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Exploring wastewater system performance under future threats: Does enhancing resilience increase sustainability?

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ABSTRACT

Sustainability and resilience are both key considerations in the design and operation of wastewater systems. However, there is currently a lack of understanding of the relationship between these two goals and of the effects of increasing resilience on sustainability. This paper, therefore, presents a framework for analysis of the effects of resilience-enhancing interventions on sustainability, and applies this to an urban wastewater system. Given that sustainability addresses the long term, the framework includes a novel sustainability assessment approach which captures a continuum of potential future conditions and enables identification of tipping points where applicable. This method allows a wide range of potential futures to be captured whilst removing the need to develop scenarios or future projections. While it may be possible to develop interventions that are beneficial in terms of their effects on both resilience and sustainability, the results obtained from the case study demonstrate that implementing measures designed to increase resilience of an integrated urban wastewater system does not guarantee a universal improvement in sustainability. Therefore, when proposing measures to increase resilience, the potential effects on sustainability should be considered also. It is also shown that the extent of any negative effects on system sustainability can vary significantly depending on future conditions, with the case study intervention (increasing pump capacity) achieving the highest degree of sustainability if rainfall depths or imperviousness in the catchments reduce. However, trade-offs between sustainability indicators are present irrespective of future conditions. Furthermore, while an intervention that enhances resilience may be considered sustainable with respect to specific indicators under current conditions, tipping points exist and it will cease to be sustainable if future threat magnitudes exceed these.

1. Introduction

Sustainability and resilience are both key considerations in the design and operation of wastewater systems. Sustainability is a key concern due to factors such as the large quantity of energy and chemicals required (Shao et al., 2017), and there is increasing interest in building resilience in the water sector due to, for example, legislative drivers (e.g. HM Government, 2014) and challenges posed by recent extreme events.

While many different definitions have been used for sustainability (Ozkaynak et al., 2004), it is typically expressed as a set of goals that should be maintained or enhanced for future generations (Jenks and Jones, 2010). Butler et al. (2016), for example, defined it as “the degree to which the system maintains levels of service in the long-term whilst maximizing social, economic and environmental goals”. In addition to meeting these goals, sustainable water management strategies should be also ‘future-proof’ (Haasnoot et al., 2011; Walker et al., 2013) – i.e. effective now and in the future or have the flexibility to adapt to future conditions. This includes not just the foreseeable future, but also the unforeseen (Walker et al., 2013), which poses a challenge as natural, social and technological uncertainties may all affect long term water management (Haasnoot et al., 2011). Assessments of sustainability, however, are typically based on current conditions, projections or a limited number of predefined scenarios containing potential future states (based on driving pressures such as climate change), and do not capture all possibilities.

Resilience, defined as “the degree to which the system minimizes level of service failure magnitude and duration over its design life when subject to exceptional conditions” (Butler et al.,

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2016), also addresses future performance. However, the focus here is on performance under extreme events – for example, quality of wastewater treatment under a shock load to the wastewater treatment plant (WWTP). As with sustainability though, resilience needs to address performance under a range of potential futures, including those containing unforeseeable events.

Despite the apparent similarities between resilience and sustainability, there is currently limited understanding of the effects of resilience-enhancing measures on sustainability. While different theories exist on the relationship between resilience and sustainability (Marchese et al., 2018), it has been suggested that sustainability builds upon resilience (Butler et al., 2016; Scholz et al., 2012) and that increasing the resilience of a system makes it more sustainable (Marchese et al., 2018). Given that exceptional conditions may occur over the long-term timeframe considered for sustainability, resilience is necessary to ensure that the system continues to perform as required into the future and is sustainable. However, assessments of the sustainability of water systems do not typically incorporate resilience and it is unclear whether increasing resilience alone will increase sustainability (or reduce the degree of unsustainability). Birgani and Yazdandoost (2018), for example, used resilience and sustainability indicators simultaneously to rank urban drainage plans, but did not consider resilience a component of sustainability or investigate the relationship between resilience and sustainability.

This research, therefore, aims to investigate whether enhancing the resilience of an urban wastewater system is also beneficial in terms of sustainability, given uncertainty in future conditions. It also investigates whether tipping points (i.e. magnitudes of future change under which a given intervention becomes or ceases to be the most sustainable option) exist. To achieve this, a framework which incorporates resilience assessment, sustainability assessment and tipping point analysis is presented. Subsequent application to a semi-hypothetical integrated urban wastewater system (IUWS) case study demonstrates that the framework can be used to account for the effects of a continuum of scenarios that could occur in the future and analyse the effects of future conditions on the sustainability of a resilience-enhancing measure.

2. Materials and methods

2.1. Framework

The analysis framework, illustrated in Fig. 1, contains five key elements: System characterisation, resilience assessment, intervention development, sustainability assessment and tipping point analysis. System characterisation involves identification of system failure modes (including appropriate measures of magnitude and ranges for consideration) and required levels of service for a defined case study system. This provides the information necessary for subsequent resilience assessment and intervention development. The sustainability and tipping point analysis components of the framework then provide an evaluation of both the base case and the intervention that has been found to increase resilience, and explore the effects of implementing this intervention on the sustainability of the system. Further detail is given in the following sections (2.2–2.6).

2.2. System characterisation

2.2.1. Case study system

The case study used here is a semi-hypothetical IUWS which was first presented by Schütze et al. (2002) and has since been the subject of much research (Astaraie-Imani et al., 2012; Butler and Schutze, 2005; Casal-Campos et al., 2015; Fu et al., 2008, 2009; Zacharof et al., 2004). It is modelled using SIMBA6.0 (IFAK, 2009), which operates in the Matlab/Simulink environment and integrates the separate component models (detailed in the Supplementary Information). A schematic diagram is provided in Fig. 1.

The sewer system contains seven sub-catchments, four on-line pass through storage tanks and a pump at each tank outlet. The catchments are simulated using a hydrologic approach, with surface and sewer network flows modelled conceptually as a linear cascade of reservoirs (Nash cascade model (Nash, 1959)). The WWTP has an off-line pass through storm tank at the inlet and contains a primary clarifier, an activated sludge reactor for biological treatment (modelled with ASM1 (Henze et al., 2000)), and a secondary clarifier. The WWTP and combined sewer overflows (CSOs) discharge into a river, of which 45 km is modelled. Performance is evaluated over a five day period which incorporates a rainfall event with a baseline total depth of 27 mm.

For further detail on the modelling, refer to the Supplementary Information, Schütze et al. (2002) and Butler and Schütze (2005).

2.2.2. System failure modes

Potential system failure modes identified for the case study are detailed in Table 1. Also shown are their measures of magnitude and magnitude ranges for consideration in the following resilience assessment..

For internal failure modes such as component failure, percentage loss of function represents the system failure magnitude. In each case, loss of function in the range 0%–100% is modelled, thereby covering the full range of possibilities irrespective of their probability. External failure modes identified relate to changes in the sewer influent characteristics and a maximum theoretically possible increase cannot typically be determined – the exception here is the percentage increase in VSS/SS and sCOD/COD ratios, for which a maximum stress magnitude is selected so as to provide a maximum ratio of one. Other upper limits are arbitrarily set to a 100% increase with respect to the base case for the purposes of preliminary analysis, but further investigation could explore the effects of extending these limits.

