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Strategic planning of the integrated urban wastewater system using adaptation pathways

Seyed M.K. Sadr*, Arturo Casal-Campos**, Guangtao Fu, Raziyeh Farmani, Sarah Ward, David Butler

Centre for Water Systems, College of Engineering, Mathematics and Physical Sciences, University of Exeter, North Park Road, Harrison Building, Exeter, EX4 4QF, UK

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ABSTRACT

Emerging threats such as climate change and urbanisation pose an unprecedented challenge to the integrated management of urban wastewater systems, which are expected to function in a reliable, resilient and sustainable manner regardless of future conditions. Traditional long term planning is rather limited in developing no-regret strategies that avoid maladaptive lock-ins in the near term and allow for flexibility in the long term. In this study, a novel adaptation pathways approach for urban wastewater management is developed in order to explore the compliance and adaptability potential of intervention strategies in a long term operational period, accounting for different future scenarios and multiple performance objectives in terms of reliability, resilience and sustainability. This multi-criteria multi-scenario approach implements a regret-based method to assess the relative performance of two types of adaptation strategies: (I) standalone strategies (i.e. green or grey strategies only); and (II) hybrid strategies (i.e. combined green and grey strategies). A number of adaptation thresholds (i.e. the points at which the current strategy can no longer meet defined objectives) are defined to identify compliant domains (i.e. periods of time in a future scenario when the performance of a strategy can meet the targets). The results obtained from a case study illustrate the trade-off between adapting to short term pressures and addressing long term challenges. Green strategies show the highest performance in simultaneously meeting near and long term needs, while grey strategies are found less adaptable to changing circumstances. In contrast, hybrid strategies are effective in delivering both short term compliance and long term adaptability. It is also shown that the proposed adaption pathways method can contribute to the identification of adaptation strategies that are developed as future conditions unfold, allowing for more flexibility and avoiding long term commitment to strategies that may cause maladaptation. This provides insights into the near term and long term planning of ensuring the reliability, resilience and sustainability of integrated urban drainage systems.

1. Introduction

Urban wastewater management has become increasingly challenging due to deep uncertainties posed by global climate change, urbanization, population growth, economic and technological developments, and other unforeseen changing factors such as societal perspectives and preferences. As such, the level of service delivered by urban wastewater infrastructure in the future can deteriorate, causing important system failures (Brugge et al., 2005; Offermans et al., 2011). To this end, there is a growing interest to manage present and future uncertainties, particularly those in the form of exceptional disturbances that could lead to extremely adverse consequences (Maier et al., 2016; Pechlivanidis et al., 2017). In the context of urban wastewater management, emphasis has shifted towards adaptation (O'Brien, 2012), and addressing the short and long term challenges posed by deep uncertainties (Manocha and Babovic, 2018) rather than simply focusing on how change has occurred in the past (Fazey et al., 2016).

In the face of deep uncertainties and their unknown impacts and consequences, it is essential to consider the indicators that can

* Corresponding author.
** Corresponding author.
E-mail addresses: s.m.k.sadr@exeter.ac.uk (S.M.K. Sadr), a.casal@mail.com (A. Casal-Campos).

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measure system performance in the future, such as those of reliability, resilience and sustainability. The reliability of a system is measured under design conditions, whereas, resilience measures the system performance under extreme conditions when the required level of service is not achieved (Butler et al., 2017). Sustainability measures system performance from economic, environmental and socio-cultural consequences over the life span. Although these three concepts measure different aspects of system performance (Butler et al., 2017), they are interconnected to each other (Blockley et al., 2012). It has been suggested that reliability is necessary but not sufficient for resilience, and resilience is necessary but not sufficient for sustainability (Butler et al., 2014).

There is a lack of understanding regarding the long term and short term impacts of adaptation strategies on the system performance in terms of reliability, resilience and sustainability. The understanding is critical to avoid maladaptive lock-ins, reduce potential regrets and allow flexibility as conditions change over time (Maru and Stafford Smith, 2014). Such a course of action allows decision makers to consider a strategy limited in time and resources (and therefore rectify if needed) whilst still permitting them to foresee the possible long term consequences of specific adaptation pathways (Dessai and van der Sluijs, 2007; Tanaka et al., 2015). In recent years, several planning methods and policy-making approaches within the field of water and wastewater management have been developed to dynamically respond to changing circumstances and deep uncertainties (Manocha and Babovic, 2017; van Veelen et al., 2015), including Robust Decision Making (Casal-Campos et al., 2015; Lempert et al., 2006; Mortazavi-Naeini et al., 2015), Adaptive Policy Making (Walker et al., 2013), Adaptation Pathways (Bloemen et al., 2018; Haasnoot et al., 2019; Kingsborough et al., 2016; Manocha and Babovic, 2017; Maru and Stafford Smith, 2014), Uncertainty Framework/Assessment (Kundzewicz et al., 2018; Refsgaard et al., 2013), Dynamic Adaptation Policy Pathways (Haasnoot et al., 2013; Kwakkel et al., 2015), Risk Model (Merz et al., 2009; Zhou et al., 2012), Real Option Analysis (Deng et al., 2013; Zhang and Babovic, 2012).

Among these, Adaptation Pathway (AP) methods assess the adaptability potential of management strategies and evaluate system performance in different epochs (i.e. transient scenarios from the baseline year to the future horizon) with respect to different objectives and indicators to identify pathways without any maladaptive lock-ins. An adaptation pathway provides a visual representation of the potential sequencing and type of actions to be implemented (or strategies to be considered) in the future (Kingsborough et al., 2016). The core of AP approaches lies in adaptation thresholds or tipping points, which are defined as the points where changing conditions force a normally stable state of a system into another state or facilitate adaptation of the system (van Veelen et al., 2015). These methods take system vulnerabilities as the initial point to identify a range of adaptation options (Jeuken et al., 2015). Such approaches have mainly been used within the fields of stormwater management and flood risk management; for example: Barnett et al., 2014; Bloemen et al. (2018); Haasnoot et al. (2019, 2013); Kwadijk et al., 2010; Manocha and Babovic (2017); Ranger et al. 2013; van Veelen et al. (2015); Werners et al. 2013. A number of studies have applied adaptation pathway methods for long term planning of urban water supply systems (Cradock-Henry et al., 2020; Forsythe et al., 2018; Haasnoot et al., 2012; Kingsborough et al., 2016).

Some of these approaches need to be reoriented towards resilience assessment (Juan-García et al., 2017) and to consider both short and long term adaptation planning (Hecht and Kirshen, 2019). According to Gersonius et al. 2013, some of these approaches may fail in reliably addressing uncertainties and non-stationarity in future drivers such as climate change. This is due to the fact that they only consider one future scenario at a time and cannot identify solutions with high levels of confidence (Adger et al., 2009; Jafino et al., 2019). To date, APs have not been applied to IUWWSs with socio-economic complexities that assess reliability, resilience and sustainability simultaneously.

The aim of this paper is, therefore, to develop an AP approach to assess the compliance and adaptability potential of various strategies in reliability, resilience and sustainability domains, both individually and conjunctively along the pathway of transient scenarios (future scenarios every 5 years) in an IUWWS. It will focus on the identification and application of adaptation strategies associated with the management of stormwater and wastewater in urban areas as to ameliorate a number of impacts and consequences used to describe system performance. Casal-Campos et al. (2015) assessed the relative performance of green and grey strategies in multiple impact categories on an integrated catchment using a regret-based approach. Casal-Campos et al. (2018) further investigated the robustness of a number of strategies in delivering reliable, resilient and sustainable wastewater services in the future. Although these two studies assessed the performance of strategies in the year 2050 (long term), they did not identify possible adaptation pathways that span from the baseline year to the future horizon. In the present study, a novel approach is developed for the dynamic assessment of interventions that leads to adaptive management of the IUWWS in both the short and long terms. The proposed approach brings the time domain to adaptation planning and identifies possible adaptation pathways based on different adaptation thresholds for individual and conjunctive performance domains of under different future scenarios (defined as transient scenarios assessed every 5 years) every 5 years (here they are defined as epochs or transient scenarios) for the period 2015–2050.

Section 2 provides an overview of the proposed methodology through two steps: Step 1: Identification of compliant domains and Step 2: Evaluation of compliant domains via regret indices. Section 3 describes the case studies including definition and description of the integrated urban wastewater system, future scenarios, adaptation strategies and decision indicators. Section 4 reports the results and a wider discussion of their implications. Finally, Section 5 summarises the conclusions and implications of this study.

