

Enhancing resilience in urban water systems for future cities

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ABSTRACT

In future cities, urban water systems (UWSs) should be designed not only for safe provision of services but should also be resilient to emerging or unexpected threats that lead to catastrophic system failure impacts and consequences. Resilience can potentially be built into UWSs by implementing a range of strategies, for example by embedding redundancy and flexibility in system design, or by rehabilitation to increase their ability to maintain acceptable customer service levels during unexpected system failures. In this work, a new resilience analysis is carried out to investigate the performance of a water distribution system (WDS) and an urban drainage system (UDS) during pipe failure scenarios. Using simplified synthetic networks, the effect of implementing adaptation (resilient design) strategies on minimising the loss of system functionality and cost of UWSs is investigated. Study results for the WDS case study show that the design strategy in which flexibility is enhanced ensures that all customers are served during single pipe failure scenarios. The results of the UDS case study indicate that the design strategy incorporating upstream distributed storage tanks minimises flood volume and mean duration of nodal flooding by 50.1% and 46.7%, respectively, even when system functionality is significantly degraded. When costs associated with failure are considered, resilient design strategies could prove to be more cost-effective over the design life of UWSs.

Key words | flexibility, pipe failure, redundancy, resilience, urban water systems

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INTRODUCTION

Although progress has been made towards achieving more sustainable urban water management, urban water systems (UWSs) are increasingly subject to stresses from emerging threats such as urbanisation, climate change and long-term asset degradation (Djordjević *et al.* 2011; Butler *et al.* 2014; IPCC 2014a). The impacts of emerging global climate change threats are concentrated in cities and urban areas due to the potentially high density of people, infrastructure, assets and economic activities exposed to these threats. Urbanisation impacts are also exerting significant pressure of existing UWSs (Urich & Rauch 2014). As of 2011, 52% of the global population live in urban areas and this is projected to grow to between 64 and 69% (5.1–7.1 billion) by 2050 (IPCC 2014b). The impact of these threats on existing

urban water infrastructure could lead to significant consequences such as reduced customer service levels for water supply and flood protection in the event of unexpected system failures.

Conventional ('Safe') design of UWSs has been greatly focussed on enhancing system *reliability* that is, minimising the level of service failure frequency over a given system's design life when subject to standard loading (Park *et al.* 2013; Butler *et al.* 2014; Jung *et al.* 2014). However, 'Safe' design approaches eliminate vital attributes, such as buffer and redundant capacity, that could enable the system to minimise failure magnitude and duration when subjected to exceptional conditions that lead to failure (Watt & Craig 1986; Wildavsky 1988; Hassler & Kohler 2014). It is

therefore argued that embedding *resilience* in UWSs is key to minimising their vulnerability to the emerging threats and to maintaining acceptable customer service levels in cities that they serve (Blackmore & Plant 2008; Lansey 2012; Butler *et al.* 2014). Extensive literature on concepts and definitions of resilience has been led by ecological system research, in which resilience is interpreted as a measure of a system's ability to persist by maintaining its basic structure and function (*system integrity*) when subject to shocks or disturbances (Holling 1996). In contrast to ecological systems, which exhibit dynamic and multiple stability domains, engineering systems are intentionally designed to provide continuous (uninterrupted) services to society in an efficient manner (Holling 1996; Blackmore & Plant 2008; Park *et al.* 2013). Consequently, the goal of engineering system resilience is essentially to ensure *continuity* and *efficiency of system function* during or after occurrence of failure (Lansey 2012; Park *et al.* 2013; Butler *et al.* 2014).

This paper builds on recent work on Safe & SuRe Water Management that seeks to ensure that UWSs are designed not only for safe (reliable) provision of services during normal (standard) loading conditions but also to be more resilient to unexpected or exceptional loading conditions (Butler *et al.* 2014). *Resilience* 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' (Butler *et al.* 2014). By utilising the Safe & SuRe approach, UWSs can be designed to minimise the level of service failure magnitude and duration when subjected to both standard and exceptional conditions. However, guidelines or standards for operationalising resilience in specific UWSs or sub-systems are still lacking, necessitating further investigation (Butler *et al.* 2014).

