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Assessing the resilience of circularity in water management: a modeling framework to redesign and stress-test regional systems under uncertainty

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ABSTRACT
Contrary to the 'make-use-dispose' linearity of conventional management, circular economy design principles have been proposed as a resource management alternative that reduces waste and promotes efficiency. These principles also find use in water management, offering an alternative against centralized models. Despite the intrinsic links between circularity and resilience, few studies have advanced the identification and discussion of linkage beyond a theoretical or conceptual level. This study presents quantitative links between circularity and resilience, by demonstrating how different circular water management strategies lead to improved resilience performance for a regional urban-rural water system. A stress-testing framework based on a water cycle model is presented, where different circular interventions are evaluated in terms of their overall resilience against future uncertainty. The results demonstrate that circular water options lead to more resilient water systems. The more circular dimensions are addressed through interventions, the more robust resilience profiles become across different water cycle domains.

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Resilience; water simulation; sustainability; circular economy; urban water cycle models; decentralised technologies

1. Introduction

Circular economy (CE) has been proposed as a promising alternative to the linear 'make-use-dispose' resource management models conventionally used in human societies, which are known to contribute to pollution, excessive waste production and environmental degradation (Stahel 2016). CE works by introducing return loops to linear management models and ensuring that a resource is used more extensively – and for different uses – in the system before being safely disposed. It does so through the so-called fundamental '3 R' dimensions of (a.) reducing resource demands at the consumer level, (b.) reusing resources as much as possible to minimize waste, (c.) recycling waste back to resource (Heshmati 2017; Goyal, Esposito, and Kapoor 2018).

Most discussions about the principles of CE revolve around economic flows and materials. However, the same principles are also applicable to water systems (WS) (Sauvé et al. 2021), where there is a need to reconsider conventional, centralized management strategies that collect, transfer and dispose water in a linear fashion. With regard to the application of CE principles in water, it is useful to view decentralized reduce-reuse-recycle interventions as building blocks of a transition towards a circular water system (Bouziotas et al. 2019). A circular water system can be defined as a system with a water management strategy that introduces loops, promotes circularity and maximizes the value of clean water provided by its sources. Viewing water as a resource in CE has received increasing importance in recent years, with ongoing large projects that focus on the transition of the water sector towards circularity at both national and international levels (Morseletto, Mooren, and Munaretto 2022). This importance can be also viewed by the growing body of published works where the role of water in the CE is explored (Morseletto, Mooren, and Munaretto 2022; Nika et al. 2020; Arup and E.M.F. 2018).

As a cyclic management practice which bears resemblance to natural system behaviour, CE is conceptually linked to both sustainability and resilience (Kennedy and Linnenluecke 2022; Suárez-Eiroa, Fernández, and Méndez 2021; Geissdoerfer et al. 2017). CE has been only recently conceptually integrated within the sustainable development framework (Suárez-Eiroa et al. 2019; Morseletto 2022), while recent studies acknowledge that further integration with resilience thinking is nascent and is clearly needed (Suárez-Eiroa, Fernández, and Méndez 2021; Kennedy and Linnenluecke 2022), as resilience can be viewed as a prerequisite to sustainability (Suárez-Eiroa, Fernández, and Méndez 2021). Evidently, this intuitive link is only infrequently backed by quantitative methods that demonstrate how different CE measures contribute towards a more sustainable and resilient system (Suárez-Eiroa, Fernández, and Méndez 2021), with most of the proposed frameworks reaching only the conceptual level (Nika et al. 2020; Moreno et al. 2016). Likewise, in the context of water, individual and combined decentralized options have been shown to contribute towards more sustainable (Lee, Younos, and Parece 2022; Makropoulos and Butler 2010) and more resilient (Helmrich et al. 2021) urban water

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systems (UWS), but a unifying framework that quantifies integrated, circular water strategies and also evaluates their resilience against future uncertainty is lacking, especially when real cases at large spatial scales are considered.

Aiming to contribute towards this direction, this study presents a simulation-based framework for the design, quantification and evaluation of different circular water strategies at a regional (provincial) scale, as well as the assessment of their resilience for a range of possible futures (Makropoulos et al. 2008). Based on previous works about circularity for water at a neighbourhood scale (Bouziotas et al. 2019) and about urban water system resilience in general, defined as the degree to which an urban water system continues to perform under progressively increasing disturbance (Makropoulos et al. 2018; Nikolopoulos et al. 2019), the framework uses a simulation testbed to quantify the hydrological response of the provincial water system and evaluate the performance of different circular strategies at different domains of the water cycle, i.e. drinking water (DW), wastewater (WW), irrigation water for horticulture and rainwater-runoff (RW). Besides a comparative performance evaluation, the framework explores the resilience of different strategies and proposes relevant key performance indicators (KPIs), which are system properties, related to water quantity and derived from simulation, that can be easily communicated to decision-makers. The proposed framework supports, using evidence-based information, provincial stakeholders to compare different circular strategies, quantify their vision of circularity in the water system and evaluate both their utility in present-day conditions and their ability to cope with uncertain futures. The framework is applied in the real-world case of Delfland, a large, integrated urban-rural water system (URWS) representing a province in the Netherlands that includes urban zones as well as significant horticulture areas, in order to evaluate the performance and assess the resilience of four different regional circular water system redesigns.

2. Materials and methods

2.1. Circularity in water and the role of strategic planning

CE is a promising paradigm to transform unsustainable linear production-consumption systems and increase the share of renewable and recycled resources (Suárez-Eiroa, Fernández, and Méndez 2021), with the main goal of adjusting the system to the requirements of environmental sustainability (Suárez-Eiroa et al. 2019). To further define circularity in the context of water, and in line with recent advances, this study utilizes the definition seen in Morseletto, Mooren, and Munaretto (2022), considering CE for water as 'a paradigm for reducing, preserving and optimising the use of water, as a primary resource, through waste avoidance, efficient utilisation and quality retention while ensuring environmental protection and conservation'. CE is further operationalized through the so-called R frameworks (Morseletto, Mooren, and Munaretto 2022; Kirchherr, Reike, and Hekkert 2017), which frame it as bundles of actions – known in literature as dimensions (Kirchherr, Reike, and Hekkert 2017) or strategies[1] (Blomsma and Brennan 2017; Morseletto, Mooren, and Munaretto 2022) – that promote circularity and help realise CE objectives. In this study, we employ the so-called 4 R framework (Kirchherr, Reike, and Hekkert 2017) that introduces resource recovery as the fourth 'R', expanding the 3 R-dimensional space of reduce-reuse-recycle explained in the previous section. This framework is at the core of the EU Waste Framework Directive (Backes 2020), with all four dimensions being referred to in the EU Circular Economy Action Plan (Domenech and Bahn-Walkowiak 2019) as well. To adapt this for WS, we further conceptualize the fourth 'R' as including the recovery of water at both the local scale (for example, locally recovered water using a constructed wetland) and at the larger scale of the natural water cycle, i.e. replenished water in natural surface bodies, aquifers and other sources. To better communicate this inclusion, we hereinafter refer to the fourth dimension of circularity with the inclusive term 'Recover-Replenish-Restore', where: (a.) recovery refers to the production of clean water from effluent at the local scale, (b.) replenishment refers to the managed replacement of water back to surface or ground sources, and (c.) restoration refers to the reversal of degraded water-related systems to a state that preserves relevant ecosystems. This fourth dimension is aligned with other proposed extensions of the 3 R framework to the water sector found in literature, such as the 6 R framework (Kakwani and Kalbar 2020) that further separates resource recovery and restoration in three individual dimensions (recover, reclaim, restore). We also focus on the provision, (re-)use, recycling and recovery of water as the primary resource of interest, thus excluding other aspects of circular water (re-)use comprising multiple resources, such as water-energy interactions or obtaining nutrients from urban water streams (Plevri et al. 2020).

In the context of urban water management, every dimension of this 4 R framework can be addressed by creating loops in the predominantly linear (i.e. produce-use-dispose) management practice (Haski-Leventhal 2020) and introducing an array of centralized or decentralized interventions at different scales within a regional water system. In contrast to linear water management, we thus define circular WS as systems that introduce such loops and include both centralized and decentralized options targeting some or all of the '4 R' dimensions. An analogous concept has been explained at the neighbourhood level in previous research (Bouziotas et al. 2019). These interventions may target one or multiple streams of urban water (such as drinking water (DW), wastewater (WW), rainwater (RW) or its consequent runoff-stormwater (SW)), and are known with a plethora of terms (Makropoulos and Butler 2010; Fletcher et al. 2015). Key technology examples of relevance to this regional study that contribute to circularity are: (a) Rainwater Harvesting (RWH) interventions (Jamali, Bach, and Deletic 2020), aiming at capturing, storing and treating rainwater at a local or regional scale, (b) Greywater Recycling (GWR) interventions (Memon et al. 2007), aiming at treating and recycling light (grey) wastewater streams produced by households at a local or decentralized scale, (c) Sustainable Urban Drainage (SUDS) (Fletcher et al. 2015), which is an umbrella term for decentralized interventions that aim at draining, retaining and storing SW at a local or decentralized scale, (d) Green-Blue (GB) areas (Rozos, Makropoulos, and Maksimović 2013) which are stormwater management practices co-designed within urban green spaces, (e) nature-based solutions (NBS), a term to describe solutions inspired and supported by nature, aimed at protecting, managing and restoring ecosystems (Oral et al. 2020; Ghafourian et al. 2021), (f) subsurface management solutions such as Aquifer Storage and Recovery (ASR) and Managed Aquifer Recharge (MAR) (Alam et al. 2021), aiming at recharging subsurface water and/or efficiently recovering water from the subsurface, (g) wastewater treatment plant (WWTP) effluent treatment and reuse for irrigation, industry or groundwater replenishment (Pronk et al. 2021). While these examples are not exhaustive, they constitute basic building blocks of decentralized water management that contribute towards circularity in the province, as they are conceptually linked to one or more of the 4 R circularity dimensions. The way these interventions contribute towards circularity dimensions is further analysed in Appendix A.

