# A TOOL FOR GLOBAL RESILIENCE ANALYSIS OF WATER DISTRIBUTION SYSTEMS

**C.Sweetapple[1], K.Diao[2], R.Farmani[3], G.Fu[3], D.Butler[3]**

[1,3] Centre for Water Systems, College of Engineering, Mathematics and Physical Sciences, University of Exeter, North Park Road, Exeter, Devon EX4 4QF

[2] De Montfort University, The Gateway, Leicester LE1 9BH

*[1]C.Sweetapple@exeter.ac.uk*

## ABSTRACT

A comprehensive assessment of resilience requires consideration of system performance under exceptional conditions, including those that are unforeseen, and can be achieved using a previously developed methodology called 'global resilience analysis' (GRA). GRA captures the effects of both probable and highly improbable (unknown probability) system failures and requires no knowledge of threats. Here, a simple, user-friendly tool that automates the simulations required for GRA of a water distribution system and assists comprehension of the results is presented. Provided the user can supply an Epanet .inp file for the system and that this contains demand data (an understanding of Epanet and system failure modelling is not necessary), the tool can be used to quantify the resilience of the system to pipe failure, pump failure, demand increase and contaminant intrusion. An interactive results explorer allows the user to easily identify critical system components based on the selected level of service type and failure measure (e.g. pressure, supply or contamination and failure magnitude or duration). A map of the network can be used to either color-code components based on their criticality in a single component failure analysis or to identify specific combinations of components which result in the greatest level of service failure magnitude or duration when failed simultaneously. 'Stress-strain' type response curves can also be automatically generated and key findings automatically extracted. Additionally, the tool enables systems to be compared on a like-for-like basis, enabling the effects of proposed interventions on resilience to be quantified and visualized.

**Keywords:** Global resilience analysis; Tool; Water distribution system

## 1 Introduction

Resilience can be 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" [1]. Evaluation of system performance under identifiable threats is insufficient to obtain a complete picture of a system's resilience, since not all threats that may occur are foreseeable. However, a methodology – global resilience analysis (GRA) – that utilizes 'stress-strain' type curves and focusses on the response to system failure modes instead of threats has been developed under the Safe & SuRe project [1] and demonstrated in urban drainage [2] and water distribution [3] systems. Since system failures are more easily identifiable than threats, and all threats (known or unknown) that result in level of service failure will only do so if they also affect the system, this approach enables a more comprehensive analysis of resilience without the need for knowledge of unknowns.

GRA requires a large number of model evaluations (a system with just 20 components that can fail has 1,048,576 potential failure scenarios, for example), and thus the analysis must be carried out programmatically. However, a lack of automated software for such analyses poses a barrier to wider uptake of the methodology. Therefore, a simple, user-friendly tool that automates the simulations required for GRA of a water distribution system is presented here. Provided the user can supply an Epanet .inp file for the system and that this contains demand data, this tool can be used to calculate the resilience of the system to a) pipe failure; b) pump failure; c) demand increase; and d) contaminant intrusion, with no computer programming knowledge necessary. The ability to consider a range of system failure modes is an important feature since resilience to each may differ: increasing connectivity in the network to increase resilience to pipe failure, for example, may reduce resilience to contaminant intrusion.

Simulations are completed automatically and an interactive results explorer allows the user to easily identify critical system components based on the selected level of service type and failure measure (e.g. pressure, supply or contamination and failure magnitude or duration). A map of the network can be used to a) color-code components based on their criticality in a single component failure analysis (i.e. stress magnitude = 1), or b) identify specific combinations of components which result in the largest or smallest level of failure magnitude or duration when failed simultaneously (i.e. the extremes). 'Stress-strain' type response curves (discussed in the following section) can also be automatically generated and key findings automatically extracted. Additionally, the tool enables the resilience of two systems, or one system with and without an intervention, to be compared on a like-for-like basis.

The tool is freely available and can be found at www.safeandsure.info.

## 2 Global resilience analysis concept and methodology

GRA [2, 3] utilizes a 'stress-strain' concept (illustrated in Figure 1), where 'stress' represents the system failure magnitude (e.g. number of pipes failed) and 'strain' represents the resultant level of service (e.g. water supply) failure magnitude or duration. A more resilient system, illustrated by the green line in Figure 1, is one that results in smaller strain values across a range of stress magnitudes. This approach provides an overview of the response to *all* possible system failure magnitudes (e.g. from a single pipe failure to simultaneous failure of every pipe in the system), irrespective of their probability, instead of focusing on specific pre-defined scenarios.