This paper therefore focuses on preliminary testing of both promising resilience characterisation methods and potential resilience-enhancing strategies. To achieve this, model simulations are carried out using a simplified synthetic water distribution system (WDS) and a synthetic urban drainage system (UDS) modelled in EPANET v2.0 (Rossman 2000) and the Storm Water Management Model (SWMM) (Rossman 2010), respectively, to investigate system performance under pipe failure conditions. Adaptation strategies in which flexibility and redundancy attributes are enhanced are tested with the aim of minimising the magnitude and

duration of level of service failure, and outline costs associated with each strategy are quantified.

STRATEGIES FOR ENHANCING RESILIENCE IN URBAN WATER SYSTEMS

Potential strategies for enhancing resilience in UWSs are widely known and practised. They can be broadly categorised in three ways: mitigation, adaption and coping (Butler *et al.* 2014). In this work, the focus is placed on adaptation as an intervention strategy for enhancing UWS resilience. Adaptation entails targeted actions or adjustments carried out in a specific system in response to actual or anticipated threats in order to minimise failure consequences (IPCC 2014a; Jones & Preston 2011). Adaptation is used in this paper to refer to local responses to increasing threats such as modifying specific attributes of the system to enhance its capacity to minimise the magnitude and duration of failure to both standard (i.e. to increase system reliability) and exceptional loading conditions (i.e. to increase general or design resilience). General resilience is used in this context to refer to the state of the system that enables it to limit failure duration and magnitude to any threat (Butler *et al.* 2014; Hassler & Kohler 2014).

It is postulated in this work that by implementing adaptation strategies in a specific water system, both reliability and resilience could be enhanced. This could be achieved by altering the system configuration to enhance its flexibility and redundancy properties. *Flexibility* is defined as inbuilt system capability to adjust or reconfigure so as to maintain acceptable performance levels when subject to multiple (varying) loading conditions (Vugrin *et al.* 2010; Spiller *et al.* 2015). Flexibility can be increased in a given system through intentional one-off or phased interventions that enhance inbuilt system attributes such as flatness (less system hierarchy), buffering capacity (head room), homeostasis (feedbacks) and omnivory (diversification) (Watt & Craig 1986; Wildavsky 1988; Butler *et al.* 2014; Hassler & Kohler 2014). It could also be increased by ensuring that more resources (e.g. trained repair crews or emergency water supplies) are readily available at any given time to facilitate rapid response to an unexpected failure event (Lansey 2012; Butler *et al.* 2014; Hassler & Kohler 2014). Based on this, flexibility could in principle be increased in a given UWS through use of spatially distributed

(decentralised) systems (e.g. [Sitzenfrei *et al.* 2013](#)), modular systems (e.g. [Spiller *et al.* 2015](#)) or through provision of back-up capacity (e.g. [Ahern 2011](#); [Cabinet Office 2011](#)).

Redundancy, on the other hand, refers to the degree of overlapping function in a system that permits the system to change by allowing vital functions to continue while formerly redundant elements take on new functions ([Watt & Craig 1986](#); [Wildavsky 1988](#)). In UWSs, redundancies could be multiple elements or components providing similar functions, to minimise failure propagation through the system, or to enable operations to be diverted to alternative parts of the system during exceptional loading conditions ([NIAC 2009](#); [Ahern 2011](#); [Cabinet Office 2011](#)).

[Table 1](#) provides examples of potential adaptation strategies that could in principle (*a priori*) improve UWS flexibility and redundancy properties. However, it is still unclear how each of these adaptation options actually enhances the resilience a given UWS in the event of unexpected system failures ([Ofwat 2012](#); [Park *et al.* 2013](#); [Butler *et al.* 2014](#)). In this study therefore, a new resilience analysis applied is applied to characterise the resilience of case study UWSs and to quantify the effect of implementing a range of adaptation strategies on enhancement of system resilience.