2. Methodology: adaptation pathways

Mathematical models are developed and used in order to understand the current and future states of the wastewater system (Haasnoot et al., 2011). There are numerous uncertainties that hinder our understanding of the system and constrict the predictive capacity of models regarding its future state (Asselt, 2000; Walker et al., 2003). If future conditions happen to be different from the predicted conditions, adaptation strategies may fail to deliver their expected performance (McInerney et al., 2012). Adaptation strategies are therefore required to respond to the new conditions when the future state unfolds (Manocha and Babovic, 2017). When the future is revealed, adaptation measures need to be updated based on what is experienced and learnt. Therefore, in order to establish a framework to manage the future, a planning approach is required that consists of a strategic vision of the future (Kingsborough et al., 2016), committing to both short term and long term plans and actions (Bloemen et al., 2018). The approach of adaptation pathways has recently received growing attention from researchers and decision makers (Fazey et al., 2016) and is being applied as a planning and foresight tool to help evaluate the adaptability of management strategies in both the short and the long terms. Adaptation pathways have several definitions, and different studies examine the approach from distinctive perspectives (Wise et al., 2014). For example, Leach et al., 2010 defined this approach as: “alternative possible trajectories for knowledge, intervention and change, which prioritize different goals, values and functions”. They considered temporal uncertainties in the long term future for adaptation to climate change. Haasnoot et al. (2013) defined it as “an analytical and foresight approach for exploring and sequencing a set of possible strategies along the planning timeline”. Haasnoot et al. (2019) adapted their aforementioned definition to the following: “an approach that explores alternative sequences of investment decisions to achieve objectives over time in the context of uncertain future developments and environmental changes”. In this study, an adaptation pathway is defined as a pathway in which a strategy (or a combination of strategies) is compliant with the adaptation threshold(s) along the planning timeline. An overview of definitions for the adaptation pathways is presented in the Supporting Information (SI), Section S1.

Fig. 1 illustrates a flow chart of different steps considered in the proposed AP approach, highlighting the preliminary steps (Steps 0.1 to 0.5) and main steps (Steps 1 and 2) of the methodology. In this study, a novel AP approach is introduced to identify possible pathways (the possible compliant domains in different future states) along the planning timelines with respect to different adaptation thresholds (Step 1: Section 2.1), and facilitates a detailed regret-based analysis of each management strategy in the form of reliability, resilience and/or sustainability (Step 2: Section 2.2). Prior to the above steps, the following preliminary steps should be considered: specifying the water systems and identifying the variables (Step 0.1: Section 3); identifying or defining future scenarios (Step 0.2: Section 3.1); identifying adaptation strategies (Step 0.3: Section 3.2); identifying the performance domains and assessment indicators/criteria (Step 0.4: Section 3.3); and defining suitable adaptation thresholds (Step 0.5: Section 3.4).

2.1. Step 1: identification of compliant domains

The core of the AP approach is the “adaptation threshold”, which is defined as the condition beyond which a management strategy is no longer able to meet a defined objective (or objectives) across a timeline; at this point, alternative adaptation strategies should be considered. This is similar to an “adaptation tipping point”, the term which is normally used in the climate change community (Manocha and Babovic, 2017; Renaud et al., 2013). An adaptation threshold is also known as the “recovery threshold” i.e. at this point measures should be adopted to meet the objectives (van Veelen et al., 2015). Adaptation thresholds are used to identify the

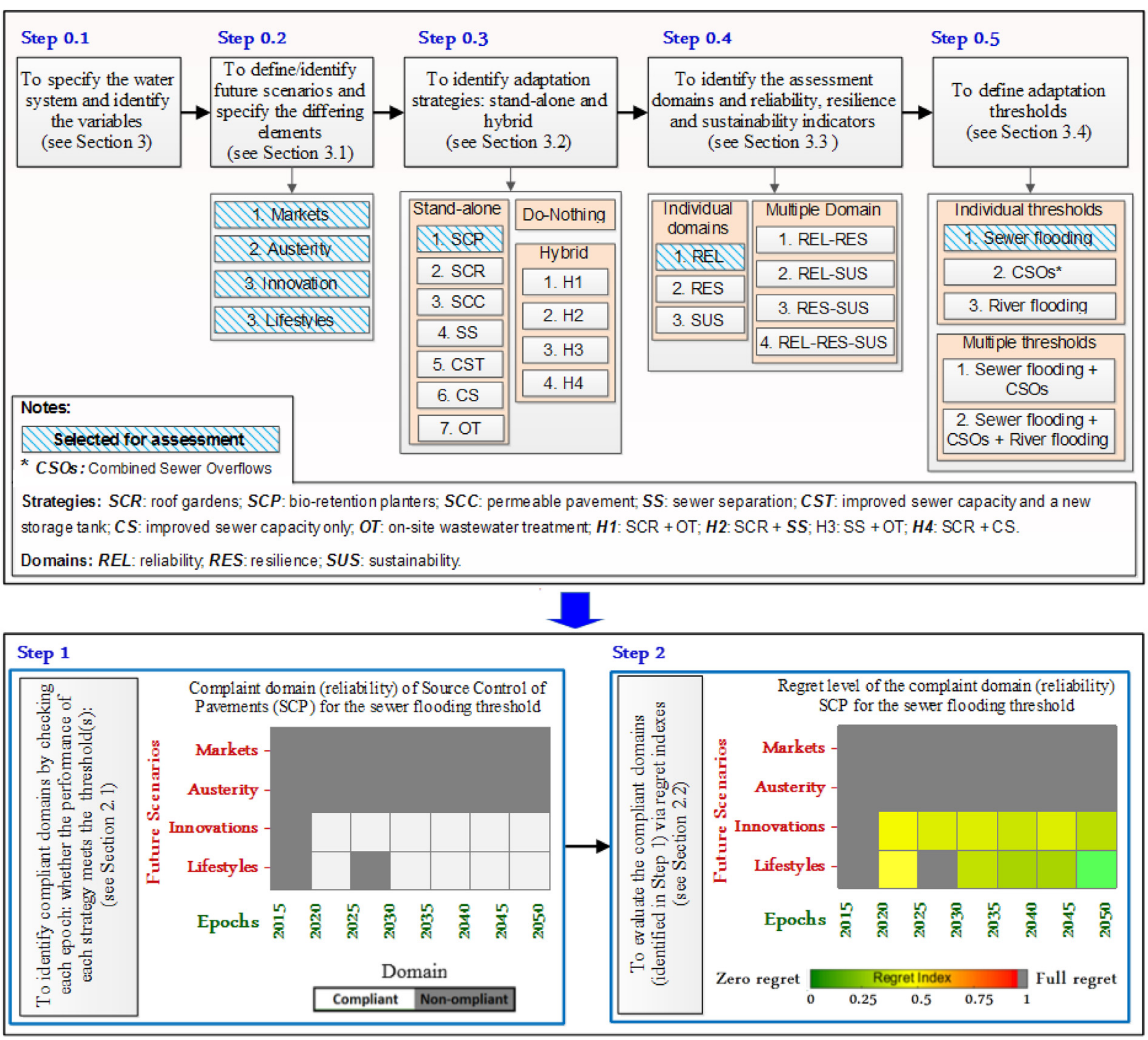

Fig. 1. The adaptation pathways methodology.

compliant domain of each strategy (described in Section 3.2) along the planning timeline; further details on adaptation thresholds are discussed in Section 3.4. In this study, each strategy is assessed under future scenarios (defined in Section 3.1) at time intervals of 5 years (i.e. epochs or transient scenarios), defining a pathway that spanned from the baseline year 2015 to the future horizon 2050.

The particular scenario conditions and their variation along the timeline are considered by setting 5-year assessment periods, i.e. epochs in 2020, 2025, 2030, 2035, 2040, 2045 and 2050, see Fig. 2. The time epoch when a strategy violates an adaptation threshold (the system no longer complies with a specific objective value) is referred to as its “sell-by-date” (Haasnoot et al., 2013), i.e. the period when a strategy is expected to require adaptation or additional measures due to an interruption of its satisfactory performance across pathway of transient scenarios (van Veelen et al., 2015). The assessment at the end of each epoch (e.g. 2020 for the period 2015–2020) is assumed to be representative of the full period, which may well be the case when considering, for example, asset investment plans in the UK or similar regulatory or planning horizons in other contexts.

In the proposed method, the compliant domain is evaluated in two complementary ways: (i) the number of complying epochs across the scenarios and (ii) whether the pathways are uninterrupted (i.e. compliant) or interrupted (i.e. non-compliant) in relation to one or more adaptation thresholds across the entire timeline. This is achieved by assessing the compliance of each strategy with specific adaptation thresholds in different future scenarios and epochs. When an adaptation threshold is reached, another strategy or measure should be considered for implementation (van Veelen et al., 2015). For example, in Fig. 2, Strategy A is compliant along the Lifestyles and Innovation scenarios. However, the Market and Austerity scenarios (see the description of each future scenario in Section 3.1) are interrupted after 10 years and 25 years, respectively. Therefore if future conditions resemble those of the Austerity scenario, for instance, another adaptation strategy is required in 2040.