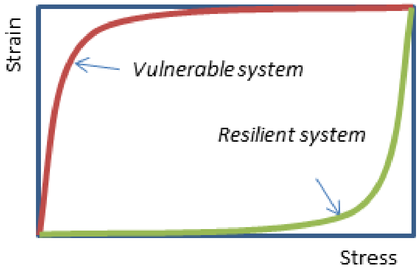
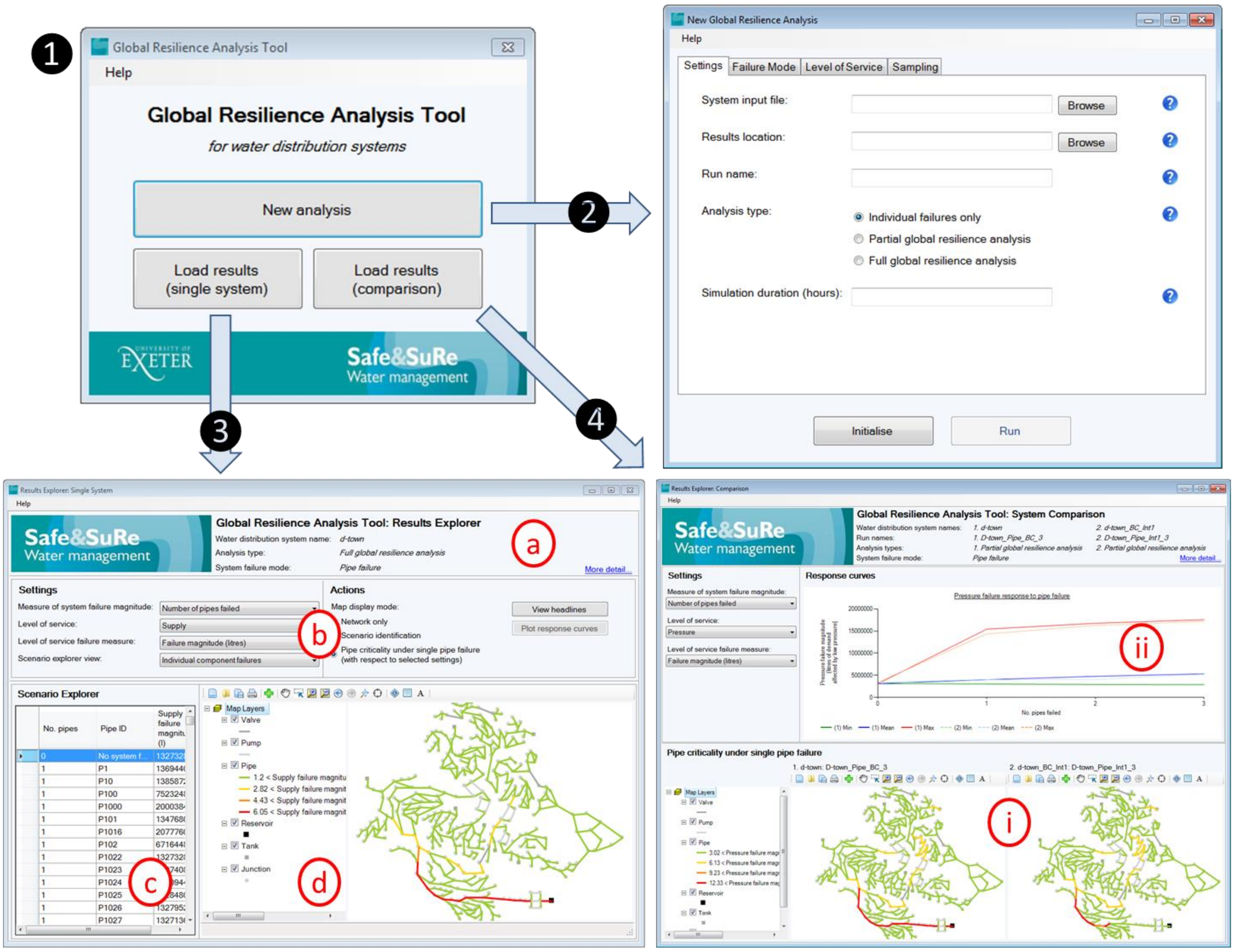