STUDY APPROACH

The conventional UWS design and rehabilitation approach is to build reliable systems that can achieve

expected customer service levels under normal or standard loading conditions ([Butler *et al.* 2014](#); [Jung *et al.* 2014](#)). Reliability-based approaches such as *least cost design* formulations ensure that systems are designed to satisfy minimum acceptable service levels within given standard range of operation conditions but may eliminate vital redundancies that are required to meet the required customer services levels when system loading exceed *normal* conditions ([Lansey 2012](#); [Jung *et al.* 2014](#)) It is now recognised that UWSs should not only be reliable but also resilient to *unexpected* or exceptional loading conditions. In this work, the resilience of a given UWS is illustrated through assessment of the effect of failure scenarios that could occur when the system is subjected to a wide range of unexpected threats (e.g. [Johansson 2010](#)). Pipe failure is considered for the two case studies. [Figure 1](#) illustrates the study approach based on middle (failed) state-based global resilience analysis that is adopted in this research. The developed approach enables system resilience to be assessed without the need to quantify the probability of occurrence of threats that lead to system failure. In the case of the WDS, single pipe failure is investigated using a simplified synthetic network that requires rehabilitation due to increased water demand. Pipe failure is used to model potential structure failure modes in WDSs that lead to pipe breakage such as pipe bursts, leakages and collapse ([Kleiner & Rajani 2001](#)). The effect of two rehabilitation strategies involving pipe replacement on resilience is evaluated and the capital costs associated with each strategy computed.

In the UDS case study, cumulative pipe failure is investigated using a synthetic network that requires rehabilitation to minimise the flooding magnitude and duration. Pipe failure is used to model potential structural failure modes in UDSs that include pipe collapse, blockages and bed load sediment deposition ([Butler & Davies 2011](#)). Two adaptation strategies in which redundancy and flexibility may be enhanced are investigated, namely, downstream centralised storage (CS) and upstream distributed storage (DS) strategies, respectively. The effect of the strategies on minimising the loss of system functionality is evaluated and the discounted total cost of each strategy is evaluated considering a design life of 50 years.

Table 1 | Examples of potential adaptation strategies

Urban water sub-system	General (design) resilience attribute	
	Flexibility	Redundancy
WDS	Pipe replacement (critical pipes)	Increase storage tank size
	Looping (network reconfiguration)	Parallel pipes
	Back-up pumps	
Urban drainage system	Distributed source control	Add centralised storage tanks
	Roof disconnection	Pipe replacement
	Rain water harvesting	Parallel pipes
	Multifunctional urban spaces	

