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Reliable, Resilient and Sustainable Urban Drainage Systems: an Analysis of Robustness under Deep Uncertainty

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ABSTRACT

Reliability, resilience and sustainability are key goals of any urban drainage system. However, only a few studies have recently focused on measuring, operationalizing and comparing such concepts in a world of deep uncertainty. In this study, these key concepts are defined and quantified for a number of gray, green and hybrid strategies, aimed at improving the capacity issues of an existing integrated urban wastewater system. These interventions are investigated by means of a regret-based approach, which evaluates the robustness (that is the ability to perform well under deep uncertainty conditions) of each strategy in terms of the three qualities through integration of multiple objectives (i.e. sewer flooding, river water quality, combined sewer overflows, river flooding, greenhouse gas emissions, cost and acceptability) across four different future scenarios. The results indicate that strategies found to be robust in terms of sustainability were typically also robust for resilience and reliability across future scenarios. However, strategies found to be robust in terms of their resilience and, in particular, for reliability did not guarantee robustness for sustainability. Conventional gray infrastructure strategies were found to lack robustness in terms of sustainability due to their unbalanced economic, environmental and social performance. Such limitations were overcome, however, by implementing hybrid solutions that combine green retrofits and gray rehabilitation solutions.

1. INTRODUCTION

Emerging threats affecting urban areas now and in the future may significantly contribute to the deterioration of the level of service delivered by critical infrastructure, such as urban drainage systems (or urban wastewater systems). Indeed, climate change, population growth, urbanization, and other changing factors could be particularly damaging when simultaneously acting upon any of these systems, posing an important challenge to their future performance.[1,2] In addition to this, the deep uncertainty nature of future conditions may question the robustness of conventional and alternative solutions to adapt to future changes, given their unknown magnitude and extent of impacts over the long-term.[3]

Under these circumstances, urban wastewater infrastructure may need to undergo adaptive improvements in order to become less vulnerable to future conditions, whether these are typical or extraordinary.[4] Indeed, it is expected that the urban wastewater system is reliable, able to minimize failure frequency and deliver a satisfactory level of service most of the time, while behaving resiliently in order to reduce the duration and magnitude of a failure when this eventually happens.[5]

At the same time, these adapted systems should also pursue sustainability in the long-term, i.e. to achieve economic, environmental and social goals altogether. However, adaptation strategies that provide a high level of technical performance (i.e. are reliable and resilient) may not necessarily be financially viable, environmentally balanced (e.g. protecting the aquatic environment at the expense of other environmental issues), or socially equitable.[6]

Understanding the attributes and existing relationships between these operational (reliability and resilience) and strategic (sustainability) qualities thus becomes paramount in devising strategies likely to be successful now and in the future. In spite of revived efforts to understand these attributes (in particular from a resilience point of view)[6] in the context of urban wastewater systems,[7–10] there currently exists limited knowledge regarding the extent and qualities of such relationships, especially as related to their metrics and methods of assessment. Consequently, it is largely uncertain how to ensure that any drainage strategy can maintain its reliability, resilience or sustainability qualities over time and in the face of changing conditions. Moreover, it is unclear what type of solutions (e.g. centralized or decentralized alternatives) are capable of delivering reliable, resilient and sustainable outcomes now and in the future.[11–13]

In addition to this, the need to satisfy an ever increasing variety of objectives, whether these are related to economic (e.g. capital and operational costs), social (e.g. acceptability, equity) or environmental (e.g. water quality, carbon emissions) drivers, may further challenge our aspirations to plan for robust solutions that satisfy levels of service under a wide range of changing circumstances.

The aim of this paper is therefore to analyze, quantify and compare the robustness of urban drainage system enhancement strategies in terms of reliability, resilience and sustainability when subject to uncertain future changes (e.g. climate change, population growth). Such analysis is carried out using a regret-based approach that relatively assesses the multi-objective performance metrics (reliability, resilience and sustainability) of conventional gray infrastructure strategies and green infrastructure retrofits across four future scenarios. The present study builds on the work developed by Casal-Campos et al.,[14] which developed a regret-based approach to compare the relative performance of green and gray strategies on an integrated catchment. This paper applies the same regret-based method to investigate the robustness of green, gray and hybrid strategies in delivering reliable, resilient and sustainable wastewater services in the future. The outputs of the research provide further insight into the ability of adaptive wastewater management policies to ensure enhanced levels of performance in the future.

2. MATERIALS AND METHODS

2.1. Overview

Each strategic intervention applied to the case study is assessed under four different future scenarios in terms of its relative performance regarding multiple objectives (sewer and river flooding, river water quality, operational Greenhouse Gas (GHG) emissions, Combined Sewer Overflow (CSO) spills, whole-life costs and acceptability). A brief description of the model, scenarios and interventions is provided below; the reader should refer to Casal-Campos et al.[14] for further details.

2.2. Case Study and Future Scenarios

2.2.1. Case Study Overview

The urban wastewater catchment employed for this investigation is a semi-hypothetical benchmark case originally defined by Schütze et al.[15]. The integrated case study consists of three main sub-systems, namely: urban catchment and sewer system, wastewater treatment plant system (WWTP), and river system; see the Supporting Information (SI), **Figure S1**. The catchment system is defined by 15 individual sub-catchments, served by a simplified combined sewer network (main trunk sewers with 1.2 meters diameter pipes). The excess flows forwarded from the sewer network are stored in a storm tank (off-line pass-through tank, 6750 m^3), overflowing to the river system. The wastewater flow entering the treatment process follows a typical activated sludge arrangement. The river defined for the case study is a hypothetical 40-km river divided in 40 equal stretches. The river base flow is 1.5 m^3/s (129,600 m^3/d), which results in a 1:5 dilution factor of dry-weather treatment plant discharges to the river.

The catchment is modeled as an integrated urban wastewater system (IUWWS) using SIMBA 6.0.[16] This is a modeling tool based on the MATLAB/SIMULINK environment, which allows users to construct and develop specific modeling modules tailored to their needs (e.g. wastewater treatment processes, elements of the catchment and sewer network, etc.) This included using SWMM 5 to model the sewer network and river systems, as well as IWA's state-of-the-art Activated Sludge Model No.1 (ASM1) to model the WWTP. The original integrated model has been extensively used to report on the benefits of integrated real time control strategies to improve river water quality (i.e. dissolved oxygen and ammonia) through control of diurnal patterns of WWTP and CSO discharges.[17–19] Detailed information on the case study and the simulation model can be found in the SI, Section S1 (Pages S5-S9) in the study of Casal-Campos et al. [14].

Using an IUWWS that simulates the different parts of the wastewater system allows evaluating the performance of any intervention holistically, reducing the risk of partially assessing any strategies (e.g. by emphasizing good performance on one sub-system while masking poor performance on another). Further, such an approach permits enriching the operationalization of concepts such as reliability, resilience and sustainability, for each concept can be described by multiple metrics affecting different sub-systems.

2.2.2. Future Scenarios

Climate change is one of the major uncertainties that affect urban wastewater systems planning. This obliges water utilities to develop more reliable, resilient and sustainable urban systems under future uncertainties [20]. To this end, four future socio-economic scenarios were used to test the IUWWS under a range of different conditions: Markets, Innovation, Austerity and Lifestyles. The future scenarios were mainly defined based on the planning horizon used in the UK and Western Europe [21–27] as well as previous work on UK/EU water-associated future scenario planning exercises [3,22,28–31]. Such alternative future conditions are constituted by an ensemble of nine different parameters (see **Table 1**), representative of the range of uncertain circumstances facing the IUWWS, and their influence on system performance is simulated in the integrated model. **Figure S2** (in the SI) summarizes the main characteristics of each future scenario. The scenarios are depicted based on two drivers: (1) governance (economic growth vs. environmental awareness); and (2) values (consumerism vs. conservationism) [14]. These two drivers are often used as key features (for their ability) to facilitate a more diverse and transparent possibility space [32].

Based on the two drivers, each of the four future scenarios is characterized by four key scenario factors associated with the management of the IUWWS: (I) regulation: level of regulatory control of stormwater and wastewater management activities; (II) centralized maintenance: the level of activity in each scenario aimed at preserving the existing wastewater infrastructure; (III) public attitudes: public willingness towards the decentralization of responsibilities concerning urban drainage; and (IV) technology: the level of technological development occurring under each scenario.

Table 1: Parameter estimates affecting case study conditions under each future scenario (adapted from Casal-Campos et al.[14], Copyright (2015) American Chemical Society).

Parameter	Baseline	Markets	Innovation	Austerity	Lifestyles
Misconnections (L/s)	0	7.8	0.9	4.1	1.7
Urban creep (ha)	0	87.7	58.4	70.1	29.2
Water use (L/head/day)	155	165	125	140	110
Infiltration (1) (L/s)	52.4	163.7	40.5	200.1	135.5
Siltation (2)	0.97	0.92	1	0.84	0.92
Population (inhabitants)	181,000	262,450	244,350	217,200	226,250
CC precipitation uplift (%)	0	10	10	10	10
Impervious area in new developments (ha)	0	290.0	226.0	129.0	161.0
Acceptability preference (3)	C	C	C/D	D	D

(1) It refers to infiltration of groundwater into the sewer system.