*Figure 1. Application of the stress-strain concept to resilience assessment*

Generation of 'stress-strain' type response curves requires evaluation of the level of service provided by the system under every system failure magnitude. However, it is not feasible to model every possible scenario for each system failure magnitude since for a system with $n$ potential component failures there are $\sum_{r=0}^{n} C_r^n$ possible failure combinations (for a system with just 20 potential component failures and a single simulation time of 2 seconds this would take 24 days to model). Therefore, the GRA tool uses targeted scenario development for each stress magnitude, based on an adaptation of the nearest neighbor method [4], to identify scenarios resulting in the minimum and maximum strain with a reduced number of computations. Further information on the targeted scenario development is provided by Diao et al. [3]. The component failure combinations at each stress magnitude are also enriched at each stress magnitude with a user-specified number of randomly generated scenarios, which enables calculation of the mean response.

# 3 Global resilience analysis tool

The global resilience analysis tool for water distribution systems automates the generation of response curves detailed in Section 2, based on a user-specified analysis configuration, and enables a detailed exploration of the results using an interactive and intuitive graphical user interface (illustrated in Figure 2). Generation and evaluation of system failure scenarios is automated using C, with Epanet used for modelling of water distribution system performance, and the user interface is developed using C#.



Global Resilience Analysis Tool: Results Explorer
Water distribution system name: d-town
Analysis type: Full global resilience analysis
System failure mode: Pipe failure

Measure of system failure magnitude: Number of pipes failed
Level of service: Supply
Level of service failure measure: Failure magnitude (litres)
Scenario explorer view: Individual component failures

Global Resilience Analysis Tool: System Comparison
Water distribution system names: 1. d-town 2. d-town_BC_Int1
Run names: 1. D-town_Pipe_BC_3 2. D-town_Pipe_Int1_3
Analysis types: 1. Partial global resilience analysis 2. Partial global resilience analysis
System failure mode: Pipe failure

Measure of system failure magnitude: Number of pipes failed
Level of service: Pressure
Level of service failure measure: Failure magnitude (litres)

*Figure 2. Global resilience analysis tool launch page, new analysis options, single system results explorer and results comparison*

Upon launching, the tool provides options to run a new analysis, load results for a single system or load results for a comparison (windows 2, 3 and 4 respectively in Figure 2). Running a new analysis requires multiple user inputs, which are detailed in Section 3.1. Following the analysis, results are presented in the single system results explorer and also saved for later reference (including comparison with the results of another analysis). Further information on the functionality of the results explorer and a selection of illustrative examples are provided in Sections 3.3-3.4. All results shown when illustrating the outputs of the tool are for the water distribution system D-Town [5], which contains 442 pipes, 11 pumps and 407 nodes and has a total daily demand of 22.8 Ml.

## 3.1 User inputs and available options

User inputs required and available options for the analysis include:

1) Analysis type ('Individual failures only', 'Partial GRA' or 'Full GRA')

Selecting 'Individual failures only' provides an analysis in which the effects of any single system component failure on level of service provision is evaluated. This is not a GRA as it considers only one system failure magnitude; however, it provides very quick results and may be used to obtain a preliminary indication of critical components. 'Partial GRA' considers system failure magnitudes from zero to a user specified maximum (e.g. up to 10 simultaneous pipe failures); this is faster than a full GRA and can be used to restrict the analysis to smaller / more probable system failure magnitudes. 'Full GRA' provides a comprehensive resilience analysis in which all system failure magnitudes, from 0% to 100%, are evaluated.

2) Simulation duration
3) Stress characteristics:
    a. System failure mode ('Pipe failure', 'Pump failure', 'Demand increase' or 'Contaminant intrusion')
    b. Maximum system failure magnitude (only required if the analysis type selected is 'Partial GRA')
    c. System failure start time and duration
    d. Demand increase (only required if the selected system failure mode is 'Demand increase')
    e. Contaminant mass booster flow rate, if applicable (only required if the selected system failure mode is 'Contaminant intrusion')
4) Strain specification:
    a. Minimum allowable pressure
    b. Maximum allowable contaminant concentration (only required if the selected system failure mode is 'Contaminant intrusion')
5) Parameters for random sampling (number of random samples for each system failure magnitude and seed options for random sample generation; not required if the analysis type selected is 'Individual failures only')

Results shown when presenting the Results Explorer (Sections 3.3-3.4) are for analyses with a simulation duration of 168 hours, system failure duration of 6 hours and system failure start time of 16:00 on day 1. All system failure modes are evaluated, using a demand increase of 50% and contaminant mass booster flow rate of 25 g/min where applicable. The minimum allowable pressure is 25m and maximum allowable contaminant concentration 0.0005 mg/l.