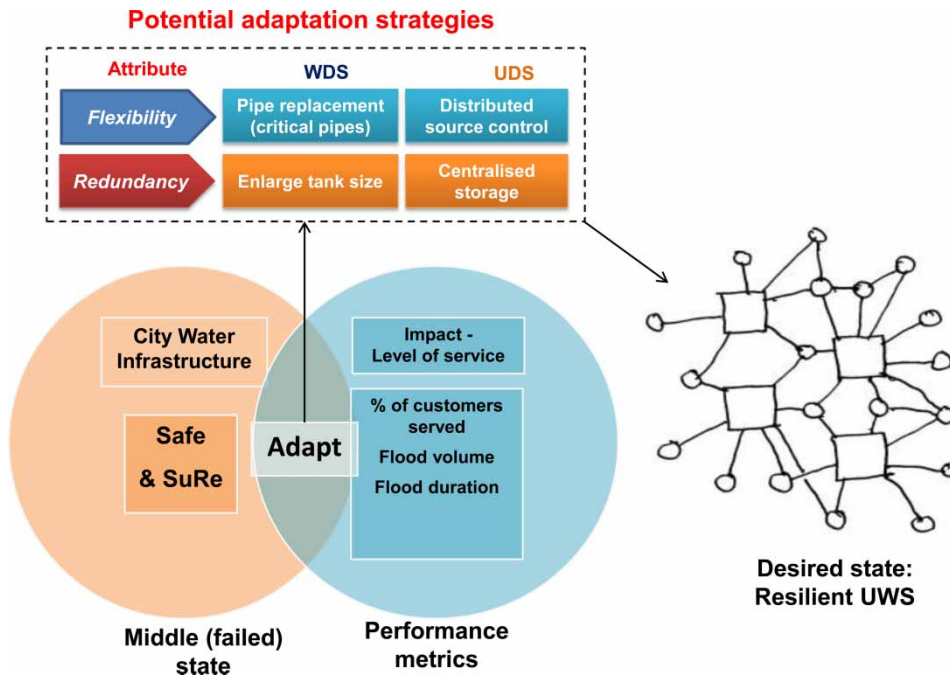


Figure 1 | Study approach based on middle (failed) state global resilience analysis of UWSs (Johansson 2010; Butler et al. 2014). The figure on the right that illustrates the desired resilient UWS is adopted from Mehaffy & Salingaros (2013).

RESULTS AND DISCUSSION

Case study 1 – WDS

WDS resilience is illustrated by testing the performance of the system under single pipe failure scenarios. The resulting loss of system functionality for a given UWS can be quantified using social and economic impacts such as loss of supply or repair costs. A WDS is said to be resilient (to pipe failure) if it can maintain the required level of service during the considered failure scenarios.

A synthetic WDS reported in Todini (2000) is used in this work (Figure 2(a)). The system requires rehabilitation due to water demand increase. The system consists of one storage tank, nine nodes and 15 links. The actual pipe lengths are as follows: the pipe connecting the reservoir (node 0) is 2,000m long, the contour pipes are all 1,000 m long and all the internal pipes connected to node 9 are 1,210 m long. Two rehabilitation strategies are compared. Strategy B (Figure 2(b)) is a design scenario in which single pipe failure scenarios are not initially considered during the design but occur during the period of operation.

In Figure 2(c), single pipe failure scenarios are taken into consideration and flexibility is introduced into the system by ensuring that for each node at least two possible paths (links) with larger diameters are provided (Strategy C). Table S1 (available in the online version of this paper) provides details of the design scenario including demand and required minimum head for each node. Further details on the network configuration and the design scenario considered are provided in Todini (2000).

The capital costs of all the considered strategies are calculated according to diameter classes using the cost data provided in Table S2 (available in the online version of this paper). Given the significant variability of land costs in different city contexts, land costs are not included in the capital cost calculations (e.g. Todini 2000; Farmani et al. 2005). Model simulations are carried out in EPANET to investigate the effect of single pipe failure scenarios on the ability of the UDS to minimise the resulting loss of system functionality. Loss of system functionality is quantified by computing the total water demand at the failed nodes. Comparing the two strategies described, strategy C, in which failure scenarios are considered at the design stage, cost slightly more (1.9%)