(2) The effect of siltation, which represented system capacity loss in sewer pipes due to deposited sediment, was modeled as the corresponding reduction in pipe diameter under each scenario (corresponding to full-pipe area reduction); 1: no reduction, 0: full reduction.

(3) The acceptability of interventions under each scenario is assessed in terms of the preference for either centralized or decentralized options. The Innovation scenario shows a mixed preference for centralized interventions, where decentralization is also promoted.

Regulations under the Lifestyles and the Innovation scenarios are high (see **Table 2**) due to the environmental-awareness drive prevalent in these states of the world, whereas the regulatory climate under Markets and Austerity is low relative to the previous two scenarios to ensure low prices and austere policies, respectively. Innovation shows the highest level of technological development encouraged by strict regulation and a drive for sustainable outcomes. This is followed by Markets, which prioritizes cheap and quick solutions over high-tech developments. Lifestyles and Austerity are the scenarios with the lowest level of technological development given the limited resources available under these states of the world.

Table 2: Qualitative strength (H: high, M: medium, L: low) of key scenario factors affecting the management of the IUWWS under the considered scenarios

Future Scenario	Regulation	Centralized Maintenance	Public Attitudes	Technology
Markets	L	M	L	M
Innovation	H	H	L	H
Austerity	L	L	M	L
Lifestyles	H	L	H	L

The level of centralized maintenance is the highest for Innovation, due to high technological developments that allow a very cost-effective maintenance of the existing infrastructure. In contrast, the decentralized responsibilities encouraged under Lifestyles and Austerity importantly affect the level of centralized maintenance, which is low relative to those under Innovation. Markets can still maintain a medium level of maintenance of the centralized sewer infrastructure due to favorable economic conditions, but limited by regulatory commitments. The public attitudes toward decentralized drainage infrastructure are highest for Lifestyles, given the conservationist views of this scenario, which strongly favor the decentralization of responsibilities. Although decentralized responsibilities are also prevalent in the Austerity scenario, these are constrained by economic issues (e.g. upfront costs or running costs) which may limit the extent of decentralization. In contrast, centralized responsibilities are dominant under Innovation and Markets, given the consumerist views of these scenarios, resulting in a low level of attitudes to decentralization.

The parameters, considered in this study, were mostly related to changes in catchment permeability and to the variation of sewer inflows, which could hinder system capacity in the future. Permeability changes were represented by the rate of urban creep occurring in the baseline catchment (i.e. loss of pervious area to impervious area in the original catchment) and by the increase in impervious area occurring as a consequence of urbanization (i.e. new developments built consistently with population growth in each scenario). Urban creep was modeled as the loss of a fraction of pervious area which was added to the impervious area fraction in each sub-catchment. The urban creep fraction remained connected to the combined sewer system, as opposed to the impervious area added due to new developments, which was considered to be managed by separate sewers. More details on the characteristics of the future scenarios can be found in Casal-Campos et al. [14].

Sewer inflows in each sub-catchment were determined by the combination of misconnections, groundwater infiltration, and water use flow rates occurring under each future scenario. Foul sewers misconnected to storm sewers were considered a factor that could deteriorate future background water quality in the river, as wastewater is discharged untreated directly into the watercourse, along with surface runoff from new developments and intermittent CSO spills. Misconnections only occurred as a consequence of urban development (no misconnections in the baseline case), since the baseline river quality was assumed to account for any existing background pollution. In each scenario, population growth relative to the baseline determined the amount of misconnected foul sewers discharging into surface sewers occurring in each sub-catchment (based on the rate of misconnections assumed under each future scenario). The new dry-weather flow for each sub-catchment was then calculated by adding the new domestic water users (i.e. new population) and deducting the misconnected flow. Misconnections were assumed to have the same flow and pollutant concentration patterns as domestic wastewater.

Infiltrated groundwater was considered as an extraneous inflow evenly distributed throughout the catchment. Groundwater flows infiltrating into combined sewers were modeled as a rate of the total dry weather flow from each sub-catchment. This resulted in an external flow being added to each sub-catchment throughout the year, independently of rainfall events, with an assumed pollutant load equivalent to rainfall runoff.

Finally, the annual precipitation increase due to climate change was modeled using an annual average uplift for rainfall intensities. The rainfall time series used for the purpose of the study is a representative data series for annual precipitation (621.5 mm) in the catchment. This was introduced in the model in the form of a 5-minute intensity time varying data file and modified by applying the 10% uplift due to climate change, expected for annual average conditions in the year 2050 in the UK or Western Europe [23,25]. The allocation of specific estimates for each parameter (to each scenario) is described in the SI (Section S2).

2.3. Strategic Interventions

A number of adaption strategies associated with the management of urban stormwater and wastewater have been proposed to ameliorate the impacts and consequences used to describe system performance in the IUWWS (see Table 3).

Table 3: Main characteristics of proposed stand-alone strategies.

Stand-alone strategies				
Strategy	**Description**	**Area type/system served**	**Impervious area served as % of catchment**	**Strategy type**
SCC	Permeable pavement	Urban creep in driveways	5-15	Decentralized
SCP	Bio-retention planters	Residential roads	28	Decentralized
SCR	Rain gardens	Residential roofs	44	Decentralized
SS	Separate sewers	All types (in 50% of the existing catchment)	50	Centralized
CS	Improved sewer capacity	Enhanced sewer pipes (ϕ1.5m diameter)	100	Centralized
CST	Improved sewer capacity and storage	Sewer pipes (ϕ1.5m) and storage (25,000 m^3)	100	Centralized
OT	On-site wastewater treatment	Half of new developments	NA (only wastewater)	Decentralized

These provide a wide portfolio of interventions that can be implemented in different parts of the IUWWS, namely: the existing sewer infrastructure, existing urban areas and new developments in the urban catchment. Further, these attempt to capture two main groups of strategies that are usually proposed in order to address drainage issues in urban catchments: conventional gray infrastructure options that focus on end-of-pipe solutions (rehabilitation, sewer retrofits and new development options); and a range of alternative green retrofits that affect different urban area types (private driveways, roofs and public roads). Due to the scope mentioned above, we did not include all emerging concepts such as resources and nutrient recovery, which should be studied in the future. Regarding retrofit interventions, infiltration options (permeable pavement and bio-retention planters) have been prioritized due to their complete removal of stormwater, which would improve the hydraulic performance of combined sewers when compared to less effective alternatives (e.g. green roofs or rainwater harvesting intercept an initial fraction of the stormwater).

A number of hybrid strategies, combining interventions in existing (i.e. retrofit) and new developed areas, were proposed in addition to the above stand-alone solutions (see Table 4). Such "hybrid strategies" were considered potentially more feasible and achievable, given the reduced implementation rates for each of the considered strategy types. Hybrid strategies (in particular mixed centralized and decentralized technology options) may additionally provide a higher degree of flexibility and adaptability to urban water systems [33–35]. These multi-concept strategies (as opposed to the previous mono-concept stand-alone strategies) become particularly important when considering robust solutions across different world views that aim at satisfying a number of stakeholders and objectives, finding compromises that reflect the complexities of water infrastructure policies [36].

Table 4: Main characteristics of proposed hybrid strategies.

Hybrid strategies				
Strategy	**Description**	**Area type/system served**	**Impervious area served as % of catchment**	**Strategy type**
H1	Rain gardens and *on-site wastewater treatment*	50% of residential roofs and *31.5% of new developments*	22	Decentralized
H2	Rain gardens and	50% of residential roofs and *20%*	22 + *20*	Decentralized/

	separate sewers	*separation in the existing catchment*		*Centralized*
H3	Separate sewers and *on-site wastewater treatment*	20% separation in the existing catchment and *31.5% of new developments*	20	Centralized/ *Decentralized*
H4	Rain gardens and *improved sewer capacity*	All residential roofs and *combined sewer system improvement (ϕ1.5m)*	44 and *56*	Decentralized/ *Centralized*
H5	Rain gardens and *combined sewer storage*	50% of residential roofs and *combined sewer system (25,000 m^3 tank)*	22 and *78*	Decentralized/ *Centralized*

Hybrid strategies were proposed as a combination of fractions of original stand-alone mono-concept strategies, namely: roof disconnection, sewer separation and on-site wastewater treatment. These three strategies were selected as representative for retrofit decentralized, retrofit centralized and new development solutions, respectively. The resulting hybrid strategies removed a similar annual volume of stormwater or wastewater from the wastewater system. This was calculated equivalent to: disconnecting half of the residential roofs in the catchment (50% of SCR), providing on-site wastewater treatment to an average of 31.5% of new developments across scenarios (i.e. similar to implementing 63% of the OT strategy), or introducing separate sewers for 20% of the existing catchment (i.e. 40% of the SS strategy). As many as two strategies were combined in order to better understand the contributing effect of each intervention to the hybrid option. Further, it was assumed that a higher number of combined strategies may be unfeasible to implement across all the considered future scenarios, given their differing views on centralized and decentralized interventions.