2.2.3. Levels of service

Receiving water dissolved oxygen (DO) and un-ionized ammonia (AMM) concentrations are chosen to represent the urban wastewater system level of service measures. DO is selected as it is a good measure of the 'health' of the water body, since all higher forms of river life require oxygen (Butler and Davies, 2010). Un-ionized ammonia is also important to monitor since it is particularly toxic to fish, and its conversion can exert an oxygen demand. As only total ammonia is modelled dynamically in SIMBA, un-ionized ammonia is estimated using a conversion factor of 0.0195 (based on a temperature of 20 °C and a pH of 7.7) (Schütze et al., 2002). Other potential indicators of water quality include, for example, temperature, pH, total suspended solids and chemical oxygen demand (Kannel et al., 2007); however, these cannot be extracted from the case study model. Although evaluation of only DO and ammonia is common practice in integrated urban wastewater system studies (e.g. Benedetti et al., 2013; Vanrolleghem et al., 2005), additional level of service measures could be considered for other case studies using the proposed framework to provide a more detailed picture of the river water quality.

A minimum DO concentration of 4 mg/l (DO_{lim}) and a maximum AMM concentration of 0.068 mg/l (AMM_{lim}) are required to provide an acceptable level of service. This DO limit is commonly used in IUWS studies (e.g. Astaraie-Imani et al., 2012; Solvi et al., 2006) and is equal to the 1 year return period, 1 h limit for salmonid waters (i.e. limit which should not be breached for a 1-h period more than once a year) (Defra, 2014). The AMM limit is the recommended

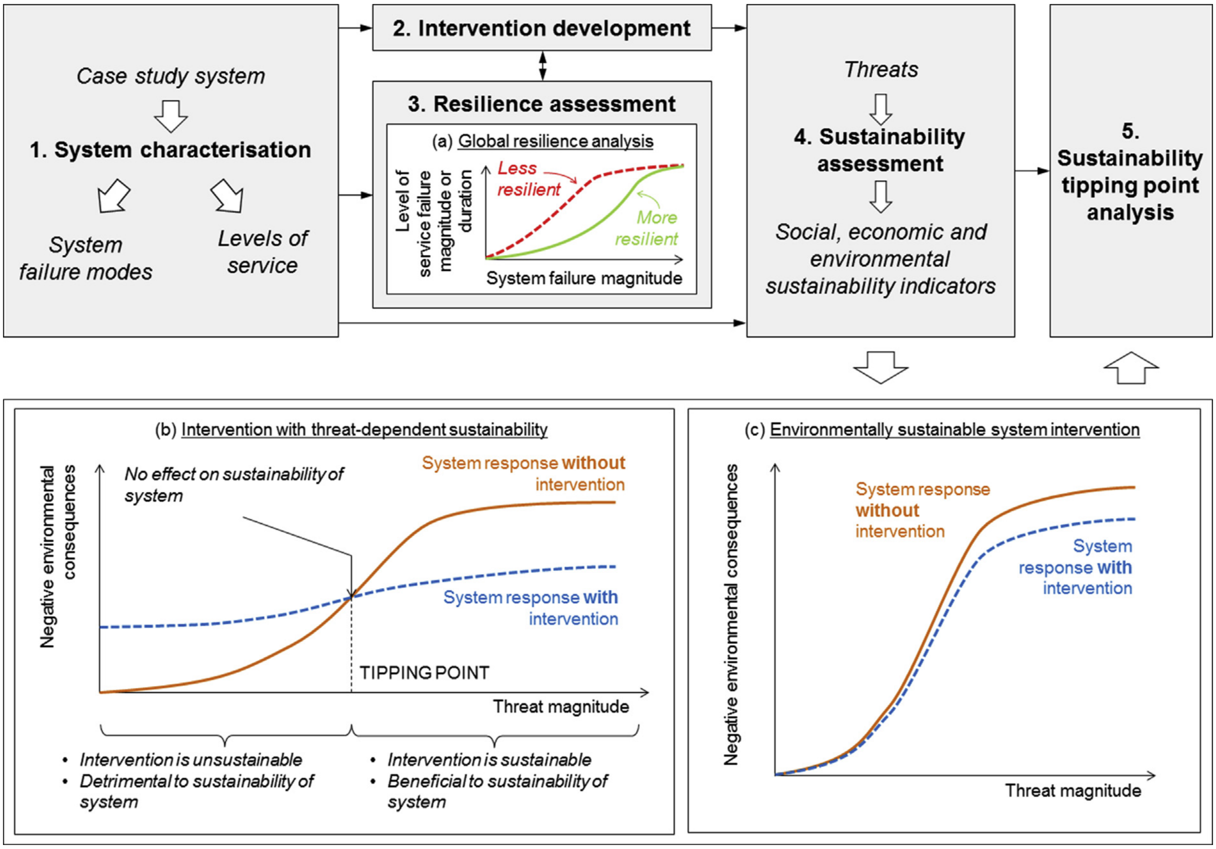

Fig. 1. 5-Stage analysis framework, including conceptual illustration of: (a) application of global resilience analysis in stage 3; and, for stages 3 and 4, response curves illustrating (b) an intervention with threat-dependent sustainability; and (c) an environmentally sustainable system intervention. Detailed explanation is provided in Sections 2.2-2.6.

Table 1
System failure modes and magnitudes. Refer to Fig. 2 for tank numbers.

System failure mode	Measure of magnitude	Magnitude range (%)
A. Increased sewer influent flow	Increase in flow rate	[0 100]
B. Increased sewer influent suspended solids (SS)	Increase in SS concentration	[0 100]
C. Increased sewer influent volatile suspended solids (VSS)	Increase in VSS/SS ratio	[0 36.69][a]
D. Increased sewer influent chemical oxygen demand (COD)	Increase in COD concentration	[0 100]
E. Increased sewer influent soluble COD (sCOD)	Increase in sCOD/COD ratio	[0 117.39][a]
F. Increased sewer influent NH_4	Increase in NH_4 concentration	[0 100]
G. Failure of pump to primary clarifier	Reduction in pump 2 capacity	[0 100]
H. Failure of return activated sludge pump	Reduction in pump 4 capacity	[0 100]
I. Failure of primary clarifier	Reduction in primary clarifier efficiency	[0 100]
J. Failure of tank 2 outflow pump	Reduction in maximum tank 2 pumped outflow	[0 100]
K. Failure of tank 4 outflow pump	Reduction in maximum tank 4 pumped outflow	[0 100]
L. Failure of tank 6 outflow pump	Reduction in maximum tank 6 pumped outflow	[0 100]
M. Failure of tank 7 outflow pump	Reduction in maximum tank 7 pumped outflow	[0 100]
N. Failure of activated sludge aeration	Reduction in aeration rate	[0 100]

[a] Gives a maximum ratio of 1.

predicted no-effect concentration for freshwater, based on the 96 h median lethal concentration for pink salmon (Johnson et al., 2007). Failure to comply with either of these limits constitutes a level of service failure.