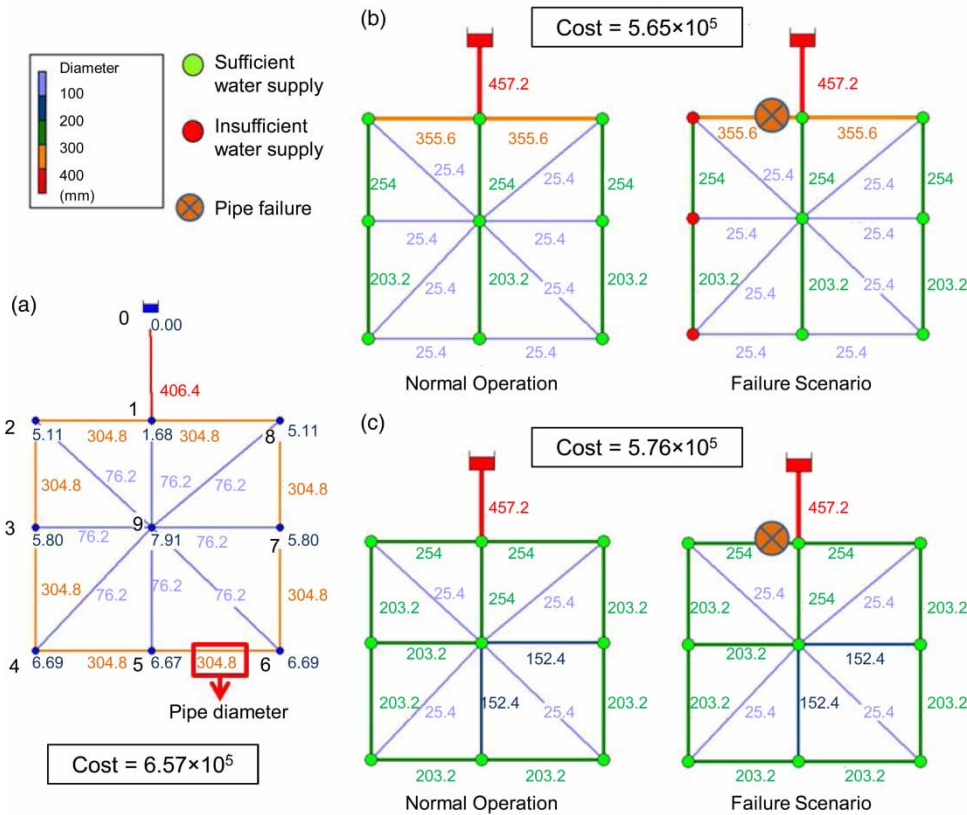


Figure 2 | (a) Original design of the WDS; (b) rehabilitation strategy without failure scenarios considered (reproduced from Todini 2000); (c) rehabilitation strategy with failure scenarios considered.

but enables the system to cope with all single pipe failure events, i.e. no loss of supply. Contrarily, one-third of customers would be unserved in the other strategies. The reason why strategy C results in a more resilient WDS is because there are at least two paths formed by large pipes (i.e. diameter ≥ 203 mm) to each node. This ensures that the system capacity is better allocated compared to the other two designs.

Case study 2 – UDS

The existing UDS with no storage (business as usual, BAU) requires rehabilitation because its current configuration leads to unacceptable surface flooding during extreme rainfall events (Figure 3(a)). This system is a baseline configuration in which the pipes provide the hydraulic capacity of the system with no storage devices. The system consists of 26 nodes and 25 links with diameters ranging from 600 to 1,500 mm, and slopes ranging from 0.5 to 2.25% and has been designed

based to satisfactory convey flows resulting from an observed 100 minute rainfall event with a total depth of 66.2 mm (Sliuzas et al. 2013), with no flooding at any node in the system. The UDS drains a total catchment area of 22.5 hectares with an average slope of 0.5% and percentage imperviousness of 25%. In addition, two adaptation strategies are modelled and used to test their effect on enhancement of system resilience: (a) CS strategy, a large storage tank is introduced upstream of pipe C24 to minimise downstream flooding by enhancing peak flow attenuation effects (Figure 3(b)); and (b) DS strategy, 9 spatially distributed upstream storage tanks (same total storage volume as the CS strategy) are introduced at the outlets of each sub catchment to enhance flexibility at critical points in the network at sub-catchment level (Figure 3(c)).

Model simulations are carried out in SWMM v5.1 to investigate the effect of cumulative pipe failure on resulting loss of functionality (surface flooding) for the three system

