View metadata, citation and similar papers at core.ac.uk

brought to you by CORE

provided by Open Research Exeter

Subscriber access provided by the University of Exeter

Policy Analysis

An Integrated Environmental Assessment of Green and Gray Infrastructure Strategies for Robust Decision Making

Arturo Casal-Campos, Guangtao Fu, David Butler, and Andrew Moore

Environ. Sci. Technol., **Just Accepted Manuscript** • DOI: 10.1021/es506144f • Publication Date (Web): 11 Jun 2015

Downloaded from http://pubs.acs.org on June 15, 2015

Just Accepted

"Just Accepted" manuscripts have been peer-reviewed and accepted for publication. They are posted online prior to technical editing, formatting for publication and author proofing. The American Chemical Society provides "Just Accepted" as a free service to the research community to expedite the dissemination of scientific material as soon as possible after acceptance. "Just Accepted" manuscripts appear in full in PDF format accompanied by an HTML abstract. "Just Accepted" manuscripts have been fully peer reviewed, but should not be considered the official version of record. They are accessible to all readers and citable by the Digital Object Identifier (DOI®). "Just Accepted" is an optional service offered to authors. Therefore, the "Just Accepted" Web site may not include all articles that will be published in the journal. After a manuscript is technically edited and formatted, it will be removed from the "Just Accepted" Web site and published as an ASAP article. Note that technical editing may introduce minor changes to the manuscript text and/or graphics which could affect content, and all legal disclaimers and ethical guidelines that apply to the journal pertain. ACS cannot be held responsible for errors or consequences arising from the use of information contained in these "Just Accepted" manuscripts.

ACS Publications
High quality. High impact.

Environmental Science & Technology is published by the American Chemical Society. 1155 Sixteenth Street N.W., Washington, DC 20036

Published by American Chemical Society. Copyright © American Chemical Society. However, no copyright claim is made to original U.S. Government works, or works produced by employees of any Commonwealth realm Crown government in the course of their duties.

An Integrated Environmental Assessment of Green and Gray Infrastructure Strategies for Robust Decision Making

Arturo Casal-Campos[*,†], *Guangtao Fu*[*,†], *David Butler*[†] *and Andrew Moore*[‡]

[†]Centre for Water Systems, College of Engineering, Mathematics and Physical Sciences,
University of Exeter, North Park Road, Harrison Building, Exeter, EX4 4QF, United Kingdom

[‡]Northumbrian Water Ltd., Boldon House, Wheatlands Way, Pity Me, Durham, DH1 5FA,
United Kingdom

ABSTRACT

The robustness of a range of watershed-scale "green" and "gray" drainage strategies in the future is explored through comprehensive modelling of a fully integrated urban wastewater system case. Four socio-economic future scenarios, defined by parameters affecting the environmental performance of the system, are proposed to account for the uncertain variability of conditions in the year 2050. A regret-based approach is applied to assess the relative performance of strategies in multiple impact categories (environmental, economic and social) as well as to evaluate their robustness across future scenarios. The concept of regret proves useful in identifying performance trade-offs and recognizing states of the world most critical to decisions. The study highlights the robustness of green strategies (particularly rain gardens, resulting in half the regret of most options) over end-of-pipe gray alternatives (surface water separation or sewer and storage rehabilitation), which may be costly (on average, 25% of the total regret of these options) and tend to focus on sewer flooding and CSO alleviation while compromising on downstream system performance (this accounts for around 50% of their total regret). Trade-offs and scenario regrets observed in the analysis suggest that the combination of green and gray strategies may still offer further potential for robustness.

TOC/ABSTRACT ART

1. INTRODUCTION

The pursuit of sustainability in urban water systems requires finding solutions that are valid now and are also able to accommodate future changes (e.g. climate change or urban development). This is a crucial consideration to ensure adequate performance and to minimize the vulnerability of the system now and in the future.[1] The uncertain nature of these changes and their impacts requires to identify mitigation and adaptation measures which consistently deliver satisfactory levels of service under variable conditions[2], that is strategies that involve low or no regrets in the face of future uncertainty.

Notions of sustainable water management incorporating these ideas have been recently proposed[3–6] in order to support strategies which are: effective (i.e. complying with multiple objectives); robust (i.e. coping with a wide range of uncertainties); and flexible (i.e. allowing for unforeseen changes in physical and social conditions).

Retrofit solutions for the management of stormwater, and particularly green infrastructure, are deemed to offer great potential as they simultaneously provide multiple benefits, whether these are environmental, economic or social in nature.[7–10] There is however a lack of evidence concerning the magnitude and extent of such beneficial effects when these strategies are implemented at the watershed-scale.[11] Although several studies[12–16] have evaluated the broader impacts of green and gray infrastructure (water quantity and quality impacts as well as energy and carbon emissions), the application of complex physical models that integrate the whole urban wastewater system for this purpose has not been attempted. The present study fills this gap by means of a comprehensive integrated model that provides detailed representation of all relevant processes taking place in the wastewater system and their interactions.[17]

The use of scenarios for uncertainty analysis in urban drainage systems has been extensively reported, particularly regarding climate change and urban development impacts.[16,18–20] However, uncertainties related to the management of legacy infrastructure, such as the condition of combined sewers in the future, and the direct influence of social drivers in system performance have been largely ignored. Four future scenarios are developed in this study incorporating all these factors to construct a richer representation of future uncertainty in the year 2050.

The robustness of green and gray strategies under uncertain future conditions has been frequently overlooked, limiting our ability to adequately inform long-term decisions, which will require judgment of complex issues from a variety of stakeholders. It has not been until recently that formal methods[4,5,21] were applied to evaluate the robustness and adaptation potential of green and gray infrastructure to such conditions. However, a broader set of uncertainties, objectives and alternatives need to be explored to better understand this issue. The regret-based approach applied in this paper tackles some of these shortfalls by evaluating the relative robustness of green and gray strategies based on an integrated environmental assessment of multiple impact categories (environmental, social and economic) across four different future states of the world. Such an approach facilitates the comparison of alternatives and the identification of performance trade-offs. Further, the method permits to recognize promising strategies and states of the world most critical to decisions.

2. MATERIALS AND METHOD

2.1. Case Study Overview

The integrated case study[22] used for the purpose of this investigation consists of three main subsystems: an urban watershed served by a combined sewer system, a wastewater treatment plant (WWTP), and an urban river (see Figure 1).

Six different drainage strategies were proposed within the watershed (see Table 1): three “gray” strategies and three “green” source control strategies. The gray strategies include: i) separation of half of the existing combined sewer system by retrofitting storm sewers (SS strategy); ii) rehabilitation of the existing combined sewer pipes and expansion of centralized storage (CS); iii) on-site treatment (OT) of wastewater flows for half of new developments. The green strategies include: i) storage and infiltration of half of road runoff through retrofit bioretention planters (i.e. Source Control of Pavements or SCP strategy); ii) disconnection of roof downspouts into retrofitted rain gardens (SCR, Source Control of Roofs); iii) “urban creep” mitigation by using permeable pavement in residential driveways (SCC, Source Control of urban Creep). This last strategy aims at mitigating the gradual loss of permeable area to impermeable area in the catchment (commonly known as “urban creep” in the UK) due to, for example, the paving of residential front gardens to create driveways. A “do-nothing” alternative (i.e. no improvements in the system) was also used to evaluate the marginal impacts of individual future scenario conditions.