In addition to this, the disconnection of roofs (SCR) and the rehabilitation of combined sewers in the network (CS) have been also combined (H4) to compare the performance of decentralized infiltration (in the form of rain gardens) against centralized storage (large tunnel storage implemented in the CST strategy). A combination of centralized storage (CST strategy without sewer pipe rehabilitation) and roof disconnection was also considered (H5) to assess the extent to which decentralized runoff control could complement the installation of centralized sewer storage schemes while reducing sewer replacement requirements. Apart from the mono-concept and hybrid strategies, we considered a “do-nothing” strategy, which represents the current system without any interventions, for comparison with other intervention strategies. The “do-nothing” option was assumed a zero-cost (in terms of capital expenditure) and low-acceptability alternative throughout all scenarios, since it is expected that improvements will be needed in the system by the year 2050.

2.4. Performance Metrics

The performance impacts and socio-economic consequences derived from performance failures (e.g. capacity exceedance) cover a broad range of objectives of interest. These are typical key objectives used by the UK water industry to make strategic decisions regarding the improvement of the levels of service and urban wastewater infrastructure (i.e. associated with cost, environmental impact, flood control, customer acceptability). These objectives are represented by specific performance indicators, which reflect the main attributes of reliable, resilient and sustainable IUWWS. Note that these metrics are proposed for a holistic assessment of the integrated urban wastewater system, presenting advantages when compared with the separate management and regulation of individual sub-systems with isolated objectives (i.e. surface water drainage system, sewer system, wastewater treatment system and receiving water system). This allows for the assessment of the performance of decentralized systems, such as bio-retention planters (SCP), rain gardens (SCR) and on-site treatment (OT), from an integrated perspective using a wide range of metrics. Performance indicators for reliability, resilience and sustainability affected by a number of selected objectives are presented in **Table 5**.

It has been recognized that an urban drainage system must be first reliable under standard design conditions and then built upon by resilience under exceptional conditions, with an ultimate aim to improving and/or achieving sustainability in the long term[5]. Due to the pyramidal structure of reliability, resilience and sustainability, the indicators are inevitably interlinked; however, they measure different aspects of system performance, as shown in Table 5. The consideration of different objectives (reliability, resilience and sustainability) responds to different conditions that decision-makers cannot be sure of in an uncertain future (or under conditions of deep uncertainty). Such an approach would help decision makers to evaluate their required levels of compliance/service with regards to the scale and degree of complexity of their problem. For example, in a low uncertainty situation, a decision-maker may be satisfied using reliability metrics without considering further failure impacts; however, they may still find value in the resilience and sustainability metrics to address additional needs under higher uncertainty conditions.

Table 5: Performance indicators used to describe performance objectives.

Objective	Reliability indicator	Resilience indicator	Sustainability Indicator
Sewer Flooding	% time free of flood	Summation of duration-weighted flood volumes [m^3]	Total flood volume [m^3]
River DO	% time DO >4 mg/L	Summation of duration-weighted DO minima [mg/L]	6-hour minimum dissolved oxygen [mg/L]
River AMM	% time AMM <4 mg/L	Summation of duration-weighted AMM maxima [mg/L]	99 percentile total ammonia [mg/L]
CSO	% time free of spills	Summation of duration-weighted spill volumes [m^3]	Total spill volume [m^3]
River Flooding	-	-	Total flood volume [m^3]
GHG Emissions	-	-	Operational emissions from pumping and treatment [tCO_2]
Cost	-	-	Present value of whole-life costs [£]
Acceptability	-	-	Acceptability of strategies [1/2/3] (*)

(*) [1/2/3] represents the expected acceptability of strategies [high/med/low] based on future scenario narratives. In scenarios with a preference for centralized solutions (denoted by C in Table 1), decentralized strategies score poorly (low acceptability, score: 1), and vice versa.

It is important to note that IUWWSs are very site-dependent systems whose performance may be significantly affected by local characteristics (e.g. climate), monitoring regimes, operational conditions (e.g. influent pollutant concentrations) and the age of the system itself, often presenting a wide variability of values [37].

2.4.1. Reliability Indicators

In this study, reliability is defined as the degree to which the system minimizes level of service failure frequency over its design life when subject to standard loading[5]. Service failure here means failing to comply with the levels required by regulations, not considering mechanical failures, such as those from pumps and aerators, as the focus is on the long-term urban wastewater system planning under uncertain future conditions.

The reliability indicators presented in **Table 5** are characterized by the consistency of acceptable levels of service (used for the system design), measured as the probability that no failure occurs within a fixed period of time[38] (i.e. a given threshold is not violated within the one year assessment). The general mathematical expression describing reliability indicators is,

$$\text{Reliability} = 1 - \sum_{i} \frac{d_i}{T} \qquad [\,1\,]$$

Where d_i represents the duration of each failure occurring within the total assessed period T (i.e. one year). Reliability therefore denotes the annual fraction of time free of failure (See **Figure 1**), and is mainly used for system design.

Failure thresholds for the sewer flooding and CSO objectives were set at zero, so that only a complete avoidance of spill or flood events could translate into full reliability under these objectives. Water quality failure thresholds were defined as critical concentrations of river dissolved oxygen and river total ammonia (i.e. 4mg/L), after Schütze et al.[15].

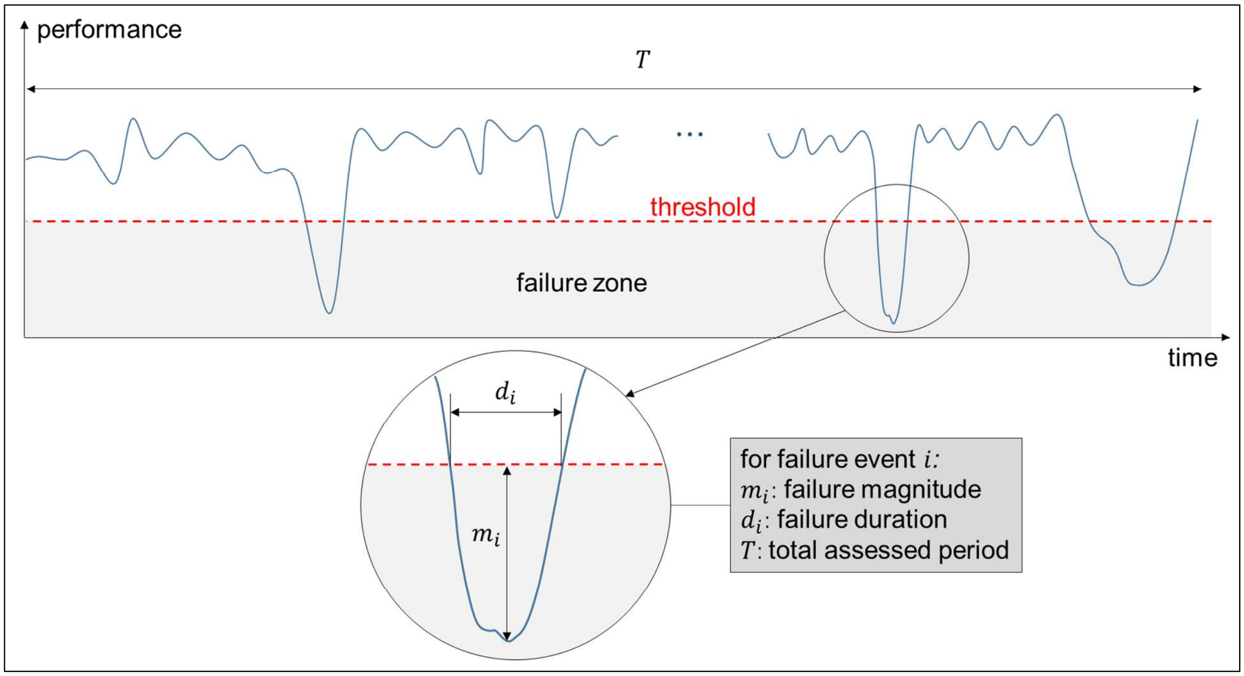


Figure 1: A generic description of failure and its components as used in this study. When system performance falls below a predefined threshold, a failure occurs. Magnitude and duration are key attributes describing the operational implications of a failure.

2.4.2.Resilience Indicators

To face future challenges, it must be ensured that drainage solutions operate safely (i.e. fail-safe, reliably) as far as practicably possible, but that they also respond safely to failure (i.e. safe-to-fail, resiliently) [40]. These systems can behave more flexibly and recover quickly in order to reduce damage (and the disruption to the level of service) when failure occurs [41]. To capture the attributes described above, resilience is here defined as the degree to which the system minimizes level of service failure magnitude and duration when subject to exceptional conditions, represented here by a threat or combination of threats [5].

