# General resilience: conceptual formulation and quantitative assessment for intervention development in the urban wastewater system

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## ABSTRACT

General resilience addresses the resilience of a water system to any threat including unknowns, in contrast to specified resilience to individual identified threats. However, quantification of general resilience is challenging and previous assessments have typically been qualitative or based on system properties that are assumed to be indicative of resilient performance. Here we present a General Resilience Assessment Methodology (GRAM), which uses a middle-state based approach to decompose general resilience into contributing components to provide a quantitative and performance-based resilience assessment. GRAM enables the accounting of the effects of any threat if all modes of system failure are identifiable. It is applied to an integrated urban wastewater system where five interventions are explored. The results obtained show that whilst substantial improvements in specified resilience are achieved, increasing the general resilience of the system is challenging. However, general resilience analysis enables identification of system failure modes to which level of service is least resilient and highlights key opportunities for intervention development. GRAM is beneficial as it can inform the development of interventions to

increase the resilience of a system to unknowns such as unforeseeable natural hazards in a quantifiable manner.

*Keywords: adaptation, general resilience, middle state, specified resilience, urban wastewater system*

## 1 INTRODUCTION

Water systems have traditionally been designed to achieve a high level of reliability, i.e. to minimise failure frequency. This, however, has become more challenging due to increasing threats such as natural disasters and climate change. A threat is defined here as an event which can potentially reduce the level of system service and is equivalent to a wide variety of other terms used in literature, including hazard, driver, perturbation, disturbance, shock, and crisis. A paradigm shift from reliability to resilience is required for water management (Butler et al., 2017). The concept of resilience has received much attention since the seminal work of Holling (1973) and is becoming increasingly common in practice, both in the water industry (e.g. Ofwat 2015, USEPA 2021) and more widely (e.g. Australian Government 2010, Government of Canada 2013, IWA 2021). The term is used in a range of fields, from ecology to engineering (Holling 1996), and has many subtly different definitions (Francis and Bekera 2014). However, it is typically used in reference to a system's recovery from failure, and is defined as "*the degree to which the system minimises level of service failure magnitude and duration over its design life when subject to exceptional conditions*" by Butler et al. (2017). Resilience may also be classified as either specified or general, depending on the threat(s) to which resilience is being considered: Specified resilience is the "*resilience of* *some particular part of a system… to one or more identified kinds of shocks*”, whereas general resilience is the “*resilience of any and all parts of a system to all kinds of shocks, including novel ones*” (Folke et al. 2010). Building general resilience is important since not all possible threats are foreseeable and it is desirable to minimise the magnitude and duration of failure should unanticipated threats occur.

Existing quantitative assessment methodologies typically address specified resilience in response to only a limited number of threats of a specified magnitude (e.g. Liu et al. 2012, Vugrin et al. 2011). For example, the resilience of an urban wastewater system is assessed considering extreme rainfall (Wang et al., 2019; Leandro et al., 2020; Zhang et al., 2021), climate change and urbanisation (Salerno et al., 2018) and shock loading (Sukias et al., 2018). Even frameworks which claim to account for uncertainties only consider identifiable threats (Francis and Bekera 2014). As such, they only provide a measure of specified resilience and do not address “*all kinds of shocks, including novel ones*”, as required for general resilience. However, as has been evidenced with events such as the 2005 New Orleans floods, the 2011 Fukushima nuclear disaster and the current COVID-19 pandemic, unanticipated magnitudes of threats can have devastating impact. The effects of such threats may be reduced by building general resilience, but if the concept of general resilience is to be operationalised, it is important that it can be quantified. Whilst specified resilience contributes to general resilience (Woolley 2014), there are also trade-offs between the two types (Walker and Salt 2012) and increasing resilience to a specific threat may be detrimental to general resilience (Cork 2011). It is important, therefore, that specified resilience is not considered in isolation and assessment of general resilience is included in the evaluation of interventions.

Assessment of general resilience is difficult – indeed, it has been suggested impossible (Walker and Salt 2006) – due to the need to consider the response to unknown threats, and building resilience to these unknown threats is a recognised challenge (Carpenter et al. 2012, Labaka et al. 2016). Past studies which address unknown or unspecified threats have typically been qualitative or based on system properties that are assumed to be indicative of resilience (e.g. Labaka et al. 2015, Shirali et al. 2013, Yazdani et al. 2011). Some system attributes can provide resilience to a range of shocks (O'Connell et al. 2015) and assessment frameworks may recommend consideration of properties such as diversity, modularity and social capital (Cork 2011). Increasing redundancy is also often considered a means by which resilience can be increased (Bruneau et al. 2003). However, it is important to distinguish between properties and performance, since specific properties such as these do not guarantee resilient performance (Meng et al. 2018). Performance-based methods can help move the focus from the threats to the system process itself and provide an insight into system properties that contribute to improving system resilience.

Progress may be made with a middle-state based resilience assessment ( Diao et al. 2016; Mugume et al. 2015), which is performance-based and investigates the system response to a given system failure mode rather than a specific threat. To date, this has only been applied in the case of specified resilience (Diao et al. 2016; Zhang et al., 2020), but its potential for use in assessment of general resilience is clear, as knowledge of the threat(s) causing system failure (which may be unknown) is not required. The global resilience analysis (GRA) methodology (Mugume et al. 2015), which has so far only been applied to the concept of specified resilience, may also be useful in assessment of general resilience since it enables a range of event magnitudes to be accounted for, including those that are considered highly unlikely and cannot be assigned a probability.

This paper aims to provide a General Resilience Assessment Methodology (GRAM) for performance assessment of water systems, taking into account the effects of unknown threats, and demonstrate how this may be used to guide the development of resilience-enhancing interventions. GRA, a middle-state based assessment approach, applies a stress-strain test to assess the response curve to a specific system failure. GRAM decomposes general resilience into multiple combinations of specified resilience, each of which is assessed using GRA, to provide a quantitative and performance-based resilience assessment (Sweetapple et al. 2018). GRAM provides an entirely new methodological approach and, in principle, may be applied to any system subject to threats. However, the better characterised the system, the better the evaluation of general resilience will be. Using an integrated urban wastewater system (IUWS) case study, it is shown that multiple implementations of a middle-state based GRA can address the effects of *any* threat on level of service provision if all system failure modes are identifiable, and provide a picture of its general resilience. The general resilience components can then be analysed to identify threats or threat combinations to which the IUWS level of service provision is least resilient, thereby highlighting key opportunities and priority areas for interventions to increase general resilience. A detailed analysis of any potential interventions also ensures that any inadvertent negative effects on specified resilience are not overlooked.