2.2. Step 2: Evaluation of compliant domains via regret indices

The first step of the proposed AP approach, described in Section 2.1, is to identify the compliant epochs and uninterrupted pathways in accordance with the adaptation thresholds. The identified compliant epochs and pathways are further assessed using a regret-based multi-criteria analysis model that provides additional benefits and details of system performance. Regrets are calculated in the form of reliability ($\overline{Rel}(s,f)$), resilience ($\overline{Res}(s,f)$) or sustainability ($\overline{Sus}(s,f)$) indices, see Eq. (1), Eq. (2) and Eq. (3):

$$\overline{Rel}(s,f) = \sum_i \left[w_i^f \times \frac{Regret_i(s,f)}{\max\limits_{s'}[Regret_i(s_{rel},f)]} \right] \quad \text{for } i = 1,\dots,M \tag{1}$$

$$\overline{Res}(s,f) = \sum_j \left[w_j^f \times \frac{Regret_j(s,f)}{\max\limits_{s'}[Regret_j(s_{res},f)]} \right] \quad \text{for } j = 1,\dots,N \tag{2}$$

$$\overline{Sus}(s,f) = \sum_k \left[w_k^f \times \frac{Regret_k(s,f)}{\max\limits_{s'}[Regret_k(s_{sus},f)]} \right] \quad \text{for } k = 1,\dots,Q \tag{3}$$

Where w_i^f, w_j^f and w_k^f are the importance weights (assigned by a group of water experts) of the i^{th} reliability indicator, j^{th} resilience indicator, and k^{th} sustainability indicator in future state f respectively. In this study, five reliability indicators ($M = 5$), five resilience indicators ($N = 5$) and eight sustainability indicators ($Q = 8$) are taken into account. The adaptation indicators, and the assigned weights in different future scenarios are discussed in Section 3.3. $Regret_i(s,f)$, $Regret_j(s,f)$ and $Regret_k(s,f)$, see Eq. (4), Eq. (5) and Eq. (6), represent the regret (or opportunity loss) of strategy s under a

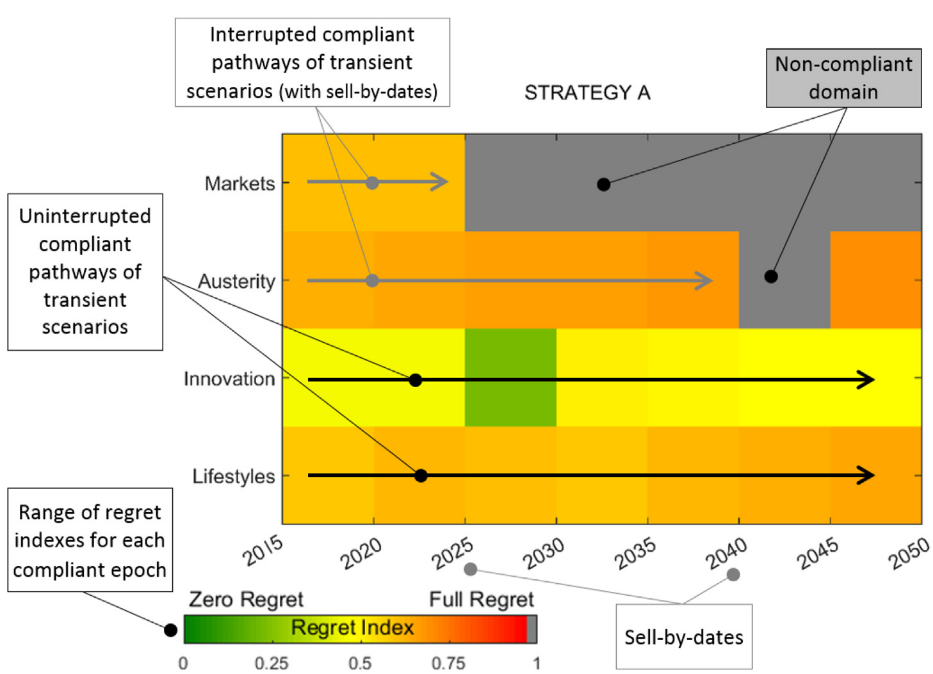

Fig. 2. An example representation of adaptation pathways for a generic strategy. The compliant domain (coloured) and non-compliant domain (grey) of transient scenarios are shown relative to adaptation threshold(s). Coloured shades refer to regret expressed by reliability, resilience or sustainability indices for each transient scenario. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

future state f with respect to ith, jth or kth indicator, respectively (Casal-Campos et al., 2015). The regret of strategy s under a future state f is defined as the difference between the performance P of s (for reliability objective i, resilience objective j, or sustainability objective k) and that of the best-performing strategy s' for the same future scenario f and objective i, j, or k.

$$Regret_i(s,f) = \left| max_{s'}[P_i(s',f)] - P_i(s,f) \right| \quad (4)$$

$$Regret_j(s,f) = \left| max_{s'}[P_j(s',f)] - P_j(s,f) \right| \quad (5)$$

$$Regret_k(s,f) = \left| max_{s'}[P_k(s',f)] - P_k(s,f) \right| \quad (6)$$

$max_{s'}[P(s',f)]$ is the best-performing strategy s' under future scenario f with respect to indicator i, j or k. $P(s,f)$ represents the performance of strategy s under the same future scenario and allied with the same indicator (Lempert et al., 2006). Regret index for multiple (i.e. conjunctive or mutual) performance domains ($\overline{Index_M}$), e.g. reliability + resilience + sustainability, is determined as the average of reliability, resilience and sustainability indices for each epoch within each scenario (Eq. (7)):

$$\overline{Index_M}(s,f) = \frac{\overline{Rel}(s,f) + \overline{Res}(s,f) + \overline{Sus}(s,f)}{n} \quad (7)$$

where n denotes the number of individual indices (reliability, resilience and sustainability) considered concurrently.

For this assessment, if a strategy's regret is one (i.e. full-regret) in any transient scenario, being therefore the worst performing solution for all category objectives, then the strategy is defined as "non-compliant" for that transient scenario, regardless of compliance with the adaptation threshold as described in Section 3.4 (that transient scenario is added to those epochs that do not comply with the adaptation threshold in a grey shade in Fig. 2). This means that if a regret index of a strategy is 0.99, the strategy is still compliant for transient scenario, but the level of reliability, resilient and/or sustainability is very low. In Fig. 2, coloured shades refer to different levels of regret expressed by reliability, resilience or sustainability indices for each transient scenario. For example, in Fig. 2, Strategy A in the Innovation Scenario for the epoch between 2025 and 2030 (in green colour) performs well and is highly reliable, resilient, and/or sustainable, as the level of regret is very low or nearly zero. Whereas, this strategy does not perform well under the Austerity Scenario from 2045 to 2050 (the epoch is in orange colour) meaning the regret index is high (i.e. not very reliable, resilient and/or sustainable).

If there are more than one performance domain and/or one adaptation threshold (which is the case in the current study), the domains for each strategy need to be first identified for reliability, resilience and sustainability thresholds individually for single and multiple thresholds. The domains will then be overlapped to recognize the multiple domain of reliable, resilient and sustainable performance for the adaptation thresholds (individually and mutually). The overlapping process is done using the mathematical intersection where a multiple domain of $X \cap Y$ (the intersection of X and Y) is formed of the epochs compliant in both X and Y (see Fig. 3). This can also be calculated by the union of $X' \cup Y'$; where X' and Y' denote the non-compliant epochs of X and Y, respectively. The identified compliant domains will then be further analysed by the regret indices relative to the strategies (in terms of reliability, resilience and/or sustainability regret).

One of the main benefits of the AP approach is that it takes a step further in operationalizing multi-objective/criteria planning, which would be crucial in the future as adaptation thresholds change overtime and require improved performance; for example, planning for multi-functionality to incorporate ecosystem services (Hansen and Pauleit, 2014). The method can also help to balance between addressing current pressing issues in the IUWWS and increasing the capacity to adapt to future needs and challenges that may emerge in the long term.

3. Case study overview

The integrated urban wastewater system (IUWWS) has been used as a case study to test the previously described approach. This hypothetical IUWWS consists of three subsystems (Casal-Campos et al., 2015; Fu et al., 2008): (1) an urban watershed with a combined sewer system: this consists of 15 urban sub-watersheds with a total area of 758.9 ha and a population of 181,000 inhabitants; (2) a wastewater treatment plant (WWTP) with a conventional activated sludge process (CASP) and average dry-weather flow (DWF) of 377.1 l/s; and (3) an urban river with the mean flow rate (MFR) of 129,600 m^3/d. The catchment is modelled using SIMBA 6.0 (Ifak, 2007), a simulation tool that allows users to create and develop specific modelling modules tailored to the requirements of their project. Further details on the IUWWS and the simulation tool can be found in the SI, in the S1 Section of Casal-Campos et al. (2015), and in the S1 Section of Casal-Campos et al. (2018).