The same four objectives used for reliability are employed to measure resilience as listed in **Table 5**; however, they are calculated differently, with a combination of both the magnitude and the duration of failure events occurring within the assessed time period (See **Figure 1**). This resembles current definitions of failure severity in urban water systems (or better, the complement of resilience) which refer to measures of the loss of functionality in the system [9,42]. The expression proposed here is the weighted summation (relative to failure duration) of failure magnitudes,

$$\text{Severity} = \sum_{i} \frac{m_i \times d_i}{T} \qquad [\ 2\ ]$$

where m_i and d_i represent the magnitude and duration of the failures occurring within the total assessed period T (i.e. one year), respectively.

The severity of each failure event (and its units) was therefore described by the main magnitude of interest for that failure, namely: volume for sewer flood and CSO failures; minimum in-river concentration for dissolved oxygen; and maximum in-river concentration for total ammonia. Resilience was thus understood as the complementary attribute of severity, so that maximum severity translated into minimum resilience and vice versa [43]. Equation [2] is a simplified expression that combines the magnitudes and durations of the failures expected in a typical year for comparative purposes in the assessments carried out in this study. Thus, this does not intend to be an accurate representation of the absolute severity of failures but rather a proxy for comparing the relative failure severity of different options under the same annual conditions.

2.4.3.Sustainability Indicators

The adopted definitions of reliability and resilience refer to the operational performance of urban wastewater systems when facing future change, whether this is before or after a failure occurs. Indeed, these are attributes of how a system endures, responds to stress and recovers from failure to minimize any potential impacts.

In contrast, the concept of sustainability is defined here as “the degree to which the system maintains levels of service in the long-term whilst maximizing social, economic and environmental goals” [5]. Thus sustainability is associated with the performance of the system in the long term (even beyond the design life), including failure and non-failure periods. When impacts derived from failure (i.e. from how reliable and resilient the system is) extend to the wider social, environmental and economic systems in urban areas, they become consequences that affect the system's sustainability [5]. As operational impacts (e.g. magnitude or duration of flooding events) interact with the three pillars of sustainability in the form of consequences (e.g. damages to society, the environment and the economy), threats are transferred to the recipients of water services (i.e. society, natural environment and economic systems).

Sustainability indicators in **Table 5** are related to the likely consequences of failure to the economy, the environment and society. These wider implications include four new objectives (river flooding, GHG emissions, cost and acceptability) not accounted for in the reliability and resilience indicators. Their omission in reliability and resilience illustrates the operational nature of reliability and resilience, since there is no clear association of any of these additional objectives with operational performance failure. Instead, these were considered "consequential" objectives, which not only derived the operational performance of the system, but also became paramount when looking at the overall long-term economic, environmental and social (i.e. consequences) trade-offs of investment decisions [44] initially triggered by operational drivers (e.g. flooding or water quality objectives). GHG emissions are calculated from the energy use required for wastewater pumping and treatment processes during one year operational period[14]. Whole-life costs are calculated as the present values of capital and maintenance costs during an operational life of 35 years with a discount rate of 3.5% [14], see the SI (Section S3).

2.5. Robustness Indexes for Reliability, Resilience and Sustainability

The scenarios presented earlier in the text described some of the numerous uncertainties that may affect our predictions concerning IUWWSs in the future. Indeed, a characteristic of long-term policy analysis is working under conditions of *deep uncertainty*, i.e. where analysts do not know or the parties to a decision cannot agree on: (1) the appropriate conceptual models that describe the relationships among the key driving forces that will shape the long-term future; (2) the probability distributions used to represent uncertainty about key variables and parameters in the mathematical representations of these conceptual models; or (3) how to value the desirability of alternative outcomes [45]. This is fundamentally different from other types of uncertainty which could be quantified using various approaches such as probabilities, imprecise probabilities, intervals and fuzzy sets.[3,45]

The variety of alternatives considered and the uncertainty over future conditions recommends the exploration of robust strategies. These are strategies that perform reasonably well compared to other alternatives across a wide range of plausible scenarios [46]. In a context of deep uncertainty, a robust strategy will generally trade optimal performance for less sensitivity to broken assumptions, performing satisfactorily (although sub-optimally) over a range of possible futures [47,48].

2.5.1. Performance regrets

The approach used in this study evaluated the robustness of strategies by assessing their relative performance loss (i.e. regret) across all the objectives and future scenarios previously described[14]. Such performance loss was assessed through each of the performance indicators presented in **Table 5**, representing the relative impacts and consequences of failure in the form of performance regrets.

The concept of regret (or opportunity loss), as introduced by Savage[49], was used to make decision recommendations on mutually exclusive strategies. The regret of strategy s under a future state f is defined as the difference between the performance of s (for objective i) and that of the best-performing strategy s' for the same future scenario f and objective i [47],

$$\text{Regret}_i(s,f) = \left| max_{s'}\ \left[\text{Performance}_i\left(s',f\right)\right] - \text{Performance}_i(s,f) \right| \qquad [\,3\,]$$

The regret of selecting a specific drainage strategy s , as calculated in Equation [3], is understood as the missed opportunity to choose an alternative strategy which would have resulted in a more beneficial outcome once the future is materialized under scenario f [50]. Thus, the basis of regret-based approaches is to select the strategy that minimizes the opportunity loss or regret accrued from all the considered objectives across all future scenarios.

As discussed in the previous section, we consider different ranges of indicators and objectives to assess reliability, resilience and sustainability of the system in different future states. Some of the indicators are evaluated on an operational basis; few others (e.g. costs) are assessed over the lifetime of the system/intervention. In order to ensure consistency in the results and credibility of the approach, performance regrets concerning any objective i under any future scenario f were normalized relative to the most regrettable alternative s^* in that objective and scenario (i.e. the one with the largest regret according to [3]). Thereby, the proposed equations ([4], [5] and [6]) worked as a utility function that assigned normalized regret scores according to performance (i.e. between 0 and 1, from best to worst performance) for each strategy and future scenario [14].

$$Rel_i(s,f) = \frac{\text{Regret}_i(s,f)}{\underset{s^*}{max}[\text{Regret}_i(s_{rel},f)]} \quad \text{for } i = 1, \dots, 4 \qquad [\ 4\ ]$$

$$Res_j(s,f) = \frac{\text{Regret}_j(s,f)}{\underset{s^{**}}{max}[\text{Regret}_j(s_{res},f)]} \quad \text{for } j = 1, \dots, 4 \qquad [\ 5\ ]$$

$$Sus_k(s,f) = \frac{\text{Regret}_k(s,f)}{\underset{s^{***}}{max}[\text{Regret}_k(s_{sus},f)]} \quad \text{for } k = 1, \dots, 8 \qquad [\ 6\ ]$$

$Rel_i(s,f)$ represents the normalised performance regret of strategy s under scenario f for the ith reliability objective (one for each of the five reliability indicators in **Table 5**). An analogous description of $Res_j(s,f)$ and $Sus_k(s,f)$ applies to the j^{th} resilience indicator and the kth sustainability indicator in **Table 5**, respectively. The worst performing strategies in each case are represented by s_{rel}, s_{res} and s_{sus}.

2.5.2.Reliability, Resilience and Sustainability Indexes

By using Equations [7]-[9], the reliability, resilience and sustainability of each strategy under each future scenario can be encapsulated in a single multi-criteria regret index. Each of these indexes has therefore been used to compare the relative overall performance (in terms of reliability, resilience or sustainability) of each strategy within each future state. This reduces the problem of assessing multiple utilities (i.e. five normalised performance regrets for reliability and resilience indexes, or eight for the sustainability index) into one of assessing a one-dimensional weighted utility [51].

$$\overline{Rel}(s,f) = \sum_i \left(w_i^f\ Rel_i(s,f)\right) \qquad \text{for } i = 1, \dots, 4 \qquad [\ 7\ ]$$

$$\overline{Res}(s,f) = \sum_j \left(w_j^f\ Res_j(s,f)\right) \qquad \text{for } j = 1, \dots, 4 \qquad [\ 8\ ]$$

$$\overline{Sus}(s,f) = \sum_{k} \left(w_k^f \, Sus_k(s,f) \right) \qquad \text{for } k = 1, \dots, 8 \qquad [9]$$

$\overline{Rel}(s,f)$ represents the reliability index of strategy s under future scenario f as the weighted summation of reliability normalised performance regrets $Rel_i(s,f)$. Analogous descriptions apply to resilience index $\overline{Res}(s,f)$ and sustainability index $\overline{Sus}(s,f)$. w_i^f, w_j^f and w_k^f represent the relative weights of the ith, jth and kth objectives (associated with reliability, resilience and sustainability, respectively) in future scenario f; with $\sum_i w_i^f = \sum_j w_j^f = \sum_k w_k^f = 1$.

Weights for each future scenario (**Table 6**) were calculated using the Analytical Hierarchy Process (AHP) method with help of a panel of (four) decision makers (from both academia and water authorities in the UK). A pairwise comparison between the criteria was carried out with the ultimate goal of determining the relative weights of different indicators. The pairwise comparison was implemented by establishing a reciprocal matrix wherein scores are assigned based on the relative importance of one objective relative to another [52]. More details on the AHP method and how the pairwise comparison was carried out are provided in the SI (Sections S4 and S5).

