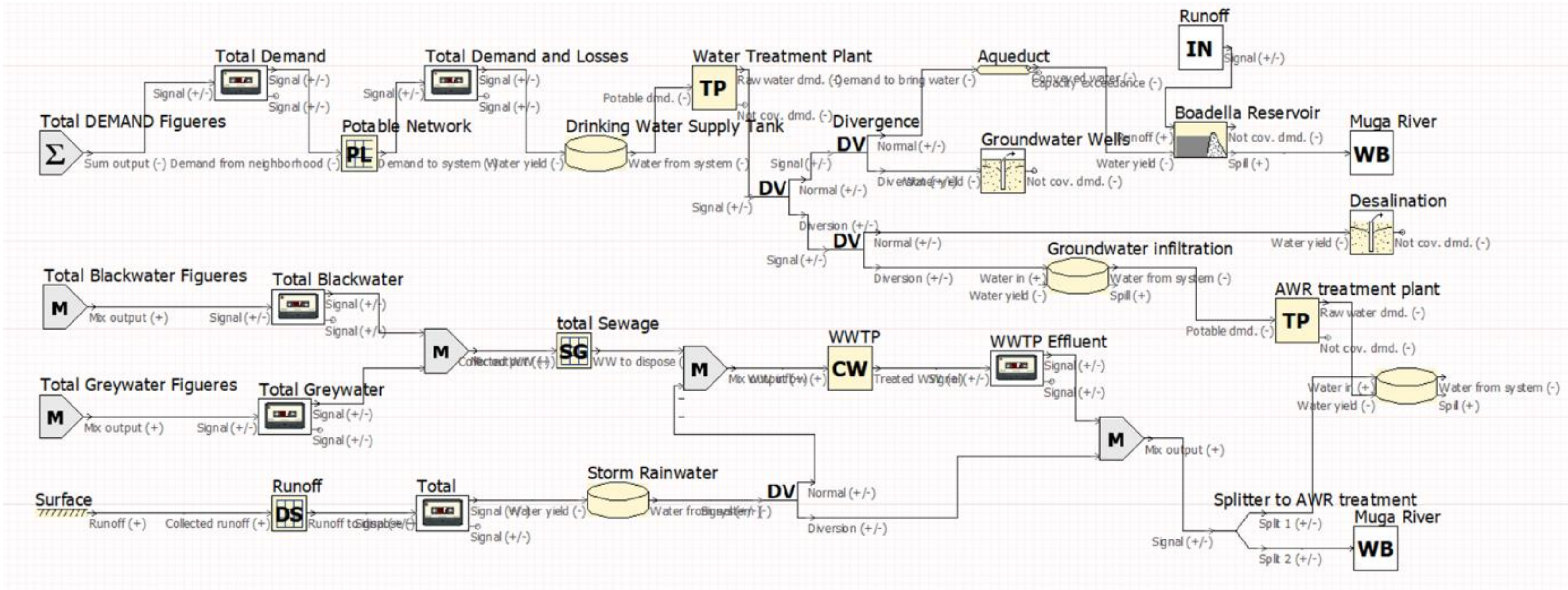

Figure 11: UWOT model with AWR intervention for Costa Brava.

5.4.4 KPIs

Some useful indicators for the case study of the Costa Brava (Muga catchment) are listed below. This list is not exhaustive, and those indicators aim at assessing different parts of the studied system. Indicators include water quantity and availability, water quality and status, water supply chain, water treatment and treatment cost, water reuse and cost, precipitation and drought events. The system resilience can then be assessed based on those KPIs and/or an aggregated form of those by assigning them with appropriate weights.

Environment

- The following indicator expresses the quantitative status of groundwater bodies:

$$GW\ (Change\ Index) = \frac{Future\ GW\ Level - Baseline\ GW\ Level}{Optimum\ GW\ Level - Baseline\ GW\ level}$$

  The Future GW Level represents the projected or observed groundwater level under specific conditions (drought, increased pumping, recharge, recovery). The Baseline GW Level is the reference level, representing the groundwater level under normal or historic conditions. The Optimum GW Level is the target threshold value, representing the sustainable or ideal groundwater level for the aquifer.

- The **Overall Water Availability Indicator** (OWAI) expresses the overall available water as a sum of reservoir reserves and groundwater reserves relative to a benchmark for water demand or an optimum storage level:

$$OWAI = \frac{\alpha R + \beta G}{D_{ref}}$$

$$OWAI = \frac{R + G}{R_{opt} + G_{opt}}$$

  R is the current reservoir storage,

  G is the current groundwater storage,

  α and ß are weighting factors that account for the relative reliability, quality, renewability of reservoir vs groundwater levels,

  D_{ref} represents a reference demand or an optimum storage benchmark (sum of ideal reservoir and groundwater levels),

  R_{opt} and G_{opt} represent the optimal reservoir and groundwater levels needed to meet sustainable water supply targets.

Society

- The **Potable Water Supply-Demand Indicator (PWSDI)** expresses the demand for potable water in relation to the production capacity of wells, provision by reservoirs and production of desalination plants:

$$PWSDI = \frac{D_{pot}}{C_{wells} + C_{reservoir} + C_{desal}}$$

  D_{pot} is the demand for potable water,
  C_{wells}, $C_{reservoir}$ and C_{desal} are the production capacity for wells, reservoir and desalination, respectively.