3.1. Future scenarios

The uncertain nature of threats affecting the performance of the

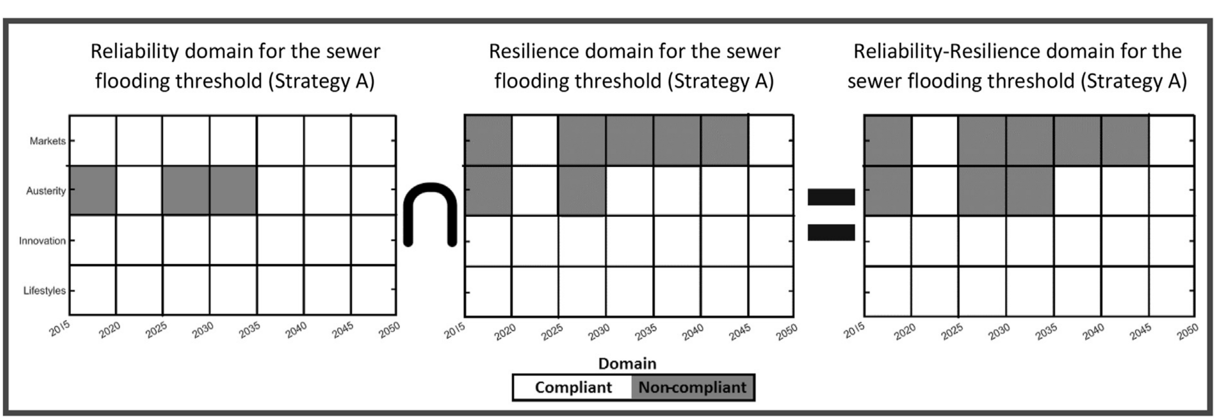

Fig. 3. An example of how to identify multiple domains for a specific threshold using the mathematical intersection.

Table 1
General description of future scenarios considered in this study and key driving factors in the management of the IUWWS (after Casal-Campos et al. (2015)).

Future scenarios	Market	Innovation	Austerity	Lifestyles
Characteristics of society	Low value on resources	Reliance on technology	High value on resources due to economic decline	High value on resources
	Lenient regulations to maintain unrestricted economic growth	Innovative and centralized efficiency to address stringent policy issues whilst enjoying prosperous life	Weak regulations and lack of investment in public infrastructure	Individual lifestyles are key means to address strict regulations and support sustainable development
	Highly consumerist society			
Characteristics of IUWWS	Low regulations	High regulations	Low regulations	High regulations
	Medium maintenance	High maintenance	Low maintenance	Med-low maintenance
	Low public attitude	Low public attitude	Medium public attitudes	High public attitude
	Medium technology	High technology	Low technology	Low technology

IUWWS in the future requires exploration of internal and external driving forces that may cause significant physical or social changes. The equiprobable socio-economic scenarios considered in this study are characterized by two main drivers, namely: governance (economic growth vs environmental awareness) and values (consumerism vs. conservationism) (Casal-Campos et al., 2018). Based on these drivers, four future scenarios are considered to assess the reliability, resilience and sustainability of the IUWWS in the planning timeline between 2015 and 2050 under various conditions: (1) Markets, (2) Innovation, (3) Austerity, and (4) Lifestyles. The general description of each future scenario is illustrated in Table 1.

Each of the above future scenarios is characterized by four key scenario factors associated with the management of the IUWWS, namely: regulation (i.e. level of regulatory control of stormwater and wastewater management activities); centralized maintenance (i.e. the level of activity in each scenario aimed at preserving and caring the existing wastewater infrastructure); public attitudes (i.e. public willingness towards the decentralization of responsibilities concerning urban drainage); and technology (i.e. the level of technological development occurring under each scenario) (Casal-Campos et al., 2015). The future scenarios differ from one another with respect to nine parameters (variables), indicative of various IUWWS uncertain conditions: (1) Misconnections (L/s); (2) Urban creep (ha); (3) Water use (L/head/day); (4) Infiltration (L/s); (5) Siltation; (6) Population (inhabitants): (7) Precipitation uplift (%); (8) Impervious area in new developments (ha); and (9) Acceptability preference. The selected parameters address main issues relevant to the management of stormwater and wastewater in the context of UK sewer systems which have been investigated in the past and can therefore be assigned with reasonable estimates in the year 2050 (Casal-Campos et al., 2018). The description of each parameter and their values in different scenarios are provided in the SI, Section S2. Further details about the narratives of the future scenarios, modeling of scenario parameters, definitions of uncertainties future scenarios and literature estimates of uncertain future threats/parameters can be found in Section 2.2 and in the SI Section S2 of Casal-Campos et al. (2015) and in the SI Section S2 of Casal-Campos et al. (2018). The allocation of specific estimates from the literature to each scenario was carried out through the following three steps: 1) Associating internal threats with key scenario factors; 2) Estimating the relative strength of threats under each scenario; 3) Allocating threat estimates to each scenario.

For simplicity, it is assumed that all scenario parameters vary linearly along the 2015–2050 timeline until they reach the levels defined for the year 2050. The implementation of each strategy along the timeline is also assumed to occur in a linear fashion, so that each 5-year epoch represents the lead-time required to implement the proportional fraction of each strategy to achieve completion in 2050.

3.2. Adaptation strategies

Various adaptation strategies are considered to investigate their effects on two types of urban areas in the catchment: 1) the existing baseline area: the original urban area, presented in Casal-Campos et al. (2015) and 2) the new development area (occurring as a consequence of urbanization due to population growth in the catchment under future scenarios. In this context, strategies only implemented in the baseline area are defined as "retrofit" strategies (Casal-Campos et al., 2018), as opposed to those strategies which are implemented in new developments, or those that serve both area types (e.g. rehabilitation of the combined sewer network). To this end, adaptation strategies are divided into the following two categories: stand-alone (Section 3.2.1) and hybrid strategies (Section 3.2.2).

3.2.1. Stand-alone strategies

Stand-alone strategies can be categorized into three groups:

a. Green strategies: (1) **S**ource **C**ontrol of **P**avements (SCP): stores and infiltrate half of road runoff through retrofit bio-retention planters; (2) **S**ource **C**ontrol of **R**oofs (SCR) strategy: disconnects roof downspouts into retrofitted rain gardens; and (3) **S**ource **C**ontrol of urban **C**reep (SCC) strategy: mitigates the effects of urban creep (the term "urban creep" is used in the UK to describe the gradual loss of permeable area to impermeable area in the urban environment (Casal-Campos et al., 2015) by using permeable pavement in residential driveways).
b. Grey strategies: (1) **S**eparation of combined **S**ewers (SS): Separates the existing combined sewer system by retrofitting storm sewers; (2) Rehabilitation of **C**ombined **S**ewer infrastructure with a new storage **T**ank (CST): Rehabilitates the existing combined sewer pipes without a new storage tank; (3) Rehabilitation of **C**ombined **S**ewer infrastructure (CS): Rehabilitates the existing combined sewer pipes but does not include a new storage tank; and (4) **O**n-site **T**reatment (OT) is considered for wastewater treatment and disposal of half of new developments.
c. "**D**o-**N**othing" (D-N) is considered to estimate the impacts of future scenario conditions without any interventions and is regarded as a base case for comparison.

3.2.2. Hybrid strategies

In this study, four hybrid strategies are considered, each developed as a combination of two original stand-alone strategies out of the four: (1) roof disconnection (SCR), (2) sewer separation (SS), (3) on-site wastewater treatment (OT), and (4) rehabilitation of combined sewers in the network (CS). Table 2 shows the hybrid solutions by integration of stand-alone fractions. The first three stand-

Table 2
Hybrid strategies and their fractions across the case study catchment (adapted from Casal-Campos et al. (2018)).

Strategy	SCR	SS	OT	CS	Area type or system served	Impervious area served as % of catchment	Strategy type
Hybrid1 (H1)	0.50	–	0.315	–	50% of residential roofs and *31.5% of new developments*	22	Decentralized
Hybrid2 (H2)	0.50	0.20	–	–	50% of residential roofs and *20% separation in the existing catchment*	22 + 20	Decentralized/ *Centralized*
Hybrid3 (H3)	–	0.20	0.315	–	20% separation in the existing catchment and *31.5% of new developments*	20	Centralized/ *Decentralized*
Hybrid4 (H4)	1	–	–	1	All residential roofs and *combined sewer system improvement*	44 + 56	Decentralized/ *Centralized*

SCR: Roof Disconnection; **SS**: Sewer Separation.
OT: On-Site Wastewater Treatment; **CS**: Rehabilitation Of Combined Sewers In The Network.

alone strategies (SCR, SS, and OT) are selected as representative for retrofit decentralized, retrofit centralized and new development solutions, respectively (Casal-Campos et al., 2018). The SCR strategy is used as the reference to define hybrid options, mainly due to the results reported in the literature that SCR strategy shows the most promising stand-alone performance (Casal-Campos et al., 2015). For each hybrid solution, two stand-alone strategies were combined so that the resulting solution removes an annual volume of stormwater and wastewater equivalent to that of runoff removed by SCR from the system. The only hybrid strategy that does not consist of SCR is H3 representing 20% sewer separation in the existing catchment (SS) and 31.5% of new developments (OT). The assumptions made in Table 2 are in accordance with common practice in the UK and based on what has been proposed in Casal-Campos et al. (2018, 2015). The main design considerations for hybrid strategies are presented in the SI, Section S4.