Table 6: Weights applied to performance objectives for each future scenario (first row refers to reliability and resilience weights w_i^f, w_j^f; second row to sustainability weights w_k^f).

$w_i^f = w_j^f$ w_k^f	**Sewer Flooding**	**River DO**	**River AMM**	**CSO**	**River Flooding**	**GHG Emissions**	**Cost**	**Accept.**
Markets	0.53	0.12	0.12	0.23	-	-	-	-
	0.19	0.06	0.06	0.10	0.19	0.04	0.27	0.10
Innovation	0.51	0.11	0.11	0.27	-	-	-	-
	0.22	0.08	0.08	0.14	0.20	0.05	0.19	0.04
Austerity	0.43	0.10	0.10	0.37	-	-	-	-
	0.17	0.06	0.06	0.12	0.22	0.04	0.29	0.04
Lifestyles	0.10	0.36	0.36	0.20	-	-	-	-
	0.05	0.19	0.19	0.11	0.05	0.19	0.03	0.19

2.5.3. Robustness Indexes

There has been some debate about the definition and evaluation of robustness, since some authors define this term as the contrary of vulnerability [53,54] while others consider it a characteristic attribute of resilient systems [55–57]. Schoen et al.[56] defines robustness as “strength, or the ability of the system to withstand a given level of stress or demand without suffering degradation or loss of function”. In this study, the robustness of a strategy in the future is defined as its ability to perform well regardless of future conditions. A “robustly reliable” (or robustly resilient or robustly sustainable) drainage strategy is therefore one that is reliable (or resilient or sustainable) under a number of future scenarios.

Equations [10]-[12] express how robust the qualities of reliability, resilience and sustainability are for each strategy across all future scenarios. The four reliability indexes $\overline{Rel}(s,f)$ obtained through [7] were combined to calculate the reliability robustness index for strategy s or $Rob_{Rel}(s)$ (see [10]). Resilience indexes $\overline{Res}(s,f)$ and sustainability indexes $\overline{Sus}(s,f)$ are similarly merged into a resilience robustness index $Rob_{Res}(s)$ and a sustainability robustness index $Rob_{Sus}(s)$, respectively (see [11] and [12] below).

$$Rob_{Rel}(s) = \frac{\sum_f \left(\overline{Rel}(s,f)\right)}{4} \qquad \text{for } f = 1, \dots, 4 \qquad [\ 10\ ]$$

$$Rob_{Res}(s) = \frac{\sum_f \left(\overline{Res}(s,f)\right)}{4} \qquad \text{for } f = 1, \dots, 4 \qquad [\ 11\ ]$$

$$Rob_{Sus}(s) = \frac{\sum_f \left(\overline{Sus}(s,f)\right)}{4} \qquad \text{for } f = 1, \dots, 4 \qquad [\ 12\ ]$$

The arithmetic mean applied to either set of four scenario indexes (reliability, resilience or sustainability indexes) was considered an adequate representation of overall regret, providing an integral picture of robustness across performance objectives and scenarios for each strategy. Consequently, the strategies with the smallest reliability, resilience and sustainability robustness index (i.e. the smallest mean value) were regarded as the most robust alternatives in reliability, resilience and sustainability terms.

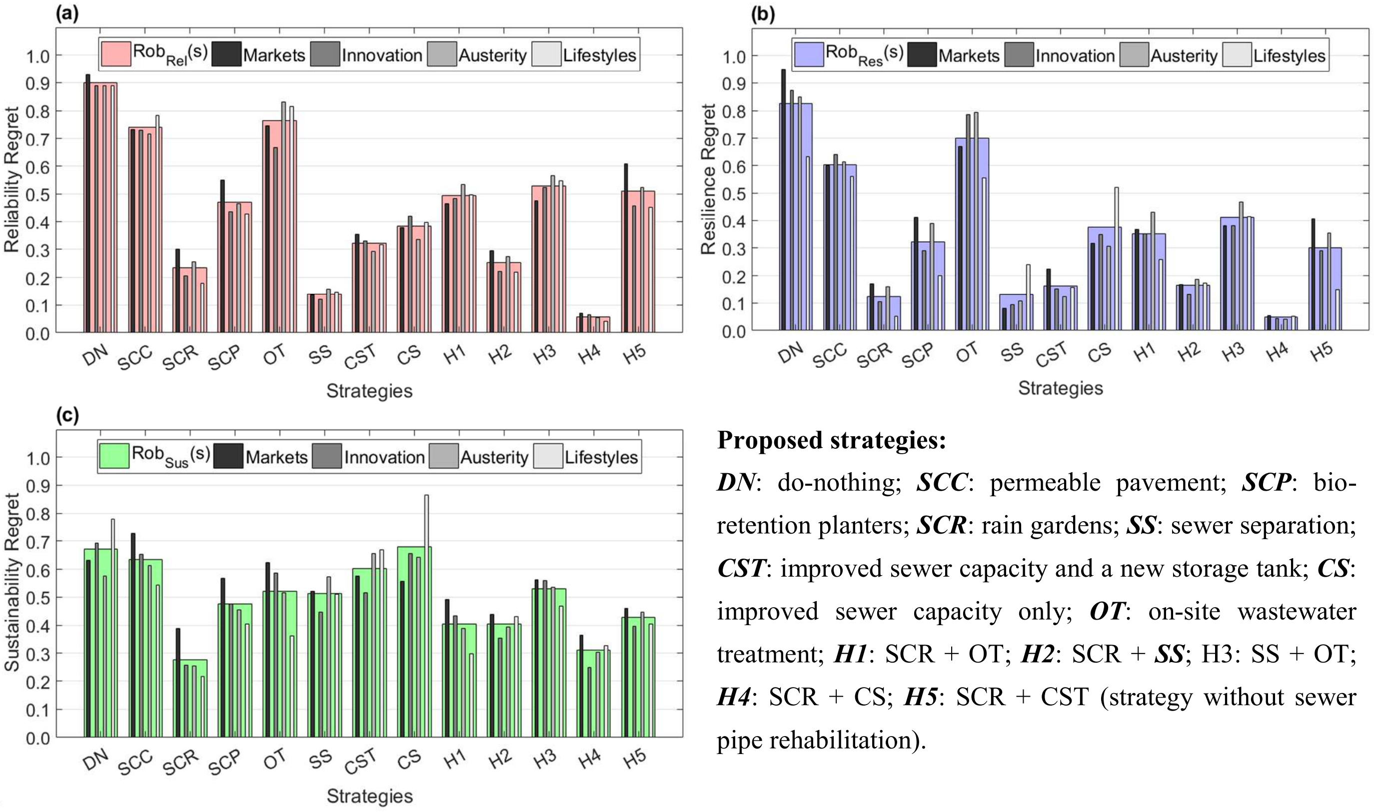
3. RESULTS AND DISCUSSION

As mentioned in Section 2, 12 strategies, including 7 stand-alone and 5 hybrid options, are assessed under the proposed future scenarios (i.e. Markets, Innovation, Austerity, and Lifestyles). Note that these strategies are not designed for a specific future scenario due to the deep uncertainties involved. On the basis of the performance assessment carried out, the regrets of each strategy are calculated for each scenario and robustness indexes determined across all scenarios, as shown below separately for reliability, resilience and sustainability. Additional details for reliability, resilience and sustainability performance indicators are provided in the SI.

3.1. Reliability Robustness

The reliability robustness index for each strategy implemented ($Rob_{Rel}(s)$) is presented in **Figure 2(a)**, along with their specific scenario reliability indexes ($\overline{Rel}(s,f)$). The most robust strategy regarding reliability (i.e. most "robustly reliable" option) was the mixed implementation of sewer rehabilitation and decentralized retrofit rain gardens for roofs (H4 strategy). This strategy was followed by the stand-alone disconnection of roofs using rain gardens (SCR). The reliability index of H4 (CS + SCR) under Markets shows the worst performance compared to those of this strategy under the other three future scenarios, although better than the reliability index of SCR. Therefore, the implementation of SCR could be enough if future conditions are lenient towards Markets, avoiding the expansion of sewers included in H4 and requiring less investment effort.

The least robust alternatives were "do-nothing" (i.e., no improvements in the system) and on-site wastewater treatment for new developments (OT); the latter with a reliability robustness index similar to the mitigation of urban creep using permeable pavement (SCC). The high reliability regret of these strategies illustrate the limited failure duration improvements obtained relative to "do-nothing" across scenarios.