- The **Drought** adjusted **Water Use Efficiency Factor** (DWUEF) expresses the amount of water that is available for essential use. The Drought Severity Factor reflects the intensity of drought conditions, which increases when reservoir levels are significantly below normal and/or normal precipitation is severely reduced. This makes the indicator sensitive to how severe a drought is.

$$DWUEF = \frac{Effective\,Water\,Supplied}{Population\,Served \cdot Drought\,Severity\,Factor}$$

- The **Water Use Efficiency Factor (WUEF)** captures the extent to which the three key sectors, population, industry and agriculture adopt to water saving policies. This factor compares water use under new policies to a baseline water use scenario.
  - The baseline water use determines the current water consumption for each sector (W_P^{base}, W_I^{base}, W_A^{base}).
  - The Effective Water Use under Policies estimate water use after adoption of low volume household appliances, circular water economy practices in industry and change of crop types and irrigation in agriculture ($W_P^{eff}, W_I^{eff}, W_A^{eff}$).
  - The Effective Water Use can be calculated by applying the degree of adoption within each sector, where A_P is the Adoption Rate and S_P the Saving Factor (% of reduction in water use when fully adopted):
    $W_P^{eff} = W_P^{base} \cdot [1 - A_P \cdot S_P]$
  - Weighting factors (w_P, w_I, w_A) reflect the relative importance or contribution of each sector to overall water use. These weights can be based on economic, environmental, or regional societal factors.
  - The overall baseline water use: $W_{base} = w_P W_P^{base} + w_I W_I^{base} + w_A W_A^{base}$
  - The overall effective water use: $W_{eff} = w_P W_P^{eff} + w_I W_I^{eff} + w_A W_A^{eff}$

  - Water Use Efficiency Factor (WUEF):

$$WUEF = \frac{W_{eff}}{W_{base}}$$

    with WUEF < 1 indicating improved efficiency
  - The Overall WUEF with the degree of adoption:

$$WUEF = \frac{w_P W_P^{base}(1 - A_P \cdot S_P) + w_I W_I^{base}(1 - A_I \cdot S_I) + w_A W_A^{base}(1 - A_A \cdot S_A)}{w_P W_P^{base} + w_I W_I^{base} + w_A W_A^{base}}$$

- The **AWR Supply Ratio (AWR Ratio)** expresses the share of water from AWR interventions relative to the total water consumption. A high AWR ratio indicates a greater reliance on alternative water resources.

$$AWR(Ratio) = \frac{Q_{WWTP} + Q_{MAR}}{Q_{total}}$$

Q_{WWTP}: Effective volume of WWTP effluent reused for potable and non-potable purposes
Q_{MAR}: Effective volume of water recharged into the aquifer via MAR
Q_{total}: Total water consumption/supply in the system

- The **Managed Aquifer Recharge (MAR) Efficiency Index** is a key performance metric that quantifies how effectively recharged water is retained within the aquifer. It provides insights into the sustainability and effectiveness of MAR systems in replenishing groundwater supplies.

$$MAR_{efficiency\ Index} = \frac{Net\ stored\ Water\ in\ Aquifer}{Total\ Recharge\ Volume\ Applieed}$$

$$MAR_{eff} = \frac{Q_{recharge,\ effective}}{Q_{recharge,\ applied}}$$

- WWTP Effluent Reuse Factor:

$$WWTP\ Reuse\ Factor = \frac{Q_{WWTP,\ reused}}{Q_{WWTP,\ produced}}$$

Economy

- The cost per Unit of Water Reuse indicator quantifies the economic efficiency of a water reuse project.

$$Cost\ [per\ Unit\ of\ Water\ reused] = \frac{Total\ Cost\ of\ Reuse}{Total\ Volume\ of\ Water\ Reused}$$

- The Composite Economic Factor uses the Levelized Cost of Water (LCOW) for the water reuse portfolio:

$$LCOW = \frac{C_D \cdot Q_D + C_{AWR} \cdot Q_{AWR}}{Q_D + Q_{AWR}}$$

Q_D: Total volume of water produced by desalination
C_D: Unit cost (capital, operational, maintenance) for desalinated water
Q_{AWR}: total volume of water produced via AWR
C_{AWR}: Unit cost for water produced through AWR

6. Early considerations and plan of future work

6.1 Early considerations

This report (D4.1) serves as an interim report for the formulation of the resilience assessment methodology and sets the definitions and concepts to be used hereafter in the RECREATE project. It is also used to guide the collaborative work on CSs in order to implement the necessary actions, i.e. identify a preliminary set of KPIs per water system under examination, as well as conceptualize and then develop the necessary modelling chains required for stress testing the systems. Furthermore, this report conceptualizes the basic framework and the requirements for the delineation of adaptation pathways in the CSs with regards to resilience maximization and other criteria, although some details are subject to change as work progresses in T4.2.