The application of CE concepts in water is frequently viewed as a combination of (some of) the aforementioned 4 R framework dimensions, but it also necessitates a shift in perspective across influential stakeholders and has to be backed by a strategic vision towards circularity (Kirchherr, Reike, and Hekkert 2017; Morseletto, Mooren, and Munaretto 2022), leading to structural changes in the water system. To enable the transition towards circular WS, we describe a circular water strategy as a tangible, comprehensive plan towards circularity in a region or city that can be easily communicated among stakeholder groups. The vision comes with a clear narrative, a set time horizon and domain-specific goals on how to perform the transition towards a circular water system. Such a transition depends on the water system's characteristics and embedded context (Arup and E.M.F. 2018), in which different technological, regulatory, socio-cultural and economic factors can act as barriers or drivers (Afghani, Hamhaber, and Frijns 2022). Circular water strategies can be simple or more ambitious, depending on the available investment, as well as the corresponding intensity, scale and complexity of the interventions that are included; targeting one or many of the 4R dimensions. A tabular overview of the way different interventions contribute towards the 4 R dimensions and how they are connected in the proposed circular strategies of the case study is provided in Appendix A.

2.2. A simulation-based framework to (re-)design and stress-test circular water systems

Circular water technologies may be introduced at any combination and at multiple scales in a water system, from smaller spatial units, such as circular water neighbourhoods or households with RWH/GWR (Bouziotas et al. 2019), to regional interventions, such as blue-green recreational areas or water banking systems (Bacchin et al. 2014; Megdal and Dillon 2015). Regardless of the combination and scale of their application, introducing these circular interventions in an integrated fashion leads to multiple effects on urban water cycle domains (DW, WW, SW). When multiple circular interventions are combined, these effects need to be managed and quantified in unison, otherwise the effects of particular interventions and the overarching strategy on all of these domains cannot be evaluated. In the DW domain, there is reduction in the clean water requested from central services, as regions increase their autonomy and recycle water resources. Local sources, such as RW, are captured and used in place, while the introduction of a RWH scheme also affects SW retention leading to a slower and lower runoff response at the outlet. Finally, part of the generated WW in the neighbourhood is reclaimed, treated locally and reused, thus reducing the quantity of WW propagated downstream, e.g. to centralized sewer services.

In a quantitative assessment framework, these multi-domain effects need to be part of an integrated performance assessment that is inclusive of all considered water management dimensions (DW, WW, SW) and evaluates them in a systematic way to allow the estimation of their effects. Moreover, such an integrated framework needs to allow for a cross-comparison of multiple combinations of circular water strategies (i.e. different circular redesigns of the water system) and also reach beyond the urban water cycle to quantify the impact of external driving factors, such as climate change, behavioural client shifts, demographic changes etc., in order to account for the deep uncertainty influencing water management. These driving factors are also directly related to the system resilience as they are considered stressors of the uncertain future (Makropoulos et al. 2008).

To quantify the resilience of circular options, this study uses an assessment framework that relies on water cycle model simulation (Mitchell, Mein, and McMahon 2001) as a technique to mimic the response of the whole system ex ante. The simulation testbed that is used is the Urban Water Optioneering Tool (UWOT), a model developed by the Urban Water Management and Hydroinfromatics (UWMH) Group of the National Technical University of Athens (NTUA)[2] able to simulate the complete urban and peri-urban water cycle by modelling individual water uses and technologies/options for managing them at multiple scales (Rozos and Makropoulos 2013). UWOT simulates water cycle flows at multiple domains, i.e. potable water, wastewater and runoff, as well as their integration in terms of harvesting, reuse and recycling at different scales (from the household and neighbourhood up to the city scale) (Rozos, Makropoulos, and Maksimović 2013), so it's by definition fit for the application of circular water in question. The use of this simulation model against other options for Delfland is justified by the accumulated experience of applications in circular water systems in Dutch settings (Bouziotas et al. 2019; Nikolopoulos et al. 2019). Moreover, the model has affinity with most circular intervention options, which can be readily included as model components as they have been developed in previous studies (Rozos, Makropoulos, and Maksimović 2013).

Using a simulation testbed such as UWOT provides a detailed picture of the whole system response – in terms of requested DW, produced WW and simulated runoff – for a given (re)design that includes a specific combination of technologies. The framework then combines the simulation testbed with Key Performance Indicators (KPIs) that transform raw model output, which comes in the form of daily timeseries for water cycle streams (DW, SW, and WW), to statistical quantities meaningful to decision-making. The methodology has been described in detail in a previous study for the neighbourhood level (Bouziotas et al. 2019), but is extended in this study so as to: (a) be applied to regional (urban and peri-urban) systems and include corresponding regional technologies, such as

SUDS and water banking, (b) include KPIs specifically for resilience, (c) pair with the notion of circular water strategies, used to design comprehensive scenarios of interventions, (d) run recursively over different scenarios of stressors, while past applications only focused on baseline conditions.

A schematic view of the assessment framework is provided in Figure 1, comprising the following steps (also numbered in the schematic):

(1) Formulation and selection of a circular water strategy, i.e. a comprehensive view of the changes that need to be materialized in the system to transform it into a circular one.
(2) Operationalization of the selected strategy, where a mapping between the vision for CE in water and the corresponding interventions that need to be materialized is created. The end result of this step is a list of circular water interventions aligning with the selected strategy and conforming to other limitations, such as the proposed time horizon of realization and budgeting. Further operationalization is performed by bridging the selected interventions to the modeling domain (Bouziotas et al. 2019), i.e. modeling them as UWOT components and parts of the signal-based model topology.
(3) Stress-testing the selected strategy against one scenario of stressors. At this step, external driving factors (in terms of climate, demographics, social drivers etc.) typical of the present-day or possible future conditions are chosen and parameterized in UWOT. The selected strategy can be then simulated and raw model output is generated, in terms of time series of DW, SW, WW and water used in horticulture.
(4) Reduction of the complexity of raw output data by calculating KPIs (scalars, representing different statistics) from the output time series of UWOT. Specific KPIs that correspond to system resilience are conceptualized as part of this study and are described in the sections that follow.
(5) Formulation of more scenarios of stressors and stress-testing the selected strategy for an array of possible futures. This iteration is a crucial step in resilience assessment, allowing calculation of resilience metrics, where the system response is evaluated against multiple futures with stressors of varying magnitude (Makropoulos et al. 2018). A relevant definition of resilience that is defined vis-à-vis multiple future scenarios is given in the section that follows.
(6) Evaluation of the performance of the selected circular strategy by reflecting on the overall resilience and corresponding KPI values.

The proposed framework is demonstrated in a regional application in this study, where KPIs directly related to the system resilience are calculated for a set of different circular water strategies and for a range of possible futures. The demonstration is twofold, including an analysis against different individual stressor values, as well as a probabilistic analysis against multiple scenarios of combined stressors.

2.3. *Circularity and resilience: conceptual links and definitions*

To proceed with the application of the assessment framework, one first needs to conceptualize the concept of resilience for water systems. Following previous work on operationalizing resilience for urban water (Makropoulos et al. 2018; Nikolopoulos et al. 2019), this study uses an operational definition where resilience is connected to a simulation-based, stress-testing framework and defined as 'the degree to which a WS continues its designed performance under progressively increasing disturbance' (Makropoulos et al. 2018). Besides urban water, this definition is consistent with how resilience is interpreted in CE

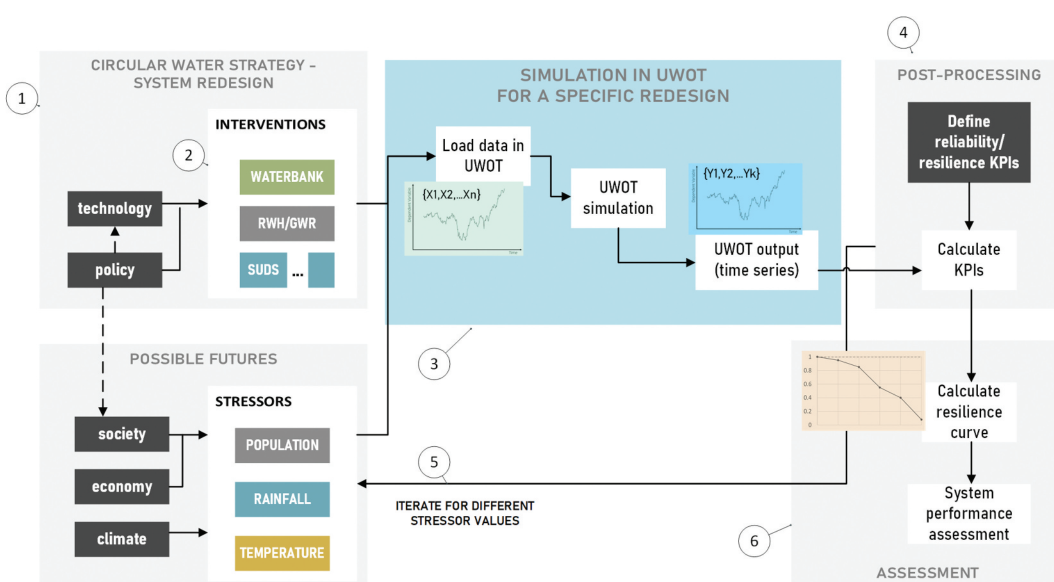

Figure 1. Schematic overview of the proposed resilience assessment framework for circular water systems.