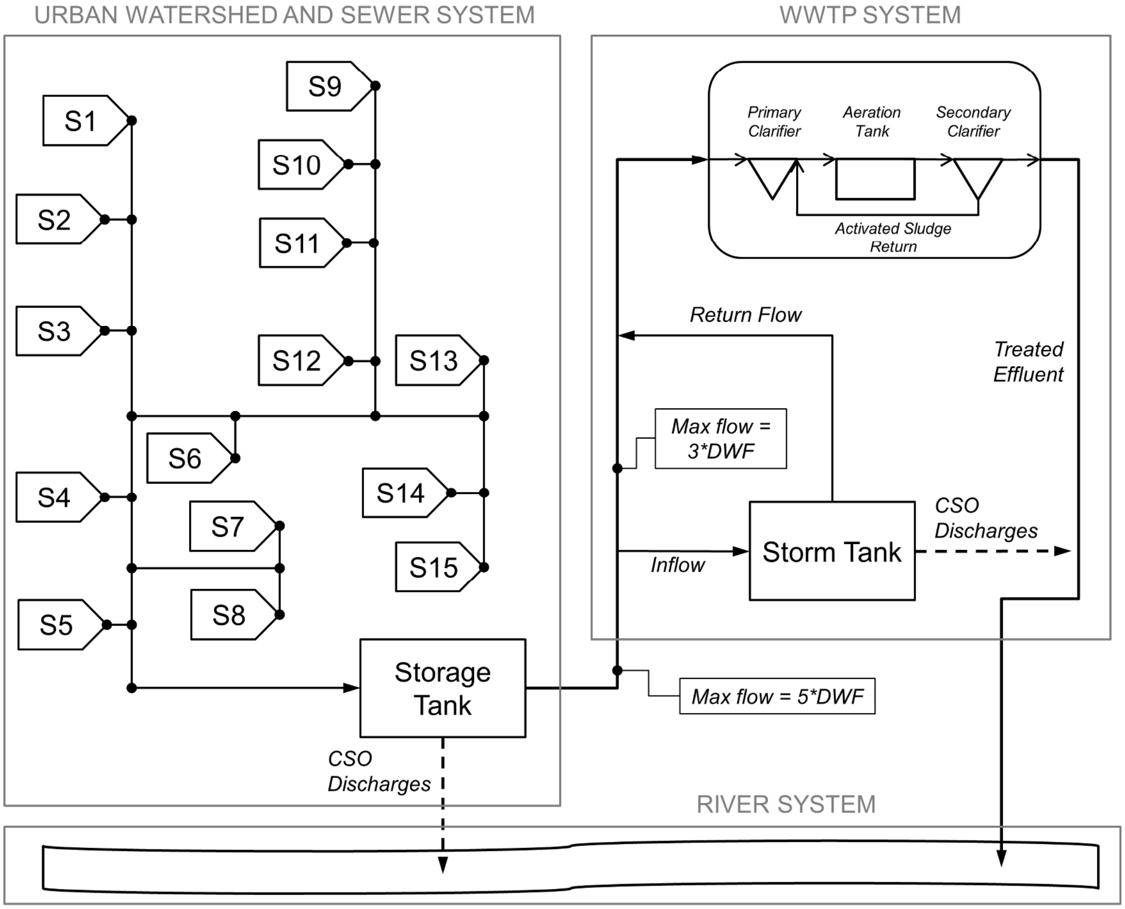


Figure 1. Schematic representation of the integrated urban wastewater system. Watershed: 15 urban sub-watersheds with a total area of 758.9 hectares and a population of 181,000 inhabitants. Average dry-weather flow (DWF) = 377.1 L/s. Combined sewer: 29 main sewers and manholes and an online pass though storage tank (7000 m^3). WWTP: a storm tank (6750 m^3) and a

conventional activated sludge treatment process. River: mean flow rate 129,600 m^3/d. Additional details provided in the Supporting Information (SI).

The implementation of each alternative was considered in isolation for simplicity and to fully realize the beneficial or detrimental performance of one strategy relative to the others. A one-year rainfall time series (5-minute resolution, 621.2 mm) was used to evaluate the present baseline performance and the performance of each drainage strategy in the future.

Table 1. Main characteristics of the proposed strategies (more details are provided in the Supporting Information).

	SCC	**SCP**	**SCR**	**SS**	**CS**	**OT**
Area type or system served	Urban creep	Roads	Residential roofs	50% of baseline watershed	Combined sewers	50% of new developments
Impervious area served as % of watershed	5-15[a]	28	44	50	100	-
Type of intervention	Permeable pavement[b]	Bioretention planters[b]	Rain gardens[b]	Surface water sewers[c]	Improved sewers and storage[d]	On-site treatment of wastewater[e]
Strategy type	Decentralized	Decentralized	Decentralized	Centralized	Centralized	Decentralized

[a] Variable upon future scenario conditions. [b] Strategy stores and infiltrates the runoff generated by the served area. [c] Storm sewers discharge half of the watershed runoff directly into the river. [d] Sewer pipes are enlarged (from 1.2m to 1.5m) and new storage provided (50,000m^3). [e] Half of wastewater from new developments is locally treated and discharged into the river, bypassing the combined sewer system.

2.2. Future Scenarios 2050

The performance of each drainage strategy was explored in four different equiprobable future scenarios (Markets, Innovation, Austerity and Lifestyles), which represented the uncertain conditions affecting the urban wastewater system in the year 2050. These future conditions were defined by the alteration of various parameters from present baseline values (see Table 2). Such alterations are based on scenario narratives (developed on the basis of previous UK water-related scenario analysis[23–26]) and the application of estimates available in the literature (for more information on scenario narratives and parameter estimates refer to SI).

The parameters summarized in Table 2 are mostly related to changes in watershed permeability and the variation of sewer inflows which could threaten system capacity in the future. Permeability changes are represented by the rate of urban creep in the baseline watershed (i.e. loss of permeable area in the original watershed) and the impervious area increase occurring as a consequence of urbanization (i.e. new developments). Sewer inflows are determined by the combination of misconnections, groundwater infiltration and water use flowrates 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. Misconnections only occurred as a consequence of urban development (no misconnections in the baseline case), since the baseline river quality is assumed to account for any existing background pollution. Infiltrated groundwater was considered as an extraneous inflow evenly distributed throughout the watershed. Details on pollutant loads and patterns are available in the SI.