# 2 GENERAL RESILIENCE ASSESSMENT

## 2.1 Middle state approach

General resilience does not define the part of the system that might fail, nor the type of threats which the system must endure (Folke et al. 2010) – assessment of general resilience must, therefore, address the response of *any* part of the system to *any* threat. In this form it cannot be calculated since not all threats can be identified. However, for any threat (known or unknown) to have an impact on level of service that a water system provides, it must first result in abnormal system states, referred to as abnormal middle states. These occur as a result of threats and represent all the potential modes of failure for a given system. System failure can be categorized as 1) mechanical (structural) such as sewer blockage, pump failure and sensor failure, and 2) hydraulic (functional) failure such as increased influent flow. The Safe & SuRe framework (Butler et al. 2017) describes how threats lead to system failures, system failures lead to level of service impacts, and level of service impacts lead to societal, economic and environmental consequences. In general, engineering systems are better known, characterised and understood than threats; therefore, it is more feasible to identify all the ways in which they might fail than to identify all the threats that may cause failure. Considering a closed system, all system failure modes can (theoretically) be identified: whether they result from a known or unknown threat is irrelevant. Therefore, if ‘resilience of a water system’ is rephrased as ‘resilience of a water system to any system failure’, it encompasses the response to all threats (known and unknown) and yet does not require knowledge of unknowns. This approach is a form of ‘middle-state based’ analysis.

If all system failure modes can be identified and the effects of these on level of service be modelled, then the general resilience can be calculated through evaluations of individual failure modes and their combinations, each of which provides a component of general resilience. Multiple system failures may occur simultaneously, and the combined effects of two or more events may be greater than when they occur independently (Park et al. 2013). Therefore, as well as considering resilience to each system failure mode individually, resilience to every possible combination of failure modes must contribute to assessment of general resilience.

This concept is illustrated in Figure 1, which shows all the components of general resilience for a simple, closed system with three failure modes and one level of service measure. Knowledge of the threats (known or unknown) that result in each system failure mode is not required. Human error (a threat), for example, may have an effect on level of service, but this is indirect: human error may result in one or more of the identified system failure modes, which in turn may result in a level of service impact. Since system failure modes can be identified without knowledge of what causes them, it is not necessary to know the specific details of every possible human error.

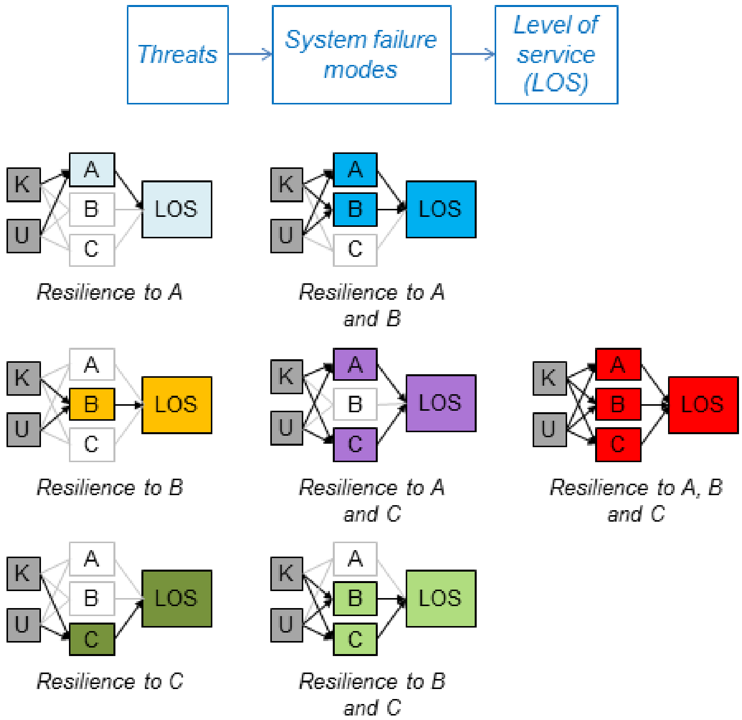


**Figure 1:** General resilience components for a simple system with three failure modes (A, B and C). Known and unknown threats are denoted by *K* and *U* respectively; *LOS* represents a level of service. Each combination of system failure mode and level of service represents a component of general resilience.

This simple example has just seven general resilience components. However, real systems are much more complex and contain many more modes of failure. The total number of system failure mode combinations to which resilience must be evaluated, *C*, is given by

$$C = \sum_{r=1}^{N} \frac{N!}{r!\,(N-r)!} \qquad \text{Eq. 1}$$

Where $N$ is the total number of system failure modes. The number of general resilience components increases exponentially as the number of failure modes increases. For a system with ten failure modes, for example, the effects of 1,023 different system failure mode combinations on level of service provision must be evaluated if a comprehensive assessment of general resilience is to be made. For 20 failure modes, this increases to 1,048,575.

Resilience to each type of system failure or combination of failures may be evaluated using GRA (Diao et al. 2016, Mugume et al. 2015). GRA accounts for the effects of a range of event (threat or system failure) magnitudes and durations, rather than a single event with pre-defined characteristics, and has previously been used in assessment of resilience to a single specified threat or system failure mode. Multiple applications of the GRA methodology enable every magnitude/duration of every combination of system failure modes to be addressed for quantification of general resilience.

In this application of GRA, the system failure mode is considered as a type of stress, and the impact on level of service resulting from a given stress magnitude a strain. Pipe failure, for example may be considered a failure mode / stress, and the stress magnitude may vary from 0% (no pipes failed) to 100% (all pipes failed). This stress-strain concept enables response curves of the form shown in Figure 2 to be developed for each stress or stress combination and for each level of service measure. The area under each curve may be considered an indicator of the specified resilience to the relevant stress, with a smaller area denoting greater resilience. For example, the response curves in Figure 2 show that the level of service provision is more resilient to failure mode B than A.