literature as 'the ability of ecosystems and human society to cope with – and continue functioning after – shocks and disturbances that may lead to change' (Kennedy and Linnenluecke 2022). Using this definition, the quantitative response of the system can be then evaluated, with the use of a model, for a number of increasingly severe future scenarios, and special types of curves termed 'resilience profile graphs' can be drawn to communicate the performance of the system to meet its objective through a metric of reliability (in the y-axis), while the x-axis describes the

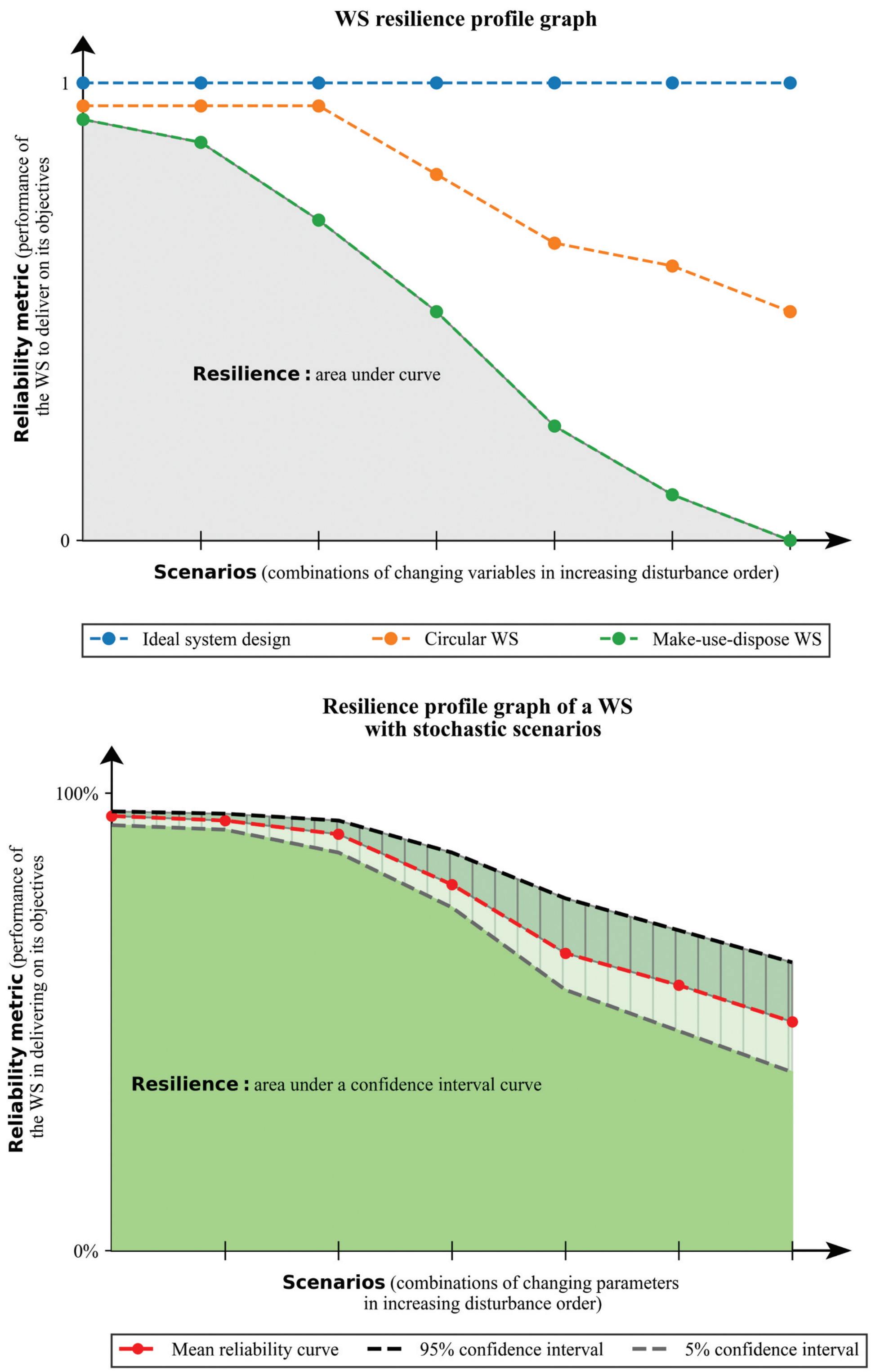

Figure 2. The concept of resilience profile graphs, adapted for circular water systems.

scenarios of increasing disturbance. The graphic profile can be thus constructed from a given (re-)design of the water system (i.e. comprising all centralized and decentralized water management (WM) measures in place) and resilience is measured as the area under the curve, i.e. the integral of reliability over all future scenarios. To scale resilience in [0,1], this area is compared to the idealized situation of a fully reliable and robust design across all future scenarios.

Figure 2 (upper panel) displays these concepts as a series of resilience profile graphs, with the ideal system design being a horizontal line of perfect reliability (i.e. 1.0) across all scenarios, while real water system designs display a loss of reliability that increases as the possible future stress scenarios become more severe. Arguably, if circularity is positively connected to resilience, the authors hypothesize that, when compared with the conventional, linear water management design, any circular water strategy and its corresponding redesign will result in increased resilience and, thus, a resilience profile graph closer to the ideal one, with increased reliability in present-day conditions and with higher retained reliability as stress increases (i.e. a decreasing slope of reliability loss). This hypothesis is reflected in Figure 2. In case of a probabilistic framework, there are stochastic properties in each variable leading to multiple realizations for each scenario; this results in resilience profile graphs appearing as envelopes of confidence interval curves, such as the curves presented in the bottom panel of Figure 2.

A question that follows from this definition is on what exactly constitutes a reliability metric R. In general, the reliability metric could be any quantity that describes the WS performance and the impact stressors have on its role and function (Nikolopoulos et al. 2021; Hashimoto, Stedinger, and Loucks 1982). In a simulation-based framework, this metric can be derived from the output of a model of the WS, e.g. a water resources or a hydrological model, and is further divided in two main categories (Makropoulos et al. 2018):

(1) event- (or time-)based reliability R_t, defined in a simulation-based environment as the portion of time (%) that the system operated well. This is generally defined as:

$$R_t = 1 - P_f = 1 - \frac{n_f}{n_{total}} \quad (1)$$

where P_f is the probability of failure or inefficiency (Bouziotas et al. 2019; Moraitis et al. 2020), equivalent to the relative frequency of failed/inefficient time steps n_f against the total time steps of simulation n_{total}. This is the most typical definition of reliability seen in literature (Makropoulos et al. 2018), related to the relative frequency of interruptions as an approximation of probability.

(2) volumetric reliability R_V, defined in a simulation-based environment as the ratio of delivered (serviced) water volume to the demanded (requested) volume by the end users:

$$R_V = \frac{\sum_t V_{supply}}{\sum_t V_{demand}} = 1 - \frac{\sum_t V_{deficit}}{\sum_t V_{demand}} \quad (2)$$

where V_{supply} is the supplied volume of water, V_{demand} is the requested volume of water and $V_{deficit}$ is the resulting demand deficit, in case supply cannot meet demand. The aggregation operator in eq. (2) denotes aggregation over a specific simulation period. While more uncommon, the volumetric reliability is useful for WS studies (Karim et al. 2021) as it is affected by the magnitude and intensity of failure, i.e. the quantity of non-serviced water, instead of the frequency, which affects event-based reliability.

By definition, both metrics lie in [0,1], with $R = 1$ meaning perfect reliability for the entire simulation and $R = 0$ meaning no reliability (i.e. failure at all time steps or zero serviced volume of water respectively). They are thus consistent with the intrinsic perception of reliability as a probability and the graphical constraints seen in Figure 2, where all individual points (reliability for a given stressor) lie in [0,1], with the upper threshold $y = 1$ representing the ideal situation.

2.4. The case study of delfland

The proposed framework is demonstrated in the region of Delfland, part of the western and most populated province in the Netherlands (South Holland). Spanning in a total area of c. 410 km^2, Delfland features urban and industrial areas of high density, as well as extensive greenhouse complexes in the Westland region used for horticulture. Delfland is one of the most densely populated spaces in the Netherlands, with approximately 1.2 million inhabitants living and working in a total of c. 520,000 households and 40,000 businesses and industries (Dijcker et al. 2017), so it has a strong potential to benefit from smarter circular water options.

The region is renowned for its intensive glasshouse horticulture, with many horticulture companies having irrigation demands in the range of 3000–10000 m^3/ha/year, depending on the crops grown. Horticulture companies in Westland presently rely on RWH through (shallow) water basins for demand coverage. With an average volume capacity of c. 800 m^3/ha, this system is widely used but cannot always cover demand peaks – particularly in dry, summer periods – and often cannot store all precipitation (particularly in winter), as the storage capacity is relatively low due to space limitations and property prices. This results in a mean annual irrigation water demand deficit that needs to be covered from other sources. Additional freshwater for irrigation is provided from brackish groundwater extraction and desalination by reverse osmosis. This currently used practice is unsustainable, as it leads to net withdrawals from the aquifer that are associated with further salinization and, in part of the area, with subsidence. Moreover, desalination produces a residual flow of saltier concentrate that is currently discharged by infiltration into the deeper subsurface, a practice currently under debate of not being in line with the Groundwater Directive (EEA 2006).