The effect of climate change in precipitation was modelled by increasing the rainfall time series values (total rainfall depth) by 10%, a figure consistently used by governmental agencies[34] and regulators[27] in the UK for the considered period. This uplift was assumed independent of future scenario conditions based on the annual precipitation projections for the UK under low, medium and high emission scenarios for the period 2040-2069.[35]

Table 2. Future scenario conditions based on parameters affecting the urban wastewater system of study.

Parameter	Baseline	Markets	Innovation	Austerity	Lifestyles
Urban creep (ha)[27,28]	0	87.7	58.4	70.1	29.2
Impervious area from new developments (ha)[a]	0	290	226	129	161
Misconnected foul sewers (l/s)[29]	0	7.8	0.9	4.1	1.7
Groundwater infiltration (l/s)[27,30,31]	52.4	163.7	40.5	200.1	151.2
Water use (l/person/d)[23]	155	165	125	140	110
Population (inhabitants)[23,32]	181,000	262,450	244,350	217,200	226,250
Siltation in sewers[b,33]	0.97	0.92	1	0.84	0.92
Climate change uplift[27,34,35]	-	+10%	+10%	+10%	+10%
Acceptability preference[c]	centralized	centralized	centralized/ decentralized	decentralized	decentralized

[a] This area is served by separate sewers and was estimated assuming typical values of house occupancy (2.4 inhabitants/property) and development characteristics (terraced development: 90 houses/ha and 77% of impermeable area). [b] The effect of siltation in sewers is represented by a full-pipe area reduction factor, 1: no reduction, 0: total reduction. [c] Centralized (decentralized) future scenarios have a high acceptability of centralized (decentralized) strategies and a low acceptability of decentralized (centralized) ones. Innovation scenario has a medium acceptability of decentralized options and a high acceptability of centralized ones.

2.3. Components of the Integrated Environmental Assessment

The performance of drainage strategies in each of the above future scenarios was assessed through eight impact categories (see Table 3), which encapsulated the fundamental components of sustainability within the study.

The integrated modelling framework consisted of the software platform SIMBA 6.0[36] and the hydrodynamic sewer model SWMM 5.0,[37] both coupled to model the integrated urban wastewater system (including watershed, sewer network, wastewater treatment plant, and river models) during one year of extended period simulation. This permitted detailed model representation of hydrologic and quality processes in the watershed (rainfall-runoff generation), sewer hydraulics, physical and biochemical treatment processes, as well as hydrologic and water quality processes taking place in watercourses (more details of the modelling framework are provided in the SI).

Table 3. Impact categories and indicators used to assess the performance of each strategy under future scenarios.

Impact category	**Indicator (units)**	**Comments**
Sewer flooding	Total annual sewer flood volume (ML)	Accumulated flood volume from sewer manholes during the one-year simulation.
River flood risk	Annual river peak flow (m^3/s)	Peak flow measured 1 km downstream of the last urban drainage discharge point.
River dissolved oxygen	Minimum 6-hour dissolved oxygen concentration (mg/L)	Evaluates the effect of discharges on aquatic life[38] at the worst river reach.
River Ammonia	99 percentile total ammonia concentration (mg/L)	Evaluates the effect of discharges on aquatic life[38] at the worst river reach.
Health and esthetics	Annual CSO spill volume (m^3)	Surrogate indicator of both esthetic pollution (e.g. litter, smell) and potential public health impacts (e.g. pathogenic organisms).
GHG emissions	Operational annual emissions (tCO_2)	Emissions due to pumping[a] and treatment[b] of wastewater during the one-year simulation.
Costs	Present value of capital and maintenance costs ($ million)	Unit cost estimates found in the literature[39–44] and other considerations,[c] assuming an operational life of 35 years and a discount rate of 3.5%.[d]
Acceptability	High/medium/low (1/2/3 score)	Scores are assigned according to the acceptability preference of each future scenario.[c,e]

[a] Conversion factor of 0.523 kg CO_2/kWh_e.[45] [b] A conventional activated sludge process emits 88 kg CO_2/ML of wastewater treated.[45] [c] The "do-nothing" option was assumed a zero-cost and low-acceptability alternative in all future scenarios, since it is expected that improvements will be needed in the system by 2050.[d] Details on whole life cost estimations are provided in the SI. [e] See Table 2 and footnotes (acceptability preference).

2.4. A Regret-Based Approach to Robust Decision Making

The variety of alternatives considered and the uncertainty over future conditions recommends the exploration of robust strategies. In a context of deep uncertainty, a robust strategy will generally trade optimality for less sensitivity to broken assumptions, performing satisfactorily over a range of possible futures.[46,47] The approach used in this study evaluates the robustness of strategies by assessing their relative performance loss (i.e. regret) across all impact categories and future scenarios described above. The regret of a decision made now (i.e. by selecting a specific drainage strategy) is understood as the missed opportunity to choose an alternative path of action which would have resulted more beneficial once the future is revealed.[48] Thus, the basis of the method is to select the strategy that minimizes the opportunity loss or regret accrued from all the considered future states (more details on regret score calculations are available in the SI).

2.4.1. Category regrets

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

$$\text{Regret}_i(s,f) = |max_{s'}[\text{Performance}_i(s',f)] - \text{Performance}_i(s,f)| \tag{1}$$

In Equation 1, depending on the indicator used (i.e. the-higher-the-better or the-lower-the-better), maximum performance could be either the maximum or the minimum value of the indicator, respectively. The best-performing option within each impact category is represented by zero regret (and by a positive value of regret otherwise).

2.4.2. Category regret scores

Category regrets concerning any impact category *i* under any future scenario *f* were normalized relative to the most regrettable alternative s^* in that impact category and scenario (Equation 2). This equation works as a utility function that assigns normalized regret scores according to performance (i.e. between 0 and 1, from best to worst performance).

$$R_i(s,f) = \frac{\mathrm{Regret}_i(s,f)}{\max_{s^*}[\mathrm{Regret}_i(s^*,f)]} \tag{2}$$

The mean value of category regret scores for all future scenarios was also calculated to realize the trade-offs between impact categories consistently observed for each strategy (these are presented and commented in the results section).

2.4.3. Scenario regret scores

To compare the performance of strategies within each future state, category regret scores for each future scenario *f* and strategy *s* were aggregated into a single scenario regret score by applying an additive utility function (Equation 3). This reduced the problem of assessing multiple utilities (i.e. eight category regret scores) into one of assessing a one-dimensional weighted utility.[50]

$$\overline{R}(s,f) = \sum_i \left(w_i^f \, R_i(s,f)\right) \tag{3}$$

where w_i^f represents the relative weight of impact category *i* in future scenario *f*, with $\sum_i w_i^f = 1$. Weights for each future scenario (Table 4) were elicited by judgement of the importance that a swing in scores in one category has relative to the swing in another category (i.e. "swing weighting").[51]

Table 4. Weights applied to impact categories in each future scenario. Values in bold indicate the relative preference of objectives within a scenario (1: low; 2: medium; 3: high).