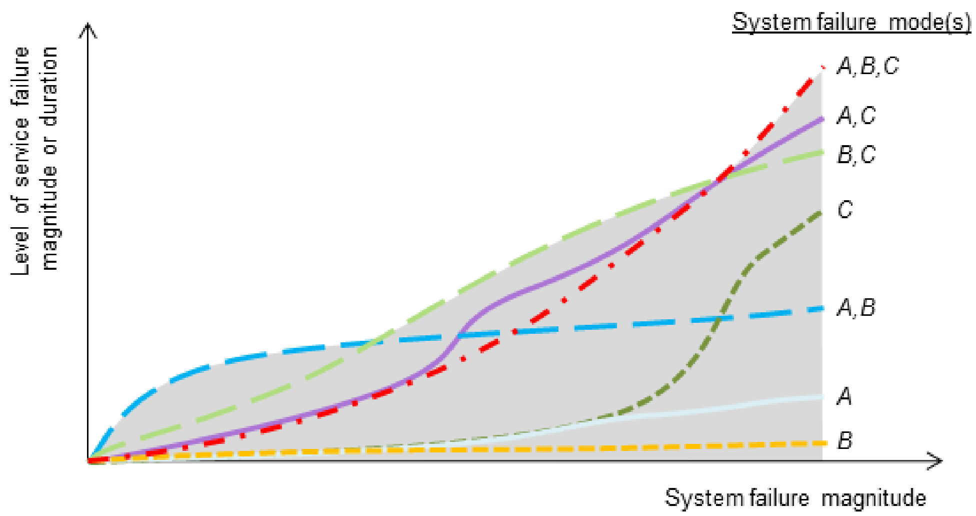


**Figure 2.** Response curves contributing to a general resilience measure for the system in Figure 1. Each curve represents the response to a different combination of system failure modes. The area under the overall maximum curve (shown in grey) provides a quantitative measure of the general resilience, with a smaller area indicating greater resilience.

In the example given, there are few enough response curves that individual analysis of each is feasible. However, in a more complex system with several thousand (if not more) stress combinations to consider, this is not practical; a method by which general resilience can be quantified without reporting every component is needed. We propose that the maximum strain resulting from each stress magnitude is selected to produce a 'maximum response curve'. This may incorporate multiple response curves: in Figure 2, for example, simultaneous application of stresses A and B results in the greatest strain at low stress magnitudes, whereas application of all three stresses produces the greatest strain at high stress magnitudes. The area under this maximum response curve (shown in grey) provides a quantitative measure of general resilience and can be improved by targeting the stress combinations which contribute to it. However, using any single indicator to represent general resilience will mask a lot of detail (inevitably, given the large number of contributing components), and additional information will be required to inform the development and assessment of resilience-enhancing interventions. Furthermore, the shape of the maximum response curve generated is dependent on the system-specific failure modes identified and the corresponding stress durations and magnitudes assumed in the analysis. If not all system failure modes are identified then this approach will provide only a partial representation of general resilience.

### 2.2 General resilience assessment methodology (GRAM)

Based on the general resilience assessment concept discussed in Section 2.1, the detailed methodology is as follows:

1. Identify all potential system failure modes, for example pipe failure or pump failure. These represent stresses on the system.
2. Determine a measure of magnitude for each stress and range of stress magnitudes to which resilience should be assessed. For pipe failure, for example, the percentage of pipes failed may represent the stress magnitude and the magnitude can range from 0% to 100%.
3. Identify all possible combinations of stresses to which the system may be subject and to which resilience must be evaluated, for example just pipe failure, just pump failure or simultaneous pipe and pump failures. For a system with $N$ potential failure modes, this includes every combination of 1 to $N$ stresses, yielding a total of $C$ combinations (as in Eq. 1).
4. Identify all level of service measures for the system, for example water pressure and water quality indicators. These represent types of strain.

5. Determine acceptable level of service limits, i.e. requirements which if not met represent a level of service failure.
6. Specify the number of model evaluations, $R$, to be used to estimate each response curve. A higher value yields higher resolution response curves but will also increase computational demand.
7. Calculate every point on the response curves for the first combination of stresses as follows:
    a. Simulate system performance when no system failures are present (i.e. every stress magnitude equals zero). Record failure magnitude and duration for every level of service measure. These are measures of each type of strain resulting from a stress magnitude of zero, and each contributes to a different response curve. The assessment of 'no system failures' is used to determine the starting point of each system performance curve.
    b. For $i = 1{:}R$, simulate system performance when the magnitude of every system failure present in the first set of stresses is set to $i$ / ($R$-1) times the corresponding maximum stress magnitude. All other stresses are set to zero. Record failure magnitude and duration for every level of service measure. These are the strains resulting from a normalised stress magnitude of $i$ / ($R$-1).
    c. Plot response curves using the strain and normalised stress values from steps 7a-b.
8. Repeat step 7 for stress combinations 2-$C$.
9. Calculate maximum strain values resulting from each stress magnitude in each set of response curves (i.e. maximum level of service failure magnitude and duration resulting from any combination of stresses of a given magnitude): This gives the

maximum response curve, the area under which provides an indicator for general resilience.

## 3 CASE STUDY INTEGRATED URBAN WASTEWATER SYSTEM

The case study is a well-characterised IUWS which was first presented by Schütze (2002) and has since been the subject of much research (e.g. Astaraie-Imani et al. 2012, Butler and Schutze 2005, Casal-Campos et al. 2015, Fu et al. 2008, 2009, Zacharof et al. 2004). This is modelled using SIMBA6.0 (IFAK 2009), which operates in the Matlab/Simulink environment. Whilst SIMBA6.0 is fit for purpose in this study, newer SIMBA versions or other software tools could also be used. A schematic diagram is given in Figure 3.

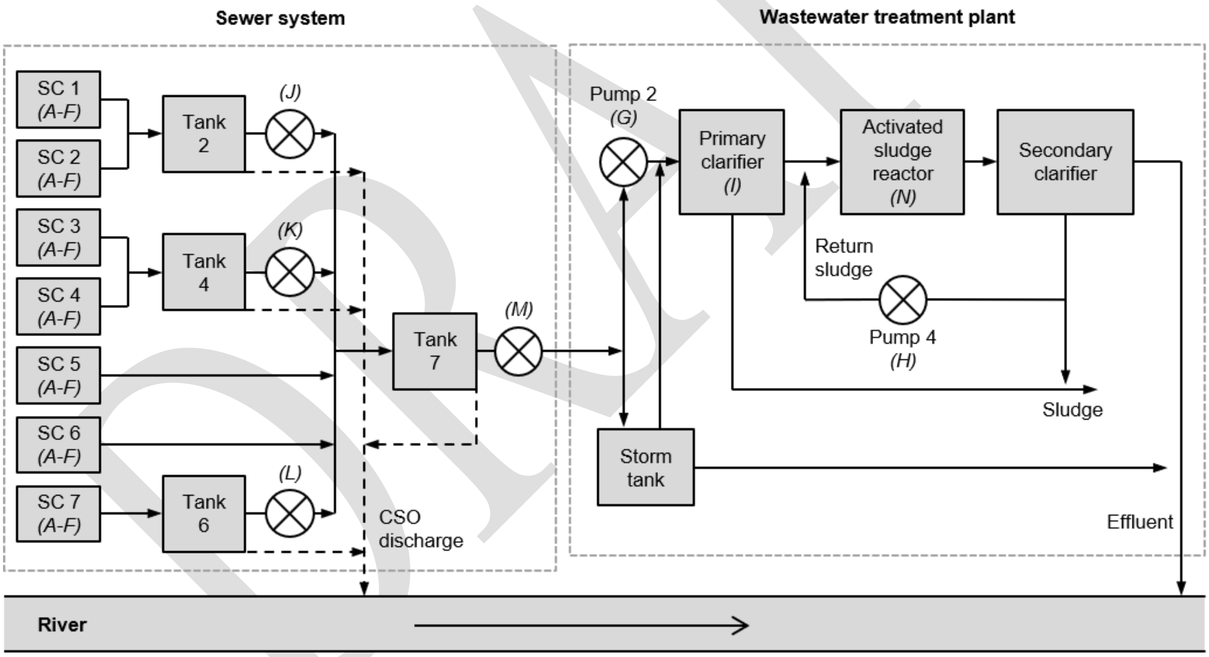


**Figure 3.** Schematic diagram of IUWS case study. SC denotes sub-catchment. Letters *A*-*N* correspond with stresses detailed in Table 1.