To prepare the regional case study for the proposed framework, available data from different sources (see Appendix B) are first collected, evaluated and inserted into one common database that includes spatial files and tabular data. The obtained data are used to model the baseline scenario in UWOT (abbr. BAU), which reflects the present-day, predominantly linear water management strategy (where all households are connected to the central DW system, while all greenhouses work with shallow basins). As a next step, pervious and impervious surfaces in urban zones are calculated and validated by aggregating land use raster data from the most recent year of reference (2018) (Büttner et al. 2004). The process, including collected data, validation, and insertion in the model, is described in more detail in Appendix B. For the rural domain, horticulture data are collected from recent works that employ sectoral water resource models (Stofberg et al. 2021; Stofberg and Zuurbier 2018), including horticulture areas, crop types and the corresponding demands, as well as shallow basin characteristics. Horticulture is then included in UWOT with a lumped approach, assuming that greenhouses from a specific company behave as a single characteristic Horticulture Unit (HU) that has specific seasonally variable demands and that features a shallow basin system, representative of the present-day design, to store rainwater. An arbitrary number of HUs can be then modeled, which for the current conditions in the region equals to 1291 (Stofberg et al. 2021). An overview of how the present-day topology is translated to the modeling domain of UWOT can be seen in Appendix B.

The formulation of a baseline scenario allows the model to be validated, as it represents the present-day reality that can be checked against real information collected from the water system. To validate the baseline, a combination of real data measurements (where possible) and model results are used to evaluate model accuracy across water cycle domains (DW, SW, WW). The results of the validation process are presented in detail in Appendix B; in general, UWOT is able to capture the present-day reality in terms of both urban water demands (as well as corresponding outflows) and horticulture irrigation demands and runoff, with a deviation from third-party results that is, on average, less than 5%.

3. Analysis - redesigning the system towards circularity

3.1. Formulation of circular water strategies

The first step in the simulation-based framework includes the selection of circular water strategies, i.e. the proposal of alternative setups for water management. These setups include a number of circular water interventions, at any or multiple of the included modeling domains (drinking water, stormwater management, wastewater and horticulture water management). Generally, these alternative setups are products of multiple factors (Ghisellini, Cialani, and Ulgiati 2016; Iacovidou, Hahladakis, and Purnell 2021), such as:

- introduction of new policies or policy changes, translating to WM interventions. Such a policy change is, for instance, legislation to actively support the uptake of rainwater harvesting (RWH) systems at neighborhoods or in urban parks.
- materializing a regional vision, i.e. a cross-sectoral master planning for the region that is linked to an integrated WM theme, such as climate change proofing, achieving circularity, or becoming water-smart. Despite the use of diverse terminology, these strategic actions generally involve one or multiple interventions that target one of the 4 R dimensions of CE (see also Table A2) and can be thus perceived as circular.
- behavioral or cultural shifts, for instance resulting from an increased level of customer awareness. An example of such a shift is the introduction of water-saving devices in houses, for instance due to a larger portion of customers becoming water-aware.
- upscaling a promising circular WM technology, such as Aquifer Storage and Recovery (ASR) or waterbanking to a regional level. Typically, these technologies are demonstrated first at a pilot level, before being upscaled to multiple sites at the region (Plevri et al. 2020). For Delfland, small-scale pilots exist for promising technologies, including a pilot for waterbanking under development, as well as a wastewater reuse pilot for greenhouse horticulture. It would be thus worthwhile to explore scenarios where pilots are upscaled and become regionally important.

With the aforementioned aspects in mind and to demonstrate the framework of Figure 1, a number of circular redesign scenarios are conceptualized for Delfland as part of this study. These scenarios represent redesigns that correspond to different circular water strategies of varying ambition and technological complexity that could be materialized within the present decade (end of 2030). They include an array of different circular intervention measures (see Appendix A) that conceptually follow each strategic narrative. These redesigns have the following narratives:

(1) The circular residence neighborhood (abbr. CIRCN) redesign, where circular technologies are introduced to a percentage of households in Delfland as a result of an active uptake policy that includes hybrid RWH/GWR systems in new houses and retrofitting in existing properties. As a result, *x*% of households in the region have a hybrid RWH/GWR system installed by 2030.
(2) The water-banking circular (abbr. WATBANK) redesign, where the circular household technologies seen in redesign (1) are complemented by active Demand Reduction Measures (DRMs) at the household level via the introduction of water-saving devices. Moreover, the concept of circularity extends in the horticulture system by introducing water banking at the regional level, where *c* greenhouse units (out of the 1291 total HUs in the regions) infiltrate excess rainwater to deeper groundwater layers. The use of water banking to cover horticulture needs is an upscaled version of the potential seen in local pilots (Stofberg et al. 2021).
(3) The green roof (abbr. GREEN) redesign, focusing on flood-proofing the region and using rainwater as a resource. In that regional strategy, RWH is extended beyond the household level and includes regional-scale interventions as well, such as green roofs in *y*% of office spaces and certain public impervious areas (*z*% of total impervious areas), as well as a waterbanking system for *c* green houses in Westland. As the focus of this strategy is now on rainwater retention, circular households do not contain a GWR system.

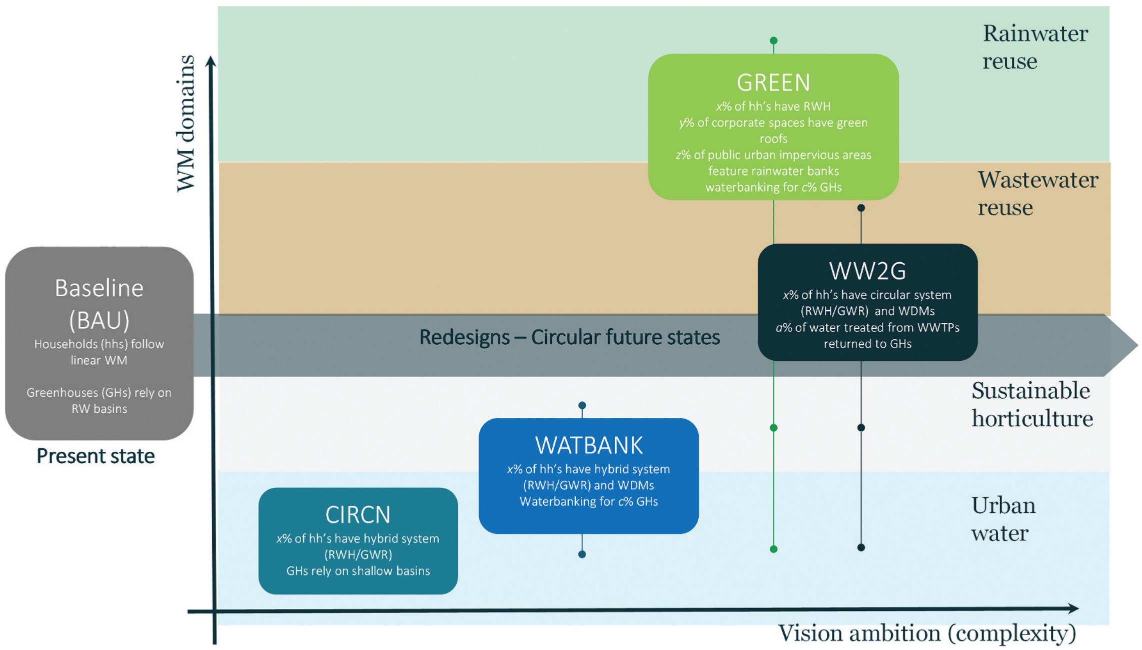

Figure 3. Mapping of the circular redesigns against their WM domain specificity and strategic complexity.

(4) The black to green (abbr. WW2G) redesign, where urban circularity technologies (including DRMs) are paired with the (re)use of urban wastewater effluent as a resource for horticulture in the region. In this, scenario the urban and rural domain of the URWS are connected by treating the waste from urban areas as a resource (to meet horticulture demands), through added treatment followed by infiltration of the treated effluent to groundwater layers in proximity to the groundwater withdrawal points of the HUs. The result is that, by 2030, *a*% of the water treated from one of the regional WWTPs will be reused to cover greenhouse demands deficits. The use of treated WW effluent to cover part of the horticulture needs is an upscaled version of the potential seen in local pilots (Krajenbrink et al. 2021).

The four circular water strategies are mapped, in terms of their strategic ambition and WM domain specificity, in Figure 3. The operationalization of each strategy (step (2) in the framework, see Figure 1) is realized by clarifying and communicating their parameters in a simple tabular manner, seen in Table A1 (Appendix A). This table is interpretable both by stakeholder groups and modeling experts and is then linked to the UWOT model through relevant internal (component) parameters. Moreover, Table A2 also includes the correlation of each strategy with the domains seen in the 4 R framework; evidently, more complex strategies (WATBANK, GREEN and WW2G) include interventions across different CE ('R') dimensions.

3.2. The impact of system redesigns under present-day conditions

Once formulated and parameterised, circular water strategies can be modeled with the use of UWOT. Corresponding model topologies are made using the model user interface (see Figure B2 in Appendix B), with each circular water strategy having a unique schematic to represent the interplay of different (linear and circular) WM interventions. The model topologies are then forced using present-day data, with UWOT producing results in terms of daily time-series, modeling water quantities in terms of DW, RW and corresponding runoff (SW), WW, and horticulture deficits.