## 3.2 Simulations and calculations

Scenario generation, network simulation using Epanet, and calculation of level of service failure magnitude and duration are completed automatically based on the user inputs provided. For a system failure magnitude of $x$, pipe failure is modelled by setting $x$ pipe statuses to 'closed' in Epanet at the specified time and for the specified duration. Pump failure is modelled similarly, but with relevant pump scheduling rules also removed for the system failure period to prevent inadvertent operation of failed pumps. Demand increase is modelled by increasing demand at $x$ nodes by a fixed (user specified) percentage at the specified time and for the specified duration. Contaminant intrusion is modelled by applying a contaminant mass booster (with user specified flow rate) at $x$ nodes at the specified time and for the specified duration.

For each system failure scenario, the following level of service failure (i.e. strain) measures are calculated:

1. Pressure and supply failure durations (duration for which at least one node in the system is subject to pressure / supply failure, based on the user specified pressure requirement)
2. Pressure failure magnitude (total volume of demand subject to unsatisfactory pressure *OR* maximum instantaneous fraction of demand subject to unsatisfactory pressure during the simulation period)
3. Supply failure magnitude (total volume of demand not supplied *OR* maximum instantaneous fraction of demand not supplied during the simulation period)

Given that Epanet is a demand-driven model and supply is not directly calculated, supply ($S$) at each node and time step is estimated using Eq. 1:

$$\begin{gathered} if\ P \leq 0 : S = 0 \\ if\ 0 < P < P_{lim} : S = D\sqrt{P/P_{lim}} \\ if\ P \geq P_{lim} : S = D \end{gathered} \qquad \text{Eq. 1}$$

Where $P$ is the modelled pressure and $P_{lim}$ is the user-specified minimum allowable pressure.

When the selected system failure mode is ‘Contaminant intrusion’, the following additional level of service failure measures are calculated:

4. Contamination duration (duration for which at least one node with demand has an unacceptable contaminant concentration, based on the user specified limit)
5. Contamination magnitude (total volume of supply contaminated OR maximum instantaneous fraction of supply contaminated during the simulation period)

Following completion of the simulations, minimum, mean and maximum values for each level of service failure measure are calculated at each system failure magnitude for use in response curves.

## 3.3 Results explorer: Single system

The single system results explorer displays the results of the GRA in an interactive user interface. This contains four elements, as shown in Figure 2: (a) Details of the user inputs and options used in the GRA; (b) View options (settings) and links in which the user can select – for example, their level of service failure type (pressure, supply or contamination) and measure (magnitude or duration) of interest; (c) A ‘Scenario Explorer’ table, which provides details of key scenarios based on the selected view options; and (d) A map of the network.

Among the links available in (b) is the option to automatically generate ‘stress-strain’ type response curves based on the user-specified settings (example shown in Figure 3), provided either a complete or partial GRA has been completed. Such curves provide a useful visual representation of resilience to a given system failure mode: The maximum response curve in Figure 3, for example, shows that the maximum pressure failure magnitude in D-Town can result from just four simultaneous pipe failures, although the mean response curve shows that on average this number of pipe failures would result in significantly lower impact. Further detail on the specific scenarios contributing to these response curves is provided in the ‘Scenario Explorer’ table (c), which gives precise values for the minimum, mean and maximum level of service failure magnitude and duration at each system failure magnitude.