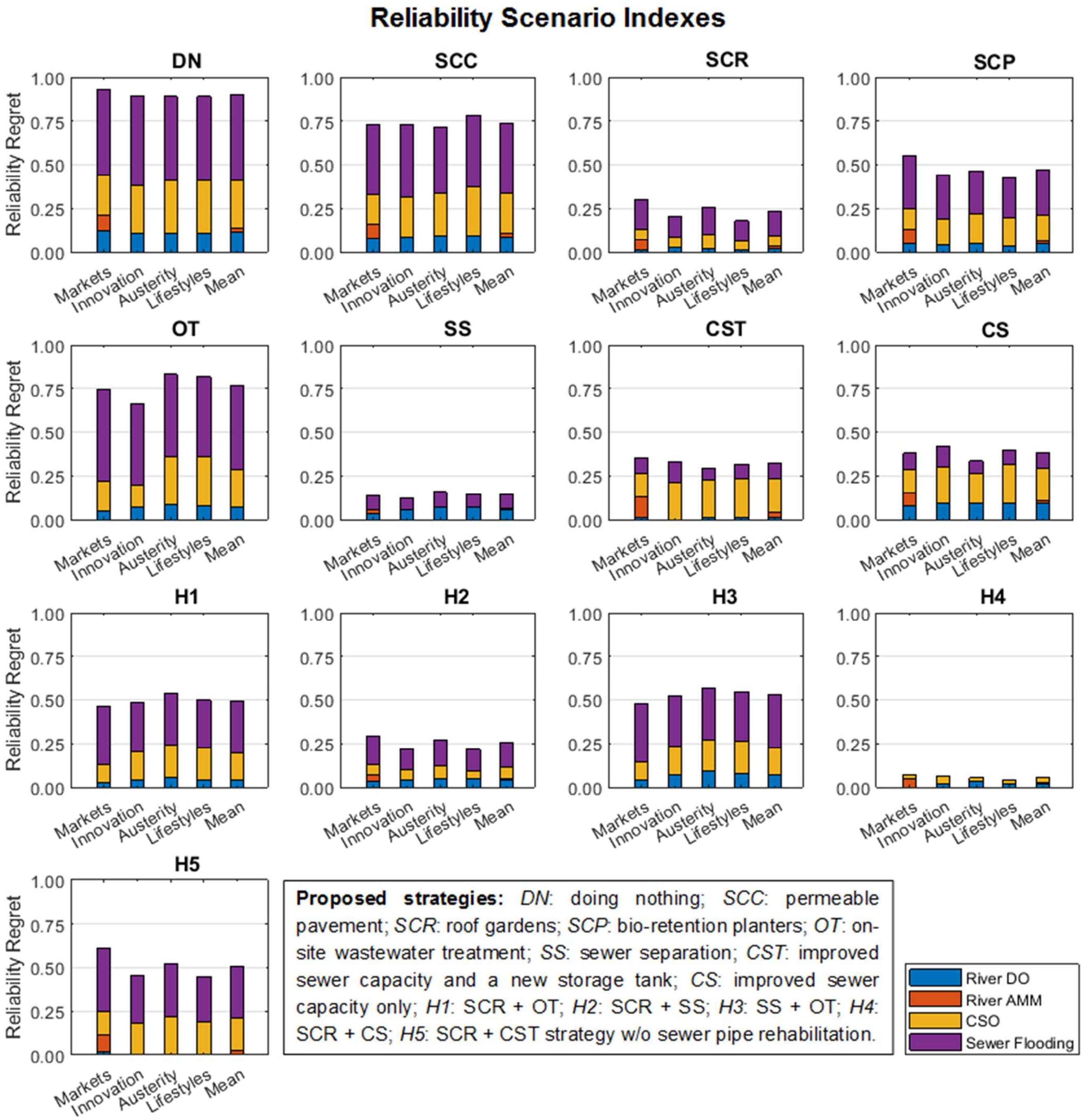


Proposed strategies:

DN: do-nothing; ***SCC***: permeable pavement; ***SCP***: bio-retention planters; ***SCR***: rain gardens; ***SS***: sewer separation; ***CST***: improved sewer capacity and a new storage tank; ***CS***: improved sewer capacity only; ***OT***: on-site wastewater treatment; ***H1***: SCR + OT; ***H2***: SCR + ***SS***; H3: SS + OT; ***H4***: SCR + CS; ***H5***: SCR + CST (strategy without sewer pipe rehabilitation).

Figure 2: (a) Reliability robustness index (red bars) and individual scenario reliability indexes (gray bars within); **(b)** Resilience robustness index (blue bars) and individual scenario resilience indexes; **(c)** Sustainability robustness index (green bars) and individual scenario sustainability indexes for the proposed strategies.

The robustness of reliability attributes in retrofit decentralized strategies (SCR, SCP and SCC) remained proportionate to the disconnected impermeable area in the existing catchment (i.e. more disconnected area, thus better performance). The scenario reliability indexes for SCR and SCP followed very similar patterns, with regrets in Markets and Austerity above the average regret (i.e. reliability robustness index) and Innovation and Lifestyles below average regret. The scenario reliability indexes for SCC presented a flatter profile, providing a more consistent amount of reliability regret across scenarios. This suggests that the mitigation of urban creep was not effective in improving the reliability of the system to failures in the least favorable scenarios (e.g. high water use, high development), while low creep mitigation rates in more favorable scenarios prevented larger reliability gains.



Proposed strategies: *DN*: doing nothing; *SCC*: permeable pavement; *SCR*: roof gardens; *SCP*: bio-retention planters; *OT*: on-site wastewater treatment; *SS*: sewer separation; *CST*: improved sewer capacity and a new storage tank; *CS*: improved sewer capacity only; *H1*: SCR + OT; *H2*: SCR + SS; *H3*: SS + OT; *H4*: SCR + CS; *H5*: SCR + CST strategy w/o sewer pipe rehabilitation.

Figure 3: Performance regrets of $\overline{Rel}(s, f)$ and $Rob_{Rel}(s)$

Figure 3 illustrates a breakdown (stacked chart) of the future scenarios and robustness indexes for reliability, where the performance of each strategy (with respect to each indicator/objective) is presented (the stacked charts for resilience and sustainability are illustrated in the SI, **Figures S3** and **S4**, respectively).

Figure 3 shows that the most dominant color is purple (representing the sewer flooding objective), followed by gold color (CSO objective). In fact, the strategies with the worst reliability indexes did not perform well under these two objectives (e.g. DN, SCC, and OT). Concerning gray infrastructure strategies, sewer rehabilitation and storage (CST) was ranked within the low-regret end of the reliability scale, followed by sewer separation (SS) and, falling back into lower reliability positions, the stand-alone rehabilitation of sewer pipes (CS). These last two strategies were not effective in enhancing the reliability of the system regarding river flooding and dissolved oxygen failure probability (see

Figure 3). The comparison of regret indexes for H4 (i.e. rain gardens and improved sewer capacity) and CST (i.e. improved sewer capacity and storage) indicates that the reliability of source control techniques such as rain gardens is higher than those of centralized storage schemes, whether or not these included system capacity rehabilitation such as sewer pipe enlargement. In a similar way, multi-concept hybrid strategies (H1 to H5) performed most reliably when retrofit roof disconnection was involved in the interventions (i.e. H4, H2 and H5). In contrast, hybrid strategies influenced by on-site wastewater treatment in new developments (H1 and H3) resulted in higher-regret reliability indexes, partly reflecting on the low reliability performance of the OT strategy.

3.2. Resilience Robustness

The resilience robustness indexes presented in **Figure 2(b)** resulted in low regrets for the H4 strategy and the SCR strategy (similar to the results of reliability robustness shown in **Figure 2(a)**), occupying the most robust positions when compared with the rest of strategies. As in the reliability case, “do-nothing” and on-site treatment (D-N and OT strategies, respectively) obtained the worst resilience robustness indexes as well as the most regretful individual scenario resilience indexes. Retrofit decentralized strategies (SCR, SCP and SCC) maintained their rank positions relative to their reliability robustness ranking. This situation contrasted with the resilience robustness of gray infrastructure alternatives (CST, SS and CS), which were displaced by the improved robustness of hybrid strategies (H2, H5 and H3, respectively).

In general, a reduction in the resilience robustness index of strategies was observed relative to their reliability robustness indexes (see **Figure 2(a)** and **Figure 2(a)**). The weighting of failure duration through failure magnitudes was mainly responsible for this, increasing the significance of the most severe annual failures and thus reducing that of the most common (i.e. least severe) ones. In this sense, the role of gray infrastructure solutions in enhancing the conveyance capacity of the system did not have a negative impact on failure durations (in particular those affecting river conditions downstream) but it demonstrated to have a more acute effect on failure magnitudes (see **Figure S3**, in the SI). This situation was most relevant for stand-alone gray infrastructure options such as SS and CS (see **Figure S3**, in the SI), whose resilience regrets under the Lifestyles scenario (i.e. high infiltration to sewers, low maintenance and low technology) increased beyond those of any other strategies relative to the reliability case. The extreme conditions defined in Markets (i.e. high creep, high population, high water use) caused an increase in river flooding regret and water quality regrets, especially for gray CST (see **Figure S3**, in the SI), that could not be fully compensated by reducing regrets in other scenarios and objectives. This meant that gray infrastructure strategies deteriorated failure conditions during adverse scenario circumstances when compared to other alternatives.