In spite of the fine granularity of the output, perhaps the most efficient way to visualize circular flows is at the higher (i.e. interannual) level, with the use of Sankey diagrams. Sankey diagrams are visualizations originally developed for energy flows, but also useful in the context of CE and circularity in water systems (Curmi et al. 2013; Pronk et al. 2021). Here, to demonstrate how different circular strategies affect the water system, Sankey diagrams are developed to summarize average annual water flows (i.e. aggregate quantities obtained through simulation) between main system elements (e.g. source, transport or demand nodes) in the water system. This results in a visualized snapshot of the average annual water balance in the region. Parts where the model cannot yield detailed output (e.g. groundwater) are not included in the visualization to keep the presentation and its underlying assumptions simple. The results for all five topologies (four circular water redesigns, as well as the baseline (BAU) case) are shown in Figure 4, with panel (a) showing BAU results and the other panels showing circular water management strategies. The urban and the rural domain of the water system are separated and colored differently to highlight process differences and links. The proposed redesigns, as expected, introduce multiple circular loops in water flows; for instance, circular households with GWR introduce an internal, reuse loop in the CIRCN, WATBANK and WW2G scenarios, while a 'recycle' loop is introduced due to RWH for the same households, linking built surface with urban demands. Differences in horticulture management are also evident in panels (c), (d) and (e), as brackish water pumping is reduced from an annual average of 3.8

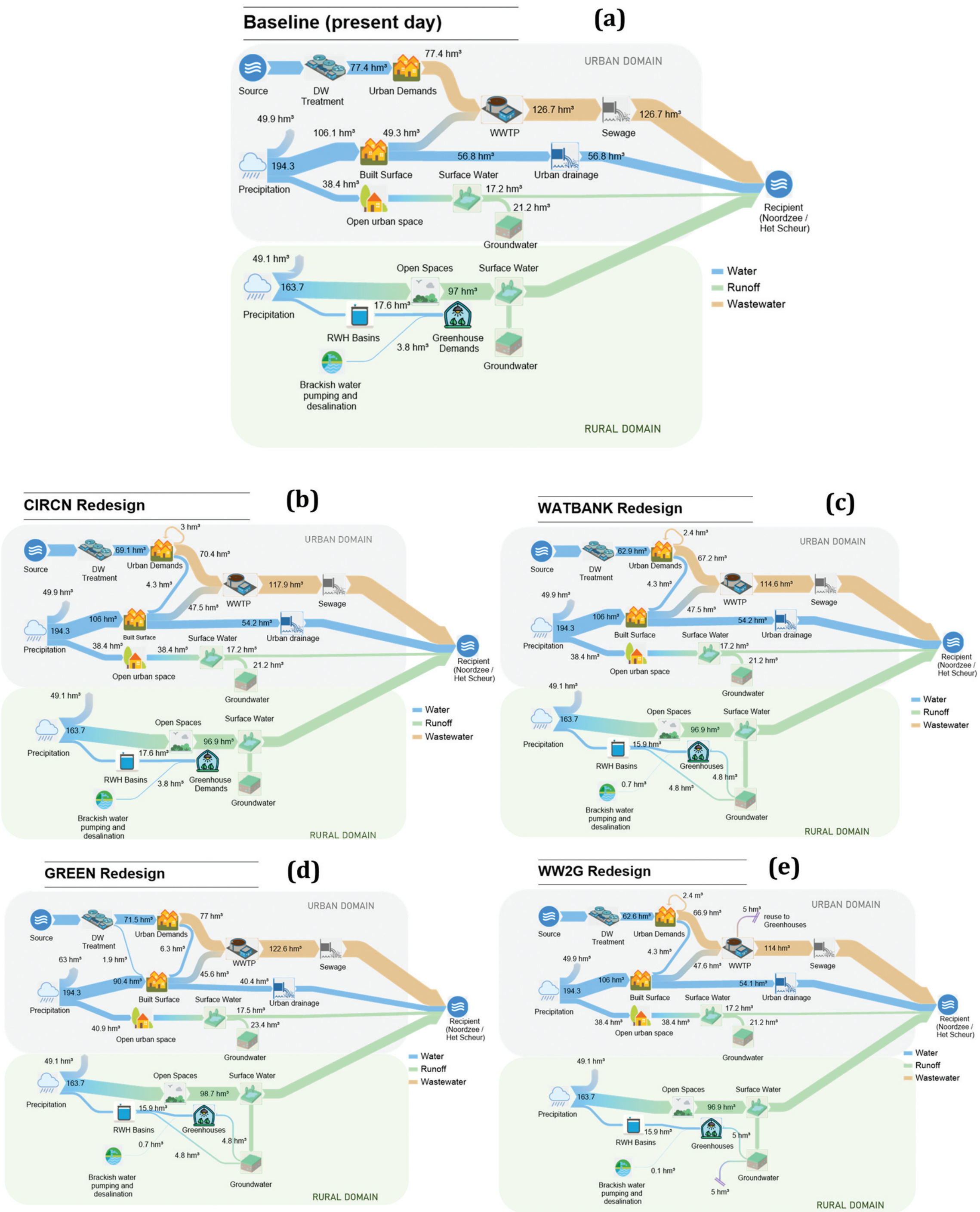

Figure 4. Sankey diagrams for the baseline conditions, as well as the four proposed circular redesigns.

hm^3/year to 0.7 and 0.1 hm^3/year, with the introduction of circular management measures (water banking, in panels (c) and (d), and wastewater reuse, in panel (e)).

4. Analysis - stress-testing against future uncertainty

4.1. Definition of resilience key performance indicators

In order to calculate resilience, the concepts of event-based R_t and volumetric reliability R_V need to be further defined in the context of the URWS in question, so as to formulate reliability-based KPIs showcasing resilience across different modeled urban water cycle domains (DW demands, horticulture demands, WW, and SW) and using the granularity (daily time-series) of the model output. Regarding event-based resilience, R_t, two KPIs are conceptualized (one for the urban and one for the rural subsystem):

1. Reliability against Capacity Exceedance (RCE), an event-based metric defined as:

$$RCE = 1 - P_{f,cap} = 1 - P(Q > Q_c) = 1 - \frac{n_{Q>Qc}}{n_{total}} \quad (3)$$

where $Q > Q_c$ is the condition that a simulated quantity Q (e.g. the drinking water requested from central services in a day, or the WW flowing in the WWTPs) exceeds the system capacity Q_c. RCE links the probability of failure $P_{f,cap}$ with the frequency of exceedance of a set capacity (threshold), Q_c, which is an intrinsic property of the URWS and depends on the DW, WW and SW designs. To quantify Q_c for Delfland for its DW and WW networks, we assume a system capacity that is equal to the maximum daily value, $Q_{t,max}$, observed through the 30-year simulation of present-state conditions; this reasonably implies that the networks are designed to deliver uninterrupted services for present-day conditions. Furthermore, and to reflect aspects of conservative network design, we assume that the system has a DW and WW design buffer b that enables it to withstand 20% more adverse demand/flow conditions, so that $Q_c = bQ_{t,max} = 1.2Q_{t,max}$. This percentage is estimated empirically to reflect present-day capacity conditions for the region. For SW, the drainage network is not designed to receive the maximum observed runoff but a lower value, based on the design return period T that typically is 5–15 years (Peleg et al. 2017). We thus assume a value $Q_c = Q_{c,runoff}$ that approximately corresponds to a 90% reliability, i.e. 10% probability of exceedance (10 years return period).

2. Reliability against Demand Deficit (RDD), an event-based metric defined as:

$$RDD = 1 - P_f = 1 - P(Q_{DD} > 0) = 1 - \frac{n_{DD>0}}{n_{total}} \tag{4}$$

with Q_{DD} being the demand deficit observed through UWOT simulation for a particular water use. This metric applies for horticulture in order to assess the net demand deficits that need to be covered by RO units.

With regards to volumetric resilience R_V, and in analogy with event-based resilience metrics, two metrics are conceptualized:

1. Present-day Coverage (PC), defined as the percentage of demands in terms of volume able to be covered from the present-day urban supply capacity:

$$PC = \frac{V_{supply,cap}}{V_{demand\ totals}} \tag{5}$$

This type of reliability is calculated based on volumes instead of individual timeseries values (flows), and can be considered the volumetric analogue of RCE as the present-day supply capacity is $V_{supply,cap} = b \sum_{i=1}^{n} Q_{t,i} dt$, with $Q_{t,i}$ being the present-day modeled supplied water and n the length of the simulation. The same parameterization of a design buffer $b = 1.2$ is considered for the DW network. For the SW and WW domains which are not based on supply and demand, we focus on the comparison of present-state with future-state volumes and thus set $b = 1.0$, calling the same metric as Volumetric Change (VC), so that $VC = \frac{Vpresent}{Vfuture}$. Values using VC can be then readily interpreted as the percentage of change between future and present conditions, as the present value is a fraction (VC%) of the future value in deteriorating conditions.