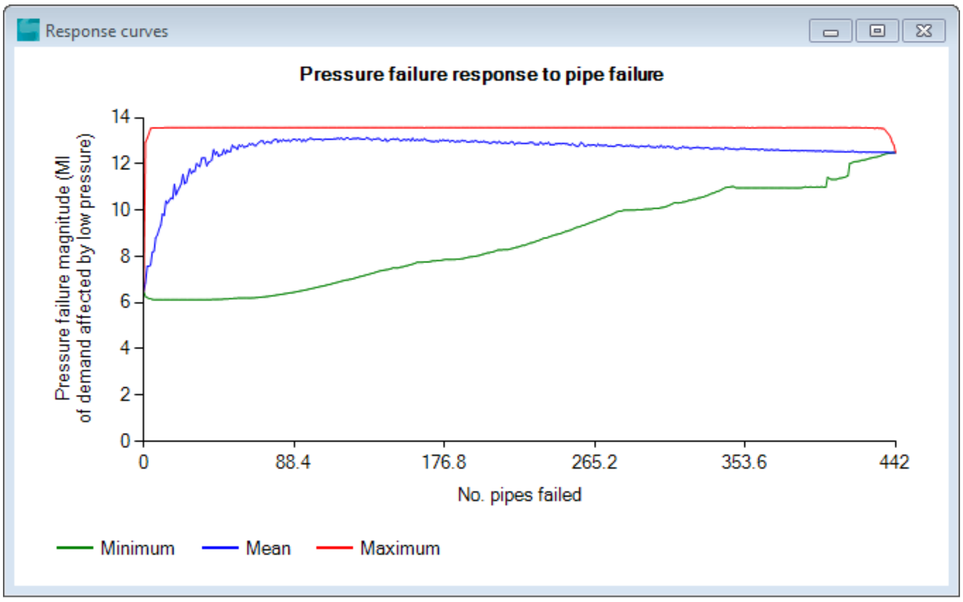


*Figure 3. Example response curves: Pressure failure magnitude response to pipe failure in D-Town*

Scenarios listed in the 'Scenario Explorer' table are automatically illustrated on the network map (d) when clicked, for example by highlighting pipes that have failed or highlighting nodes subject to contaminant intrusion. Figure 4a, for example, shows the four pipes which, if failed simultaneously, result in the maximum pressure failure magnitude. This feature of the tool enables critical combinations of component failures to be identified visually, and can help inform the development of interventions to enhance resilience. Components in the network map can also be color-coded based on their criticality in a single component failure analysis, as shown in Figure 4b. In this example, the color of each pipe represents the (system-wide) pressure failure magnitude that occurs if it fails, and the pipes which result in the greatest pressure failure magnitude if failed individually are clearly shown in red. Figure 5 illustrates the display of component criticality under the alternative system failure modes: pump failure, demand increase and contaminant intrusion.

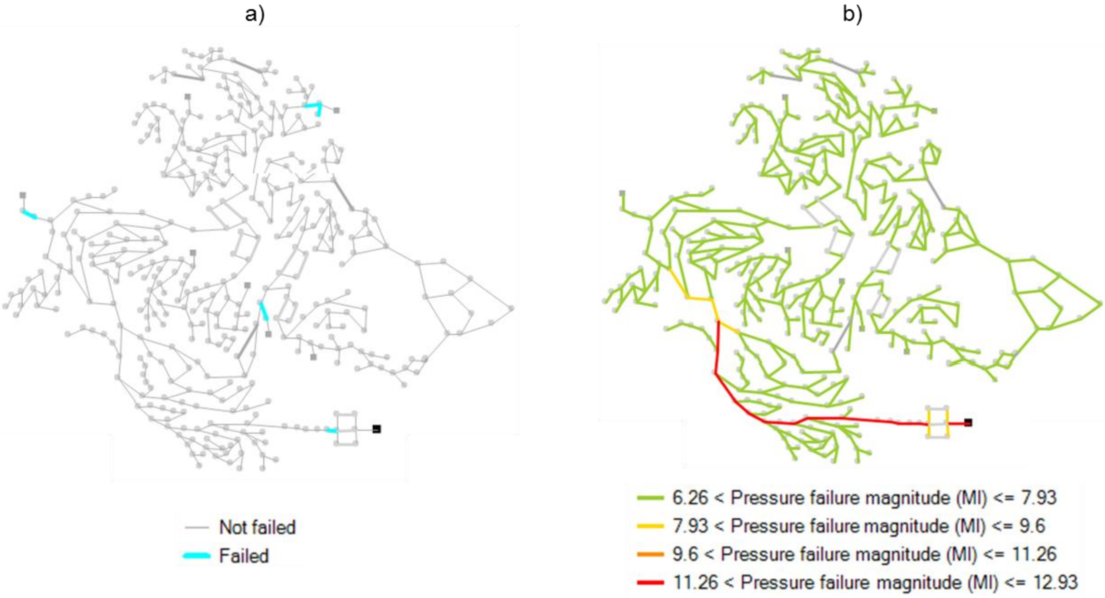


*Figure 4. Map display modes: a) Scenario identification; and b) Pipe criticality under single pipe failure (with respect to selected settings)*