Future scenario	**Sewer flooding**	**River flooding**	**River DO**	**River AMM**	**Health & esthetics**	**GHG emissions**	**Cost**	**Accept.**
Markets	**2**/12	**2**/12	**1**/12	**1**/12	**1**/12	**1**/12	**3**/12	**1**/12
Innovation	**3**/18	**3**/18	**2**/18	**2**/18	**2**/18	**2**/18	**2**/18	**2**/18
Austerity	**2**/14	**2**/14	**1**/14	**1**/14	**2**/14	**1**/14	**3**/14	**2**/14
Lifestyles	**1**/18	**1**/18	**3**/18	**3**/18	**3**/18	**3**/18	**1**/18	**3**/18

Preferences are assigned to each category based on pairwise comparisons of the importance of a swing in objective scores (these preferences changed for each future scenario). Weights were then calculated by dividing each preference value by the sum of all preferences assigned to impact categories in each future scenario.

2.4.4. Mean regret score

The four scenario regret scores obtained above for each strategy were merged to calculate the mean regret score, which was used to measure the robustness of a strategy relative to the others. The arithmetic mean of scenario regret scores was considered an adequate representation of overall regret, providing an integral picture of performance across impact categories and scenarios for each strategy. The strategy with the lowest mean regret score was considered the most robust alternative of all (we will call this the "mini-mean" criterion). This is a variation of the mini-max rule,[49] which chooses the strategy that minimizes the greatest regret possible across future states.[52,53] Mini-mean is a less conservative criterion since it allows compensating low performance in some scenarios with good performance in others. Mini-max is more risk-averse as it reduces the performance of each strategy to its single worst scenario, regardless of its performance in other states of the world. Mini-mean is preferred here as it incorporates all available information to the decision, avoiding the discrimination of specific scenarios.

3. RESULTS AND DISCUSSION

3.1. Performance Trade-Offs

Future scenario conditions in the watershed (represented by “do-nothing” black markers in Figure 2) cause the deterioration of both water quantity (Figure 2a) and water quality (Figure 2b) indicators relative to the baseline (dashed lines in Figures 2a and 2b). All alternatives contribute to improving the totality or part of these problems under most future scenarios, except urban creep mitigation (SCC) and on-site treatment in half of new developments (OT), whose performances fell short in recovering any baseline state in spite of improving most quantity and quality indicators relative to “do-nothing”.

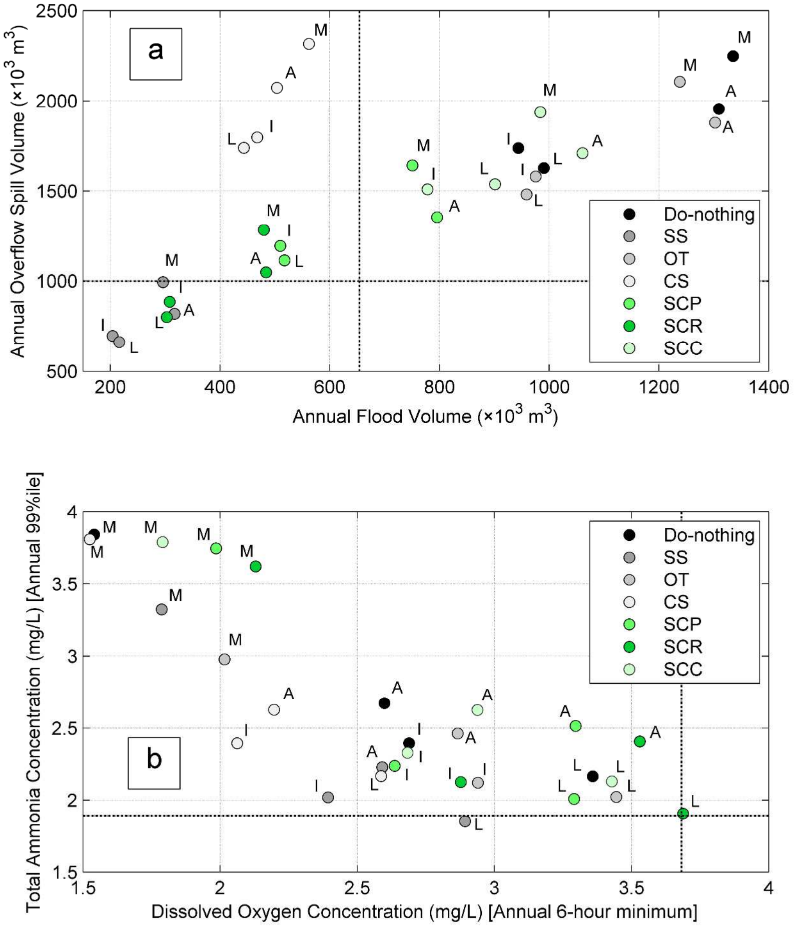


Figure 2. Performance of strategies regarding: **(a)** annual CSO spill and sewer flood volume; and **(b)** ammonia and dissolved oxygen concentration in the river under the considered future scenarios (labelled for each alternative; M: Markets, A: Austerity, I: Innovation, L: Lifestyles). “Green” and “gray” infrastructure strategies are color-coded by shades of green and gray, respectively. Dashed lines in each figure denote present baseline performance.

Figure 3 helps to identify the main performance trade-offs between impact categories consistently occurring in each strategy. Strategies with low regrets in an impact category (i.e. closer to the green line) are interpreted as “less regrettable” (i.e. better performing) than those with higher regrets (i.e. closer to the red line) in the same impact category.