6.2 Next steps

Work carried out in the next phase of task T4.1 will focus on:

- Contributing to T4.2 for the coupling of the methodology in the formulation of the adaptation pathways framework and tools.
- Synergy with T1.1 in order to formulate the future scenarios of climatic and other variables.
- Fostering the formulation of adaptation pathways, the modelling work, and the resilience assessment in the CSs' water systems
- Providing outputs to the RECREATE_WT (developed and implemented in WP3) as final resilience KPI estimations, resilience profile graphs before and after interventions, alongside the schemas of AWR adaptation pathways for each CS.
- Contributing to T4.4, as the results will form the basis for recommendations for scaling up the embedding of AWR solutions and technologies in water systems lifecycle.

7. References

Adger, W. N. (2006). “Vulnerability.” *Global Environmental Change*, 16(3), 268–281.

Adger, W. N., Hughes, T. P., Folke, C., Carpenter, S. R., and Rockström, J. (2005). “Social-Ecological Resilience to Coastal Disasters.” *Science*, 309(5737), 1036–1039.

Ahern, J. (2011). “From fail-safe to safe-to-fail: Sustainability and resilience in the new urban world.” *Landscape and Urban Planning*, Elsevier B.V., 100(4), 341–343.

Amarasinghe, P., Liu, A., Egodawatta, P., Barnes, P., McGree, J., and Goonetilleke, A. (2016). “Quantitative assessment of resilience of a water supply system under rainfall reduction due to climate change.” *Journal of Hydrology*, Elsevier B.V., 540, 1043–1052.

Babovic, F., Babovic, V., and Mijic, A. (2018). “Antifragility and the development of urban water infrastructure.” *International Journal of Water Resources Development*, 34(4), 499–509.

Baggio, J. A., Brown, K., and Hellebrandt, D. (2015). “Boundary object or bridging concept? A citation network analysis of resilience.” *Ecology and Society*, Elsevier, 20(2), art2.

Bakker, K., and Morinville, C. (2013). “The governance dimensions of water security: A review.” *Philosophical Transactions of the Royal Society A: Mathematical, Physical and Engineering Sciences*, 371(2002).

Berkes, F. (2007). “Understanding uncertainty and reducing vulnerability: lessons from resilience thinking.” *Natural Hazards*, 41(2), 283–295.

Boretti, A., and Rosa, L. (2019). “Reassessing the projections of the World Water Development Report.” *npj Clean Water*, Springer US, 2(1), 15.

Bouziotas, D., van Duuren, D., van Alphen, H.-J., Frijns, J., Nikolopoulos, D., and Makropoulos, C. (2019). “Towards Circular Water Neighborhoods: Simulation-Based Decision Support for Integrated Decentralized Urban Water Systems.” *Water*, 11(6), 1227.

Bouziotas, D., Stofberg, S., Frijns, J., Nikolopoulos, D., and Makropoulos, C. (2023). “Assessing the resilience of circularity in water management: a modeling framework to redesign and stress-test regional systems under uncertainty.” *Urban Water Journal*, 20(5), 532–549.

Brown, K. (2015). *Resilience, Development and Global Change*. Routledge, Oxon, UK.

Bruckler, M., Wietschel, L., Messmann, L., Thorenz, A., and Tuma, A. (2024). “Review of metrics to assess resilience capacities and actions for supply chain resilience.” *Computers & Industrial Engineering*, 192, 110176.

Bruneau, M., Chang, S. E., Eguchi, R. T., Lee, G. C., O’Rourke, T. D., Reinhorn, A. M., Shinozuka, M., Tierney, K., Wallace, W. A., and von Winterfeldt, D. (2003). “A Framework to Quantitatively Assess and Enhance the Seismic Resilience of Communities.” *Earthquake Spectra*, 19(4), 733–752.

Bueno, S., Bañuls, V. A., and Gallego, M. D. (2021). “Is urban resilience a phenomenon on the rise? A systematic literature review for the years 2019 and 2020 using textometry.” *International Journal of Disaster Risk Reduction*, 66.

Butler, D., Farmani, R., Fu, G., Ward, S., Diao, K., and Astaraie-Imani, M. (2014). “A New Approach to Urban Water Management: Safe and Sure.” *Procedia Engineering*, 89, 347–354.

Butler, D., Ward, S., Sweetapple, C., Astaraie-Imani, M., Diao, K., Farmani, R., and Fu, G. (2017).

“Reliable, resilient and sustainable water management: the Safe & SuRe approach.” *Global Challenges*, 1(1), 63–77.

Carlson, J. M., and Doyle, J. (2002). “Complexity and robustness.” *Proceedings of the National Academy of Sciences*, 99(suppl_1), 2538–2545.

Carpenter, S., Walker, B., Anderies, J. M., and Abel, N. (2001). “From Metaphor to Measurement: Resilience of What to What?” *Ecosystems*, 4(8), 765–781.

Cashman, A., and Ashley, R. (2008). “Costing the long-term demand for water sector infrastructure.” *Foresight*, 10(3), 9–26.

Chang, S. E., McDaniels, T. L., Mikawoz, J., and Peterson, K. (2007). “Infrastructure failure interdependencies in extreme events: Power outage consequences in the 1998 Ice Storm.” *Natural Hazards*, 41(2), 337–358.

Chen, C., Wang, J., Qiu, F., and Zhao, D. (2016). “Resilient Distribution System by Microgrids Formation After Natural Disasters.” *IEEE Transactions on Smart Grid*, 7(2), 958–966.