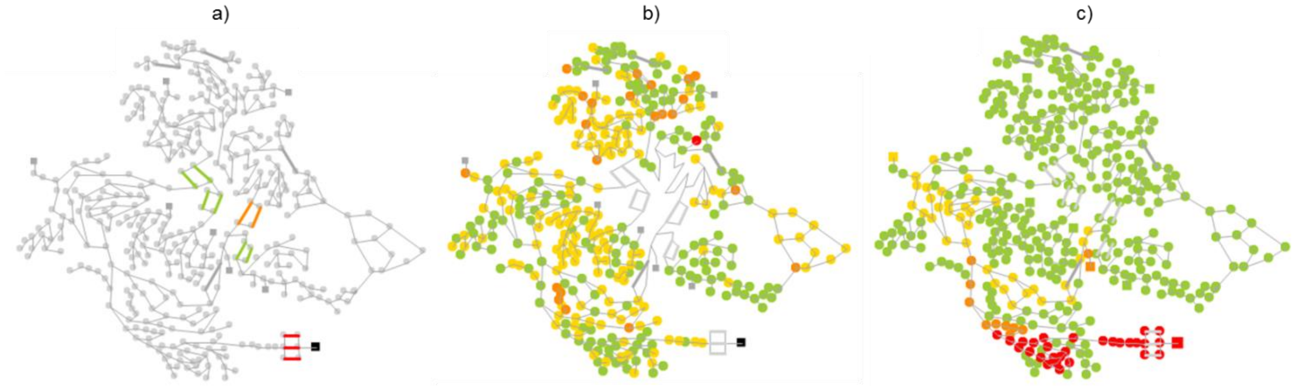


*Figure 5. Component criticality under: a) single pump failure; b) single demand increase; c) single contaminant intrusion. For illustrative purposes only, with legends omitted for clarity (red indicates highest criticality, green lowest criticality).*

To further assist interpretation and analysis of the results, a list of key findings with respect to performance with no system failures, performance under a single failure and performance under multiple failures can also be auto-generated. For resilience to pipe failure, for example, these include the volume of demand subject to unsatisfactory pressure even when there are no pipe failures, and the name of the single pipe that results in the greatest pressure failure magnitude when failed, among other key statistics.

## 3.4 Results explorer: System comparison

The tool also allows the resilience of two systems, or one system with and without an intervention, to be compared on a like-for-like basis. This enables a quantitative assessment of the effectiveness of a proposed intervention, as well as providing a clear, visual illustration of its benefits (or lack of).

Component criticality under individual component failures in each system is shown in color-coded network diagrams ((i) in Figure 2), as illustrated in Figure 6. This example demonstrates that the intervention evaluated in D-Town (duplication of critical pipes) is effective in reducing the number of pipes that result in the highest level of pressure failure when failed individually. 'Stress-strain' type response curves ((ii) in Figure 2) are also plotted for both systems (unless the analysis settings were for 'Individual failures only'), and these clearly demonstrate the effects of an intervention across a wide range of system failure magnitudes. This is illustrated in Figure 7, where (1) is the base case and (2) is the intervention.