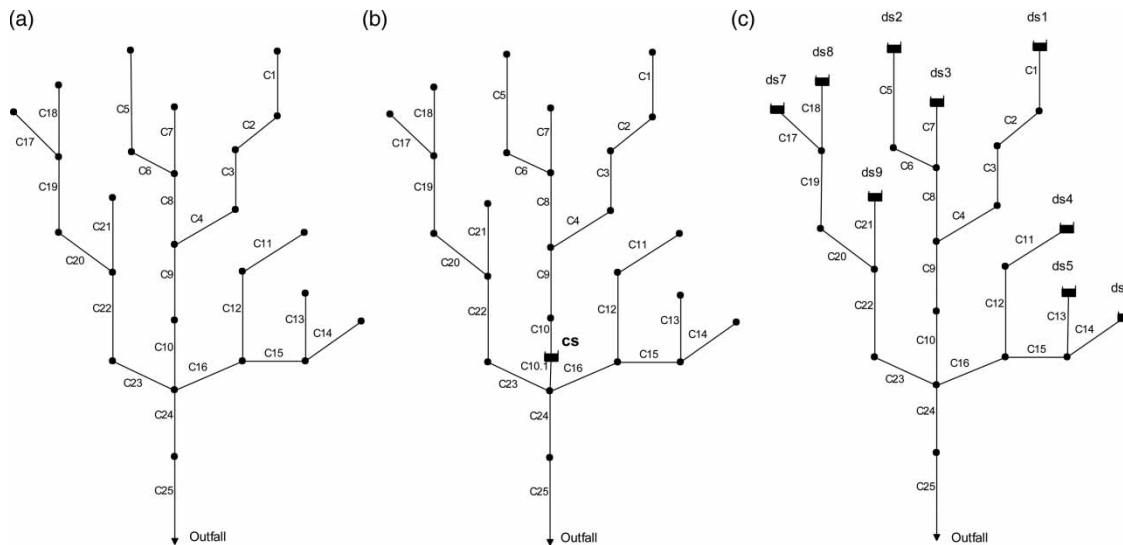


Figure 3 | Layout of (a) existing UDS with no storage (BAU), (b) UDS with centralised (downstream) storage and (c) UDS with upstream DS.

configurations represented in [Figure 3](#). Flooding is simply modelled using a flood cone with all surface flows subsequently being re-introduced into the system when hydraulic capacity becomes available ([Rossman 2010](#)). To test the performance of the BAU system during failure conditions, model simulation is carried out using an up scaled extreme rainfall event with a total depth of 141 mm and duration of 100 minutes (i.e. change factor of 2.14 is applied to scale the event return period, T from 2 to 50 years). Simulation results indicate that pipes in existing system (*initial state*) experiences hydraulic overloading that leads to flooding in most parts of the network (total flood volume of $10,910 \text{ m}^3$ and duration of 42 minutes). A high peak flow rate of $6.95 \text{ m}^3/\text{s}$ is attained in the downstream pipes (C24) after a simulation period of 88 minutes ([Figure 4](#)).

The system is subjected to increasing (cumulative) pipe failure scenarios (stress) in order to evaluate global performance (loss of system functionality) using total flood volume and mean nodal flood duration as key performance indicators. Pipe failure is modelled by significantly reducing pipe diameters, D_p in the model from their initial values (non-failed state) to a very small value of 1 mm in order to model pipe failure (failed state), while maintaining hydraulic connectivity required for the solution of the flow equations. A simulation run is carried out for the first random pipe failure scenario, then additionally, a second pipe is randomly failed and a second simulation run carried out. This is done cumulatively

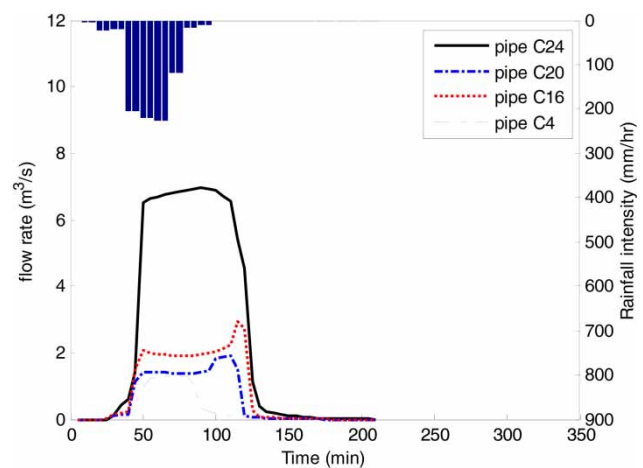


Figure 4 | Simulated flow rates in pipe C24, C20, C16 and C4 for the existing UDS with no storage (BAU).

until all pipes in the network have failed. In addition, using the proposed approach, the effect of implementing the proposed adaptation strategies on improvement of global resilience is investigated. For comparison of the strategies, the discounted total cost, PVC_T for each strategy is computed considering a design life of 50 years, using cost functions presented in [Table S3](#) (available in the online version of this paper). Similarly, given the significant local city specific factors that influence land acquisition, land cost is excluded from the capital cost calculations ([Swan & Stovin 2007](#)).