2. Sustainable Coverage (SC), a type of volumetric reliability applicable in horticulture that is defined as the percentage of demands that can be sourced and covered sustainably, i.e. by using local (harvested) or recycled water resources. The metric is defined based on the simulation-observed Demand Deficits Q_{DD} as:

$$SC = \frac{V_{supply,sust}}{V_{demand\ totals}} = 1 - \frac{\sum_{i=1}^{n} Q_{DD,i} dt}{V_{demand\ totals}} \tag{6}$$

4.2. Definition of stressors

An important step of the framework is to define possible future states where all different (re-)designs become stressed, i.e. points in the horizontal axis of Figure 2, calculated through an iterative process (step 5 in Figure 1). To formulate possible futures, one first needs to identify the underlying socio-economic drivers and relevant stressors that change in future system states and lead to system performance deterioration (see also lower left panel of Figure 1). Focusing on the main drivers behind the water cycle domains considered in this study, the following stressors are identified and used to force future states in every circular water management strategy:

- An increase in regional population and household occupancy, driven by demographic changes. This impacts aspects within the urban domain such as the DW demands and the WW output of urban areas. A relative increase in terms of percentage (%) of the initial regional occupancy is considered (abbreviated OCC) as a relevant stressor.
- An increase in horticulture water demands, driven by alterations in the type of crops within the HUs. A relative increase in terms of percentage (%) against current demands is considered (abbr. HORTI).
- Change in regional climate impacting hydrometeorological variables such as rainfall and temperature, used by UWOT to calculate runoff as well as green space and green roof evapotranspiration (Rozos, Makropoulos, and Maksimović 2013). To quantify this, data from climate scenarios provided by the Dutch Meteorological Institute KNMI for the years 2030, 2050, and 2085 are used (Klein Tank et al. 2014). Each scenario includes changes in 12 climate variables, including temperature and precipitation which are of interest to the UWOT model. In total, one scenario is available for 2030, while four scenarios are considered for 2050 and 2085: GH, GL (moderate temperature changes, high and low atmospheric pattern changes respectively), and WH, WL (larger temperature increase, high and low atmospheric pattern changes respectively). The interpolated datasets are daily 30-year timeseries that substitute point rainfall and temperature present-day information. The use of these timeseries as stressors is abbreviated as CLIMATE.
- Further variability in the rainfall regime that leads to drier or wetter futures. This variability comes as an addition to the KNMI future climate timeseries (see previous stressor), as the latter was found not to introduce significant shifts on the inter-annual amount of rainfall falling in the region, thus restricting the exploration of significantly drier/wetter settings (see Appendix C for more details). Considering the rainfall as a random variable I, this stressor is

Table 1. Stressors considered in this study.

Abbreviation	Stressor description	Defined as
OCC	Population and occupancy increase	% increase in present-day occupancy
HORTI	Horticulture demand increase	% increase in present-day horticulture water demands
CLIMATE	Regional climate regime change	KNMI climate scenario and the corresponding interpolated regional station timeseries (precipitation, temperature).
WET	Wetness increase	% increase (shift) in the values of nonzero daily rainfall.
DRY	Dryness increase	% decrease (shift) in the values of nonzero daily rainfall.

introduced by a simple linear transformation, applied in the rainfall timeseries I_t, shifting the location of the daily nonzero rainfall distribution according to a dimensionless factor α:

$$I_{t,transf} = \begin{cases} I_t \pm \alpha\mu_{\mathrm{I}}, \mathit{if}\ I_t \neq 0 \\ 0, \mathit{if}\ I_t = 0 \end{cases} \quad (7)$$

It can be shown that this transformation alters the mean value of the initial rainfall by α%, while preserving higher-order statistical properties, such as variance and skewness. Moreover, it preserves the intermittency (probability dry) of rainfall, which is an intrinsic, important property in daily timeseries (Tsoukalas, Makropoulos, and Koutsoyiannis 2018). By altering the factor of α, relative changes (in terms of percentage, %), to the (time-averaged) wetness or dryness of regional rainfall are introduced

(abbr. WET and DRY, correspondingly).

An overview of the five introduced stressors and their definition can be seen in Table 1.

5. Results

5.1. Stress-testing circular water management strategies against individual stressors

An initial resilience assessment of circular water management strategies can be performed against individual stressors (OCC, HORTI, CLIMATE, WET and DRY), in order to assess the relative importance of their potential future increase to the resilience of the regional water system. To perform this, a number of simulations are performed in UWOT where each individual stressor is increased with a granularity of 5%, with the exception of CLIMATE, where all different scenarios are evaluated as individual points. The resilience of the regional water system is then evaluated through the relevant event-based/volumetric-based metrics of RCE and PC (for the urban water domain) as well as the metrics of RDD and SC (for the horticulture domain).

The results for quantitative stressors can be seen in Figure 5, where the resilience of the affected URWS domains and their corresponding scores (both event-based, in panels (a)-(e), and volumetric, in panels (f)-(j)), can be seen. The horizontal axis includes the scenarios of the current system with present-day stress conditions (PRESENT), the circular water redesigns with present-day stress conditions (REDESIGN), as well as futures scenarios with the specific stressor increased by the set percentage (e.g. OCC_15 means that occupancy is increased by 15%). With regards to DW (panels (a) and (f)), it can be seen that the current linear water management system is the least resilient option with a significant loss of reliability as occupancy increases, which for instance means that a system with 25% increased occupancy will have less than 80% reliability in terms of delivered DW volume, which will be delivered safely only 65% of the time. The redesigns with highest resilience are WATBANK and WW2G, which graphically coincide as they introduce the same mixture of urban WM options, maintaining perfect reliability (100%) in delivering DW until a 30% increase of occupancy. The situation is analogous in WW (panels (b) and (g)), where the GREEN strategy coincides with the BAU (present-day) case as it does not introduce GWR as a measure to recycle WW streams. The situation is reversed in SW, where the GREEN strategy leads to more reliable SW networks in wetter futures. With regard to horticulture, the results demonstrate that present-day management relying on shallow basins fails 11% of the time and is only 83.7% reliable in terms of the volume of covered demands. With the introduction of circular horticulture water management interventions (through the WATBANK, GREEN and WW2G strategies), the present-day reliability drastically increases to>95% in terms of both time and volume, while being able to secure higher reliability in futures with both increased end user demands and drier conditions. A noticeable difference is that, unlike WW2G which secures a steady stream of treated WW, WATBANK and GREEN (coinciding lines) are more heavily impacted by drier futures, as they rely on (intermittent) rainwater to sustainably cover horticulture demands through the waterbanking system. System resilience has been found to be more insensitive against KNMI climate scenarios (CLIMATE stressor), which is discussed in detail in Appendix C.

5.2. Stress-testing circular water management strategies under uncertainty

Figure 5 provides useful insights on the relative importance of different stressors for the resilience of the regional system under different WM redesigns. However, it does not provide a complete picture of the possible future states of the water system, as these futures depend on multiple changes across many of the considered stressors occurring in conjunction. To proceed with an integrated resilience assessment that also accounts for future uncertainty, a probabilistic approach is employed, with the underlying basic assumption that all of the aforementioned stressors may vary randomly, according to preset distributions and bounds, which are in turn guided by regional forecasts and futures studies.

For the demonstrated regional case, and considering the lack of richer data on future uncertainty, uniform distributions for all stressors (except CLIMATE) ~$U[z_{min}, z_{max}]$ are employed, with the parameters $[z_{min}, z_{max}]$ shown in Table 2. For the stressors of population and horticulture demand increase, the bounds are guided based on available regional forecasts. The

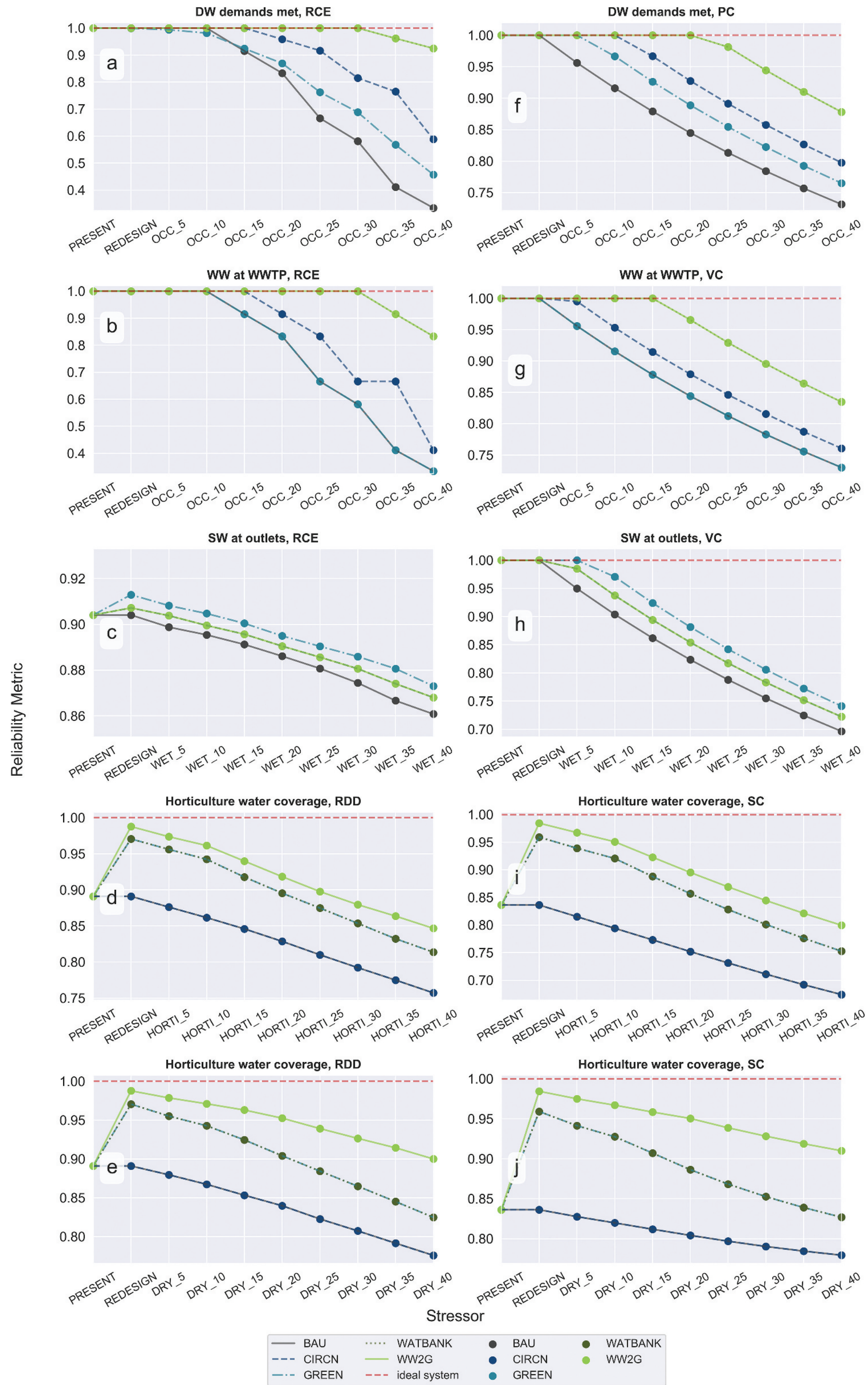

Figure 5. Resilience profile graphs of different circular water management strategies against individual stressors.