Chen, O., Mustafee, N., Evans, B., Khoury, M., Vamvakeridou-Lyroudia, L., Chen, A. S., Djordjević, S., and Savić, D. (2025). “Supporting decision-making for industrial symbioses using a hybrid modelling approach and its application to wastewater treatment.” *Water Science & Technology*, 91(5), 501–523.

Clark, R. M., Hakim, S., and Ostfeld, A. (2011). *Handbook of Water and Wastewater Systems Protection*. (R. M. Clark, S. Hakim, and A. Ostfeld, eds.), Springer New York, New York, NY.

Cosgrove, W. J., and Loucks, D. P. (2015). “Water management: Current and future challenges and research directions.” *Water Resources Research*, 51(6), 4823–4839.

Cote, M., and Nightingale, A. J. (2012). “Resilience thinking meets social theory.” *Progress in Human Geography*, 36(4), 475–489.

Cutter, S. L., Barnes, L., Berry, M., Burton, C., Evans, E., Tate, E., and Webb, J. (2008). “A place-based model for understanding community resilience to natural disasters.” *Global Environmental Change*, 18(4), 598–606.

Davoudi, S., Shaw, K., Haider, L. J., Quinlan, A. E., Peterson, G. D., Wilkinson, C., Fünfgeld, H., McEvoy, D., Porter, L., and Davoudi, S. (2012). “Resilience: A Bridging Concept or a Dead End? ‘Reframing’ Resilience: Challenges for Planning Theory and Practice Interacting Traps: Resilience Assessment of a Pasture Management System in Northern Afghanistan Urban Resilience: What Does it Mean in Planni.” *Planning Theory & Practice*, 13(2), 299–333.

Dawson, T. P., Rounsevell, M. D. A., Kluvánková-Oravská, T., Chobotová, V., and Stirling, A. (2010). “Dynamic properties of complex adaptive ecosystems: implications for the sustainability of service provision.” *Biodiversity and Conservation*, 19(10), 2843–2853.

Deppisch, S., and Hasibovic, S. (2013). “Social-ecological resilience thinking as a bridging concept in transdisciplinary research on climate-change adaptation.” *Natural Hazards*, 67(1), 117–127.

Diao, K., Sweetapple, C., Farmani, R., Fu, G., Ward, S., and Butler, D. (2016). “Global resilience analysis of water distribution systems.” *Water Research*, 106, 383–393.

Directive (EU) 2022/2557. (2022). *Directive (EU) 2022/2557 of the European Parliament and of the Council of 14 December 2022 on the resilience of critical entities and repealing Council Directive 2008/114/EC*. 164–198.

Dunn, G., Brown, R. R., Bos, J. J., and Bakker, K. (2017). "Standing on the shoulders of giants: Understanding changes in urban water practice through the lens of complexity science." *Urban Water Journal*, Taylor & Francis, 14(7), 758–767.

Eyring, V., Bony, S., Meehl, G. A., Senior, C. A., Stevens, B., Stouffer, R. J., and Taylor, K. E. (2016). "Overview of the Coupled Model Intercomparison Project Phase 6 (CMIP6) experimental design and organization." *Geoscientific Model Development*, 9(5), 1937–1958.

Falkenmark, M., and Rockström, J. (2010). "Building Water Resilience in the Face of Global Change: From a Blue-Only to a Green-Blue Water Approach to Land-Water Management." *Journal of Water Resources Planning and Management*, 136(6), 606–610.

Farrelly, M., and Brown, R. (2011). "Rethinking urban water management: Experimentation as a way forward?" *Global Environmental Change*, Elsevier Ltd, 21(2), 721–732.

Fiering, M. (1976). "The Role of Systems Analysis in Water Program Development." *Natural Resources Journal*, 16(4), 25–37.

Fiering, M. B., and Holling, C. S. (1974). "Management and standards for perturbed ecosystems." *Agro-Ecosystems*, 1(1973), 301–321.

Fiksel, J. (2003). "Designing Resilient, Sustainable Systems." *Environmental Science & Technology*, 37(23), 5330–5339.

Fiksel, J., Polyviou, M., Croxton, K. L., and Pettit, T. J. (2015). "From risk to resilience: Learning to deal with disruption." *MIT Sloan Management Review*, 56(2), 79–86.

Fletcher, S. M., Miotti, M., Swaminathan, J., Klemun, M. M., Strzepek, K., and Siddiqi, A. (2017). "Water Supply Infrastructure Planning: Decision-Making Framework to Classify Multiple Uncertainties and Evaluate Flexible Design." *Journal of Water Resources Planning and Management*, 143(10), 04017061.

Folke, C. (2006). "Resilience: The emergence of a perspective for social–ecological systems analyses." *Global Environmental Change*, 16(3), 253–267.

Folke, C., Carpenter, S. R., Walker, B., Scheffer, M., Chapin, T., and Rockström, J. (2010). "Resilience thinking: Integrating resilience, adaptability and transformability." *Ecology and Society*, 15(4).

Folke, C., Carpenter, S., Walker, B., Scheffer, M., Elmqvist, T., Gunderson, L., and Holling, C. S. (2004). "Regime shifts, resilience, and biodiversity in ecosystem management." *Annual Review of Ecology, Evolution, and Systematics*, 35, 557–581.