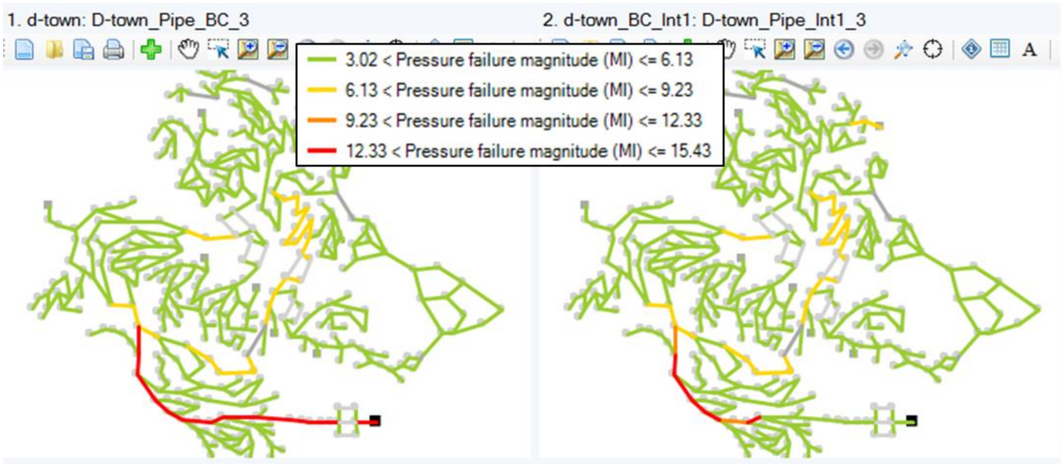


*Figure 6. Example pipe criticality results in the system comparison view (system following intervention illustrated on right)*

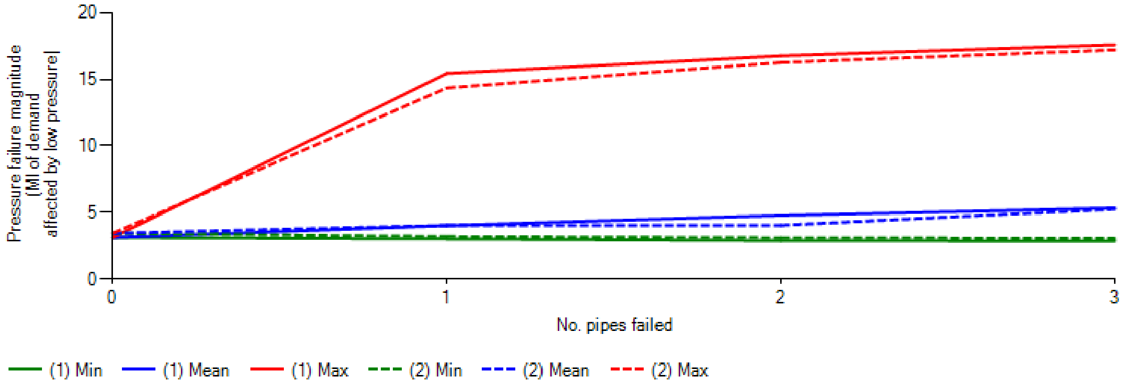


*Figure 7. Example response curves in the system comparison view for a partial GRA*

# 4 Conclusions

The tool presented in this paper automates the complex and time-consuming process of evaluating water distribution system resilience using GRA. Key benefits include:

- It enables comprehensive resilience assessments to be undertaken by users with no knowledge of coding, system failure modelling or the water distribution system modelling platform, Epanet. Furthermore, a detailed understanding of the GRA analysis methodology and scenario development process is not required.
- Both probable and highly improbable (unknown probability) failures are captured in the GRA and no knowledge of the potential causal threats is required.
- Resilience to pipe failure, pump failure, demand increase and contaminant intrusion can all be quantified using the tool, which is important as resilience to each may differ.
- Key findings are automatically extracted and critical system components can be easily identified on a network map.
- The effects of an intervention on resilience can be visualized, aiding option evaluation and justification of actions.

# 5 Acknowledgements

This work forms part of a 5-year fellowship for the last author funded by the UK Engineering & Physical Sciences Research Council (EP/K006924/1).

# 6 References

[1] D. Butler *et al.*, "Reliable, resilient and sustainable water management: the Safe & SuRe approach," *Global Challenges, doi: 10.1002/gch2.1010.*, 2016.

[2] S. N. Mugume, D. E. Gomez, G. Fu, R. Farmani, and D. Butler, "A global analysis approach for investigating structural resilience in urban drainage systems," *Water Research,* vol. 81, pp. 15-26, 2015.

[3] K. Diao, C. Sweetapple, R. Farmani, G. Fu, S. Ward, and D. Butler, "Global Resilience Analysis of Water Distribution Systems," *Water Research,* vol. 106, pp. 383-393, 2016.

[4] T. M. Cover and P. E. Hart, "Nearest neighbour pattern classification," *IEEE Transactions on Information Theory,* vol. 13, no. 1, pp. 21-27, 1967.

[5] A. Marchi *et al.*, "Battle of the Water Networks II," *Journal of Water Resources Planning and Management,* vol. 140, no. 7, Art. no. 04014009, 2014.