choice of the distribution type is justified according to the entropy maximization principle, as the uniform is the distribution type leading to a maximal measure of randomness and thus uncertainty given the lack of more detailed data (Koutsoyiannis 2014). For the WET/DRY stressors, symmetrical variability in dryness and wetness is considered for each decade, as the changing climate may lead to wetter or drier futures at a regional scale (IPCC 2014). For the CLIMATE stressor, all four KNMI emission scenarios (GL, GH, WL, WH) (Klein Tank et al. 2014) closest to the decade of reference are considered

Table 2. Combined stressors considered per decade.

year of reference	2030	2040	2050	2060	2070	2080	2090	2100
stressor								
DRY/WET % change	-	[−10%,10%]	[−20%,20%]	[−20%,20%]	[−30%, 30%]	[−30%, 30%]	[−40%, 40%]	[−50%, 50%]
CLIMATE	2030	2030	2050	2050	2085	2085	2085	2085
climate scenario			(1 of 4)	(1 of 4)	(1 of 4)	(1 of 4)	(1 of 4)	(1 of 4)
OCC	[0,5]	[0,10]	[5,15]	[5,20]	[10,30]	[10,30]	[15,40]	[15,50]
occupancy % increase								
HORTI	[0,5]	[0,10]	[5,15]	[5,20]	[10,30]	[10,30]	[15,40]	[15,50]
horticulture demands % increase								

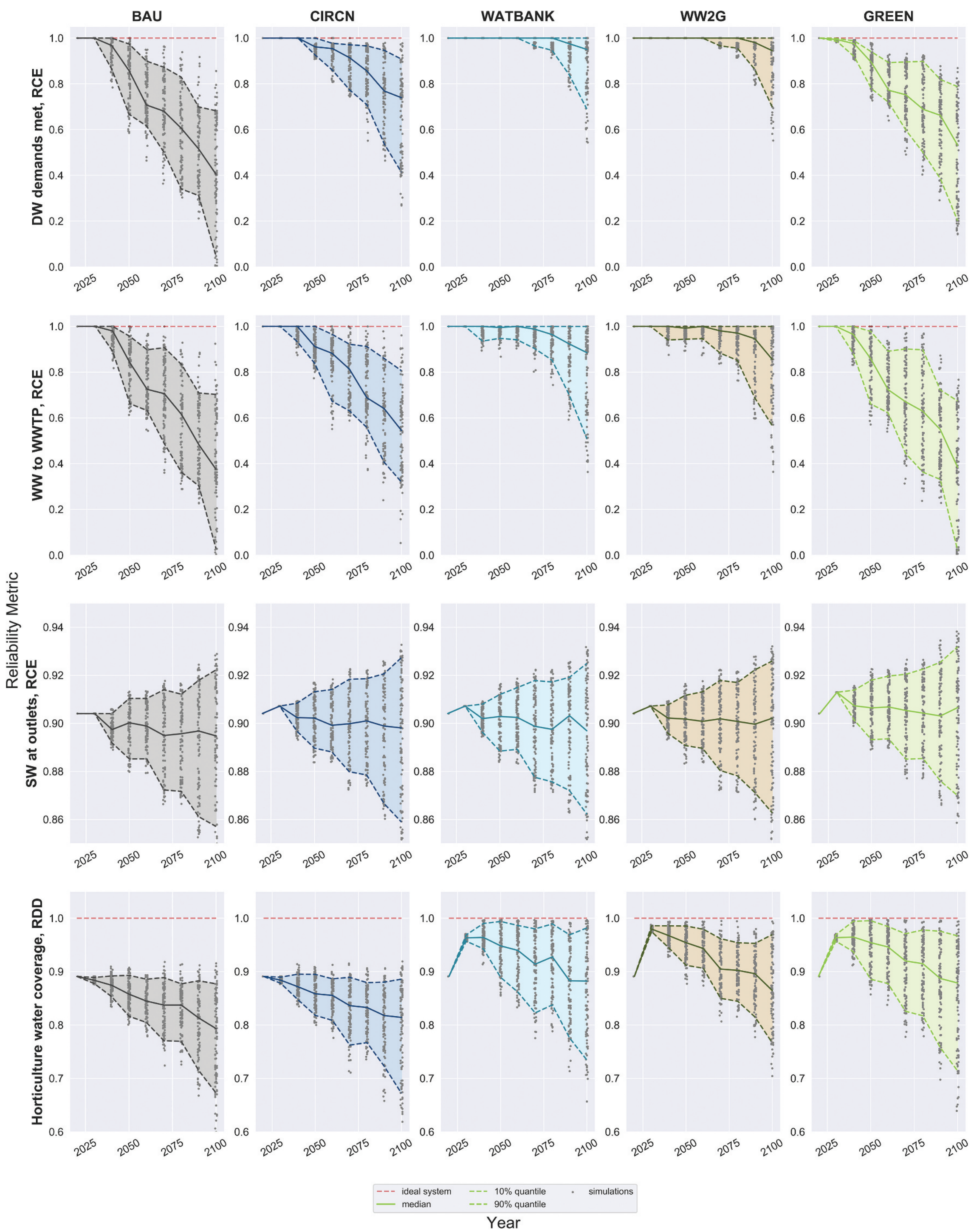

Figure 6. Probabilistic resilience profile graphs of circular water management strategies using event-based reliability metrics.

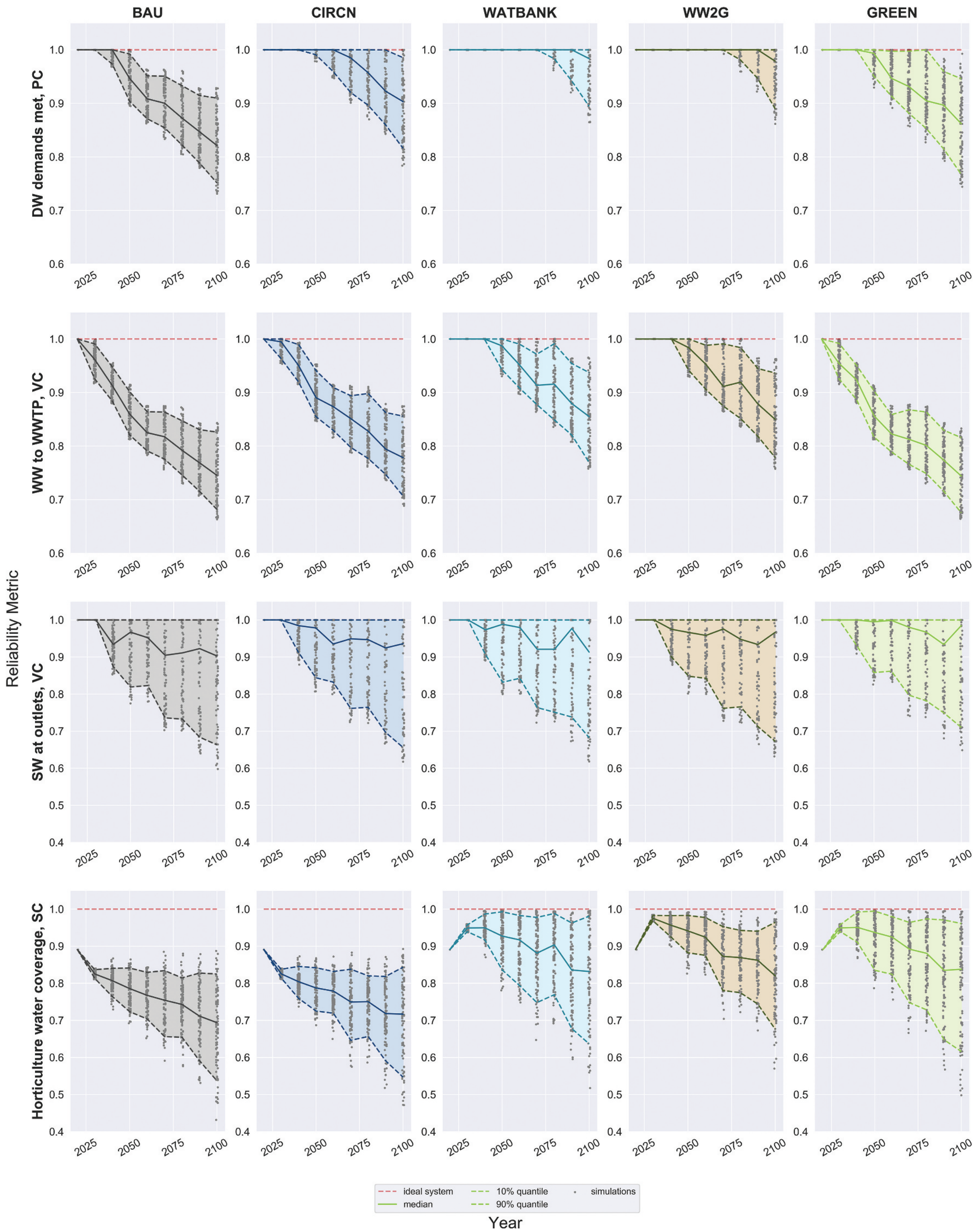

Figure 7. Probabilistic resilience of circular water management strategies using volumetric reliability metrics.

equiprobable and one of them is chosen at random. Random samples of stressors for each decade (2030–2100) are then drafted (with a sample size of $N = 100$) and used to force UWOT simulations for all different four circular water management strategies, as well as the present-day BAU case of linear WM. The result is a probabilistic resilience profile graph (Nikolopoulos et al. 2022), depicted through resilience envelopes, i.e. as time-evolving point clouds of a reliability metric, with three lines comprising the median reliability over time, as well as the 10% and 90% uncertainty bounds.