The results of the BAU case in [Figure 5](#) indicate that cumulative pipe failure leads to a rather high increase in

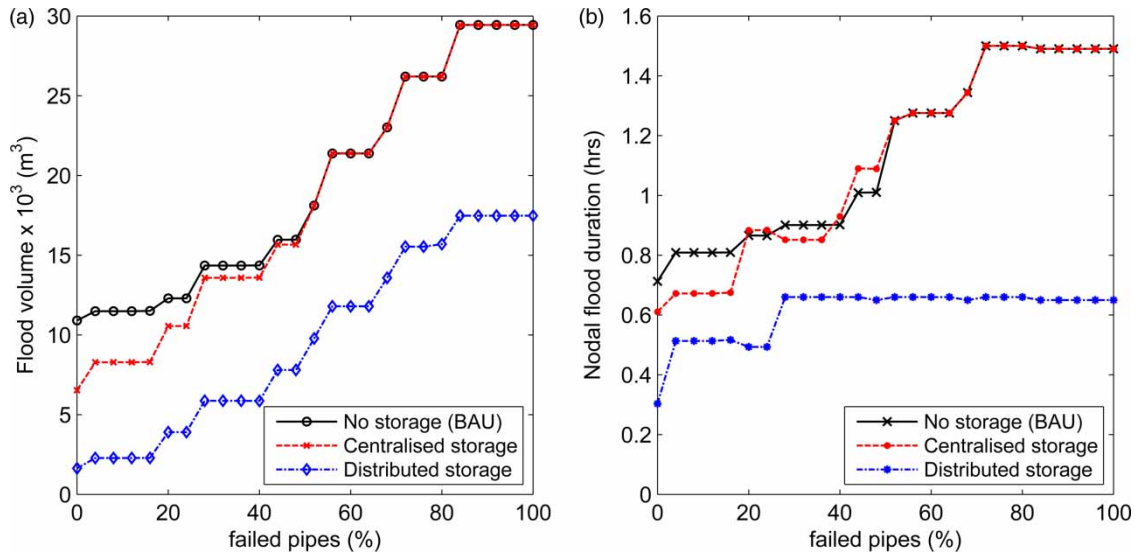


Figure 5 | Effect of cumulative pipe failure on (a) flood volume and (b) mean duration of nodal flooding.

the total flood volume and mean flood duration. This suggests that occurrence of pipe failures in UDSs lead to significant loss of system functionality, which progressively increases with increasing pipe failure levels. The occasional ‘plateaus’ in the simulated flooding impacts (Figure 5) are attributed to failure of less critical pipes (e.g. an upstream pipe conveying low flows), which leads to minimal increase in the simulated flood volume and duration despite further increase pipe failure levels. The rapid increase in simulated flooding impacts is attributed to failure of more critical pipes. Globally, the results suggest that the existing system exhibits low levels of resilience to cumulative pipe failure.

Overall, a total of 78 simulations are carried out and a summary of the results of the analysis is provided in Table 2. Implementing the CS strategy results in a slight reduction in the flood volume and mean nodal flood

duration; with the reduction being effective at low (<48%) pipe failure levels. Globally, the strategy results in minimal reduction of the total flood volume and mean flood duration of 4.8% and 1.9%, respectively, when compared to the BAU case. From the results, it can be interpreted that the CS strategy leads to minimal reduction of the loss of system functionality magnitude and duration and consequently a slight improvement in system resilience to cumulative pipe failure.

In contrast to the CS strategy, implementing the DS strategy results in a significant reduction in total flood volume at all pipe failure levels implying the effect of cumulative pipe failure (stress) on loss of system functionality magnitude (strain) is reduced. In the case of the flood duration, the strain on the system increases to a maximum of 0.66 hours and remains almost constant when pipe failure

Table 2 | UDS performance indicators considering cumulative pipe failure scenarios