3.3. Reliability, resilience and sustainability indicators

The level of reliability, resilience and sustainability of each adaptation strategy is assessed by the regret-based model (described in Section 2.2) using objectives and indicators presented in Table S3, in the SI. These are the key objectives (or criteria) considered by the UK water industry to make strategic decisions for improving urban wastewater infrastructure and the levels of service. These objectives characterise the concepts of reliability, resilience and sustainability through impacts and consequences occurring as a result of system failure. The operational side of failure (i.e. reliability and resilience) was therefore represented by impacts (for example, flooding probability, duration or magnitude) affecting these performance objectives, whereas the strategic side (i.e. sustainability) was covered by the wider consequences of failure to society, the environment and the economy (for example, material or environmental damage). It is noteworthy that weights (shown in Table 3) are assigned to each objective by scenario, so that these reflect the relevance of each objective under a specific world view. The importance of the objective is irrespective of the metric that it is used in each case, whether resilience, reliability or sustainability. As a consequence, the numerator of the weight (relative importance) within each scenario for each objective remains the same for reliability/resilience/sustainability; the only difference is the amount of objectives taken into account in each case (five for reliability and resilience, and eight for sustainability).

As mentioned in Section 2.2, there are weights associated with objectives/indicators (Table 3), which are calculated using the method of “swing weighting”. The swing weighting approach allows decision makers to assess weights by “swinging” the value measure from its worst to its best level (Parnell and Trainor, 2009). The swing weighting approach allows allocation of the relative preference of criteria as well as incorporating an evaluation of their importance in the context of the decision (DCLG, 2009; Zheng and Lienert, 2017). The weights were selected by a panel of six experts in the field of urban water and wastewater management from both academia and regulatory authorities in the UK. The weight assignment task was performed by this panel based on the defined future conditions and uncertainties described for each future scenario in the UK. Each panel member individually assigned weights to different indicators based on their expertise, opinions and preferences. The weight of each objective was next determined as the arithmetic mean of the weights assigned by all experts for that particular objective. The result was then discussed within the panel, and all panel members agreed to proceed with the calculated mean weights without applying any changes.

3.4. Adaptation thresholds

Adaptation thresholds are defined as a representation of organizational, regulatory or personal views. Potentially, any objective (or combination of objectives) could be used to set an adaptation threshold (Haasnoot et al., 2013), for example, an economic threshold that reflects the willingness to pay for avoided impacts, or environmental thresholds that represent the acceptable level of

Table 3
Adaptation objectives and their assigned weights (normalized) in different future scenarios (first row refers to reliability and resilience weights $\boldsymbol{w_i^f}$, $\boldsymbol{w_j^f}$; second row denotes sustainability weights $\boldsymbol{w_k^f}$). In bold, the preference value of objectives within each scenario (1: low; 2: medium; 3: high; 4: very high).

$w_i^f = w_j^f$ / w_k^f	Objectives							
	Sewer Flowing	River Flooding	River DO	River AMM	CSOs	GHG Emissions	Costs	Acceptability	Total
Market	**2**/7	**2**/7	**1**/7	**1**/7	**1**/7	–	–	–	7/7
	2/13	**2**/13	**1**/13	**1**/13	**1**/13	**1**/13	**4**/13	**1**/13	13/13
Innovation	**3**/12	**3**/12	**2**/12	**2**/12	**2**/12	–	–	–	12/12
	3/18	**3**/18	**2**/18	**2**/18	**2**/18	**2**/18	**2**/18	**2**/18	18/18
Austerity	**2**/8	**2**/8	**1**/8	**1**/8	**2**/8	–	–	–	8/8
	2/15	**2**/15	**1**/15	**1**/15	**2**/15	**1**/15	**4**/15	**2**/15	15/15
Lifestyles	**1**/11	**1**/11	**3**/11	**3**/11	**3**/11	–	–	–	11/11
	1/18	**1**/18	**3**/18	**3**/18	**3**/18	**3**/18	**1**/18	**3**/18	18/18

Table 4
Adaptation thresholds considered in this study for reliability, resilience and sustainability.

	Sewer Flooding	CSOs	River Flooding
Reliability	95.68 [%]	95.61 [%]	99.63 [%]
Resilience	5.4 [m^3]	1565.4 [m^3]	185.3 [m^3]
Sustainability	663.3 [m^3]	1,343,674.0 [m^3]	98,002.4 [m^3]

environmental damage (Poff et al., 2016). In this study, the following objectives are used (individually and conjunctively) to set adaptation thresholds in the future scenarios: 1) sewer flooding, 2) river flooding and 3) Combined Sewer Overflow (CSOs). Reliability thresholds are defined as percentage of time free of failure, whereas, resilience thresholds are presented as duration-weighted magnitudes of failure. Sustainability thresholds are shown as magnitude of failure associated with economic damage due to flooding and aesthetic/health effects of CSOs. The values in Table 4 are based on the baseline performance of the IUWWS in the year 2015, as described in Casal-Campos et al. (2015). Each adaptation objective refers to its threshold in terms of the reliability, resilience and sustainability indicators discussed in Section 3.3. These are considered the main objectives in the context of urban drainage planning in the UK (Shaffer et al., 2010; Stovin et al., 2013), although it is noteworthy that adaptation thresholds could change over time (Carpenter et al., 2006).

The adaptation thresholds assume that the performance of the IUWWS in 2015 (the baseline performance) is an acceptable level of performance for the future. In reality, adaptation thresholds should be set according to changing circumstances (e.g. ecological, economic or social) and management shifts as new information and views become available (Carpenter et al., 2006). For simplicity in presenting the method, the adaptation thresholds have been maintained constant across future scenarios from 2015 to 2050.

4. Results and discussion

The performance domains for each strategy were first identified for reliability, resilience and sustainability individually, using single and multiple adaptation thresholds. The domains were then overlapped to recognize the multiple domain of reliable, resilient and sustainable performance for the adaptation thresholds (individually and mutually). Table 5 categorises the results based on adaptation thresholds against reliability, resilience and sustainability. The table also signposts all the result figures (whether they are presented in the paper or in the SI). Here, an example of the results on individual domain using a single adaptation threshold is presented (see Section 4.1), then the results on the multiple domains of transient scenarios will be discussed (see Sections 4.2 and 4.3).

4.1. Individual domains for single adaptation threshold

In this section, the resilience domains for sewer flooding (Fig. 4) and for CSOs (Fig. 5) are presented and discussed (as examples of the results on the individual domains for single thresholds). The results for the other domains are illustrated in the SI (see Table 5 for the caption number of each figure). The compliant domain of each strategy in the AP approach is shown as a two-dimensional space illustrating: 1) the time periods when a strategy is expected to fulfil a (a set of) adaptation threshold(s) before it requires further adaptation; and 2) the color-coded regret indices (see Figs. 4 and 5) of that strategy for each scenario and epoch (5-year tiles).

As shown in Fig. 4, the H4 strategy (the combination of rain gardens for roofs (SCR) and sewer rehabilitation (CS)) illustrated greener shades compared to the other alternatives; this means that this strategy has the largest satisfactory resilience domain concerning sewer flooding. Improved sewer capacity and a new storage tank (CST) and CS also show an ample domain of satisfactory performance; however, the resilience indices obtained across objectives are more regretful (i.e. lighter green and yellow shades) than those of H4 (i.e. green shades). It can also be seen that CS is less resilient (i.e. more regretful in the domain of resilience) than CST, as the tiles presenting the CS strategy are yellower throughout the domain.

Both rain gardens for roofs (SCR) and sewer separation (SS) lead to less compliant domains: for SCR's compliance is interrupted in two scenarios (Markets and Austerity), but still showing less regretful performance. Although SS's compliance is interrupted in the Austerity scenario, it generally presents high regrets throughout (i.e. yellow shades). From the results shown in Fig. 4, different decision makers can select different adaptation pathways, pertaining to their beliefs and views (Haasnoot et al., 2013). For example, an environmentalist or a drainage engineer might construct a pathway of strategies that would have the lowest impacts on sewer flooding. In such a case, sewer rehabilitation (CS) may be initially implemented to ensure compliance with the adaptation threshold (sewer flooding), however its regret indices are relatively high. Consequently, if necessary (based on the future conditions), it would be possible to switch to the lower-regret CST strategy (CS plus a new storage tank) to accommodate for new future conditions.

Fig. 5 illustrates the resilience domains for the adaptation threshold of CSOs. Again H4, CST and SS outperform the other strategies across scenarios and epochs. CS, however, does not perform well for the CSOs adaptation threshold when compared to the sewer flooding threshold. There are many non-compliant epochs (i.e. interrupted pathways) under three scenarios (namely, Markets, Austerity and Innovation). Comparing Figs. 4 and 5, it can be seen that sewer flooding is more restrictive (as a threshold) because it causes more interruption in the pathways of transient

Table 5
List and caption numbers of the results (figures) presented in this study categorized by the adaptation domains and adaptation objectives; the figures highlighted in bold are presented in the main text; the rest are shown in the SI.