The IUWS consists of a combined sewer system, a wastewater treatment plant (WWTP) and a receiving river. The sewer system contains seven sub-catchments and four on-line pass through storage tanks (tanks 2, 4, 6 and 7). The catchments are simulated using a hydrologic approach, with surface and sewer network flows modelled conceptually as linear cascades 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 (modelled as detailed by Lessard and Beck (1993)). Two pumps are modelled in the WWTP (designated 'pump 2' and 'pump 4'). The WWTP effluent and combined sewer overflows (CSOs) discharge into a river, of which 45km is modelled. Performance is evaluated over a five day period which incorporates a rainfall event with a total depth of 27mm. During this time, stresses are applied as detailed in Section 3.1 and dynamic outputs are recorded as necessary to calculate the performance measures detailed in Section 3.2.

### 3.1 Failure modes and stresses

In order to calculate every component of general resilience using a middle state based approach, it is necessary to identify every way in which the system might fail. Analysis of the model structure suggests 14 potential failure modes, as detailed in Table 1. Further failure modes may exist, but these represent all those that can feasibly be included, given the model capabilities and limitations. Any omissions will imply that there are additional components of general resilience that have not been evaluated; however, the list in Table 1 is sufficient to demonstrate application of the general resilience assessment methodology and provide insight into key opportunities for resilience enhancement in the system. Should further failure modes be identified, these may be added.

**Table 1.** IUWS failure modes and measures of stress

| | Failure mode | Measure of stress magnitude | Stress range, [min, max] |
|---|---|---|---|
| Hydraulic | 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]* |
| | 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]* |
| | F. Increased sewer influent $NH_4$ | Increase in $NH_4$ concentration (%) | [0 100] |
| Mechanical | G. Failure of pump 2 (to primary clarifier) | Reduction in pump 2 capacity (%) | [0 100] |
| | H. Failure of pump 4 (return activated sludge) | 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] |

* Gives a maximum ratio of 1



To apply the system failures of the types 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. Given that general resilience assessment requires simultaneous application of multiple stresses and each stress must be applied in a comparable manner, all stresses (when applied) 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.

For mechanical failure modes, percentage loss of function represents the stress magnitude. In each case, loss of function in the range 0% to 100% is modelled, thereby covering the full range of possibilities. Hydraulic 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. Full details of the stress magnitude measures and ranges for each failure mode are provided in Table 1.

## 3.2 Level of service measures and strains

Receiving water dissolved oxygen (DO) and un-ionised ammonia (AMM) concentrations represent the IUWS level of service measures. Only total ammonia is modelled dynamically in SIMBA; however, the toxicity of ammonia is attributed predominantly to the un-ionised component (Johnson et al. 2007). Un-ionised ammonia, therefore, 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).

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 integrated urban wastewater system studies (e.g. Astaraie-Imani et al. 2012, Solvi et al. 2006) and is equal to the one-year return period, one-hour limit for salmonid waters (Defra 2014). The AMM limit is the recommended predicted no-effect concentration for freshwater, based on the 96-hour median lethal concentration for pink salmon (Johnson et al. 2007). Failure to comply with either of these limits constitutes a level of service failure.

Given that resilience relates to level of service failure magnitude and duration , the following measures of strain are used:

$$Normalised\ DO\ failure\ magnitude = \frac{\max(0, DO_{lim} - DO_{min})}{DO_{lim}} \quad \text{Eq. 2}$$

$$Normalised\ DO\ failure\ duration = \frac{T_{R,DO} - T_{F,DO}}{T_{total}} \quad \text{Eq. 3}$$

$$Normalised\ AMM\ failure\ magnitude = \frac{\max(0, AMM_{max} - AMM_{lim})}{AMM_{lim}} \quad \text{Eq. 4}$$

$$Normalised\ AMM\ failure\ duration = \frac{T_{R,AMM} - T_{F,AMM}}{T_{total}} \quad \text{Eq. 5}$$

Where $DO_{min}$ is the minimum DO concentration during the evaluation period, $AMM_{max}$ the maximum un-ionised ammonia concentration, $T_{F,DO}$ and $T_{F,AMM}$ the times at which DO and AMM failures commence, $T_{R,DO}$ and $T_{R,AMM}$ the times at which DO and AMM recovery occur, and $T_{total}$ the total evaluation period duration. Note that both failure magnitudes are normalised with respect to their corresponding failure limits and, in the case of AMM, this may result in normalised values in excess of 1.

To account for differing DO and AMM concentrations along the course of the river, these strain measures are calculated for 40 locations along the modelled stretch and the worst (i.e. maximum) values used for resilience assessment.

## 4 GENERAL RESILIENCE RESULTS AND DISCUSSION

The 14 failure modes identified yield 16,383 combinations of stresses to which the system may be subjected, and therefore 16,383 response curves for each measure of strain. These are shown in Figure 4 and represent the components of general resilience.