Failure magnitudes and durations are calculated as follows:

$$DO\ failure\ magnitude = \max(0, DO_{lim} - DO_{min}) \tag{1}$$

$$DO\ failure\ duration = T_{R,DO} - T_{F,DO} \tag{2}$$

$$AMM\ failure\ magnitude = \max(0, AMM_{max} - AMM_{lim}) \tag{3}$$

$$AMM\ failure\ duration = T_{R,AMM} - T_{F,AMM} \tag{4}$$

Where DO_{min} is the minimum DO concentration during the evaluation period, AMM_{max} the maximum un-ionized ammonia concentration, $T_{F,DO}$ and $T_{F,AMM}$ the times at which DO and AMM failures commence, and $T_{R,DO}$ and $T_{R,AMM}$ the times at which DO and AMM recovery occur.

To account for differing DO and AMM concentrations along the course of the river, these measures are calculated for 40 locations

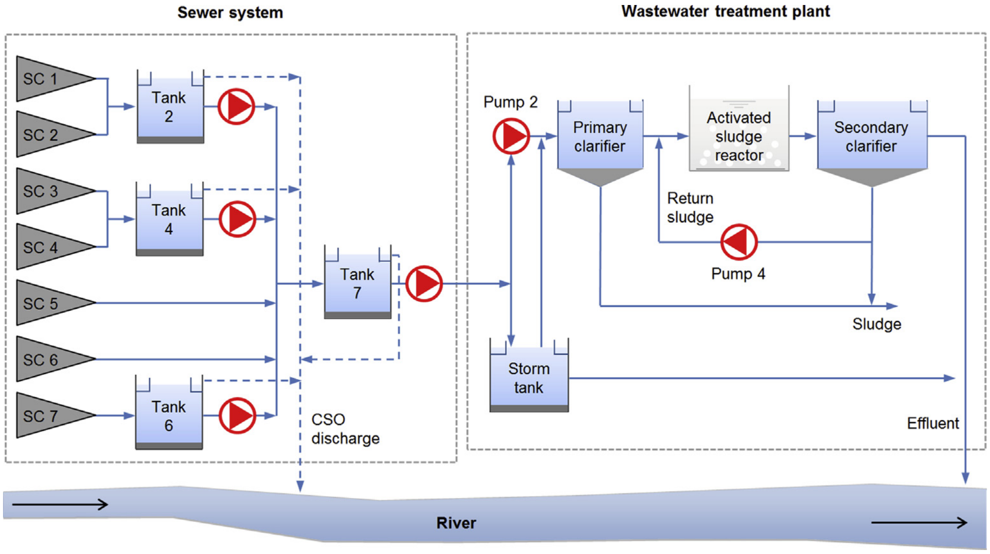

Fig. 2. Schematic diagram of the IUWS case study. SC denotes sub-catchment.

along the modelled stretch and the worst (i.e. maximum) values used for resilience assessment.

2.3. Resilience assessment

Resilience assessment is based on the ‘global resilience analysis’ (GRA) approach (Butler et al., 2016; Diao et al., 2016; Mugume et al., 2015), as illustrated in Fig. 1a. This focuses on system failure modes instead of the threats that may cause them, thereby overcoming the challenge of identifying and characterizing all possible threats (of which many are unforeseeable) and enabling the potential effects of these threats to be captured without needing to identify their root cause.

In GRA, level of service failure magnitude and duration are calculated as a function of system failure magnitude. This enables the generation of response curves which illustrate the level of service failure magnitude and duration resulting from a wide range of possible system failure magnitudes, including those that would be classified as exceptional conditions. The area under each response curve (calculated using simulations across the range of system failure magnitudes, as detailed in Section 2.5.1, and the trapezium rule) can be considered indicative of the resilience to the corresponding system failure mode: A smaller area indicates a lower level of service failure magnitude and duration over a range of conditions and, therefore, a higher resilience.

To apply the system failures listed in Table 1, it is necessary to decide not only how their magnitude can be varied, but also at what time and for how long each stress should be applied. For consistency, all system failures are assumed to occur throughout the entire simulation period – i.e. recovery of the system due to intervention (such as replacement or mending of a failed component) is not considered. This does not mean, however, that any level of service failure resulting from the system failure also lasts the entire simulation duration since recovery may be observed as the simulated storm event recedes.

2.4. Intervention development

The system with no design or operational changes (i.e. as described in Section 2.2.1) represents the base case. Evaluation of the base case resilience enables identification of system failure modes to which resilience is lowest and can inform the development of interventions. The intervention development can be an iterative process, with the intervention modified following assessment of its effects on resilience if sufficient benefits are not observed.

In the case study, resilience to increased sewer influent flow in particular is found to be poor (see results in Section 3.1) and, therefore, an increase in the outflow pumping capacity of the storm tank preceding the WWTP (tank 7) is proposed so as to increase the volume of flow passed to full treatment. This increase is arbitrarily set to 200% (from 1.59 Ml/s to 4.77 Ml/s) so as to ensure benefits are observed, although practical considerations may limit the increase that could be achieved in reality.

2.5. Sustainability assessment

In a large, complex system with many interdependencies, it is hard to know what constitutes complete sustainability due to, for example, difficulties in identifying every possible social, economic and environmental impact. As such, achieving absolute sustainability may not be considered feasible. When evaluating the effects of interventions, the concept of sustainability is more easily addressed in the relative sense – i.e. do the interventions cause the system to become more or less sustainable? This study, therefore, evaluates the sustainability of an IUWS *intervention*, rather than the absolute sustainability of the IUWS. If an intervention has a neutral or positive effect on the sustainability of the system then the *intervention* is sustainable, irrespective of the absolute sustainability of the entire system. This concept is illustrated in Fig. 1c, where the intervention does not eliminate negative environmental consequences of the system but does have a positive effect on consequences under a range of threat magnitudes that may occur. Fig. 1b shows an alternative response, where the sustainability of the intervention is dependent on the threat magnitude; in this example, the intervention is considered sustainable only if a high threat magnitude is realized.

The sustainability assessment methodology developed in this study uses response curves, in which sustainability indicator values are presented as a function of threat magnitude (as illustrated in Fig. 1b and c). This builds upon and complements the GRA approach applied in the preceding resilience assessment (Section 2.3). As in

GRA, this sustainability assessment enables the effects of a continuum of potential future scenarios to be accounted for, irrespective of their probability or expected time frame of occurrence and without the need to develop specific predictions or future projections. It also captures extreme magnitude events that would be considered unforeseen should they occur. The use of threats as the stressor, rather than system failures, also enables projected scenarios to be mapped onto the results.

This concept has been used previously in sustainability assessment (Poff et al., 2016); however, previous application to sustainability assessment considered only two performance indicators and did not enable evaluation of the relative sustainability of different strategies. Furthermore, the potential effects of resilience-enhancing measures on sustainability were not explored.