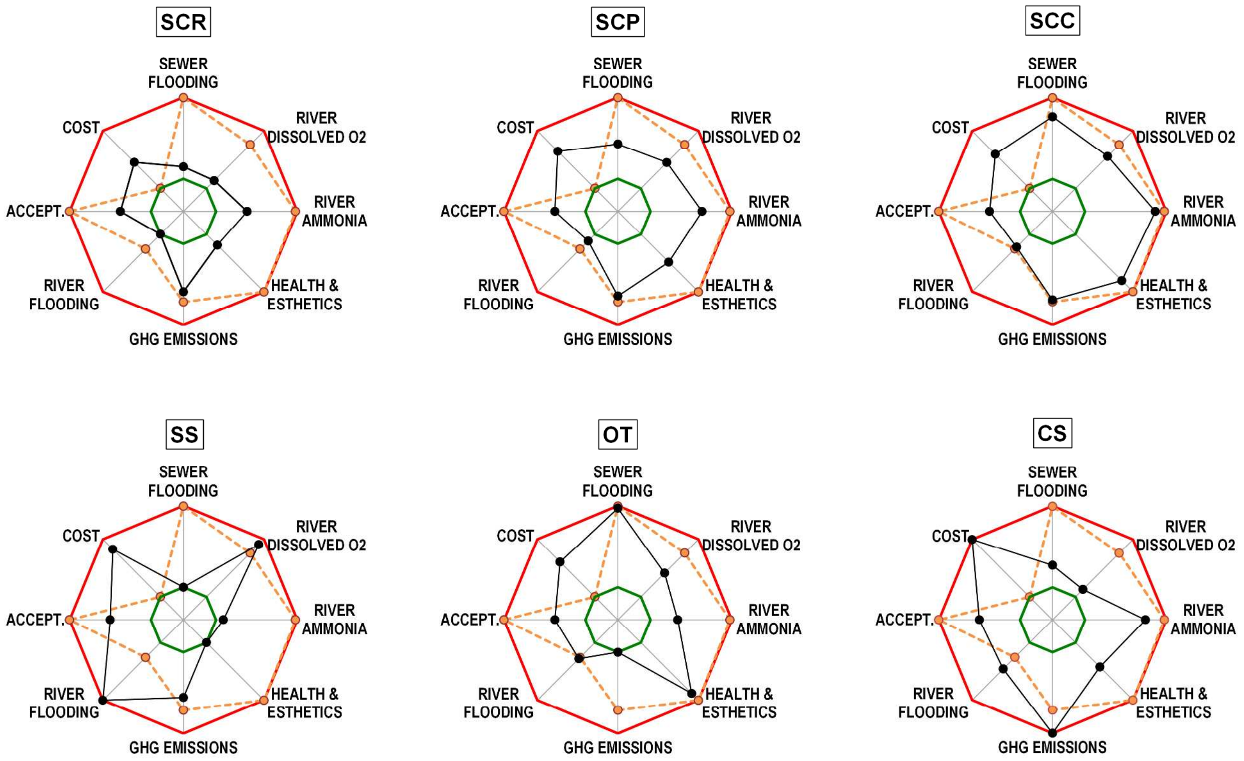


Figure 3. Mean category regret scores of strategies (black markers) across future scenarios. Scores in each category range from no-regrets (0, green line level) to full-regrets (1, red line level). The amber dashed line shows mean category regret scores for the "do-nothing" option, which are useful to realize the relative improvement or deterioration of specific objectives when implementing each strategy.

In Figure 3, roof downspout disconnection (SCR strategy) results in low regrets across most impact categories. Other decentralized green alternatives (SCP and SCC strategies) also show improved regret scores relative to "do-nothing", except in the cost category where regrets are higher for any of the considered options. The mitigation of urban creep using permeable pavement (SCC strategy) results in small performance improvements due to the small fraction of impervious area removed by this strategy. In this sense, the larger removal of contributing areas achieved by retrofitting bioretention planters (SCP strategy) and rain gardens (SCR) consistently reduced category regrets without showing significant performance trade-offs (i.e. the loss of performance in one category due to improvement in another).

The largest compromises between performance categories are found in centralized gray strategies (SS and CS in Figure 3). The separation of part of the combined sewer by retrofitting storm sewers (SS strategy) is highly efficient in reducing CSOs, sewer flooding and river ammonia regrets; however, this comes at the cost of larger regrets in the risk of river flooding, total costs, and river dissolved oxygen. Sewer and storage enlargement (CS strategy) lowers sewer flooding, dissolved oxygen and CSOs regrets at the expense of increasing those related to costs, emissions, river ammonia and river flooding risk. Indeed, as SS and CS improve the conveyance capacity of the sewers, the hydraulic response of the system is intensified, compromising performance downstream. SS deteriorates river oxygen levels because this strategy generally offsets the organic load abated from CSO spills by increasing untreated runoff discharges to the river. Stored volumes pumped for treatment in the CS strategy prolong high hydraulic loads at the WWTP, compromising on treatment performance and ammonia levels on the treated effluent.[54]

On-site treatment of wastewater (OT) shows the lowest regret regarding operational GHG emissions across future scenarios. These are mostly affected by dry weather flows, as the influence of stormwater flows is limited to sporadic rainfall events. This is demonstrated by the similar GHG emissions regrets of any other alternative relative to “do-nothing”. In particular, the high regret in GHG emissions for the CS alternative highlights the existing trade-off between reducing CSOs and increasing operational emissions in large underground storage schemes.

3.2. Robustness Analysis

Each scenario regret score in Figure 4 represents the weighted balance of category regret scores across all performance categories for each future scenario (applied through Equation 3). Mean regret scores express the overall regret of the alternatives across all the considered future scenarios.

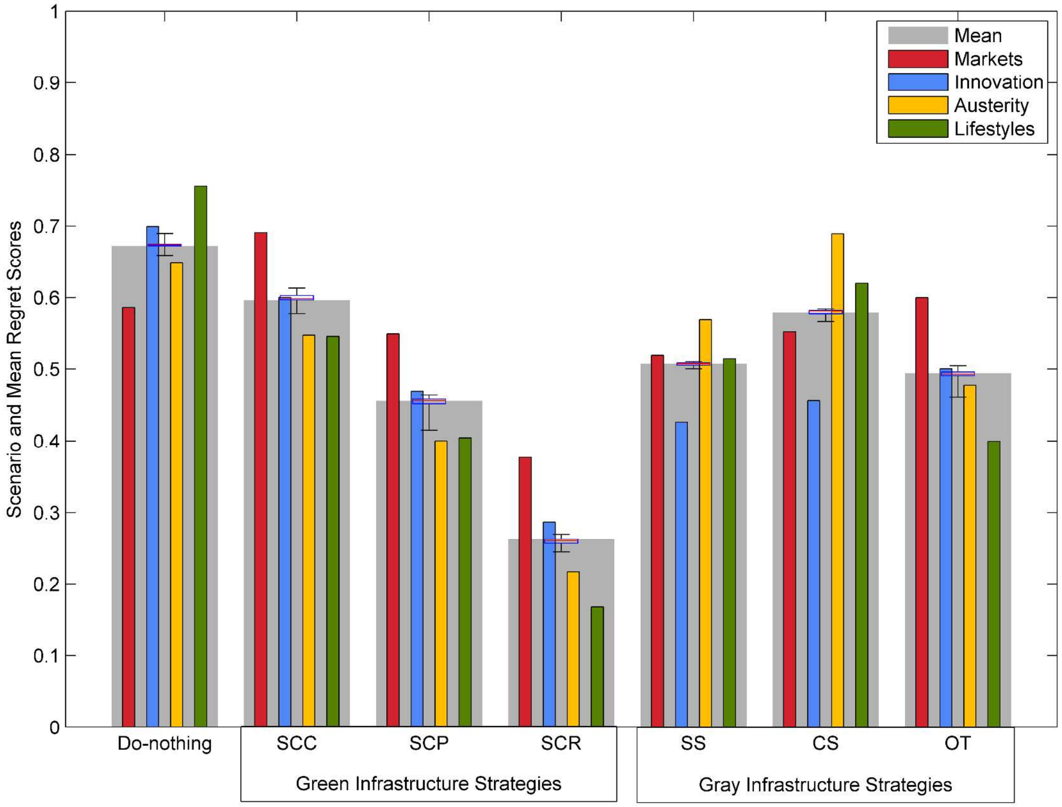


Figure 4. Scenario regret (colored bars) and mean regret (gray bars) scores of drainage strategies. Low mean regret is interpreted as robustness or consistent good performance across future scenarios (mini-mean criterion). Error whiskers and boxes plotted for each strategy show the total range and upper and lower quartiles of mean regret scores associated with uncertainty in future scenario parameters (more information available in the SI).