The results of the probabilistic analysis are displayed for multiple domains of the URWS in Figure 6 (for the event-based reliability metrics) and Figure 7 (for the volumetric reliability metrics). Both types of metrics have a general agreement in their trend, even though event-based metrics show larger median loss of reliability over time and a wider spread of system responses over the possible futures shown in Table 2.

For the domain of DW (top row of Figure 6 and Figure 7), continuation of the linear WM seen in the BAU case leads to the lowest resilience, with a substantial loss of reliability in future decades, both with regard to timesteps and volume, with drinking water being able to be delivered, on average, only 40% of the time and 80% in terms of aggregated demanded volume in 2100. This loss of reliability is mitigated by introducing circular household relying on RWH in the GREEN scenario, which shows an improved picture of resilience both in terms of spread (Figure 6), and in terms of a positively asymmetric distribution in terms of safely delivered volume (Figure 7). Improvement is more profound for the CIRCN redesign that introduced hybrid (RWH/GWR) circular households. By far, the most resilient picture is seen in WATBANK and WW2G, which combine hybrid circularity in households with DRMs; in that case, both event-based and volumetric median reliability stays>95% for all consecutive decades, future-proofing the water system.

For the domain of WW, CIRCN again shows improvement against present-state design, particularly in event-based metrics (meaning that WW overflow occurs less often), with the best resilience obtained through the WATBANK and WW2G scenarios. For SW at the region's outlets, GREEN shows the most improved picture, observable mainly via the median resilience curve, as there is significant symmetric spread through all redesigns, mainly due to the effect of the symmetric WET/DRY stressor. Finally, the introduction of circular WM in horticulture (through waterbanking or recycled WW) significantly improves reliability in the short term and leads to systems that are>90% reliable for multiple consecutive decades in the future. The WW2G redesign leads to the narrowest resilience envelope in both RDD and SC (i.e. horticulture metrics), reflecting the higher security that the recycled WW provides against future uncertainty, compared to the more sensitive waterbanking system (WATBANK and GREEN redesigns) that depends on rainwater.

6. Discussion

The aforementioned stress-testing framework offers quantitative insights on circular water management but relies on parameterisation, both in terms of its resilience metrics and with regard to the assumed stressors. Firstly, there is parameterisation in certain reliability metrics, such as RCE, which is needed to represent important aspects of the system such as present-day system capacity. This parameterisation is parsimonious and easily interpretable by stakeholders and can be estimated in case present-state data about the system are available (e.g. system capacity of DW networks). Furthermore, parameterisation is extended in the way stressors are introduced and combined; more stressors may be added or subtracted at will (based on the architecture shown in Figure 1), and the distribution types and parameters these stressors follow in the future may vary (Table 2), guided by a separate uncertainty analysis (Vousdoukas et al. 2018).

Setting and evaluating these parameters could be also a process driven by stakeholder participation (Luyet et al. 2012), as all of them have physical meaning and can be readily communicated and discussed across expert groups. Using this perspective, the ambiguity of certain parameters (like the bounds of a stressor) could be turned into a discussion point with the stakeholders on how much change can be expected – and why – or it could be sourced from multiple knowledge experts using relevant methods (Cooke and Goossens 2004). The inclusion of stakeholders is of high significance to the definition of the redesigns as well, as policy actors facilitate the selection and adoption of specific interventions (Fulgenzi et al. 2020) and thus policy can be viewed as underlying driver of technological options in water management (see Figure 1). Regarding the demonstrated case, the proposed redesigns have been communicated at an early stage (i.e. before modeling results) in one of the periodic Communities of Practice (CoP) meetings for Delfland, where multiple participating stakeholders have evaluated their usefulness. The participants showed their largest interest on the WATBANK strategy (31.8%), shortly followed by the WW2G (27.3%) and GREEN (27.3%) strategies, while CIRCN received the lowest interest (9.1%). Interestingly, and without having prior knowledge of the results, this evaluation is in accordance with the overall efficiency of these strategies in terms of resilience, as WATBANK and WW2G lead to the strongest increase in the resilience profile graphs across multiple domains (Figure 6 and Figure 7).

Finally, despite the model evaluating multiple domains of the URWS, certain aspects of the regional system such as the quality of water, or water-energy-nutrient interactions in the region are not modeled due to lack of data and simulation model capacity and are excluded from the current resilience assessment. Future research could focus on these domains by expanding UWOT or by using a model ensemble to quantify the response other subdomains have. Moreover, a limitation of the framework is that the demonstrated array of circular interventions is limited, tailored to the studied region, and does not include a wider array of circular measures such as NBS. Future applications of this framework could be paired with a more rigorous approach on optioning that includes more circular water interventions and justifies how these interventions are selected. This can be done, for instance, by pairing the optioning process for any circular water strategy with cost-benefit analyses (Ghafourian et al. 2021) or by using a multi-criteria approach that includes technological complexity and maturity, as well as potential energy and resource needs (Carriço, Covas, and Almeida 2021).

7. Conclusions

In this paper, the link between circularity in water management and system resilience has been quantitatively demonstrated through a framework that combines recursive, model-based stress-testing with appropriate resilience stressors. A water cycle model has been used to evaluate the response of the regional case of Delfland, considered as a combined urban-rural water system (URWS), with its resilience being evaluated for present-day and future conditions using a previously developed method of quantification for urban water (Makropoulos et al. 2018). Expanding upon this method, resilience metrics fit for a regional application have been developed as part of this study, using both time-based and volumetric reliability as the basis for quantification. The framework has been demonstrated (a.) firstly deterministically, by exploring the impact individual stressors have on resilience across different WM domains (DW, WW, SW, horticulture water management), (b.) probabilistically, by calculating stochastic resilience curves against combinations of multiple changing stressors in future decades.

To explore the impact different circular water management strategies have on resilience, four alternative circular water redesigns of varying complexity (CIRCN, WATBANK, GREEN, WW2G) are formulated, modeled and compared against present-day, linear water management. The results show that all of the proposed circular water management strategies lead to improvements on the resilience of the URWS across one or multiple domains, with the linear WM design showing the poorest resilience profile graph and the highest loss of reliability against future uncertainty. This indicates that the cost of inaction might be significant if regional actors do not advance into more circular water management in the near future, as safe, drinking water will be delivered less often and in lower volumes. Interestingly, the robustness of circular water management redesigns (and thus the improvement in the system's resilience profile graph) is stronger and more multi-faceted in strategies that promote a combination of circular interventions across different circularity (i.e. so-called 'R') dimensions (see also Appendix A and Table A2). Moreover, the findings show that circularity in water management also promotes sustainability, for instance in the horticulture domain, where net deficits treated from unsustainable sources (deep groundwater) can be minimized with the introduction of circular interventions such as waterbanking (resource recovery) and reuse of urban wastewater (resource recycling).

The work provides explicit linkages that connect Circular Economy (CE) concepts to resilience and sustainability within a water system, thus addressing a point brought by many CE critics against previous works that focus only on conceptual links (Kirchherr, Reike, and Hekkert 2017). Furthermore, it demonstrates how these concepts can be adapted and employed for water management, in alignment to previously adopted terminology that focuses on decentralized, sustainable interventions, thus expanding the theoretical foundations laid by previous researchers on CE for water (Morseletto, Mooren, and Munaretto 2022; Sgroi, Vagliasindi, and Roccaro 2018). Focusing on the water infrastructure effects these interventions have, this method is viewed as one step in the multi-step process that assesses how circular water measures affect water management in terms of technology, governance, regulation, and community knowledge (Reymond, Chandragiri, and Ulrich 2020; Hoffmann et al. 2020). The authors envision that the provided methodology can be a useful addition in the arsenal of decision-support methods on circular water management at a regional scale, with relevant actors being able to co-design interventions and strategies, reflect on their comprehensive parameterization, co-create stressors that lead to possible futures and evaluate how the proposed designs lead to more robust and resilient water systems, with similar adaptations possible for circular systems in the city, neighborhood and household scale.

Notes

1. The term 'R dimension' is used throughout this text, while the term 'strategy' is reserved for circular redesigns of the water system.
2. For more information please see the relevant model webpage: https://uwmh.civil.ntua.gr/products/86-uwot.html.

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