Statistic	Flood volume (x10 ³ m ³)			Mean duration of nodal flooding (hrs)		
	No storage	Centralised storage	Distributed storage	No storage	Centralised storage	Distributed storage
Mean failure	19.30	18.37	9.64	1.14	1.12	0.61
Standard deviation	6.98	8.05	5.84	0.29	0.33	0.09
Min failure	12.33	10.32	3.80	0.85	0.79	0.52
Max failure	26.28	26.42	15.48	1.43	1.45	0.70
Mean reduction		4.8%	50.1%		1.9%	46.7%
		[-0.5–16.3%]	[41.1–69.2%]		[-0.9–6.7%]	[38.8–51.4%]

levels exceed 32%, which suggests that increasing the spatial distribution of control options in upstream parts of the network ensures optimal global performance during pipe failure scenarios. This design strategy is therefore more resilient to cumulative pipe failure when compared to the other two strategies as demonstrated by the significant mean reduction in the total flood volume and duration of nodal flooding of 50.1% and 46.7%, respectively. For comparative assessment of cost effectiveness of proposed strategies, the results of the discounted total cost calculations are presented in Figure 6.

The capital costs of the centralised and DS strategies are higher by 27% and 35%, respectively, due to the addition of storage devices. When direct tangible flooding costs are taken into consideration, the CS strategy leads to 14.5% reduction in discounted total costs. Conversely, the DS strategy results into a 39.2% reduction in discounted total cost, which is attributed to the reduced direct tangible flooding costs.

CONCLUSIONS

The resilience of UWSs to unexpected threats can be enhanced by embedding redundancy and flexibility in system design, retrofit or rehabilitation. In this study, redundancy is enhanced by introducing a centralised storage tank (UDS case). Flexibility on the other hand is enhanced by increasing network connectivity (WDS case) and use of smaller distributed storage tanks (UDS case). Simplified synthetic networks are used to investigate ways to evaluate resilience in existing systems and to test effectiveness of implementing various adaptation strategies in minimising

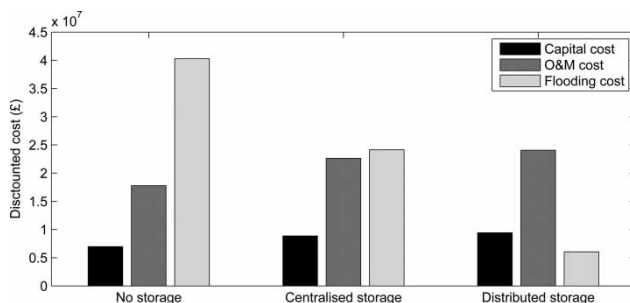


Figure 6 | Discounted total cost of UDS design strategies.

the loss of system functionality and cost during pipe failure scenarios.

In the WDS case study, although the strategy in which flexibility is enhanced (strategy C) initially increases capital costs by 1.9%, it results in minimal loss of system functionality and consequently ensures adequate customer service levels during single pipe failure scenarios. In the UDS case study, the DS strategy minimises the total flood volume and mean flood duration by 50.1% and 46.7%, respectively, and hence is more resilient to cumulative pipe failure. Although this strategy has higher initial capital costs due to the additional cost of distributed storage tanks, it results in a significant reduction of 39.2% in the total discounted total costs when direct tangible surface flooding costs over the system's design life are taken into consideration.

This study has demonstrated that loss of system functionality during exceptional loading conditions can be minimised if failure scenarios are taken into consideration during UWS design (i.e. resilient design). The study results also suggest that enhancement of system flexibility attributes, for example through increasing connectedness and spatial distribution of control options enhances the ability of UWSs to minimise the resulting loss of functionality during unexpected system failures. The study also indicates that by taking into account the cost of failure, *resilient design* strategies could prove to be more cost-effective over the design life of UWSs. It is concluded that embedding resilience in UWSs provides a promising and potentially cost-effective approach to maintain acceptable customer service levels during unexpected failures and to contribute to more sustainable water management in cities in view of emerging threats. Further research using the presented approach is recommended to investigate resilience in existing real world systems and to test the effectiveness of strategies that enhance spatial distribution and connectedness properties such as city scale dual-purpose rainwater harvesting systems (e.g. DeBusk 2013) and multifunctional green infrastructure (e.g. Ahern 2011).

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