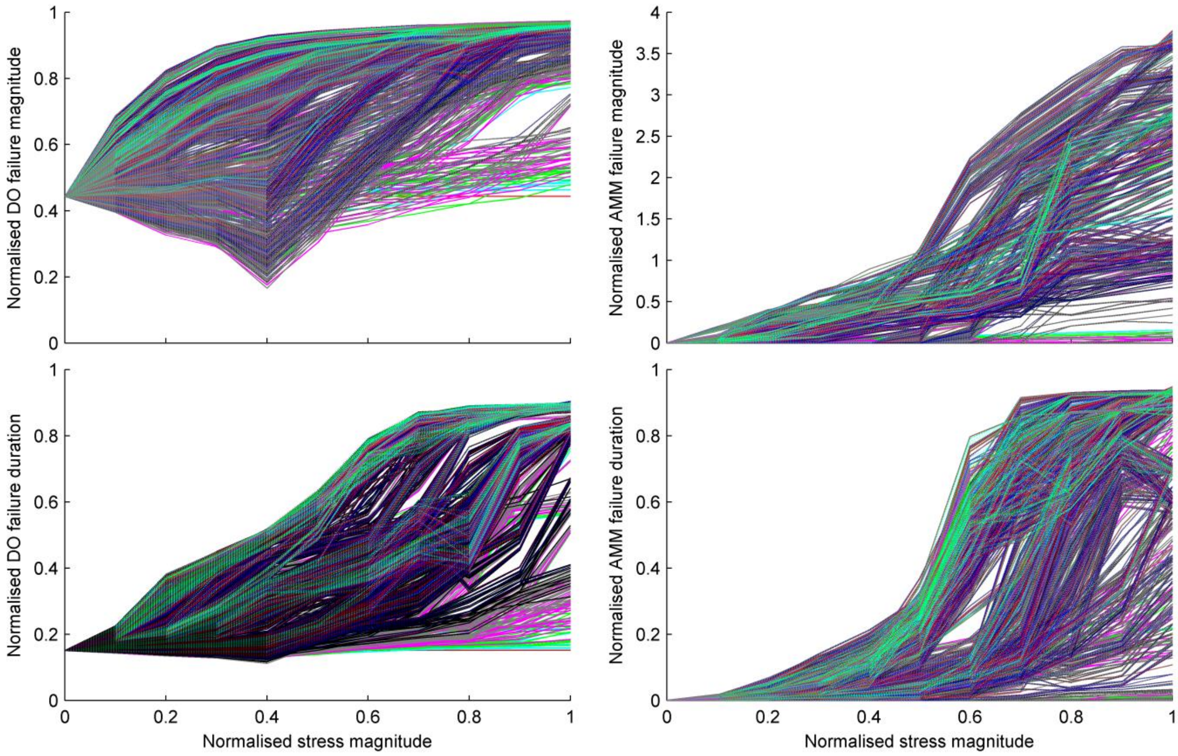


**Figure 4.** DO and AMM failure magnitude and duration response curves (general resilience components)

Some stresses or stress combinations are shown to have negligible effect on DO or AMM failure magnitude or duration, and there are even examples in which the DO failure magnitude initially decreases as the stress magnitude increases. In such instances, stress combinations all include failure of one or more of the tank outflow pumps (stresses J-M), thereby resulting in an increase in CSO discharges from the corresponding catchments. It is known that a reduction in CSOs does not guarantee improved receiving water quality (Lau et al. 2002, Rauch and Harremoes 1999) and it is suggested these CSOs may result in greater dilution of unavoidable untreated wastewater discharges by distributing them along the river, thereby reducing the maximum DO failure magnitude. Increased CSO discharges may also reduce the hydraulic load on the WWTP, resulting in an improved effluent quality and smaller impact on receiving water quality at the discharge point of the WWTP. As the stress magnitude increases further, however, the failure magnitudes resulting from these stress combinations are among the worst. This highlights the importance of considering not just the low stress levels but also the high stress levels, since their effects on failure magnitude and duration might be contradictory, as shown by DO magnitude in Figure 4 (i.e. improved performance under low magnitudes of a given stress combination but worsened performance under high magnitudes of the same stresses).

Figure 4 also shows that the magnitude and duration of level of service failure resulting from a given stress magnitude can vary significantly depending on the stress or stresses applied. Under the maximum stress magnitude, for example, normalised DO failure magnitudes in the range 0.44 - 0.97 (equivalent to minimum DO concentrations of 0.1 - 2.2 mg/l) are observed. This shows that if only a few failure modes which are perceived to be important are considered, as in a typical *specified* resilience assessment, then only a small part of the picture is obtained and scenarios to which level of service is least resilient may be overlooked. Analysis of every potential failure scenario is vital to determine the complete range of the possible level of service impacts resulting from any threat, known or unknown.

It is also found that the stress combination resulting in the worst response is not easily predictable: it may be assumed that this would be simultaneous occurrence of every system failure mode, but this is not the case. This is shown clearly in Figure 5, in which the maximum levels of service failure magnitudes and durations (i.e. the greater of the DO metric and the AMM metric) resulting from application of a) one stress (green curve), b) all 14 stresses (red curve), and c) any combination of 2 to 13 stresses (blue curve) are plotted.

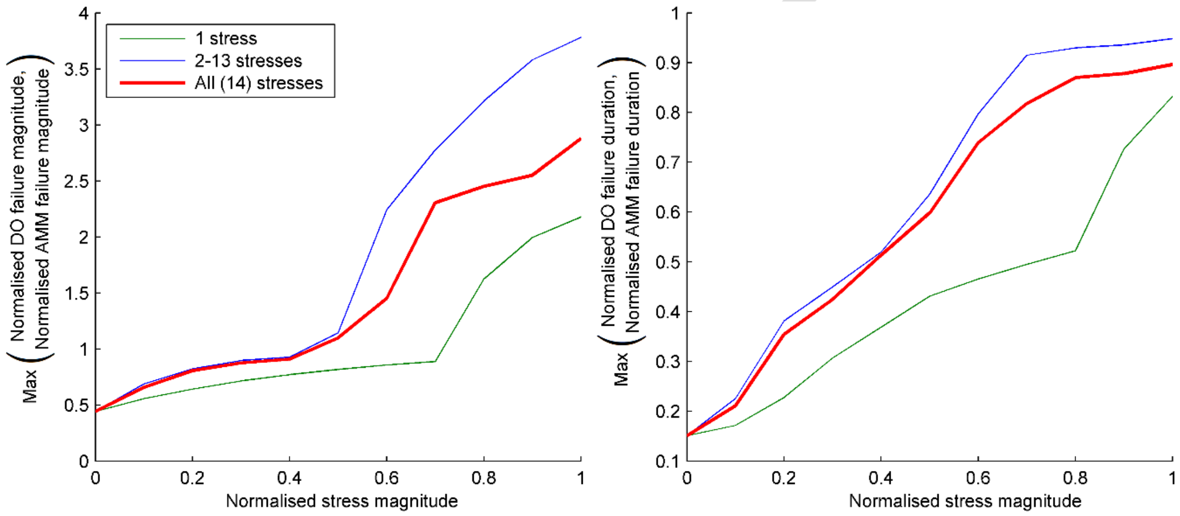


**Figure 5.** Maximum (DO or AMM) failure magnitude and duration response curves for a given number of simultaneous stresses

Figure 5 shows that modelling all 14 system failure modes (stresses) simultaneously provides a good approximation of the worst case response under relatively small stress magnitudes (up to approximately 0.4). However, application of fewer stresses can result in greater level of service failure magnitude and/or duration. This is particularly evident at high stress magnitudes, where applying every stress results in a normalised failure magnitude of 2.88 (equivalent to a maximum AMM concentration of 15.5mg/l), but removal of four stresses (A, G, K and M) increases the maximum level of service failure magnitude to 3.78. This may be attributed to a reduction in upstream CSO discharges resulting in either greater WWTP bypass or poorer WWTP performance.