Figure 4 implies that the disconnection of roofs using rain gardens (SCR) is the most robust (i.e. least regrettable) strategy overall and under each future scenario. The implementation of bioretention planters in roads (SCP) results in the second most robust strategy, even though scenario regrets of SCP for Innovation and Markets are higher than those of SS and CS. Indeed, SCP's abatement of regrets in Lifestyles and Austerity largely offsets its loss of performance in Markets and Innovation relative to SS and CS, since the margin for improvement is more constrained in these last two future scenarios (i.e. regrets are closer to each other). One of the advantages of a regret-based approach is to bring attention to states of the world most relevant to decisions, in which positive or negative outcomes may strongly depend on our choices.[47,55] The broad range of regret observed in Lifestyles (i.e. from best at 0.17 to worst at 0.76) indicates that there is greater potential to abate negative impacts and make less regrettable decisions when based on this future scenario.

On-site treatment of wastewater (OT) performs better than other gray options in these scenarios, but its robustness is largely limited by its failure to directly address stormwater management issues such as sewer flooding and CSO spills.

The least robust strategy in Figure 4 is "do-nothing", which also shows the highest scenario regrets, only exceeded by SCC and CS under Markets and Austerity, respectively. The high mean regret of urban creep mitigation using permeable pavement (SCC) reflects the costly implementation of this alternative relative to its limited beneficial effect in other impact categories across future scenarios (see Figure 3). Given the robustness of other green strategies, such as rain gardens for roofs (SCR), combining urban creep mitigation and downspout reconnection (i.e. SCC that also infiltrates roof runoff) could result in a more cost-effective investment per marginal regret abated and, consequently, a more robust alternative overall.

The mean regret of the CS strategy suggests that the costs and indirect environmental impact (i.e. operational emissions, river ammonia levels and river flood risk) of large gray infrastructure schemes exceed its immediate potential benefits (e.g. CSO reduction), constraining its robustness across a variety of possible future scenarios. Conventional gray strategies (SS and CS) are predominantly effective in addressing very specific objectives (CSO reduction and sewer flooding alleviation) while compromising their performance on costs (on average, 25% of their total regret) and less apparent issues (impacts downstream in the system). The results obtained in Figure 4 demonstrate that this unbalanced performance limits the ability of gray infrastructure strategies to be robust as they consistently accumulate regret from issues concerning downstream performance (this accounted on average for 50% of their total regret), becoming particularly vulnerable to states or the world where such objectives are more relevant to decisions (e.g. Lifestyles). In contrast, green strategies, such as rain gardens (SCR) and bioretention planters (SCP), show less pronounced performance trade-offs (i.e. see SCR in Figure 3, small cost regrets to lower many category regrets simultaneously), thus contributing to the reduction of regret in an ampler variety of objectives. Consequently, as green alternatives can become more adaptable to physical change and to shifts in the valuation of multiple objectives, they are expected to be more robust in the long-term.

3.3. Implications

Finding alternatives with low regrets spanning across a variety of future scenarios and objectives is crucial to propose sustainable drainage strategies in the long-term. The present work contributes to the advance of a growing body of literature concerned with the robustness of green and gray infrastructure options in the face of future uncertainty. The regret-based approach to robustness used here highlights how drainage strategies that may be perceived as robust options now could be critically flawed if, as anticipated by incoming legislation and research, larger and more stringent sets of performance objectives are required in the future. The approach is also useful in recognizing future states where decisions may be particularly relevant or where alternatives are individually vulnerable. This permits to quickly identify promising strategies and reduce the number of candidate options in the decision process.

The integration of multiple impact categories, regardless of their nature or the type of indicators used to describe them, permitted the realization of a broader and richer set of impacts and trade-offs for each strategy. Such integration is fundamental to evaluate the actual implications that merits or demerits of specific alternatives may have in multi-criteria decision-making at the watershed-scale. This also allows the incorporation of intangible objectives that may be difficult to quantify or monetize when using traditional cost-benefit analysis. Still, a regret approach can be adopted alongside other methods to better inform decisions.

The benefits described in this study for green strategies as compared to conventional gray solutions seem to agree with those reported in the literature[14,15,19] regarding its role in improving water quantity and quality impacts more effectively. The performance reported for centralized gray infrastructure strategies also coincides with studies[54,56] that question the use of CSO spills as an accurate indicator for water quality impacts on receiving waters.

In general, the results show that green infrastructure alternatives are more robust than their gray infrastructure counterparts, as they compromise less on performance objectives. Nevertheless, scenario regrets and trade-offs observed for green and gray alternatives suggest that a combination of these into “hybrid” strategies may have a mutually beneficial effect, offering further potential for robustness that needs to be investigated.

AUTHOR INFORMATION

Corresponding Author

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

Tel: +44 (0)1392 726652 (A. Casal-Campos); +44 (0) 1392 723692 (G. Fu)

e-mail: ac458@exeter.ac.uk (A. Casal-Campos); g.fu@exeter.ac.uk (G. Fu)

ACKNOWLEDGMENTS

The authors gratefully acknowledge financial support from the UK Engineering & Physical Sciences Research Council (EPSRC) through funding of the STREAM Industrial Doctorate Centre, and from the project sponsor (Northumbrian Water Ltd.) The authors also acknowledge support from the third author’s Safe & SuRe research fellowship funded by the UK EPSRC (EP/K006924/1).

ASSOCIATED CONTENT

Supporting Information Available

Integrated model and case study description; Definition of future scenarios; Description and representation of strategies; Whole life cost of strategies; Regret calculations & summary of results; Sensitivity analysis. This information is available free of charge via the Internet at http://pubs.acs.org.

REFERENCES

(1) Blackmore, J.; Plant, R. Risk and resilience to enhance sustainability with application to urban water systems. *J. Water Resour. Plan. Manag.* **2008**, *134* (3), 224–233.

(2) Ferguson, B. C.; Frantzeskaki, N.; Brown, R. R. A strategic program for transitioning to a Water Sensitive City. *Landsc. Urban Plan.* **2013**, *117*, 32–45.

(3) Offermans, A.; Haasnoot, M.; Valkering, P. A method to explore social response for sustainable water management strategies under changing conditions. *Sustain. Dev.* **2011**, *19*, 312–324.