To generate the response curves, it is necessary to identify relevant threats, appropriate ranges of magnitude for these, and suitable sustainability indicators. These threats may then be modelled individually or simultaneously. For a single threat acting alone, sustainability indicators are calculated for the IUWS with and without intervention under threat magnitudes within the specified range, resulting in response curves of the form shown in Fig. 1b and c. For two or more threats acting simultaneously, every combination of magnitude for each threat is evaluated. Therefore, the results cannot be presented visually in a two-dimensional plot, as in Fig. 1; however, the subsequent identification of threat magnitudes/threat magnitude combinations under which the intervention improves the sustainability of the system can still be carried out as discussed in Section 2.6.

Consideration of different possible threat magnitudes in this manner helps to address the ‘long term’ element of sustainability, as it enables the effects of a wide range of possible scenarios to be captured without the need for scenario development, projections or assigning of probabilities. It also eliminates uncertainty associated with generation of projections or scenarios. However, sustainability under any specific scenario of interest can still be determined from the curves.

By generating similar response curves for every relevant sustainability indicator and threat combination, for both the base case system and system with intervention, a detailed picture of the potential social, economic and environmental impacts of an intervention can be obtained. If a sustainability indicator is improved at a given threat magnitude by implementation of the intervention, then the intervention is considered sustainable *under that threat magnitude* and *with respect to that sustainability indicator*. Therefore, it is possible to identify specific threat magnitudes under which the intervention is or is not sustainable with respect to each sustainability indicator. As assessment of sustainability requires multiple indicators to capture the social, economic and environmental elements, it is possible that, under a specific threat magnitude, the intervention may be considered sustainable with respect to some sustainability indicators but unsustainable with respect to others; the intervention can only be considered totally sustainable under a given threat magnitude if *all* sustainability indicators are improved simultaneously.

2.5.1. Threats

Wastewater systems may be subject to a host of possible threats in the future, including both those that are known and those that are unknown. This study addresses four potential, known threats with a range of magnitudes, as detailed in Table 2. Other threats that could be included in a more extensive analysis include (but are not limited to) change in energy prices, change in the electricity production emission factor (e.g. due to increased use of renewables) and other rainfall changes. Note that unknown threats may also affect sustainability; however, by definition, these cannot be simulated directly.

The change in rainfall depth is applied as a multiplier of the baseline rainfall depth series, i.e. the intensity of the rainfall event is altered but the duration unchanged.

Arbitrary magnitude ranges are set for each threat so as to capture a wide range of possibilities, irrespective of probability. IUWS simulations are undertaken at threat magnitude intervals of 10% (e.g. −50%, −40%, … +40%, +50% change in population) to enable the generation of sustainability indicator response curves.

Only an increase in pump energy factor (the energy required to pump a unit volume of wastewater) is considered, as pumps will not become more efficient than their baseline efficiency (assuming they are initially as new) unless they are upgraded, which would have additional implications for sustainability. For the remaining threats, both an increase and decrease in magnitude are considered as either may theoretically occur and each may have different effects on sustainability. For example, impervious surface area could increase or decrease depending on the extent of future housing and green infrastructure development, and an intervention that provides improved sustainability for a catchment with high imperviousness may not for one with low imperviousness. In this paper, to illustrate the concept of sustainability assessment under future threats, a maximum of two threats are considered simultaneously; however, further analysis could investigate additional concurrent threats. Note that, although interdependencies between threats may be present in reality, they are considered here as independent variables. An increase in population may, for example, correspond with an increase in impervious catchment area – however, the relationship between these two threats is not fixed and cannot, therefore, be modelled. Furthermore, as the model does not encompass pump curves, the pump energy factors are considered to be independent of flow changes due to population increase. In reality, however, pump efficiency (and, therefore, the energy factor) will vary with flow rate. The effects of these interdependencies should be explored in future research.

2.5.2. Sustainability indicators

Sustainability is a complex multi-dimensional concept (Lozano-Oyola et al., 2012), thus multiple indicators are required to address social, economic and environmental consequences. However, to assess the sustainability of the intervention (not the system), it is only necessary to consider indicators affected by the intervention. For example, indicators of the social sustainability of wastewater treatment technologies include odours, noise, visual impact and public acceptance (Molinos-Senante et al., 2014), but installation of additional pumps as in the proposed intervention would be expected to have negligible effect on these. This study, therefore, focusses on economic and environmental sustainability indicators.

With respect to economic sustainability, financial cost (capital and operational) is the selected indicator. Whilst, in principle, social and environmental economics should be incorporated (Balkema et al., 2002), this is challenging and practice most analyses only include financial costs and benefits (Balkema et al., 2002).

Sets of environmental sustainability indicators used in literature vary, but typically address effluent quality, sludge production, combined sewer overflows and gaseous emissions (Balkema et al., 2002). Indicators used in this study are: nitrogen (N) and chemical oxygen demand (COD) not removed by the WWTP, combined sewer overflow (CSO) volume, total suspended solids production and greenhouse gas (GHG) emissions.

COD removal and N removal have previously been used as indicators for environmental sustainability (Molinos-Senante et al., 2014) and are important to prevent eutrophication of the receiving water body (Ma et al., 2015). They are expressed in this study as a percentage of the influent load *not* removed so that, for

Table 2
Threat types and magnitudes.

Threat	Baseline value	Magnitude of change (%)	
		Minimum	Maximum
Change in population	152,783	−50	+50
Change in impervious catchment area	726 ha	−50	+50
Change in rainfall depth	27 mm	−50	+50
Change in pump energy factor	See Supplementary Information (varies between pumps)	0	+100

all sustainability indicators, a lower value is preferable.

Values for each sustainability indicator are calculated under each threat type and magnitude for both the base case wastewater system and the system with intervention.

Further detail on the calculation of costs and GHG emissions is provided in the Supplementary Information.

2.6. Tipping point analysis

Adaptation tipping points have been explored in many fields and may have physical, ecological, technical, economic, societal or political causes (Kwadijk et al., 2010). In the context of climate change, for example, adaptation tipping points have been defined as “the points where the magnitude of climate change is such that the current strategy can no longer meet the pre-set objectives” (Gersonius et al., 2011).

In a more general sense, a tipping point may be considered the point at which “the magnitude of change is such that the current management strategy can no longer meet its objectives” (Kwadijk et al., 2010). Instead of evaluating performance under predefined future scenarios, a tipping point approach investigates whether or for how long current strategies will continue to be effective.

Whilst tipping points are commonly expressed as a time/year (e.g. Haasnoot et al., 2015), they can also be expressed simply as a magnitude of change, as in the above definition. In the context of this work, this would be the threat magnitude. This enables tipping points to be determined without deriving scenarios which relate the threat magnitude to time, although the identified tipping point (threat magnitude) may be mapped onto time-based scenarios to estimate when it is expected to occur, as in Gersonius et al. (2012).

If the objective is “to provide the most sustainable option”, then the tipping point would be the threat magnitude at which the intervention being evaluated has no net effect on system sustainability (and beyond which implementing the intervention would be more sustainable than not), as illustrated in Fig. 1b. Such a tipping point can only be identified when comparing multiple pre-defined design or operational scenarios, however, and cannot be used to identify the point at which a yet-to-be-decided intervention is required.