Figure 5 shows multiple system failure modes occurring simultaneously (i.e., the two top lines – blue and red) can result in significantly greater level of service failure magnitude and duration than a single system failure (i.e., the bottom line). This again highlights the need to consider more than just individual system failure modes in resilience assessment.

The area under the maximum response curves shown in Figure 5 (or Figure 4) provides a quantitative measure of general resilience. This is system specific and may not be suitable for comparing substantially different systems with different failure modes and level of service measures. However, such resilience indicators may be used to provide a quantitative basis by which resilience enhancing interventions for a given system may be evaluated and compared. Use of general resilience assessment to guide the development of interventions is discussed further in Section 5.

# 5 INTERVENTIONS DEVELOPMENT AND EVALUATION

## 5.1 Priority level of service measures

Analysis of the failure duration response curves in Figure 4 suggests that, in a general sense, the receiving water DO is less resilient than the AMM, since the area under the maximum response curve is greater (0.62 compared with 0.49). On the basis of level of service failure magnitude, AMM appears to be less resilient; however, no firm conclusions can be drawn since the units of magnitude differ for AMM and DO and are not comparable. Increasing the DO performance under zero stress conditions is also shown to be very important since level of service failures occur even when the system is fully functional (i.e. stress magnitude = 0).

This suggests that the top priority for interventions is to reduce both the occurrence and duration of DO failures. However, the effects of any interventions on AMM should not be overlooked since they may not necessarily be favourable.

## 5.2 Priority failure modes

Analysis of the general resilience components can yield knowledge of the system failure modes to which level of service provision is least resilient and inform targeted development of interventions to enhance general resilience. Figure 6 shows the prevalence of each system failure mode in the stress combinations resulting in the 500 'worst' response curves in Figure 4 (i.e. stress combinations to which level of service provision is least resilient, based on DO and AMM failure magnitude and duration).

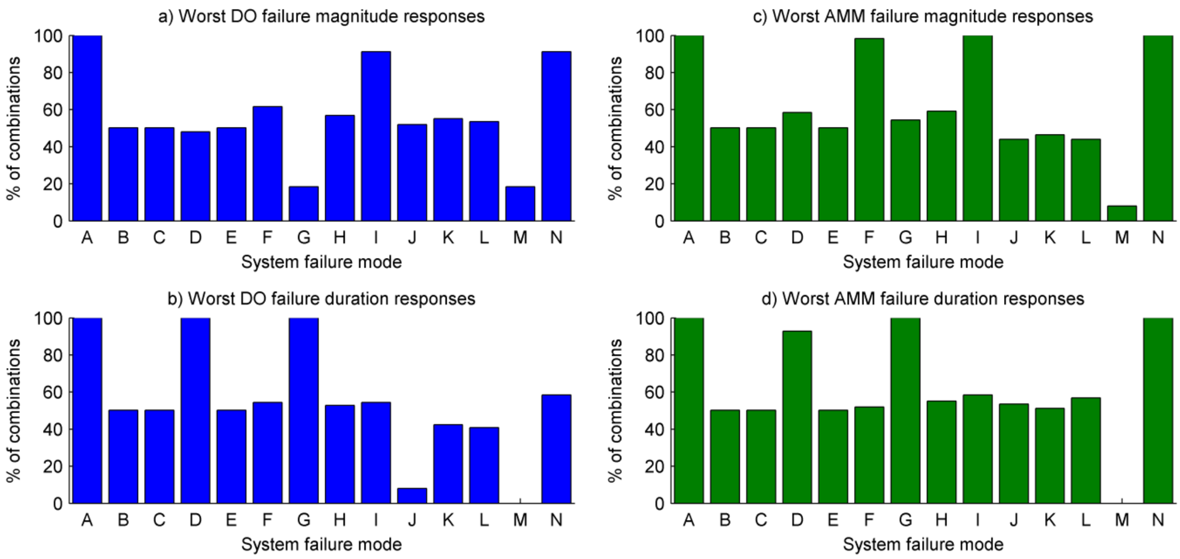


**Figure 6.** Percentage of the 500 worst system failure mode combinations (in terms of DO and AMM failure magnitude and duration responses) in which each system failure mode is included.

This demonstrates that an increase in the sewer influent flow (A) is present in all the stress combinations to which the DO and AMM levels of service are least resilient, suggesting that interventions to minimise any influent increases and/or reduce the effects of increased influent flow on receiving water quality would be highly beneficial. Failure of the activated sludge aeration (N) is also key in terms of its effects on AMM failure magnitude and duration, and increased sewer influent COD (D), failure of pumping to the primary clarifier

(G) and failure of the primary clarifier (I) are shown to be significant in terms of their effects on at least one measure of level of service strain.

Figure 6 also enables low priority failure modes to be identified. Failure of the tank 7 outflow pump (M), for example, is present in few of the stress combinations resulting in the worst effects on level of service, suggesting that interventions should be focussed elsewhere if they are to provide the greatest improvement in general resilience.

### 5.3 Interventions

Interventions employed to enhance resilience may be classified as mitigation, adaptation, coping or learning . Assessment of general resilience using a middle state-based approach, as in this study, captures the effects of adaptation measures ("actions taken to modify specific properties of the water system to enhance its capability to maintain levels of service under varying conditions" (Butler et al. 2017)). Specific threats and consequences are not identified and the effects of mitigation (which addresses threats) and coping (which addresses consequences) on general resilience cannot, therefore, be quantitatively assessed.

Multiple potential interventions for evaluation may be developed using expert engineering knowledge and taking into account the priority level of service measures and failure modes identified in Sections 5.1 and 5.2. In this study, the following interventions are proposed:

Intervention 1: Increase attenuation in the catchments (modelled by increasing the number of reservoirs used in hydrological modelling from 3 to 5). This aims to address increased sewer influent flow.

Intervention 2: Increase the maximum outflow of the storm tank preceding the WWTP (tank 7) by a factor of two. This aims to increase the volume of wastewater treated, thereby addressing increased sewer influent flow and reducing receiving water DO and AMM failures.

Intervention 3: Increase capacity of the storm tank preceding the WWTP (tank 7) by 200%. This aims to address increased sewer influent flow.

Intervention 4: Increase activated sludge aeration tank volume by 10%. This aims to increase treatment capacity and minimise the effects of increased sewer influent flow.