(4) Gersonius, B.; Nasruddin, F.; Ashley, R.; Jeuken, a; Pathirana, a; Zevenbergen, C. Developing the evidence base for mainstreaming adaptation of stormwater systems to climate change. *Water Res.* **2012**, *46* (20), 6824–6835.

(5) Gersonius, B.; Ashley, R.; Pathirana, A.; Zevenbergen, C. Climate change uncertainty: building flexibility into water and flood risk infrastructure. *Clim. Change* **2013**, *116* (2), 411–423.

(6) Butler, D.; Farmani, R.; Fu, G.; Ward, S.; Diao, K.; Astaraie-Imani, M. A new approach to urban water management: Safe and SuRe. *Procedia Eng.* **2014**, *89*, 347–354.

(7) Digman, C.; Ashley, R.; Balmforth, D.; Stovin, V.; Glerum, J. *Retrofitting to manage surface water. Report C713.*; CIRIA: London, 2012.

(8) CNT (Centre for Neibourhood Technology) and American Rivers. *The Value of Green Infrastructure. A Guide to Recognizing its Economic, Environmental and Social Benefits.*; Chicago, IL, 2010.

(9) Marlow, D. R.; Moglia, M.; Cook, S.; Beale, D. J. Towards sustainable urban water management: a critical reassessment. *Water Res.* **2013**, *47* (20), 7150–7161.

(10) Demuzere, M.; Orru, K.; Heidrich, O.; Olazabal, E.; Geneletti, D.; Orru, H.; Bhave, a. G.; Mittal, N.; Feliu, E.; Faehnle, M. Mitigating and adapting to climate change: Multi-functional and multi-scale assessment of green urban infrastructure. *J. Environ. Manage.* **2014**, *146*, 107–115.

(11) Kousky, C.; Olmstead, S. M.; Walls, M. A.; Macauley, M. Strategically Placing Green Infrastructure : Cost-E ff ective Land Conservation in the Floodplain. *Environ. Sci. Technol.* **2013**, *47*, 3563–3570.

(12) Zhou, Q.; Mikkelsen, P. S.; Halsnæs, K.; Arnbjerg-Nielsen, K. Framework for economic pluvial flood risk assessment considering climate change effects and adaptation benefits. *J. Hydrol.* **2012**, *414-415*, 539–549.

(13) Stovin, V. R.; Moore, S. L.; Wall, M.; Ashley, R. M. The potential to retrofit sustainable drainage systems to address combined sewer overflow discharges in the Thames Tideway catchment. *Water Environ. J.* **2013**, *27* (2), 216–228.

(14) De Sousa, M. R. C.; Montalto, F. a.; Spatari, S. Using Life Cycle Assessment to Evaluate Green and Grey Combined Sewer Overflow Control Strategies. *J. Ind. Ecol.* **2012**, *16* (6), 901–913.

(15) Wang, R.; Eckelman, M. J.; Zimmerman, J. B. Consequential environmental and economic life cycle assessment of green and gray stormwater infrastructures for combined sewer systems. *Environ. Sci. Technol.* **2013**, *47* (19), 11189–11198.

(16) Lundie, S.; Peters, G. M.; Beavis, P. C. Life Cycle Assessment for Sustainable Metropolitan Water Systems Planning. *Environ. Sci. Technol.* **2004**, *38* (13), 3465–3473.

(17) Butler, D.; Schütze, M. R. Integrating simulation models with a view to optimal control of urban wastewater systems. *Environ. Model. Softw.* **2005**, *20* (4), 415–426.

(18) Makropoulos, C. K.; Natsis, K.; Liu, S.; Mittas, K.; Butler, D. Decision support for sustainable option selection in integrated urban water management. *Environ. Model. Softw.* **2008**, *23* (12), 1448–1460.

(19) Semadeni-Davies, A.; Hernebring, C.; Svensson, G.; Gustafsson, L.-G. The impacts of climate change and urbanisation on drainage in Helsingborg, Sweden: Combined sewer system. *J. Hydrol.* **2008**, *350* (1-2), 100–113.

(20) Kleidorfer, M.; Möderl, M.; Sitzenfrei, R.; Urich, C.; Rauch, W. A case independent approach on the impact of climate change effects on combined sewer system performance. *Water Sci. Technol.* **2009**, *60* (6), 1555–1564.

(21) Urich, C.; Rauch, W. Exploring critical pathways for urban water management to identify robust strategies under deep uncertainties. *Water Res.* **2014**, *66*, 374–389.

(22) Butler, D.; Fu, G.; Khu, S. The relationship between sewer flood volume and receiving water quality in an integrated urban wastewater system. In *10th British Hydrological Society Symposium, 15-17 Sept, 2008*; BHS: Exeter, 2008.

(23) Environment Agency. *Water: Planning ahead for an uncertain future. Water in the 2100s. Briefing note GEHO0811BSMM-E-E*; 2010.

(24) Evans, E. P.; Ashley, R.; Hall, J. W.; Penning-Rowsell, E. C.; Saul, A.; Sayers, P. B.; Thorne, C. R.; Watkinson, A. R. *Future Flooding Volume 1: Future Risks and their Drivers*; Government Office for Science: London, 2004.

(25) Lombardi, D.; Leach, J.; Rogers, C.; Aston, R.; Barber, A.; Boyko, C.; Brown, J.; Bryson, J.; Butler, D.; Caputo, S.; et al. *Designing Resilient Cities. A Guide to Good Practice*; IHS BRE Press: Bracknell, 2012.

(26) Farmani, R.; Butler, D.; Hunt, D.; Memon, F.; Abdelmeguid, H.; Ward, S.; Rogers, C. Scenario-based sustainable water management and urban regeneration. *ICE Eng. Sustain.* **2012**, *165* (ES1), 89–98.

(27) Ofwat (The Water Services Regulation Authority). *Future Impacts on Sewer Systems in England and Wales. Summary of a Hydraulic Modelling Exercise Reviewing the Impact of Climate Change, Population and Growth in Impermeable Areas up to Around 2040*; Birmingham, 2011.

(28) UKWIR (UK Water Industry Research). *Impact of urban creep on sewerage systems (Report 10/WM/07/14)*; London, 2010.

(29) Ellis, J. B.; Butler, D. Surface Water Sewer Misconnections in England and Wales: A Review of Pollution Sources, Trends and Impact. *Sci. Total Environ.* **2015**, *526*, 98–109.

(30) White, M.; Johnson, H.; Anderson, G.; Misstear, B. *Control of infiltration to sewers - CIRIA Report 175*; CIRIA: London, 1997.

(31) Butler, D.; Davies, J. W. *Urban Drainage*, 3rd ed.; Spon Text: London, 2011.

(32) ONS (Office of National Statistics). National Population Projections, 2012-based Reference Volume: Series PP2 http://www.ons.gov.uk/ons/rel/npp/national-population-projections/2012-based-reference-volume--series-pp2/index.html.