3. Results and discussion

3.1. Resilience

This section presents the resilience assessment results for the system with and without intervention (as described in Sections 2.2.1 and 2.4 respectively), and demonstrates that the proposed intervention is successful in enhancing resilience.

GRA response curves are generated for the IUWS in its base case configuration and with intervention, using the system failure modes and level of service measures specified in Sections 2.2.2 and 2.2.3 respectively. Example response curves are provided in Fig. 3: These illustrate the effects of the intervention on the DO and AMM failure magnitude and duration (calculated using Eqs. (1)–(4)) under failure of the pump to the primary clarifier (system failure mode G). This demonstrates that the intervention provides a reduction in failure magnitude and duration under a range of pump failure magnitudes and, therefore, provides an increase in resilience to this failure mode.

Summary results showing the resilience metric (area under the response curve) for every system failure mode and level of service measure are given in Fig. 4. A shorter bar indicates higher resilience to a given failure mode. These results show that, when considering the receiving water DO in particular, the intervention provides significant improvement in resilience. The DO (failure magnitude and duration) response to every system failure mode is improved by the intervention, and DO failure magnitude is significantly reduced. The intervention is also largely beneficial with respect to AMM failure magnitude and duration, although resilience is reduced under two failure modes, i.e. increased sewer influent flow (A) and failure of the activated sludge aeration (N).

Detailed results, including level of service failure magnitudes and durations calculated under every system failure magnitude and calculation of areas under the response curves (i.e. the resilience metrics shown in Fig. 4), are provided in the Supplementary Information.

3.2. Sustainability response to individual threats

Fig. 5 shows the response of each sustainability indicator to each threat applied singly, with threats on the x-axes and sustainability indicators on the y-axes. Threat magnitudes which result in the intervention having a lower sustainability indicator value than the base case, and under which the intervention is considered sustainable with respect to a given indicator, are indicated by grey shading between the response curves. Note that a reduction in indicator value does not mean that the *system* is sustainable, just that the intervention does not reduce (and may increase) the degree of sustainability of the system with respect to that indicator (for example, if operating costs of £400/d are considered sustainable and an intervention reduces costs from £600/d to £500/d, it has increased the degree of sustainability/decreased the degree of unsustainability but not made the system completely sustainable).

Under current conditions (i.e. all threat magnitudes equal zero), increasing pump capacity is not totally sustainable: sustainability of the system is increased with respect to two indicators (N removal and CSO volume), but decreased with respect to four. Conversely, however, it cannot be argued that maintaining the base case system operation instead is a fully sustainable option under current conditions either, as this results in lower N removal and higher CSO volume. Therefore, it is evident that trade-offs are necessary, whether or not the resilience-enhancing intervention is applied. This is fully expected, as use of an indicator approach for sustainability typically results in complex multi-objective trade-offs within a subjective decision-making framework (Ashley et al., 2008).

Fig. 5 shows that proportional change in impervious surface area and rainfall depth result in very similar sustainability indicator

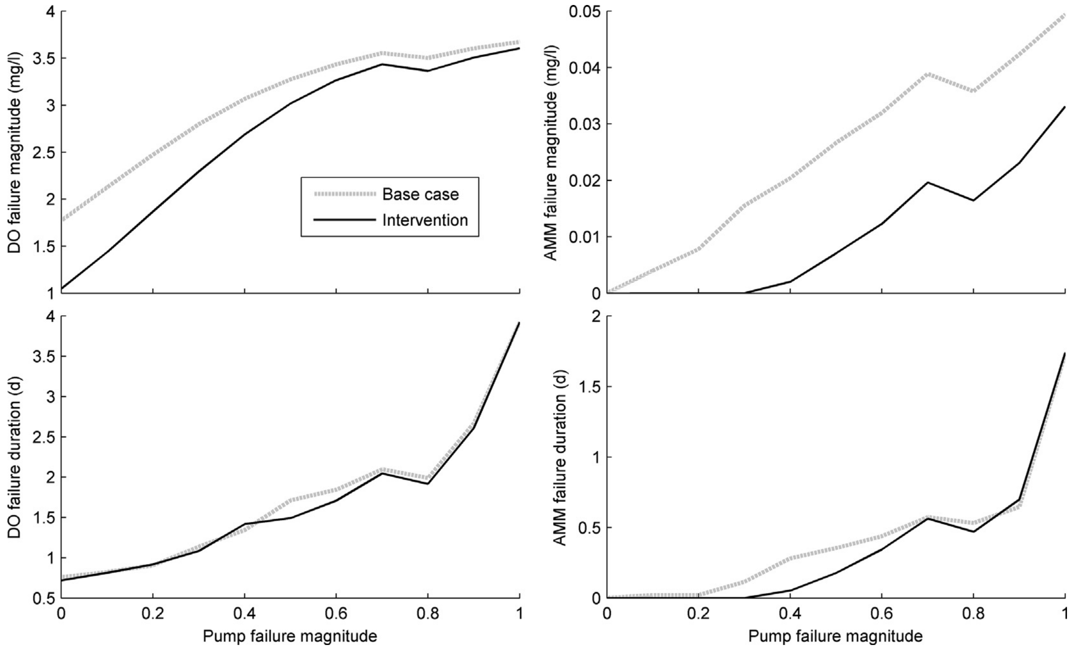

Fig. 3. Example response curve results: DO and AMM failure magnitude and duration under failure of pump to primary clarifier.

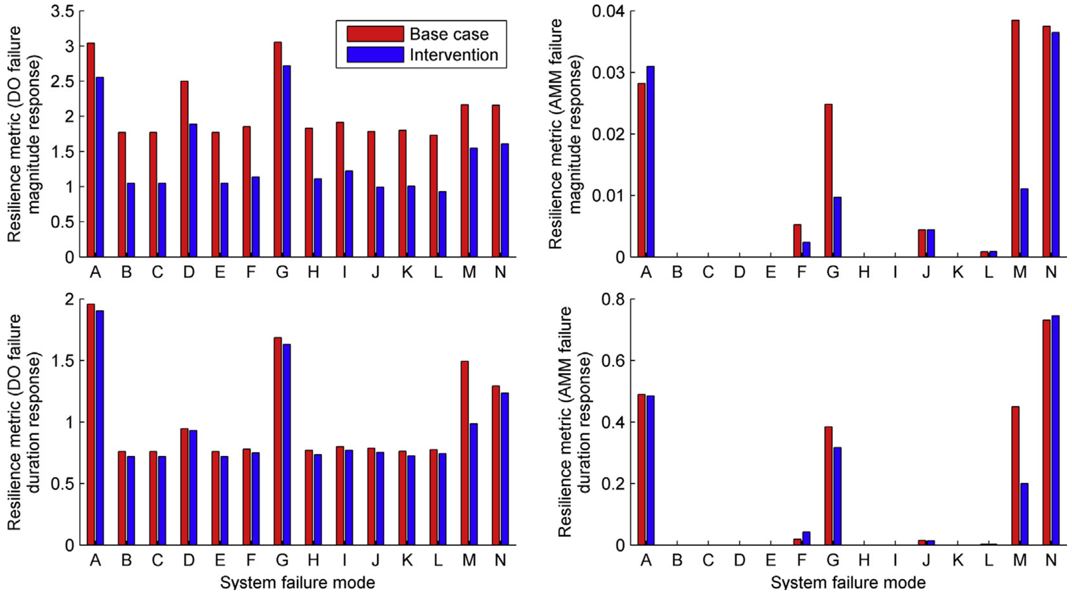

Fig. 4. Metrics for DO and AMM resilience to each system failure mode (see Table 1 for interpretation of system failure mode letters). Note that a smaller value indicates greater resilience.

responses, since both result in an increase in influent to the sewer system; however, the responses are not identical.