Intervention 5: Increase the WWTP storm tank volume by 50%. This aims to provide additional storage in the case of failure of pump 2 (to the primary clarifier) and will also address increased sewer influent flow.

Note that any interventions which add system components or control structures would increase the number of potential system failure modes, thereby exponentially increasing the number of general resilience components and further complicating the assessment process. For simplicity, the interventions suggested here only consider alterations to the existing infrastructure components and control and the expected benefits are relatively small; however, greater improvements may be achievable with more complex interventions

## 5.4 Interventions evaluation and discussion

It is not feasible to re-evaluate every component of general resilience for each intervention, due to the large number of simulations required and the high computational demand. As a screening process, initially just the resilience to each system failure mode occurring individually is calculated for every intervention. These results are shown in Figure 7, where each number presented is the area under the corresponding response curve and a lower value (i.e. closer to the centre) represents greater specified resilience.

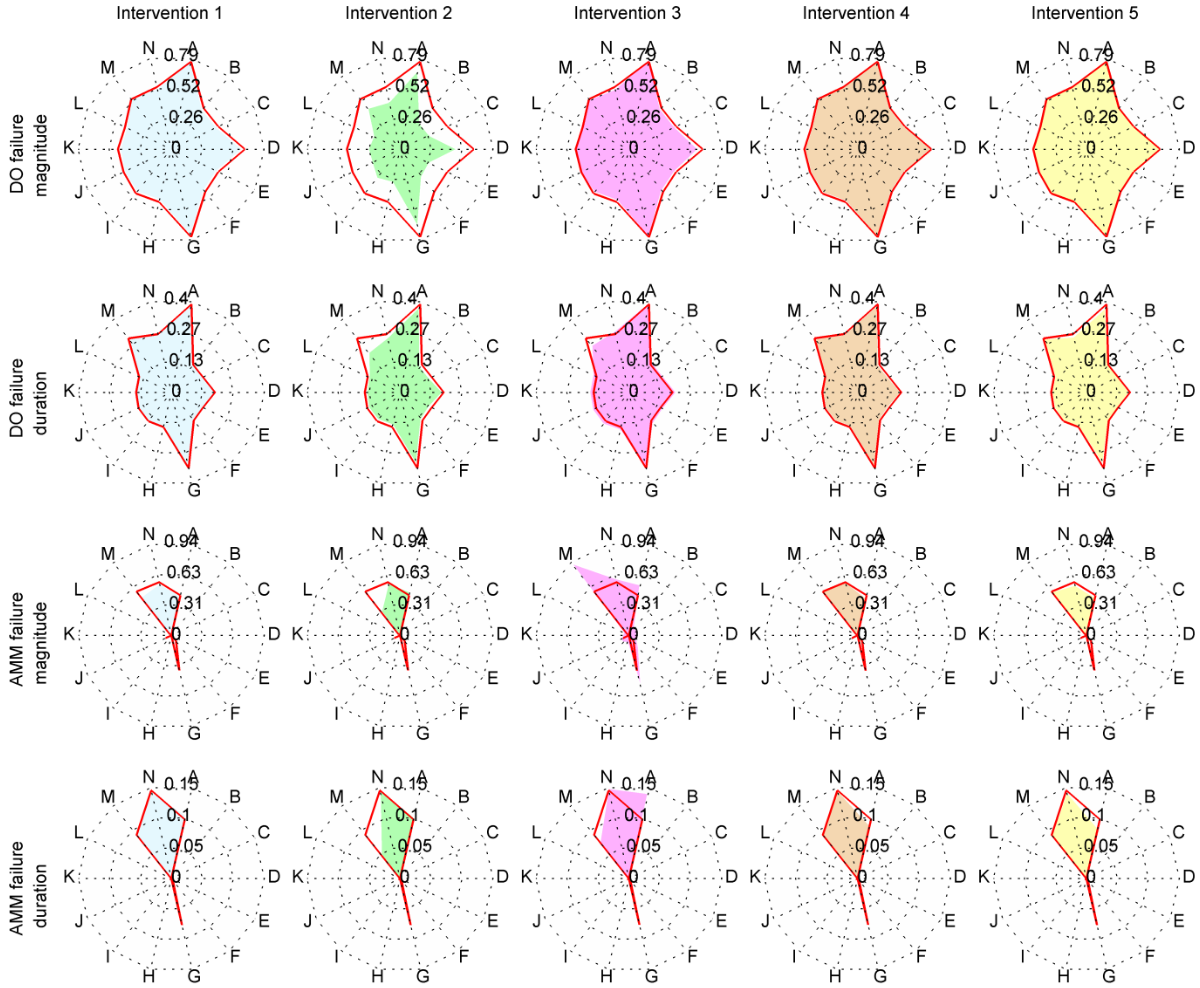


**Figure 7.** Indices for resilience to system failure modes A-N under interventions 1-5, with indices based on DO failure magnitude, DO failure duration, AMM failure magnitude and AMM failure duration. Red lines represent base case values, shaded areas represent performance with intervention, smaller values represent greater resilience.

Interventions 1, 4 and 5 show no negative effects in terms of resilience to individual system failures (although there will clearly be cost implications) and could be considered further in the development of options to increase general resilience. However, improvements in specified resilience are also negligible, suggesting that greater improvement in general resilience may be obtained with alternative interventions.

Intervention 3 provides negligible improvement in resilience to any individual system failure and is detrimental to the AMM response to increased sewer influent flow (A) and failure of the tank 7 outflow pump (M). This is not considered a good candidate for further analysis and refinement, therefore.

Only intervention 2 provides substantial improvements in specified resilience, and the greatest improvements are in the DO failure magnitude responses (with a mean reduction in area under response curves of 28%). The resilience of the receiving water DO to every system failure mode (when applied individually) is improved with respect to the base case. However, there are still trade-offs to consider: it is recognised that building resilience in one area may reduce resilience in another (Miller et al. 2010) and this is evidenced with a (very small) reduction in AMM resilience to increased influent flow (A).

Given that receiving water DO was identified as a priority level of service measure (Section 5.1) and significant improvements in this respect are provided by intervention 2, further analysis of this intervention is undertaken to determine its effects on general resilience. Decision makers must be aware of the potential increase in AMM failure magnitude and duration; however, these remain less than the DO failure magnitude and duration under individual system failures.

Figure 8 shows the effects of implementing intervention 2 on the worst 500 response curves for each measure of strain. The most notable improvement is in DO failure magnitude, which is reduced by up to 38% under low stress magnitudes, although the mean area under the response curves is only reduced by 5.3%. The effects on other stress-strain relationships (as summarised in Table 2) are small. An improvement is achieved with respect to DO failure duration, with both the mean and maximum area under the set of response curves reduced. However, this intervention is (a little) detrimental to the general resilience of the receiving water AMM, since an increase in the mean AMM failure magnitude response curve and maximum AMM failure duration response curve areas is observed.