Folke, C., Hahn, T., Olsson, P., and Norberg, J. (2005). "ADAPTIVE GOVERNANCE OF SOCIAL-ECOLOGICAL SYSTEMS." *Annual Review of Environment and Resources*, 30(1), 441–473.

Francis, R., and Bekera, B. (2014). "A metric and frameworks for resilience analysis of engineered and infrastructure systems." *Reliability Engineering and System Safety*, Elsevier, 121, 90–103.

Gallopín, G. C. (1991). "Human dimensions of global change: linking the global and the local processes." *International Social Science Journal*, 130(4), 707–718.

Godschalk, D. R. (2003). "Urban Hazard Mitigation: Creating Resilient Cities." *Natural Hazards Review*, 4(3), 136–143.

Gordon, J. (1978). *Structures*. Penguin Books, Harmondsworth, UK.

Gunderson, L. H. (2000). "Ecological Resilience—In Theory and Application." *Annual Review of Ecology* *and Systematics*, 31(1), 425–439.

Gunderson, L. H., and Holling, C. S. (2002). *Panarchy,Understanding Transformations in Human and Natural and sytems*. *Panarchy: Understanding Transformations in Human and Natural Systems*.

Gunderson, L. H., Holling, C. S., and Light, S. S. (1995). *Barriers and bridges to the renewal of ecosystems and institutions*. Columbia University Press, New York, NY, USA.

Hallegatte, S., Shah, A., Lempert, R., Brown, C., and Gill, S. (2012). *Investment Decision Making under Deep Uncertainty - Application to Climate Change*. Policy Research Working Papers, The World Bank.

Harrald, J. R. (2006). "Agility and Discipline: Critical Success Factors for Disaster Response." *The ANNALS of the American Academy of Political and Social Science*, 604(1), 256–272.

Hashimoto, T., Stedinger, J. R., and Loucks, D. P. (1982). "Reliability, resiliency, and vulnerability criteria for water resource system performance evaluation." *Water Resources Research*, 18(1), 14–20.

Heylighen, F. (2001). "The science of self-organization and adaptivity." *Knowledge Management, Organizational Intelligence and Learning, and Complexity. The Encyclopedia of Life Support Systems.*, (L. D. Kiel, ed.), Eolss Publishers, Oxford, UK, 5(3), 1–26.

Holling, C. S. (1973). "Resilience and Stability of Ecological Systems." *Annual Review of Ecology and Systematics*, 4(1), 1–23.

Holling, C. S. (1996). "Engineering resilience versus ecological resilience." *Engineering within ecological constraints*, P. . Schulze, ed., National Academy Press, Washington, DC, 31–43.

Holling, C. S., and Meffe, G. K. (1996). "Command and Control and the Pathology of Natural Resource Management." *Conservation Biology*, 10(2), 328–337.

Homayounfar, M., Muneepeerakul, R., Anderies, J. M., and Muneepeerakul, C. P. (2018). "Linking resilience and robustness and uncovering their trade-offs in coupled infrastructure systems." *Earth System Dynamics*, 9(4), 1159–1168.

Hukka, J. J., and Katko, T. S. (2015). "Resilient Asset Management and Governance for Deteriorating Water Services Infrastructure." *Procedia Economics and Finance*, Elsevier B.V., 21(15), 112–119.

Jacob, D., Petersen, J., Eggert, B., Alias, A., Christensen, O. B., Bouwer, L. M., Braun, A., Colette, A., Déqué, M., Georgievski, G., Georgopoulou, E., Gobiet, A., Menut, L., Nikulin, G., Haensler, A., Hempelmann, N., Jones, C., Keuler, K., Kovats, S., Kröner, N., Kotlarski, S., Kriegsmann, A., Martin, E., van Meijgaard, E., Moseley, C., Pfeifer, S., Preuschmann, S., Radermacher, C., Radtke, K., Rechid, D., Rounsevell, M., Samuelsson, P., Somot, S., Soussana, J.-F., Teichmann, C., Valentini, R., Vautard, R., Weber, B., and Yiou, P. (2014). "EURO-CORDEX: new high-resolution climate change projections for European impact research." *Regional Environmental Change*, 14(2), 563–578.

Johannessen, Å., and Wamsler, C. (2017). "What does resilience mean for urban water services?" *Ecology and Society*, 22(1), art1.

Juan-García, P., Butler, D., Comas, J., Darch, G., Sweetapple, C., Thornton, A., and Corominas, L. (2017). "Resilience theory incorporated into urban wastewater systems management. State of the art." *Water Research*, Elsevier Ltd, 115, 149–161.

Kjeldsen, T. R., and Rosbjerg, D. (2004). "Choice of reliability, resilience and vulnerability estimators for risk assessments of water resources systems / Choix d'estimateurs de fiabilité, de résilience et de vulnérabilité pour les analyses de risque de systèmes de ressources en eau.” *Hydrological Sciences Journal*, 49(5).

Krasny, M. E., and Tidball, K. G. (2009). “Applying a resilience systems framework to urban environmental education.” *Environmental Education Research*, 15(4), 465–482.

Krueger, E., Rao, P. S. C., and Borchardt, D. (2019). “Quantifying urban water supply security under global change.” *Global Environmental Change*, Elsevier Ltd, 56(April 2018), 66–74.