With respect to TSS production, increasing the pump capacity provides a (very small) increase under every threat type and magnitude, i.e. it is not sustainable. Similarly for cost, this is increased by the intervention under every threat type and magnitude since increasing pump capacity incurs capital costs and the results in additional operational costs. This cost figure only includes financial costs and the perceived sustainability of the intervention may be improved if social and environmental costs are included (since, for example, the intervention provides significant reduction in CSO volume); however, such accounting is challenging and rarely employed in practice (Balkema et al., 2002).

The greatest improvement provided by the intervention is with respect to CSO volume: substantial reduction is provided at every threat magnitude except those at which CSO volume is zero even without the intervention (i.e. no further improvement is possible). This is attributed to the greater pump capacity enabling a greater volume of wastewater to be conveyed to full treatment at times of high flow. The benefits also typically increase as the threat magnitude increases. For example, under a −50% change in impervious surface area, CSO volume is zero irrespective of whether the intervention is applied, since the existing pumps have sufficient capacity to convey all flow entering the system. However, if impervious surface area increases by 50%, then the existing pump capacity is insufficient and the intervention is of benefit: in this

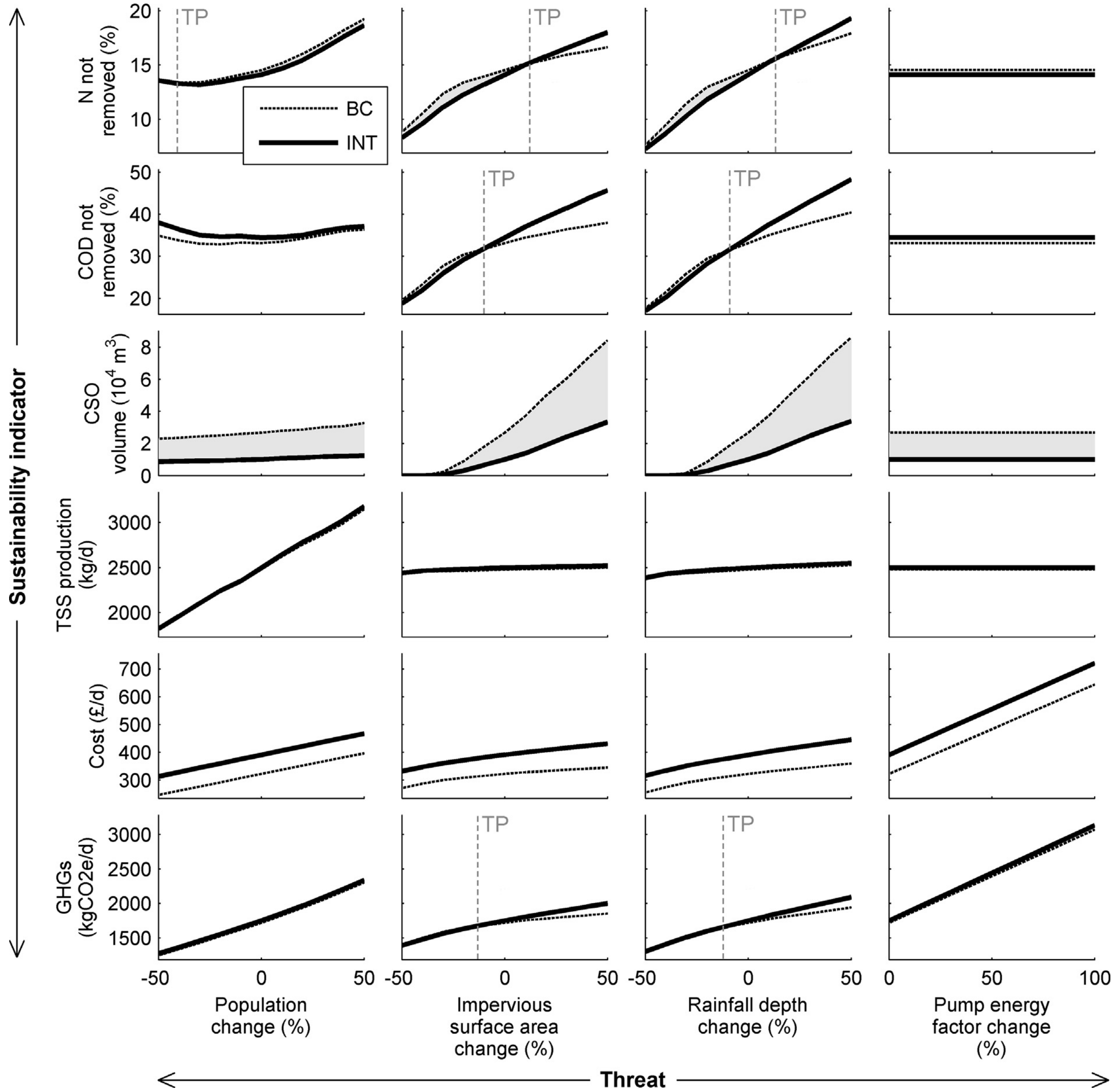

Fig. 5. Comparison of sustainability indicator responses to individual threats under the base case design (BC) and intervention (INT). Grey shading indicates that intervention does not reduce (and may increase) sustainability with respect to the given indicator. 'TP' indicates tipping point.

case, the CSO volume will be 60% lower with the intervention in place than if the base case operation is maintained (a reduction from 84,280 m^3 to 33,440 m^3), due to the additional pumping capacity provided.

3.3. Sustainability tipping point analysis

3.3.1. Under individual threats

Tipping points for some sustainability indicator and threat combinations can be identified in Fig. 5. For example, under impervious surface area change:

- N removal is improved if impervious surface area does not increase by more than 12.2%, since the intervention enables more flow to pass to full treatment; hence, the intervention is considered sustainable with respect to N removal if impervious surface area does not increase by more than 12.2%. Reduced N removal beyond this point is attributed to the increased WWTP influent flow rates (beyond the design capacity) resulting in poor performance of the plant.
- COD removal is better with the intervention than without if impervious surface area decreases by at least 11.2%; hence, the intervention is considered sustainable with respect to COD removal if impervious surface area decreases by at least 11.2%. This is attributed to the WWTP only having capacity to effectively remove COD from the additional flow received as a result of the additional pumping if the total inflow to the sewer system is reduced.
- CSO volume is reduced, irrespective of change in impervious surface area (i.e. there is no tipping point). This is directly attributable to the additional pumping capacity in the system.
- TSS production and cost are increased, irrespective of change in impervious surface area (i.e. there is no tipping point). Increased costs are due to the capital and operational costs of increasing

the pump capacity, and increased TSS production is attributed to a greater volume of wastewater (and, therefore, more solids) entering the WWTP.