Domains		Threshold (Objective)				
		Individual thresholds			Multiple thresholds	
		Sewer flooding	CSOs	River flooding	Sewer flooding + CSOs	Sewer flooding + CSOs + river flooding
Individual domain	REL	Fig. S1	Fig. S2	Fig. S3	Fig. S20	Fig. S21
	RES	Fig. 4	Fig. 5	Fig. S4	Fig. S22	Fig. S23
	SUS	Fig. S5	Fig. S6	Fig. S7	Fig. S24	Fig. S25
Multiple domain	REL-RES	Fig. S8	Fig. S9	Fig. S10	Fig. S26	Fig. S27
	REL-SUS	Fig. S11	Fig. S12	Fig. S13	Fig. S28	Fig. S29
	RES-SUS	Fig. S14	Fig. S15	Fig. S16	Fig. 6	Fig. S30
	REL-RES-SUS	Fig. S17	Fig. S18	Fig. S19	Fig. 7	Fig. 8

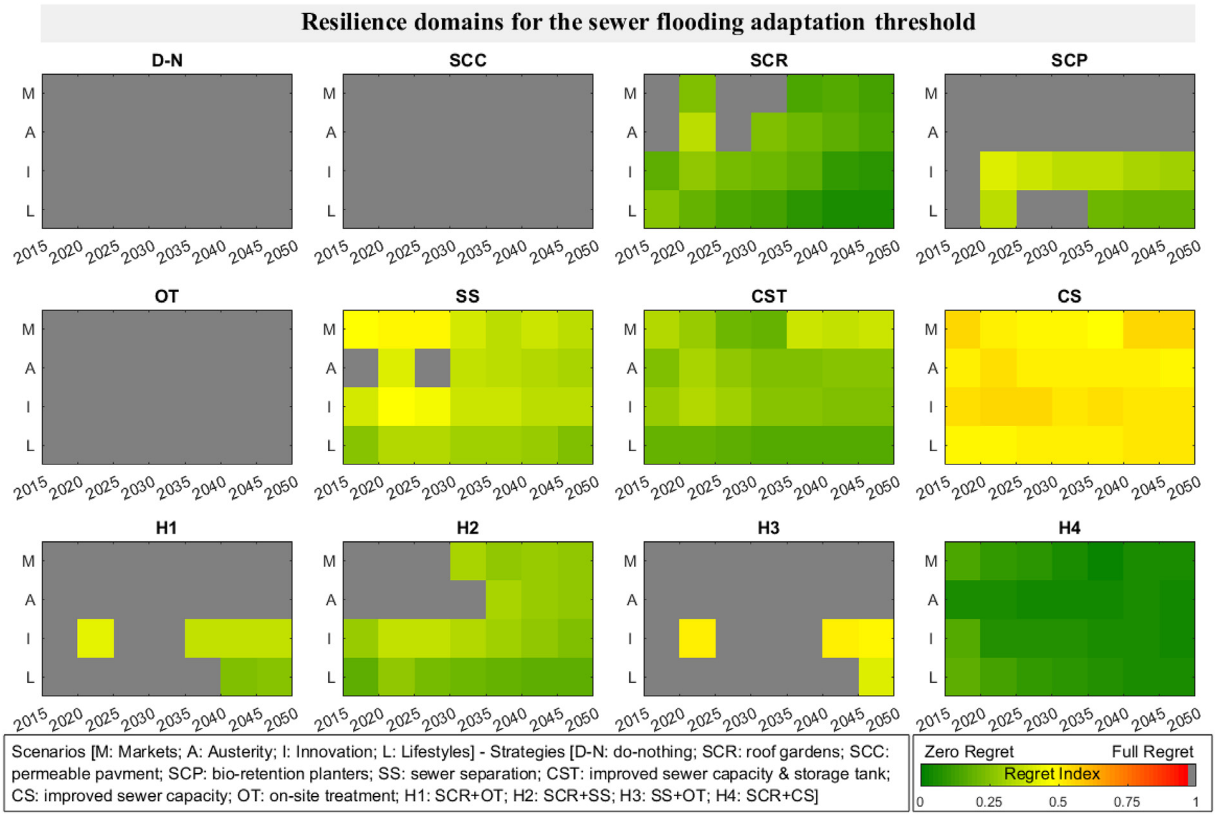

Fig. 4. Resilient domains for sewer flooding adaptation threshold. The compliant domain (coloured tiles) is described by scenario indices for each epoch, ranging from low (green) to high regret (red). Non-compliant and full-regret epochs are shown in grey. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

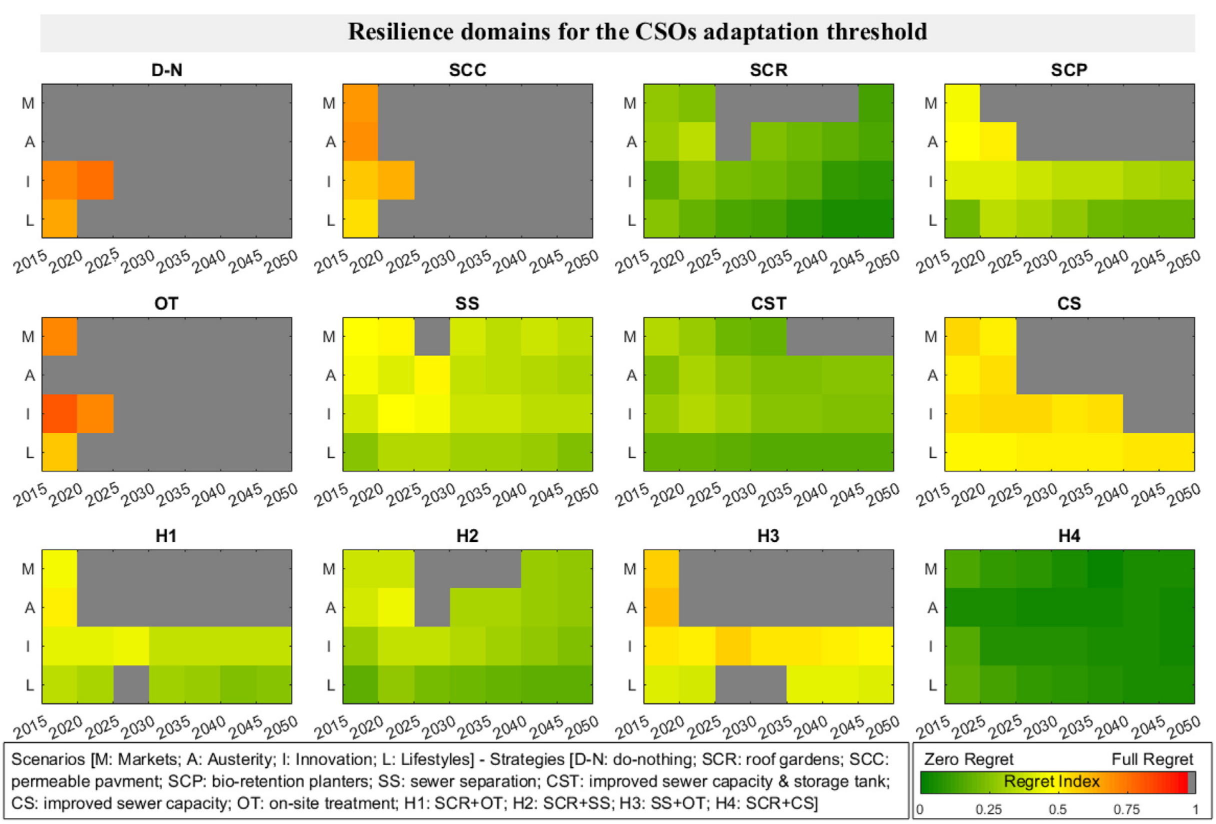

Fig. 5. Resilient domains for CSO adaptation thresholds. The compliant domain (coloured tiles) is described by scenario indices for each epoch, ranging from low (green) to high regret (red). Non-compliant and full-regret epochs are shown in grey. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

scenarios and consequently, the reduction of the compliant domains across strategies. The most restrictive threshold in this study is found to be river flooding (see Fig. S4, in the SI), where only two strategies have potential to achieve compliance for the Lifestyles, Innovations and Austerity scenarios: 1) the stand-alone implementation of rain gardens for roofs (SCR), for the Lifestyles scenario, and 2) its combination with sewer rehabilitation (H4). The results concerning sewer flooding (Fig. 4) show three strategies (D-N, SCC, and OT) without any compliant epochs (i.e. all in grey colour), whereas five strategies (D-N, SCC, OT, SS, CS and H3) did not show compliant domains for any transient scenario regarding the river flooding threshold (see Fig. S4, in the SI). Conversely, the results concerning resilience domains for the CSOs adaptation threshold illustrate that all strategies presented compliant domains for at least in three epochs (Fig. 5).

4.2. Multiple domains of transient scenarios for two adaptation thresholds

The compliant domains are jointly analysed to identify those resulting in mutually (conjunctively) satisfactory reliability, resilience and sustainability for each set of adaptation thresholds. As explained in section 4.1, river flooding is found to be the most restrictive threshold. Therefore, in this section, performance domains for resilience and sustainability are aggregated for sewer flooding and CSO objectives (See Fig. 6). The results for the multiple domain of reliability, resilience and sustainability are shown in Fig. 7. Other domain combinations are presented in the SI, Section S6.