(33) Ackers, J. C.; Butler, D.; May, R. W. P. *Design of sewers to control sediment problems - CIRIA Report 141*; CIRIA: London, 1996.

(34) Defra (Department for Environment Food and Rural Affairs). *Flood and Coastal Defence Appraisal Guidance FCDPAG3 Economic Appraisal. Supplementary Note to Operating Authorities – Climate Change Impacts.*; 2006.

(35) Murphy, J. M.; Sexton, D. M. H.; Jenkins, G. J.; Boorman, P. M.; Booth, B. B. B.; Brown, C. C.; Clark, R. T.; Collins, M.; Harris, G. R.; Kendon, E. J.; et al. *UK Climate Projections Science Report: Climate change projections.*; Met Office Hadley Centre: Exeter, 2009.

(36) Ifak. *Simulation of Sewer Systems Integrated in SIMBA. SIMBA 6.0 Sewer User's Guide*; Institute for Automation and Communication: Magdeburg, Germany, 2007.

(37) Rossman, L. A. *Storm water management model user's manual. Version 5.0*; US Environmental Protection Agency, 2010.

(38) UKTAG (UK Technical Advisory Group on the Water Framework Directive). *Updated Recommendations on Environmental Standards River Basin Management (2015-21)*; 2013.

(39) Committee on Climate Change. *Costs and Benefits of Sustainable Drainage Systems*; Petterborough, 2012.

(40) Defra (Department for Environment Food and Rural Affairs). *DEFRA WT1505 Final Surface Water Drainage Report*; 2013.

(41) Islington Council. *Comparative costing for surface water sewers & SuDS. Caledonian Road Housing, Islington, London.*; R&D Technical Report., 2011.

(42) Ofwat (The Water Services Regulation Authority). *Capital works unit costs in the water industry : Feedback on our analysis of the March 2003 water company cost base submissions*; 2004.

(43) MWH. *Thames Tunnel Needs Report. Sewer separation feasibility study.*; Final Report for Thames Water, 2010.

(44) Gray, S.; Booker, N. Wastewater services for small communities. *Water Sci. Technol.* **2003**, *47* (07-08), 65–71.

(45) Environment Agency. *Transforming wastewater treatment to reduce carbon emissions*; Environment Agency: Bristol, 2009.

(46) Lempert, R.; Groves, D.; Popper, S.; Bankes, S. A general, analytic method for generating robust strategies and narrative scenarios. *Manage. Sci.* **2006**, *52* (4), 514–528.

(47) Lempert, R. J.; Collins, M. T. Managing the risk of uncertain threshold responses: comparison of robust, optimum, and precautionary approaches. *Risk Analysis* **2007**, *27* (4), 1009–1026.

(48) Willows, R.; Reynard, N.; Meadowcroft, I.; Connell, R. *Climate adaptation : Risk , uncertainty and decision-making. Part 2.*; UKCIP Technical Report: Oxford, 2003.

(49) Savage, L. J. *The Foundations of Statistics*; Wiley & Sons: New York, 1954.

(50) Keeney, R. L.; Raiffa, H. *Decisions with multiple objectives: Preferences and value tradeoffs*; John Wiley & Sons: New York, Santa Barbara, London, Sydney, Toronto, 1976.

(51) DCLG (Department of Communities and Local Government). *Multi-criteria analysis : a manual*; Communities and Local Government Publications: London, 2009.

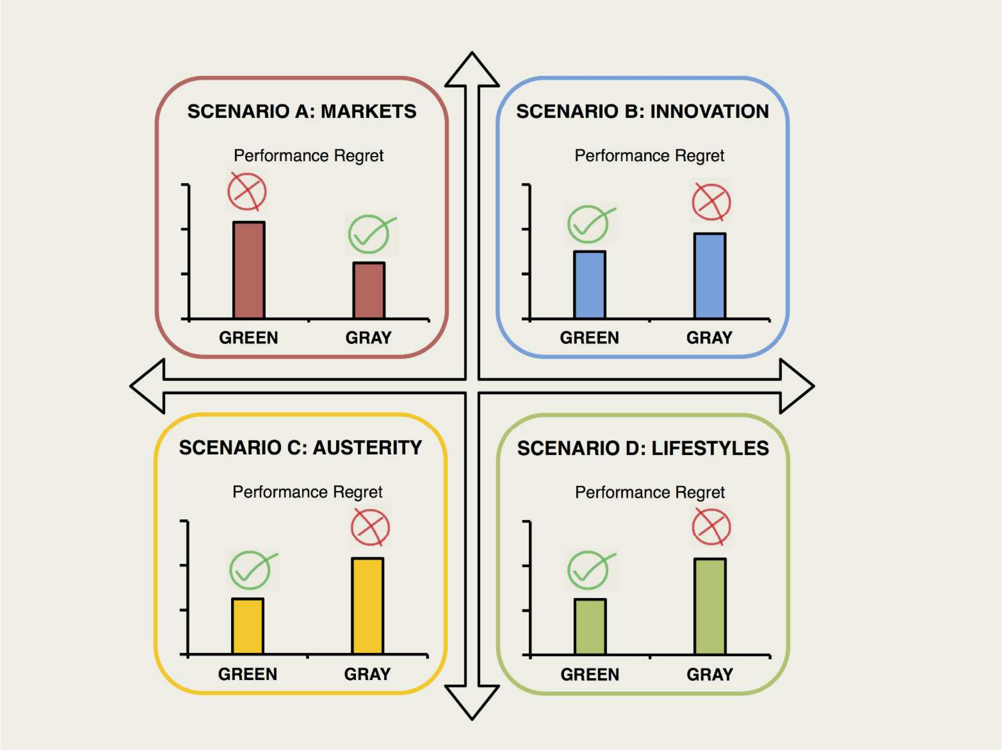
(52) Polasky, S.; Carpenter, S. R.; Folke, C.; Keeler, B. Decision-making under great uncertainty: Environmental management in an era of global change. *Trends Ecol. Evol.* **2011**, *26* (8), 398–404.

(53) Loulou, R.; Kanudia, A. Minimax regret strategies for greenhouse gas abatement: Methodology and application. *Oper. Res. Lett.* **1999**, *25* (5), 219–230.

(54) Lau, J.; Butler, D.; Schütze, M. R. Is combined sewer overflow spill frequency/volume a good indicator of receiving water quality impact? *Urban Water* **2002**, *4*, 181–189.

(55) Hall, J. W.; Lempert, R. J.; Keller, K.; Hackbarth, A.; Mijere, C.; McInerney, D. J. Robust climate policies under uncertainty: a comparison of robust decision making and info-gap methods. *Risk Analysis* **2012**, *32* (10), 1657–1672.

(56) Rauch, W.; Harremoës, P. Correlation of combined sewer overflow reduction due to real-time control and resulting effect on the oxygen concentration in the river. *Water Sci. Technol.* **1998**, *37* (12), 69–76.



254x190mm (300 x 300 DPI)