- GHG emissions are reduced if impervious surface area is reduced by at least 15.3%; hence, the intervention is considered sustainable with respect to GHG emissions only if impervious surface is reduced by at least 15.3%. This is primarily attributed to greater nitrogen removal in the WWTP and, consequently, lower indirect N_2O emissions resulting from nitrogen remaining in the sludge.

This demonstrates again that there are trade-offs and that the proposed intervention will not be entirely sustainable under any change in impervious surface area. However, the number of sustainability indicators improved by the intervention will be maximized if impervious surface area is reduced by at least 15.3%.

Due to the existence of tipping points, the number of sustainability indicators improved by the intervention varies with threat magnitude, as well as with the type of threat. Fig. 6 shows the number of sustainability indicators improved by the intervention under a range of magnitudes for any threat applied individually. Note that the indicators are not weighted, since application of weights would be subjective and may mask reductions in some indicators.

Change in pump energy factor (within the range considered) does not alter the number of sustainability indicators improved by the intervention. Additionally, an increase in population of up to 50% (the maximum evaluated) has no impact on the sustainability of the intervention, although a reduction in population of at least 45.4% reduces sustainability (due to worsening N removal with respect to the base case). The intervention is most sustainable if the rainfall depth decreases by at least 14.8% or impervious surface area by at least 15.3%, in which case four of the six sustainability indicators are improved with respect to the base case. However, it is not completely sustainable under any single threat type or magnitude as at least two sustainability indicator values always worsened. The sustainability of the intervention decreases as rainfall depth or impervious surface area increase, and it is least sustainable if rainfall depth increases by at least 13.0% or impervious surface area by at least 12.2%, in which case five of the six sustainability indicators are worsenedFive sustainability indicators are also worsened by implementation of the intervention if population reduces by at least 45.4% – this may be attributed to the reduced influent to the system rendering the additional pumping capacity unnecessary.

These results illustrate that implementing an intervention which is designed to increase resilience of an IUWS does not guarantee a universal improvement in sustainability: Whilst there are benefits, there can also be detrimental effects to some components of sustainability. However, the extent of these detrimental effects is dependent on what threats and threat magnitudes are realized in the future.

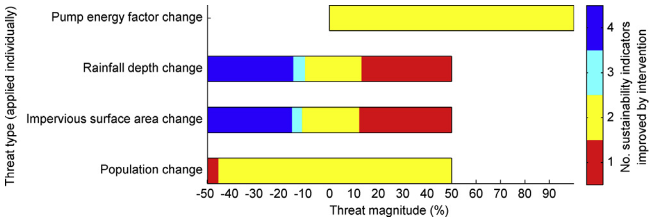

Fig. 6. Number of sustainability indicator values improved by the intervention when threats of different magnitudes occur individually.

3.3.2. Under simultaneous threats

Fig. 7 shows the number of sustainability indicators bettered with respect to the base case under two simultaneous threats of varying magnitudes. A maximum of five (out of six) sustainability indicators can be improved, and this only occurs under specific scenarios. However, it is already widely acknowledged that some of the objectives of sustainable wastewater system development can be conflicting, and that it is not always possible to find a solution that meets all the sustainability criteria (e.g. Balkema et al., 2002). As a worst case scenario, increasing pump capacity to increase resilience could result in a reduction in sustainability with respect to five (out of six) indicators.

Interestingly, reducing threat magnitudes is shown to not always be entirely beneficial in terms of sustainability. For example, under a rainfall depth reduction of 20% and a population reduction of 20%, implementing the intervention results in four sustainability indicators being bettered with respect to the base case, whereas if the population is reduced by a further 10%, the number of sustainability indicators bettered drops to three. In this instance, this is due to the intervention resulting in less COD removal than the base case when population drops by at least 40%. The total number of sustainability indicators returns to two when the population drops further, however, as the intervention then also provides a small reduction in TSS production.

Typically, fewest sustainability indicator values are improved by the intervention when the magnitude of one or more threats is large (positive). Under any combination of two high magnitude threats, a maximum of two sustainability indicators are improved by implementation of the intervention, showing that, should these conditions be realized, the intervention will be largely detrimental to the overall sustainability of the system. This demonstrates again that implementing interventions designed to improve resilience does not ensure sustainability, and supports the suggestion that resilience is necessary *but not sufficient* for sustainability (Butler et al., 2016).

3.4. Discussion

When evaluating sustainability under future threats, plots of the form shown in Figs. 6 and 7 are useful because they capture the effects of a wide range of possible future conditions, and enable identification of conditions under which an intervention will or will not be sufficiently sustainable. It is also possible to map specific scenarios onto these plots to determine how sustainable an intervention will be if they occur, and also what the effects might be if projections prove to be inaccurate. A similar approach has previously been used for analysis of the effects of drought in a water resources system (Borgomeo et al., 2015), where performance was calculated under a continuum of drought duration and deficit values, irrespective of their probability, and specific deficit and duration combinations of interest were highlighted.

To illustrate how these plots can be used to explore the effects of future scenarios that are considered likely, Fig. 8 provides an example in which population change and impervious surface area change projections provided by the Office for National Statistics (2015) and Environment Agency respectively (2013a, b) are mapped onto the corresponding results from Fig. 7. This shows that, under the range of population change values projected, the number of sustainability indicators bettered by the intervention is dependent only on the change in impervious surface area – i.e. for a given impervious surface area change scenario, the intervention would be just as sustainable if the highest population change projection is realized as if the lowest is realized. It also illustrates that, if population change projections prove to be inaccurate, this will have no effect on the sustainability of the intervention unless the