The coloured shades (see Fig. 6) representing performance regret for multiple objectives are determined as the average of resilience and sustainability indices for each epoch within each scenario. H4 outperforms the other strategies in all the four scenarios. SCR, SS, and H2 also have un-interrupted pathways in the Innovation and Lifestyles scenarios. SCR is less regrettable than the SS and H2, as it has greener shades compared to the other two.

The most noticeable difference in the results shown in Figs. 6 and 7 is that the satisfactory domain for the most compliant strategies (SCR, SS, H2, H4 and CST) regarding resilience and sustainability thresholds (Fig. 6) is superior to the satisfactory domain regarding reliability, resilience and sustainability thresholds (Fig. 7).

Most strategies are affected by a deterioration of their regret indices when the reliability adaptation threshold is removed from the assessment (Fig. 6 and the SI, Sections 5 and 6). This effect is more obvious for grey infrastructure strategies (SS, CST and CS) as these alternatives are generally favoured by reliability assessments due to their focus on failure frequency and omission of failure magnitude and duration. The details on the domain (multiple) compliance and regret indices are presented in the SI (Sections S6 and S7, respectively).

Given the domains presented in Figs. 6 and 7, several strategies could be combined to comply with adaptation thresholds while allowing for flexibility and delaying decisions until future conditions are more certain (formation and selection of different pathways). For example, the H4 strategy (rain gardens and sewer expansion) could be implemented for the first two epochs (until 2025) to ensure compliance and, if future conditions are similar to those in the Innovation and Lifestyles scenarios, then continue with SCR alone (i.e. stopping the expansion of sewers and requiring less investment effort). Alternatively, sewer separation (SS) could

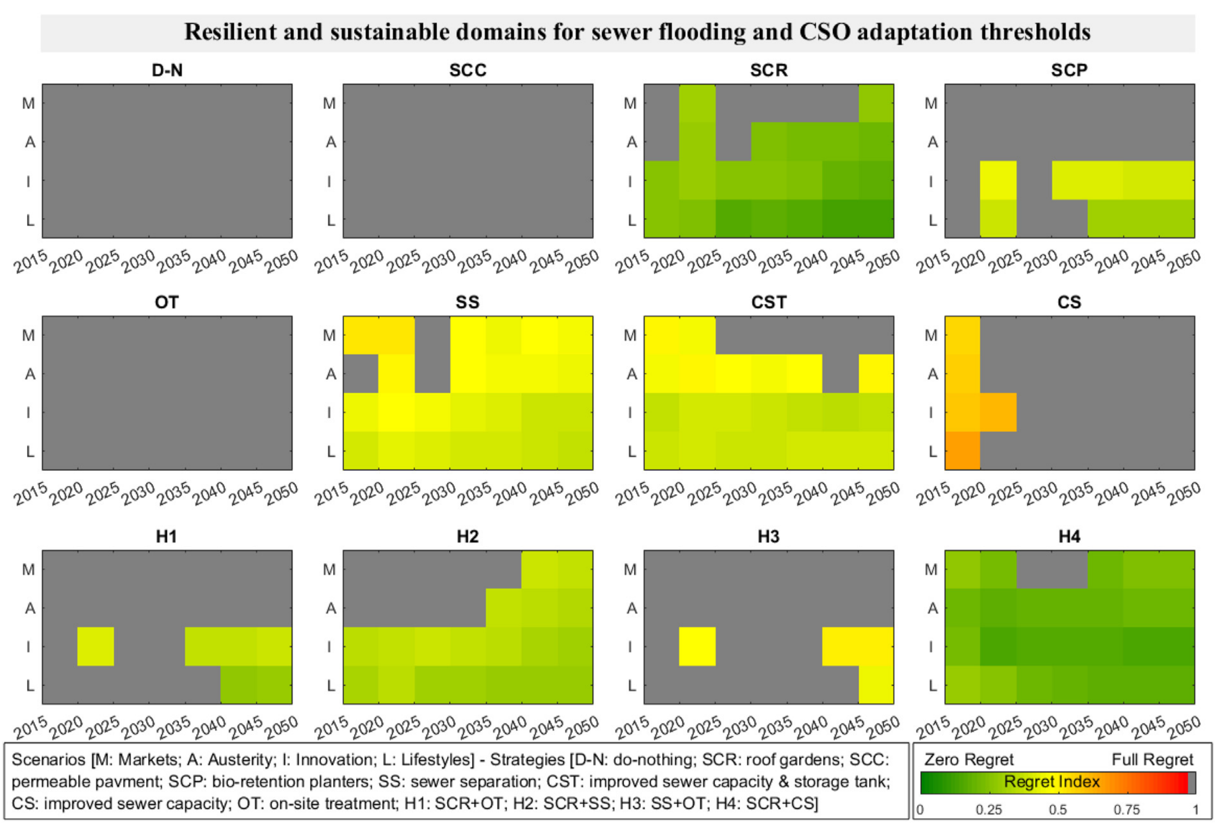

Fig. 6. Resilient and sustainable domains for sewer flooding and CSO adaptation thresholds. The compliant domain (coloured tiles) is described by mean scenario indices for each epoch, ranging from low (green) to high regret (red). Non-compliant and full-regret epochs are shown in grey. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

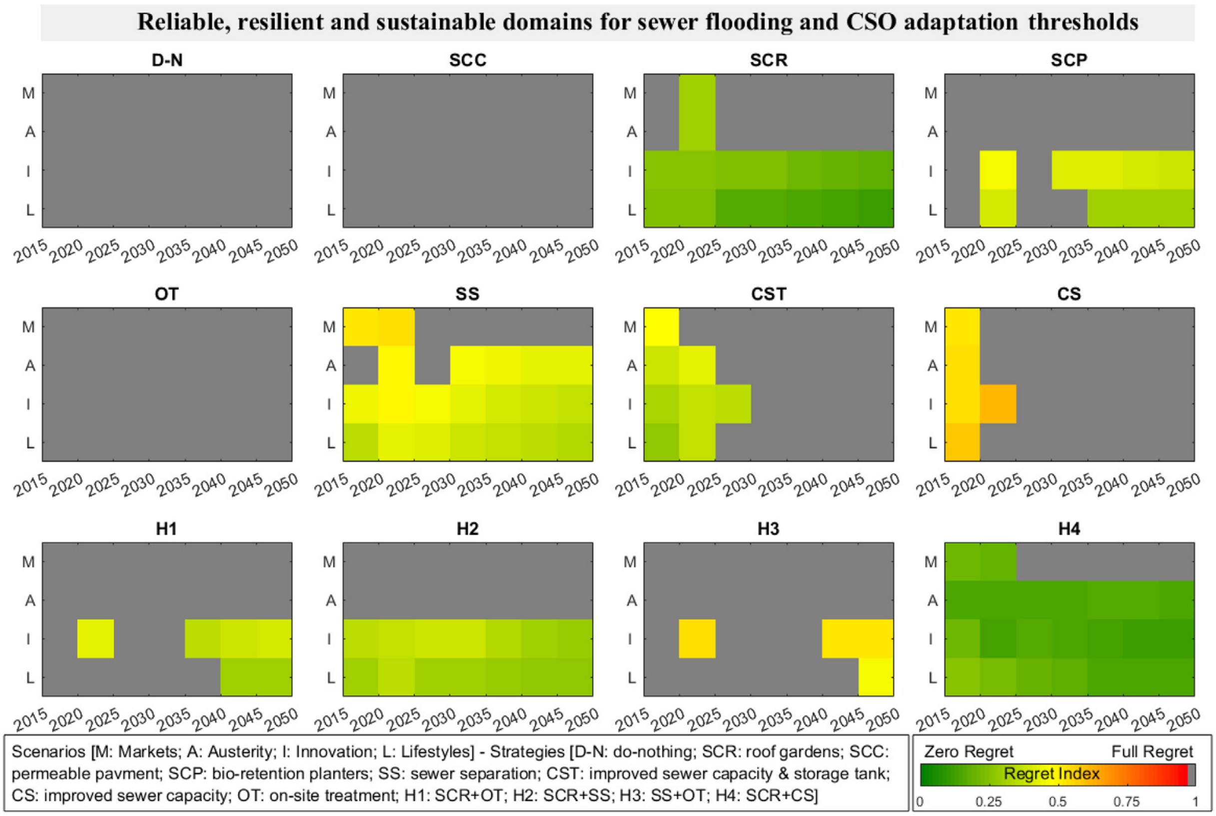

Fig. 7. Reliable, resilient and sustainable domains for sewer flooding and CSO adaptation thresholds. The compliant domain (coloured tiles) is described by mean scenario indices for each epoch, ranging from low (green) to high regret (red). Non-compliant and full-regret epochs are shown in grey. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

initially be implemented (with additional measures to comply within Austerity) and then responsible parties could wait for future conditions to unfold in order to shift to the lower-regret H2 strategy (i.e. slow down the implementation of separate sewers and intensify that of rain gardens for roofs in half of residential areas). The compatibility of strategies could be improved by increasing lead times and implementation rates as required by the adaptation thresholds. More strategies and adaptation thresholds can be incorporated as information becomes available and conditions change. Such a process would improve the potential consideration of combined strategies and the flexibility of investment in the decision making process.