Lawson, E., Farmani, R., Woodley, E., and Butler, D. (2020). “A Resilient and Sustainable Water Sector: Barriers to the Operationalisation of Resilience.” *Sustainability*, 12(5), 1797.

Lempert, R. J., Popper, S. W., and Bankes, S. C. (2004). “Shaping the Next One Hundred Years: New Methods for Quantitative, Long-Term Policy Analysis.” *Technological Forecasting and Social Change*, 71(3), 305–307.

Liao, K.-H. (2012). “A Theory on Urban Resilience to Floods--A Basis for Alternative Planning Practices.” *Ecology and Society*, 17(4), art48.

Little, R. G. (2002). “Controlling cascading failure: Understanding the vulnerabilities of interconnected infrastructures.” *Journal of Urban Technology*, 9(1), 109–123.

Mafabi, S., Munene, J., and Ntayi, J. (2012). “Knowledge management and organisational resilience.” *Journal of Strategy and Management*, 5(1), 57–80.

Makropoulos, C. (2017). “Thinking platforms for smarter urban water systems: fusing technical and socio-economic models and tools.” *Geological Society, London, Special Publications*, 408(1), 201–219.

Makropoulos, C. K., and Butler, D. (2010). “Distributed Water Infrastructure for Sustainable Communities.” *Water Resources Management*, 24(11), 2795–2816.

Makropoulos, C. K., Natsis, K., Liu, S., Mittas, K., and Butler, D. (2008). “Decision support for sustainable option selection in integrated urban water management.” *Environmental Modelling and Software*, 23(12), 1448–1460.

Makropoulos, C., Nikolopoulos, D., Palmen, L., Kools, S., Segrave, A., Vries, D., Koop, S., van Alphen, H. J., Vonk, E., van Thienen, P., Rozos, E., and Medema, G. (2018). “A resilience assessment method for urban water systems.” *Urban Water Journal*, Taylor & Francis, 15(4), 316–328.

Mallet, R. (1856). *On the Physical Conditions involved in the Construction of Artillery: an Investigation of the Relative and Absolute Values of the Materials Principally Employed and of Some Hitherto Unexplained Causes of the Destruction of the Canon in Service.* Longmans, Brown, Green, Longmans, and Roberts, London, UK.

Mallet, R. (1862). *The First Principles of Observational Seismology as developed in the Report to the Royal Society of London to Investigate the Circumstances of the Great Earthquake of December 1857*. Chapman and Hall, London, UK.

McDaniels, T., Chang, S., Peterson, K., Mikawoz, J., and Reed, D. (2007). “Empirical Framework for Characterizing Infrastructure Failure Interdependencies.” *Journal of Infrastructure Systems*, 13(3), 175–184.

Meerow, S., and Newell, J. P. (2015). “Resilience and Complexity: A Bibliometric Review and Prospects for Industrial Ecology.” *Journal of Industrial Ecology*, 19(2), 236–251.

Meerow, S., Newell, J. P., and Stults, M. (2016). “Defining urban resilience: A review.” *Landscape and Urban Planning*, Elsevier B.V., 147, 38–49.

Merriman, M. (1885). *A Text-book on the Mechanics of Materials and of Beams, Columns and Shafts, First Edition. New York: J. Wiley and sons.* John Wiley and Sons, New York, NY, USA.

Mugume, S. N., Gomez, D. E., Fu, G., Farmani, R., and Butler, D. (2015). “A global analysis approach for investigating structural resilience in urban drainage systems.” *Water Research*, Elsevier Ltd, 81, 15–26.

Munoz, A., Billsberry, J., and Ambrosini, V. (2022). “Resilience, robustness, and antifragility: Towards an appreciation of distinct organizational responses to adversity.” *International Journal of Management Reviews*, 24(2), 181–187.

Nelson, D. R., Adger, W. N., and Brown, K. (2007). “Adaptation to Environmental Change: Contributions of a Resilience Framework.” *Annual Review of Environment and Resources*, 32(1), 395–419.

Nikolopoulos, D. (2024). “Resilience assessment of cyber-physical water systems.” National Technical University of Athens.

Nikolopoulos, D., van Alphen, H.-J., Vries, D., Palmen, L., Koop, S., van Thienen, P., Medema, G., and Makropoulos, C. (2019). “Tackling the ‘New Normal’: A Resilience Assessment Method Applied to Real-World Urban Water Systems.” *Water*, 11(2), 330.

Nikolopoulos, D., Kossieris, P., Tsoukalas, I., and Makropoulos, C. (2022a). “Stress-Testing Framework for Urban Water Systems: A Source to Tap Approach for Stochastic Resilience Assessment.” *Water*, 14(2), 154.

Nikolopoulos, D., Moraitis, G., Karavokiros, G., Bouziotas, D., and Makropoulos, C. (2022b). “Stress-Testing Alternative Water Quality Sensor Designs under Cyber-Physical Attack Scenarios.” *EWaS5*, MDPI, Basel Switzerland, 17.

O’Neil, R. V., DeAngels, D. I., Waide, J. B., and Allen, T. F. H. (1994). *A Hierarchical Concept of Ecosystems*. (R. May, ed.), Princeton Universtiy Press, Princeton, New York.