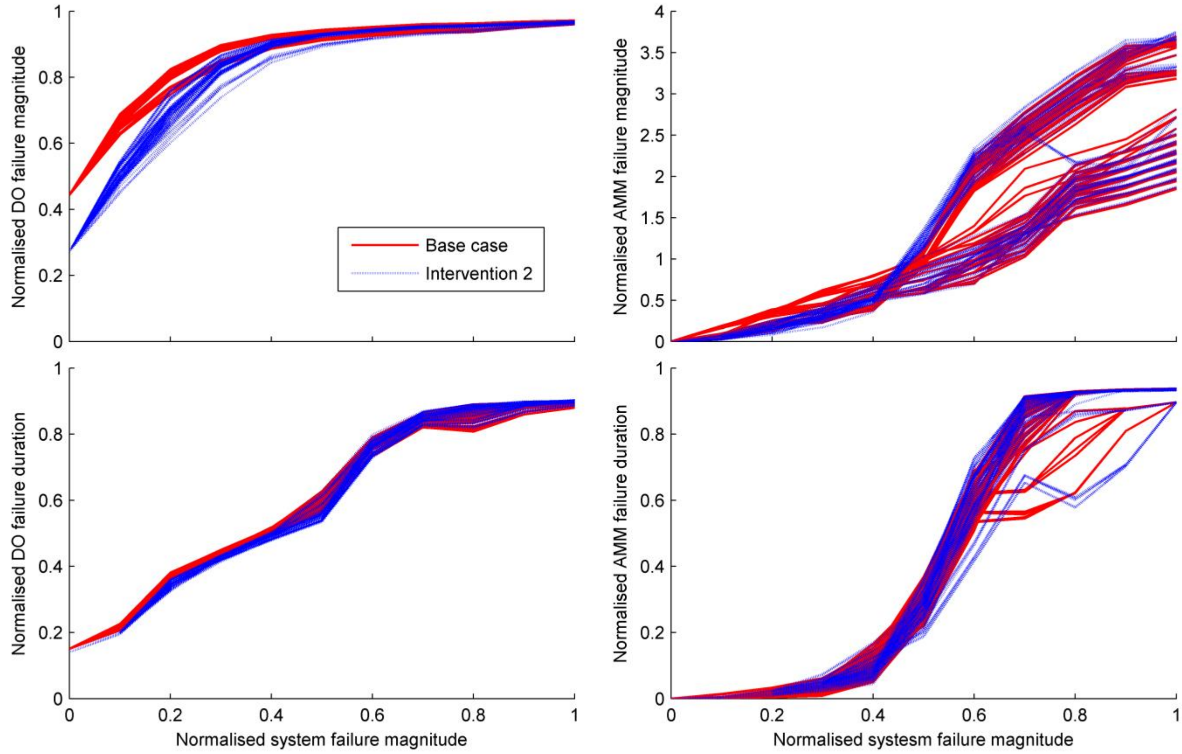


**Figure 8.** Worst 500 general resilience component response curves under base case and intervention 2.

**Table 2.** Mean and maximum areas under worst 500 response curves for each measure of strain (indicators of general resilience)

| | | Normalised DO failure magnitude | Normalised DO failure duration | Normalised AMM failure magnitude | Normalised AMM failure duration |
|---|---|---|---|---|---|
| Mean area (-) | Base case | 0.874 | 0.597 | 1.169 | 0.415 |
| | Intervention 2 | 0.828 | 0.589 | 1.169 | 0.415 |
| | *Percentage reduction* | *5.3%* | *1.4%* | *0.0%* | *0.0%* |
| Max area (-) | Base case | 0.884 | 0.617 | 1.681 | 0.459 |
| | Intervention 2 | 0.847 | 0.611 | 1.681 | 0.462 |
| | *Percentage reduction* | *4.2%* | *1.0%* | *0.0%* | *-0.7%* |

Ultimately, these results show that intervention 2 is, on balance, beneficial to general resilience as it provides an improvement in most indicators. However, they also confirm the existence of trade-offs as suggested by Walker and Salt (2012), and indicate that improvement in general resilience is difficult to achieve. Further and more universal improvements in general resilience may be achievable with more complex interventions, but these are more challenging to evaluate and likely to incur greater expense. Still, this case study successfully demonstrates that the GRAM approach may be applied to the development of interventions and can highlight potentially negative effects of measures which enhance specified resilience.

## 6 CONCLUSIONS

Quantifying general resilience is challenging due to the existence of unknown threats. However, this paper explores the general resilience of an IUWS using a newly developed assessment methodology, GRAM, and demonstrates that the results may guide development of interventions to enhance general resilience. Key conclusions drawn include:

- Using a middle state based approach, the potential effects on level of service resulting from *any* threat (known or unknown) may be determined without knowledge of unknowns if all system failure modes can be identified and modelled.
- General resilience can be decomposed into its multiple contributing components, each of which may be calculated individually using global resilience analysis. Combined, these provide a comprehensive and quantitative assessment of the general resilience of the IUWS.
- The maximum response curve derived using global resilience analysis for each combination of system failure modes represents general resilience. Efforts to increase general resilience should target system failure modes which contribute to this maximum response curve, and in the case study increased sewer influent flow and failure of the activated sludge aeration are shown to be key.
- Assessment of specified resilience of an IUWS is likely to overlook some failure scenarios to which level of service provision is least resilient. It is essential that simultaneous occurrence of multiple system failure modes is considered, since this can result in significantly greater level of service failure magnitude and duration than any individual failure. It is also important that different combinations are considered,

since simultaneous occurrence of every failure does not necessarily result in the worst response. General resilience cannot be estimated by calculating the response to failure of every system component simultaneously.

- Analysis of the components of general resilience enables identification of priority level of service measures and priority system failure modes, thereby providing an informed starting point for the development of interventions to enhance general resilience.
- Based on the assessment results of interventions, whilst substantial improvement in specified resilience may be achieved with relative ease, however, achieving significant improvement in the general resilience of an IUWS is challenging.

Although a holistic picture of the general resilience of the IUWS is useful, it requires a significantly large amount of model simulations, even with the newly developed GRAM. It should be noted that the computer model is assumed to be able to represent various failure scenarios and intervention measures in this study, but developing such a model might be challenging in practice due to resources and data required. As with any model-based analysis, confidence in the results of GRAM for assessment of a real system is dependent on the representativeness and accuracy of the corresponding model.

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