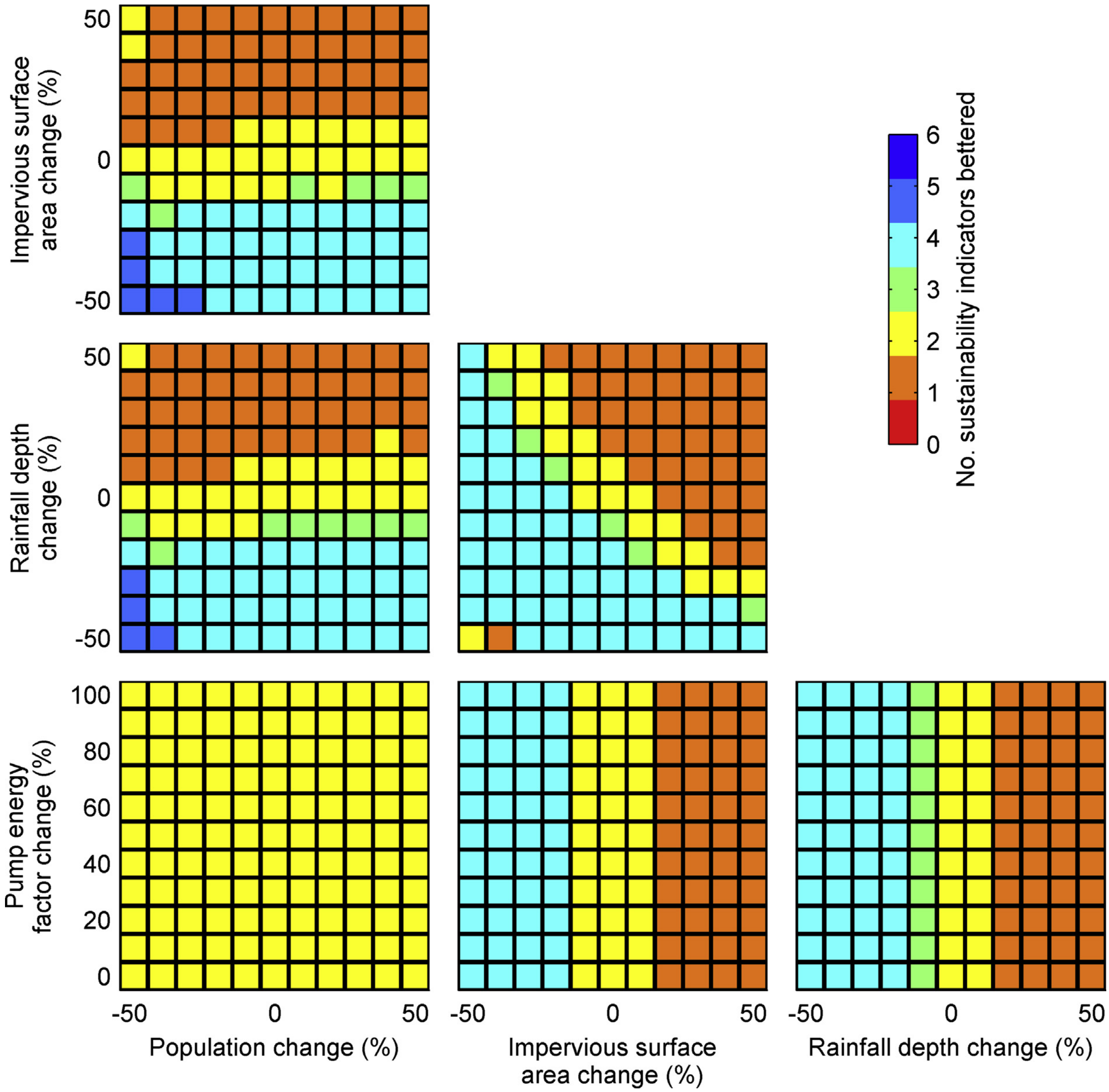

Fig. 7. Number of sustainability indicators improved by the intervention when two threats occur simultaneously.

population reduces significantly. Conversely, uncertainty in impervious surface area change may affect sustainability, as a small departure from the projected scenarios can alter the number of sustainability indicators bettered.

These results also illustrate that, despite increasing the resilience of the IUWS, increasing pump capacity will only improve sustainability with respect to a maximum of four out of six indicators under any projected future scenario. An improvement in all six sustainability indicators cannot be achieved under the range of threat magnitudes evaluated and, whilst an improvement in five can be achieved under two of the projected impervious surface area change scenarios, it can only be achieved if population change is also significantly lower (i.e. a large reduction in population) than projected. Such threat dependencies are not revealed by scenario analysis (as evidenced in the mapping of projected changes above), and are a key output of the framework developed in this paper.

It is widely acknowledged that there are similarities between the concepts of resilience and sustainability, and it has been suggested that increasing the resilience of a system makes the system more sustainable (Marchese et al., 2018). These results clearly demonstrate, however, that implementing an intervention designed to increase resilience may be detrimental to some components of sustainability, even under projected future conditions, and should more extreme threats than anticipated occur then there may be significant detriment to sustainability. There may be greater benefit (and fewer negative consequences) under a limited number of scenarios; however, these do not coincide with projected future conditions. This supports the theory that, although resilience is a prerequisite for sustainability, it does not guarantee sustainability (Butler et al., 2016), and that providing resilience does not guarantee sustainability.

4. Conclusions

Using a new analysis framework and a case study IUWS, this study explores the effects of a resilience-enhancing intervention on

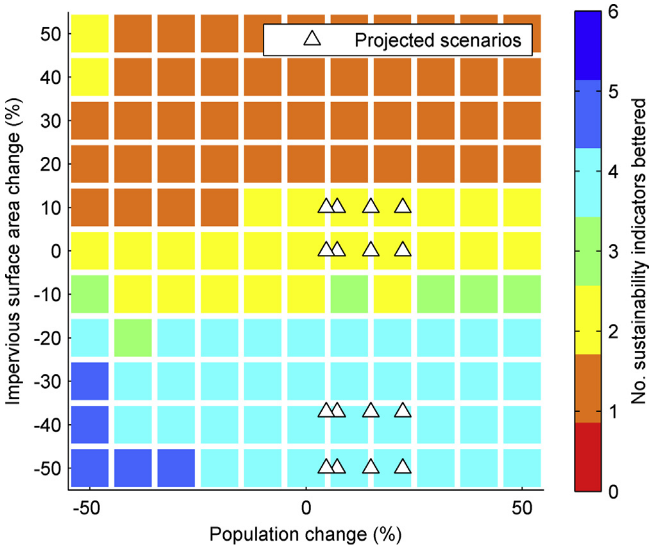

Fig. 8. Number of sustainability indicator values improved by the intervention under population and impervious surface area change projections.

sustainability under future threats. By expressing sustainability as a function of threat magnitude, the framework enables a wide range of potential futures to be addressed without the need to develop scenarios or future projections, thereby providing a more complete understanding of sustainability than can be obtained with a scenario-based methodology. This also provides a new approach to dealing with uncertainty in projections.

The key conclusions drawn from this study are as follows:

- While analysis of a single intervention would be insufficient to prove that enhancing resilience *does* always increase sustainability, this study shows that increasing pump capacity in the IUWS increases resilience but does not provide a universal increase in sustainability under any future scenario. Therefore, it demonstrates more generally that intervening to increase resilience *does not* ensure increased sustainability and that, when proposing measures to increase resilience, the potential effects on sustainability should be considered also.
- It is revealed that the sustainability of an IUWS intervention can differ greatly under different threat types and magnitudes: therefore, the degree of sustainability achieved will be dependent on future conditions. In the case of the IUWS investigated, increasing pump capacity will be most sustainable only when rainfall depths or imperviousness in the catchments reduce.
- While an intervention that enhances resilience may be considered sustainable (with respect to specific indicators) under current conditions, tipping points exist and it will cease to be sustainable if future threat magnitudes exceed these.
- Trade-offs between sustainability indicators are observed in the case study, irrespective of future conditions, under all threat magnitudes. Improvement in one or more sustainability indicators resulting from a resilience-enhancing intervention always corresponds with a negative effect with respect to at least one indicator.

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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.2018.11.025.

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