O’Neill, B. C., Kriegler, E., Ebi, K. L., Kemp-Benedict, E., Riahi, K., Rothman, D. S., van Ruijven, B. J., van Vuuren, D. P., Birkmann, J., Kok, K., Levy, M., and Solecki, W. (2017). “The roads ahead: Narratives for shared socioeconomic pathways describing world futures in the 21st century.” *Global Environmental Change*, 42, 169–180.

Pahl-Wostl, C., Jeffrey, P., Isendahl, N., and Brugnach, M. (2011). “Maturing the New Water Management Paradigm: Progressing from Aspiration to Practice.” *Water Resources Management*, 25(3), 837–856.

Panteli, M., and Mancarella, P. (2015). “The Grid: Stronger, Bigger, Smarter?: Presenting a Conceptual Framework of Power System Resilience.” *IEEE Power and Energy Magazine*, 13(3), 58–66.

Perrow, C. (1999). *Normal Accidents: Living With High-Risk Technologies*. Princeton University Press, Princeton, NJ.

Pimm, S. L. (1984). “The complexity and stability of ecosystems.” *Nature*, 307(5949), 321–326.

Pimm, S. L. (1991). *The balance of nature: ecological issues in the conservation of species and communities*. University of Chicago Press, Chicago, Usa.

Poulin, C., and Kane, M. B. (2021). “Infrastructure resilience curves: Performance measures and summary metrics." *Reliability Engineering & System Safety*, 216, 107926.

Ramphal, S. (2018). "Advance the New Normal, exploring water-energy-waste partnerships." *IWA*, <http://www.iwa-network.org/advance-the-new-normal-exploring-water-energy-waste-partnerships/> (Nov. 1, 2018).

Redman, C. L. (2014). "Should Sustainability and Resilience Be Combined or Remain Distinct Pursuits?" *Ecology and Society*, 19(2), art37.

Riahi, K., van Vuuren, D. P., Kriegler, E., Edmonds, J., O'Neill, B. C., Fujimori, S., Bauer, N., Calvin, K., Dellink, R., Fricko, O., Lutz, W., Popp, A., Cuaresma, J. C., KC, S., Leimbach, M., Jiang, L., Kram, T., Rao, S., Emmerling, J., Ebi, K., Hasegawa, T., Havlik, P., Humpenöder, F., Da Silva, L. A., Smith, S., Stehfest, E., Bosetti, V., Eom, J., Gernaat, D., Masui, T., Rogelj, J., Strefler, J., Drouet, L., Krey, V., Luderer, G., Harmsen, M., Takahashi, K., Baumstark, L., Doelman, J. C., Kainuma, M., Klimont, Z., Marangoni, G., Lotze-Campen, H., Obersteiner, M., Tabeau, A., and Tavoni, M. (2017). "The Shared Socioeconomic Pathways and their energy, land use, and greenhouse gas emissions implications: An overview." *Global Environmental Change*, 42, 153–168.

Rodina, L. (2019). "Defining 'water resilience': Debates, concepts, approaches, and gaps." *WIREs Water*, 6(2), 1–18.

Rose, A. (2007). "Economic resilience to natural and man-made disasters: Multidisciplinary origins and contextual dimensions." *Environmental Hazards*, 7(4), 383–398.

Rozos, E., and Makropoulos, C. (2012). "Assessing the combined benefits of water recycling technologies by modelling the total urban water cycle." *Urban Water Journal*, 9(1), 1–10.

Rozos, E., and Makropoulos, C. (2013). "Source to tap urban water cycle modelling." *Environmental Modelling & Software*, 41, 139–150.

Rozos, E., Makropoulos, C., and Maksimović, Č. (2013). "Rethinking urban areas: An example of an integrated blue-green approach." *Water Science and Technology: Water Supply*, 13(6), 1534–1542.

Salinas Rodriguez, C. N. A., Ashley, R., Gersonius, B., Rijke, J., Pathirana, A., and Zevenbergen, C. (2014). "Incorporation and application of resilience in the context of water-sensitive urban design: linking European and Australian perspectives." *Wiley Interdisciplinary Reviews: Water*, 1(2), 173–186.

Savic, D. (2005). "Coping With Risk And Uncertainty In Urban Water Infrastructure Rehabilitation Planning." *Acqua e citta- I convegno nazionale di idraulica urbana*, Centro Studi Idraulica Urbana (CSDU), Milano, 2005, Sant'Angello (NA),28-30 Septermber 2005.

Schlüter, M., and Pahl-Wostl, C. (2007). "Mechanisms of Resilience in Common-pool Resource Management Systems: an Agent-based Model of Water Use in a River Basin." *Ecology and Society*, 12(2), art4.

Selvakumar, A., and Tafuri, A. N. (2012). "Rehabilitation of Aging Water Infrastructure Systems: Key Challenges and Issues." *Journal of Infrastructure Systems*, 18(3), 202–209.

Sharifi, A., and Yamagata, Y. (2016). "Principles and criteria for assessing urban energy resilience: A literature review." *Renewable and Sustainable Energy Reviews*, 60, 1654–1677.