3.3. Sustainability Robustness

The implementation of retrofit rain gardens for roof disconnection (SCR strategy) resulted in the most robust alternative for sustainability, followed by the multi-concept strategy H4 (retrofit rain gardens plus rehabilitation of sewer pipes). The assessment of sustainability robustness indexes (see **Figure 2(c)**) introduced river flooding, cost, GHG emissions and acceptability criteria, which favored the stand-alone disconnection of roofs with rain gardens (SCR) due to its low cost and acceptability in scenarios where these criteria were highly valued (namely: Austerity and Lifestyles), as opposed to H4 (more costly and less acceptable in those scenarios); see **Tables S6** and **S7** in the SI.

"Do-nothing" (DN) is the least robust strategy in sustainability terms, with sewer pipe rehabilitation (CS) being penultimate in the robustness hierarchy, despite obtaining a better resilience robustness indexes compared to SCC (permeable pavement), SS (sewer separation), CS (improved sewer capacity) and CST (improved sewer capacity and storage) under Austerity scenario, mainly due to high costs and GHG emissions, and low acceptability of these four strategies in this scenario (i.e. lack of economic, environmental, and social performance). As expected DN has the best performance (i.e. the lowest regret) with respect to cost in all future scenarios (see **Figure S4**). Should investments be made in the future, the DN approach allows for flexibility to implementing new strategies when future needs become clear.

Hybrid alternatives showed increased sustainability robustness when compared to mono-concept interventions and, in particular, gray infrastructure stand-alone strategies (i.e. CST, SS and CS). In this sense, hybrid interventions involving retrofit roof disconnection with rain gardens (i.e. H4, H1, H2 and H5) improved their sustainability robustness at the expense of that of mono-concept gray infrastructure options, which failed to maintain low regrets across future scenarios.

Gray infrastructure strategies were generally penalized by their cost burden in scenarios that otherwise favored centralized solutions in the acceptability objective (e.g. CST in Markets), as well as by environmental and social issues in scenarios where cost was a less important factor to decisions (e.g. CS in Lifestyles). This situation contrasted with that of hybrid alternatives, which attained a more balanced performance, given their even distribution of regrets across objectives and scenarios.

Retrofit decentralized strategies (i.e. SCR, SCP and SCC) showed a wide variety of robustness in sustainability terms (as in reliability and resilience), mostly linked to its main trade-off; i.e. the balance between cost and operational performance. In most objectives, unpronounced trade-offs for these strategy types ensured a balanced accumulated regret for most scenarios, proportionate to the level of impermeable area intervened. However, the cost of permeable pavement implementation (SCC) and bio-retention planters (SCP) highly constrained their obtaining low-regret sustainability scenario indexes and thus low-regret robustness indexes (**Figure S4**). In particular creep mitigation using permeable pavement (SCC) proved ineffective in outweighing the cost regret in the Markets scenario, or in achieving low regrets in more operationally lenient scenarios (i.e. Lifestyles) given the limited benefits derived from low creep removal rates.

On-site treatment of part of the wastewater from new developments (OT) showed a significant improvement in sustainability robustness relative to the reliability and resilience regrets presented above. In spite of not directly addressing stormwater management issues, the OT strategy compensated these high regrets with a modest cost trade-off and large improvements in GHG emissions. This was also a factor which contributed to the improved performance of some hybrid strategies, such as H1.

3.4. Sensitivity Analysis

A two-at-a-time sensitivity analysis was carried out with a focus on the importance weight of each assessment objective (i.e. sewer flooding, river water quality, combined sewer overflow (CSO), river flooding, GHG emissions, cost and acceptability). The assigned weights were altered by ±15% in each future scenario (i.e. Markets, Innovation. Austerity and Lifestyles) for the calculation of reliability, resilience and sustainability indexes (**Figure 4**).

The sensitivity was calculated as the percentage variation in the reliability index ($\overline{Rel}(s,f)$), resilience index ($\overline{Res}(s,f)$) and sustainability index ($\overline{Sus}(s,f)$) relative to the value obtained with the originally assigned weights. **Figure 4** shows that the reliability indexes are approximately within a variation of ±3% in Markets, Innovation and Austerity, and ±5% in Lifestyles. It is also shown that sensitivity associated with the resilience indexes is very similar to that of the reliability; the only difference is shown in the results of Markets scenarios where the maximum difference from the original resilience indexes is ±2%.

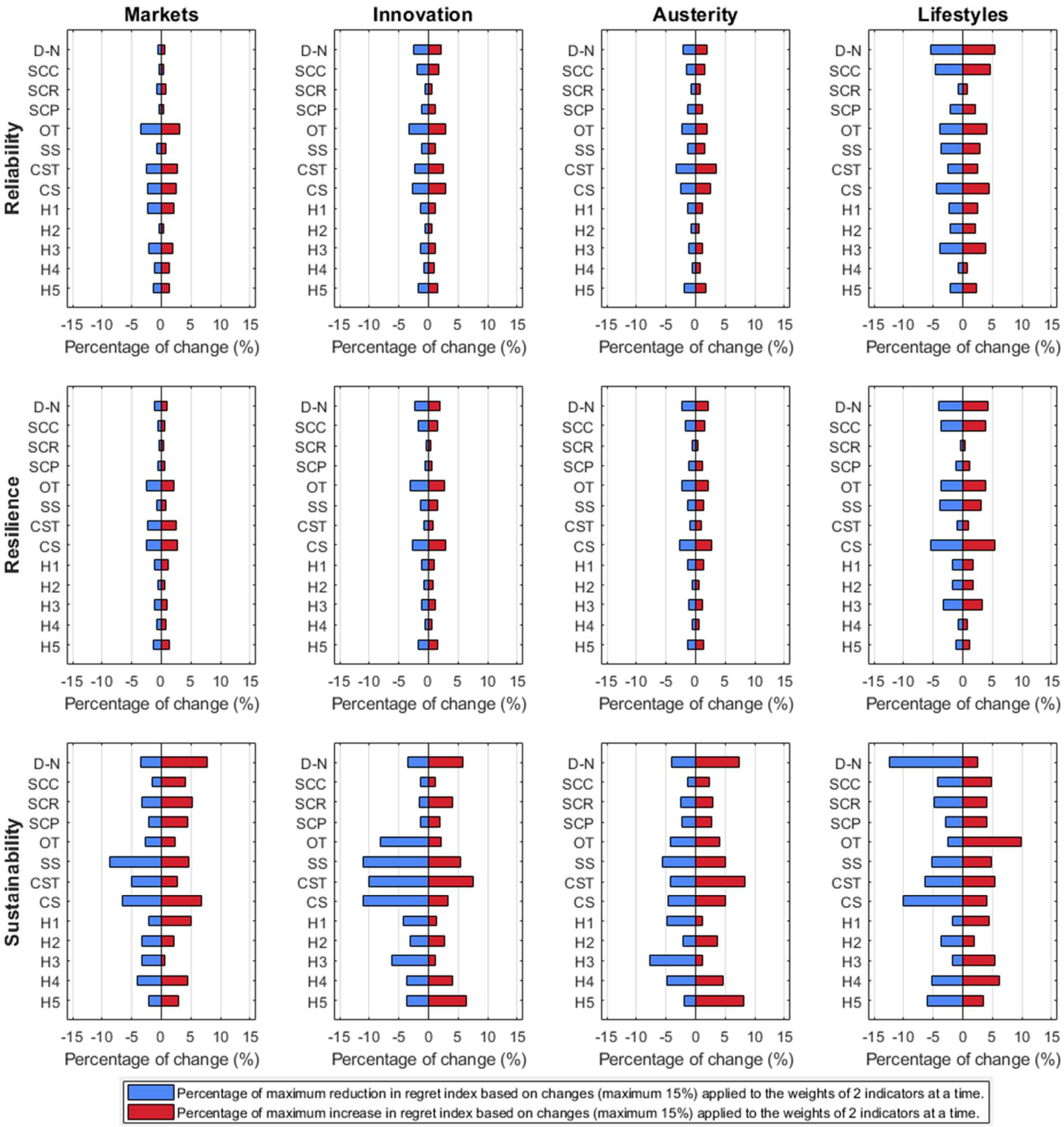


Figure 4: Sensitivity of individual scenario reliability indexes, resilience indexes and sustainability indexes to a two-at-a-time alteration of objectives' weights (±15%) for the proposed strategies. DN: doing nothing; SCC: permeable pavement; SCP: bio-retention planters; SCR: rain gardens; SS: sewer separation; CST: improved sewer

capacity and new storage tank; CS: improved sewer capacity only; OT: on-site wastewater treatment; H1: SCR + OT; H2: SCR + SS; H3: SS + OT; H4: SCR + CS; H5: SCR + CST strategy without sewer pipe rehabilitation.