4.3. Multiple domains of transient scenarios for three adaptation thresholds

The addition of river flooding adaptation thresholds for reliability, resilience and sustainability to the assessment (Fig. 8) shows that this adaptation threshold has a limiting effect in the compliant domain for all the strategies. In particular, those involving grey infrastructure interventions have a detrimental effect in increasing risk of flooding in downstream sections of the river. This can also be seen in the results of both individual and multiple domains for the single adaptation threshold of river flooding (Fig. S3, Fig. S6, Fig. S9, and Fig. S12, in the SI).

Fig. 8 illustrates that SCR and H4 strategies are again the most viable options for compliance along the scenarios, although with very limited compliance if future conditions move away from the most lenient conditions for these alternatives (i.e. Lifestyles). The consideration of resilience and sustainability alone for the three adaptation thresholds (see Fig. S30, in the SI) ensures the compliance of these strategies along the Lifestyles scenario; however, any of the remaining scenarios is continuously disrupted, failing to comply after 2025 (similar to the results shown in Fig. 8).

The reliable-resilient-sustainable and resilient-sustainable regret indices shown in Fig. 8 and Fig. S30 respectively suggest that SCR and H4 could provide additional benefits (associated with a larger set of objectives) to the IUWWS given the low regret of their sustainability indices. These additional benefits are particularly important in the sustainability assessment as a larger number of objectives and trade-offs are involved. Given these integrated assessments of performance, the implementation of rain gardens (SCR) for roof runoff infiltration and its combinations with other alternatives (e.g. sewer rehabilitation in H4 or separate sewers in H2) are the most promising options in order to comply with adaptation thresholds while providing lower regrets along the timeline. This performance is substantially improved compared to that of stand-alone grey infrastructure strategies, which could potentially provide an acceptable level of compliance regarding water quantity objectives at the cost of increased regrets associated with additional objectives along the timeline, reducing the adaptability of the IUWWS to changing adaptation thresholds and increasing the likelihood of lock-in (or maladaptation) within the scenarios.

4.4. Adaptation pathways and robustness

The attribute of robustness, as defined in (Casal-Campos et al., 2018) (i.e. low regrets across scenarios), is not a definitive characteristic to ensure compliance with adaptation thresholds for

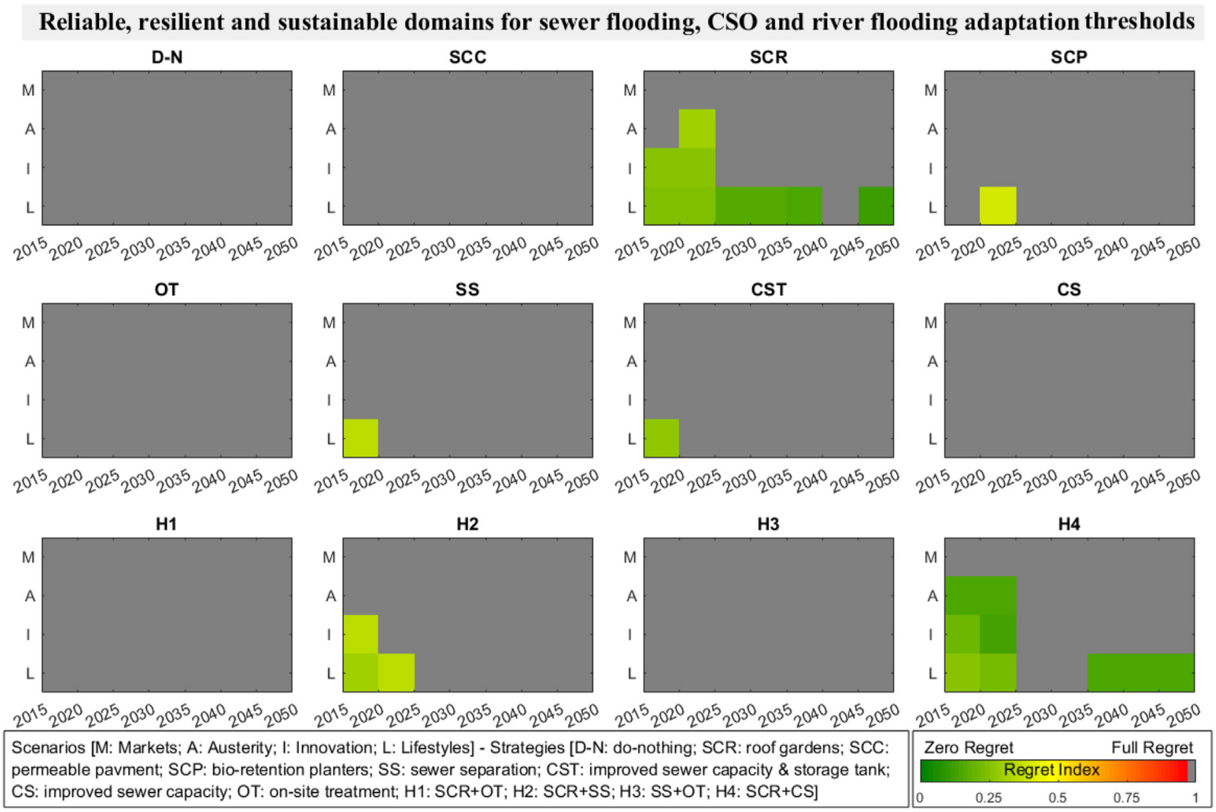

Fig. 8. Reliable, resilient and sustainable domains for sewer flooding, CSO and river flooding adaptation thresholds. The compliant domain (coloured tiles) is described by mean scenario indices for each epoch, ranging from low (green) to high regret (red). Non-compliant and full-regret epochs are shown in grey. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

reliability, resilience and sustainability along the planning timeline. However, robustness may facilitate adaptation as thresholds shift and additional or alternative objectives are introduced to redefine our views on reliability, resilience and sustainability in the future. In this sense, there is a tension between adapting to short term issues in the IUWWS (e.g. flooding, CSOs) and avoiding maladaptation when increasing the capacity to adapt to future needs and challenges that may emerge in the long term. For example, in Fig. 7, CST is compliant with the conditions up until the year 2025 (for three future scenarios), but for the epochs after that, other strategies (SS, H2, or H4) should be considered.

The compliant domains described in this study extend the concept of robustness by: (i) considering the performance of each strategy relative to the others (i.e. regret) across scenario epochs; (ii) introducing the dynamic assessment of robustness along transient scenarios (robustness understood as the capacity to maintain low regrets as scenario conditions develop); and (iii) identifying the ability of a strategy to satisfy a set of adaptation thresholds along time and across scenarios (i.e. to maximize the compliant domain regardless of future conditions or even as adaptation thresholds change). In this sense, this study contributes to a growing body of knowledge concerned with the robustness of urban drainage options in the face of future uncertainty (both short and long terms) and sheds light into the existing relationships between the qualities of reliability, resilience and sustainability in the IUWWS.

5. Conclusions

This paper presented a novel adaptation pathways approach for the dynamic assessment of green, grey and hybrid strategies for urban wastewater management in the long term. The approach first identifies the compliance of the strategies with three adaptation thresholds (i.e. regarding sewer flooding, river flooding and CSO spills) across four future scenarios, and then establishes the compliant domain for each strategy. The adaptability potential is measured using regret indices for reliability, resilience and sustainability, which are calculated by the weighted aggregation of regrets for various performance indicators from water quantity, water quality, and other social, economic and environmental aspects. The key findings of this study are summarised below:

- This new approach is able to identify adaption pathways under deep uncertainties, allowing for more flexibility and avoiding long-term commitment to strategies that may cause maladaptation. Delayed or staged investments can also be incorporated into such pathways to maximize their compliance and adaptability.
- Green strategies outperform grey strategies in balancing near-term and long-term needs for reliability, resilience and sustainability, as they are able to comply with adaptation thresholds while keeping low regrets across the compliant domains. Grey strategies are compliant with the considered thresholds but cast doubts regarding their adaptability to changing circumstances.
- Regardless of the context, the proposed hybrid strategies are shown more feasible and achievable compared to the stand-alone individual strategies. This is due to the fact that the robustness of grey strategies regarding reliability, resilience and sustainability is enhanced using green strategies with low regret values.

- One key strength of the proposed adaptation pathways approach is its scalability, in other words, it can easily be applied to other contexts or case studies in the water sector. Although the current and future conditions can vary in different parts of the world, the proposed approach could be applicable to any regions and catchments considering varying values of parameters, objectives and indicator weights.
- The present study has focused on dynamic adaptation strategies considering a fixed set of performance thresholds. Future research would benefit from including uncertainties associated with the concept of compliance and the possibility of adaptation thresholds changing in the future, i.e. changing perceptions and values that influence these thresholds.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.watres.2020.116013.

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