Shin, S., Lee, S., Judi, D., Parvania, M., Goharian, E., McPherson, T., and Burian, S. (2018). "A Systematic Review of Quantitative Resilience Measures for Water Infrastructure Systems." *Water*, 10(2), 164.

Sovacool, B. K., and Mukherjee, I. (2011). "Conceptualizing and measuring energy security: A synthesized approach." *Energy*, Elsevier Ltd, 36(8), 5343–5355.

Stakhiv, E. Z. (2011). "Pragmatic Approaches for Water Management Under Climate Change Uncertainty1." *JAWRA Journal of the American Water Resources Association*, 47(6), 1183–1196.

Taleb, N. N. (2012). *Antifragile: things that gain from disorder*. Random House, New York.

Thurston, R. H. (1874). "On the strength, elasticity, ductility and resilience of materials of machine construction." *Journal of the Franklin Institute*, 97(5), 344–356.

Tilman, D., and Downing, J. A. (1994). "Biodiversity and stability in grasslands." *Nature*, 367(6461), 363–365.

Todini, E. (2000). "Looped water distribution networks design using a resilience index based heuristic approach." *Urban Water*, 2(2), 115–122.

Tompkins, E. L., and Adger, W. N. (2004). "Does Adaptive Management of Natural Resources Enhance Resilience to Climate Change?" *Ecology and Society*, 9(2), art10.

Tredgold, T. (1818). "XXXVII. On the transverse strength and resilience of timber." *The Philosophical Magazine*, 51(239), 214–216.

Tyler, S., and Moench, M. (2012). "A framework for urban climate resilience." *Climate and Development*, 4(4), 311–326.

Vale, L. J. (2014). "The politics of resilient cities: Whose resilience and whose city?" *Building Research and Information*, 42(2), 191–201.

Ventana Systems, I. (n.d.). "User Guide - Vensim Introduction & Tutorials." <https://vensim.com/documentation/users_guide.html>.

Wada, Y., Flörke, M., Hanasaki, N., Eisner, S., Fischer, G., Tramberend, S., Satoh, Y., van Vliet, M. T. H., Yillia, P., Ringler, C., Burek, P., and Wiberg, D. (2016). "Modeling global water use for the 21st century: the Water Futures and Solutions (WFaS) initiative and its approaches." *Geoscientific Model Development*, 9(1), 175–222.

Walker, B. H., Ludwig, D., Holling, C. S., and Peterman, R. M. (1981). "Stability of Semi-Arid Savanna Grazing Systems." *The Journal of Ecology*, 69(2), 473.

Walker, B., Holling, C. S., Carpenter, S. R., and Kinzig, A. P. (2004). "Resilience, Adaptability and Transformability in Social-ecological Systems." *Ecology and Society*, 9(2), art5.

Walker, B., and Salt, D. (2006). *Resilience thinking: Sustaining ecosystems and people in a changing world*. Island Press, Washington, DC.

Walker, W. E., Lempert, R. J., and Kwakkel, J. H. (2013). "Deep Uncertainty." *Encyclopedia of Operations Research and Management Science*, Springer US, Boston, MA, 395–402.

Wang, S., Fu, J., and Wang, H. (2019). "Unified and rapid assessment of climate resilience of urban drainage system by means of resilience profile graphs for synthetic and real (persistent) rains." *Water Research*, Elsevier Ltd, 162, 11–21.

Wardekker, J. A., de Jong, A., Knoop, J. M., and van der Sluijs, J. P. (2010). "Operationalising a resilience approach to adapting an urban delta to uncertain climate changes." *Technological Forecasting and Social Change*, Elsevier Inc., 77(6), 987–998.

Westley, F., Olsson, P., Folke, C., Homer-Dixon, T., Vredenburg, H., Loorbach, D., Thompson, J., Nilsson, M., Lambin, E., Sendzimir, J., Banerjee, B., Galaz, V., and van der Leeuw, S. (2011). "Tipping Toward Sustainability: Emerging Pathways of Transformation." *AMBIO*, 40(7), 762–780.

Wildavsky, A. (1988). *Searching for safety*. Transaction Publishers, New Brunswick, NJ.

Wilkinson, C. (2012). "Social-ecological resilience: Insights and issues for planning theory." *Planning Theory*, 11(2), 148–169.

Wong, T. H. F., and Brown, R. R. (2009). "The water sensitive city: principles for practice." *Water Science and Technology*, 60(3), 673–682.

WWAP, U. W. W. A. P. (2019). *The United NationsWorld Water Development Report 2019: Leaving No One Behind.* Paris, France.

Xu, L., and Marinova, D. (2013). "Resilience thinking: a bibliometric analysis of socio-ecological research." *Scientometrics*, 96(3), 911–927.

Zahediasl, A., Bakhshipour, A. E., Dittmer, U., and Haghighi, A. (2021). "Toward decentralised sanitary sewage collection systems: A multiobjective approach for cost-effective and resilient designs." *Water (Switzerland)*, 13(14).

In case of any questions, please contact:

Dionysios Nikolopoulos

Task 4.1 Leader

Contact: nikolopoulosdio@central.ntua.gr

This project has received funding from the European Union's Horizon Europe research and innovation programme under grant agreement No. 101136598. This document reflects only the views of RECREATE consortium, neither the European Commission nor any associated parties are responsible for any use that may be made of the information it contains.