On the other hand, the sustainability indexes present more sensitivity to changes in the objectives' weights, with maximum variations of approximately +9% and -12%. The sensitivity varies from strategy to strategy, with lower extremes around -12% for the "do-nothing" strategy (DN) (for sustainability index under Lifestyles) and -11% for on-site treatment (OT) and for improved sewer capacity (CT) (for sustainability indexes under Innovation), and an upper extreme of +9% for OT (for sustainability indexes under Lifestyles). **Figure 4** illustrates that hybrid strategies are generally less sensitive to changes applied to the original weights when compared to mono-concept strategies. On average, the highest degree of confidence, when the original weights were altered by ±15%, can be seen in the results of SCR (±1.5%), H2 (±1.5%), SCP (±1.6%), H4 (±2.0%) and H1 (±2.0%), whereas, the highest variations are observed in the results of CS, DN, OT, and CST (with average variations of ±4.3%, ±3.6%, ±3.5% and ±3.4%, respectively).

3.5. Implications

The concept of regret is a useful tool for the comparative assessment of a large array of performance indicators that, given their different natures (quantitative or qualitative) and scales, are often difficult to compare and normalize. The integrative nature of regret permits analysts to operationalize complex concepts such as reliability, resilience or sustainability into indexes that can illustrate the overall robustness of the proposed strategies. The case study investigated here is in the context of UK regulations; however, the scenarios, strategies and performance metrics are typically found in Western Europe and many other countries alike. Therefore, the findings of this study can be broadly applicable to those countries and provide decision makers and utility managers with enhanced insight into the development of more reliable, resilient and sustainable urban wastewater systems using gray, green and hybrid options.

The results presented in this paper demonstrate that strategies that are robust for sustainability in the case study are likely to be robust for both resilience and reliability across future scenarios (e.g. SCR and H4), whereas robustness for resilience and, in particular, for reliability cannot ensure robustness for sustainability. In this sense, the behavior of some strategies (e.g. H1 and OT) appeared to contradict this view, since their low robustness in reliability and resilience terms later translated into higher sustainability robustness; however, these were relatively far from low-regret robustness indexes at the top of the hierarchy. Additional objectives, not accounted for in reliability and resilience assessments (river flooding, cost, GHG emissions and acceptability), made up a significant part of the enhanced performance of these strategies, while benefitting from the low performance of other options in these objectives. Therefore, reliability, resilience, and sustainability indicators cannot be used interchangeably and should be looked at and analyzed depending upon the purpose of the decision making exercise. Indeed, reliability, resilience and sustainability approaches need to be used proportionately to the complexity and scale of the problem to be solved. As mentioned earlier in the text, decision-makers may be interested in satisfying a limited number of objectives in a low uncertainty problem, where reliability is sought and a sustainability-led analysis may excessively complicate (or even hinder) their decision. Instead, they may prefer to approach a highly complex and uncertain problem from a sustainability point of view in order to better balance the potentially critical trade-offs present in a much more challenging decision exercise. Robustness for sustainability is regarded as a more demanding attribute as it focuses on economic, environmental and socio consequences, therefore, a larger number of criteria are involved in its definition and more trade-offs can affect the sustainability index.

It is important to note that such relationships are not categorical since they are dependent on the selected performance indicators and how their regrets are traded between objectives within each robustness assessment. For example, there are less known adverse impacts of gray and green options on human health (e.g. pathogen-related risks) from an integrated systems' perspective [58,59], and the objective tradeoffs might be different when these impacts are considered. This and other emerging issues should be further investigated once such data and knowledge become available. In this sense, the multi-criteria and multi-scenario assessment conditions presented in the case study favored “balanced” strategies; those without marked performance trade-offs which were generally responsible for larger regrets across future scenarios.

Gray infrastructure alternatives where environmental, economic and social objectives are more difficult to be simultaneously satisfied (e.g. cost, water quality issues) are not robust for sustainability, even in cases where they show robustness concerning both reliability and resilience. Such trade-offs are compensated for in hybrid strategies combining gray infrastructure interventions with green retrofit strategies. In this context, hybrid strategies can mitigate loss in performance by diversifying the number of interventions and by complementing the benefits and strengths obtained from each mono-concept strategy. These multi-concept strategies demonstrate that the robustness of gray infrastructure strategies for reliability, resilience and sustainability can be enhanced by using green retrofits as these are able to better negotiate their performance regrets. In this sense, decentralized infiltration through rain gardens proves to be more robust than large storage tunnel interventions when combined with sewer rehabilitation schemes across future scenarios.

Green retrofits provide consistent levels of robustness under a variety of scenarios, achieving low-regret robustness for reliability, resilience and sustainability altogether. The mitigation of urban creep using permeable pavements cannot compensate its cost regret with small operational gains in the IUWWS. Such limitation recommends: 1) the implementation of this strategy in combined sewer areas where this can be integrated with the disconnection of adjacent roofs and paved areas as to enhance its catchment benefits; 2) supporting more cost-effective alternatives for urban creep mitigation in separate areas and elsewhere.

In urban wastewater system modeling, a wide range of parameters can be used, including population, urban growth and rainfall intensities. In this study, uncertainties are mapped into and captured within a large discrete scenario space, because of the difficulties in assigning likelihoods or intervals to these parameters in a world of deep uncertainty. In the case study, robustness is calculated using a limited number of future scenarios. However, this study represents a first step to explore how to make a long-term strategic plan for the complex integrated urban wastewater system under deep uncertainty. This is essential to provide insight into which strategies are best suited to which futures, what indicators should be monitored in order to meet future compliances, and which strategy is most robust (i.e. less regrettable) no matter how the future unfolds.

ASSOCIATED CONTENT

Supporting Information (SI). Case Study Schematic Diagram. Future Scenarios. Assessment Details of Reliability, Resilience and Sustainability. Computation of indicators' relative weights using the AHP method and Pair-Wise Comparison between Objectives Under Different Future Scenarios. Reliability, Resilience and Sustainability Results. Scenario and Robustness Indexes for Reliability, Resilience and Sustainability. This material is available free of charge via the Internet at http://pubs.acs.org.

Author Contributions

All authors have given approval to the final version of the manuscript.

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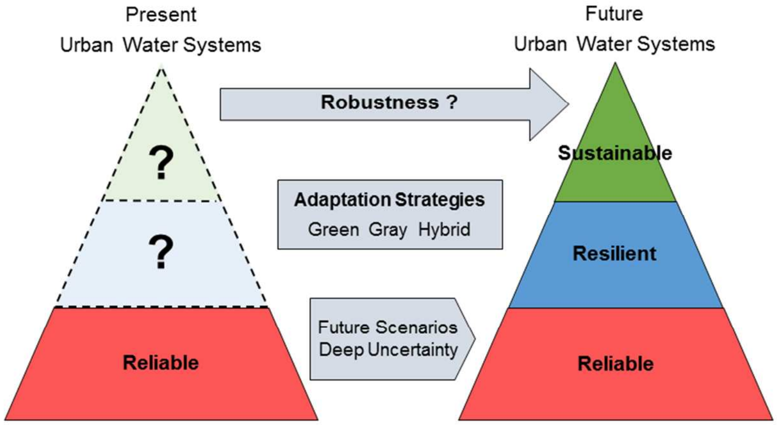
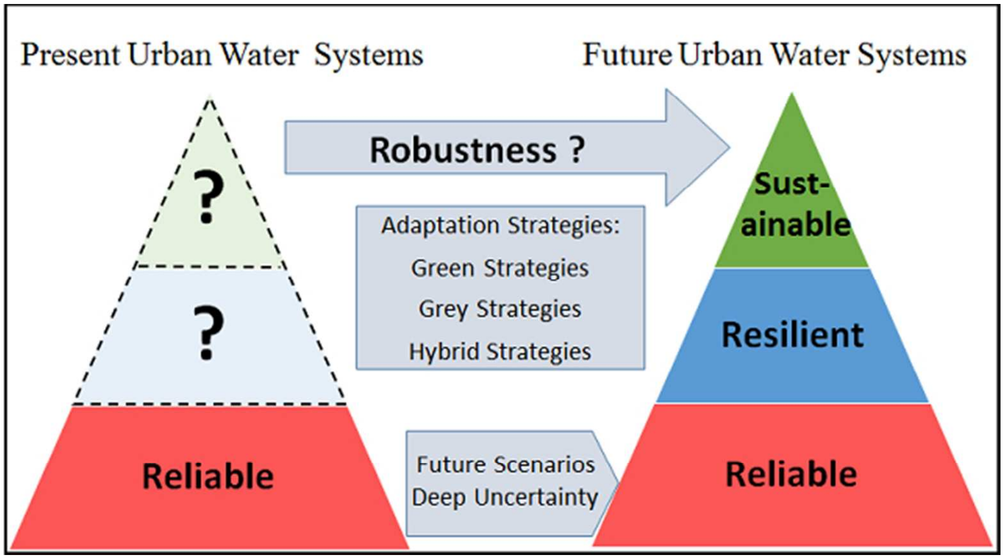
TOC/Abstract ART





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