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Resilience-based evaluation of urban drainage systems: The ‘Safe & SuRe’ Approach

Paper 16 – Session 5: Emerging technology and asset management

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Keywords: extremes, functional failure, reliability, resilience, structural failure

Abstract

The need to develop more resilient urban drainage systems (UDSs) is now widely recognised as key to maintaining acceptable flood protection service levels in cities in view of emerging climate-related, urbanisation and ageing infrastructure threats. In order to effectively operationalise resilience in urban flood management, new quantitative evaluation approaches that consider ‘all possible threats’ including existing network capacity and asset failures such as sewer collapse, blockage or equipment malfunction are required. This paper presents the *Safe & SuRe* approach that seeks to ensure that UDSs are designed or retrofitted not only for safe (reliable) provision of services during *normal* conditions but also to be more resilient to *extreme* loading conditions. Specifically, the paper describes the developed *Safe & SuRe* framework and presents a summary of results obtained by applying the middle state-based Global Resilience Analysis (GRA) method to systematically evaluate: (i) the effect of a wide range of *functional (hydraulic)* and *structural (sewer) failures* and on the ability of an existing UDS in Kampala, Uganda to minimise the resulting magnitude and duration of flooding and (ii) investigate the effectiveness of a set of promising adaptation strategies on improvement of its resilience to flooding. Study results indicate that occurrence sewer failures leads to significant loss of functionality of the existing UDS (and hence its level of resilience to flooding) that is comparable to the effect of extreme rainfall. The results further indicate that when compared to centralised storage and improved asset management, the distributed storage strategy is more effective and leads to a reduction in total flood volume and mean flood duration of up to 34% and 24% respectively even when the UDS structure is significantly degraded. The presented GRA method provides a computationally efficient approach that is suitable for evaluating resilience in large urban drainage networks without prior knowledge of threat (extreme rainfall or sewer failure) occurrence probabilities.

1. Introduction

Recent extreme flooding incidences which have occurred over the last decade have underscored the need to develop more resilient urban drainage systems (UDSs) a key strategy to maintaining acceptable flood protection service levels in cities worldwide (Djordjević et al., 2011; Hammond et al., 2014; IPCC, 2014; Mugume et al., 2015b; Park et al., 2013). Urban flooding is not only caused by external threats such as climate change, climate variability and urbanisation but also internal system failures such as sewer failures (collapse, blockages and bed load sediment deposition), equipment malfunction (pump, valve or sensor failure) and insufficient hydraulic conveyance capacity in existing systems (Kellagher et al., 2009; Möderl et al., 2014; Mugume et al., 2015a, 2015b). However, current hydraulic reliability-based approaches only focus on prevention of hydraulic failures for example due to occurrence of an extreme rainfall event of a given return period and fail to consider the contribution of other causes (threats) that could also lead to negative flooding impacts and consequences (Mugume et al., 2015b).

Consequently, the operationalisation of resilience in urban flood management requires new evaluation approaches that consider ‘*all possible threats*’ such as extreme rainfall, existing network

capacity constraints and asset (structural) failures such as sewer collapse, blockage, bed load sediment deposition or equipment malfunction (Kellagher et al., 2009; Mugume et al., 2015b). Taking the example of the UK water sector, the main goal of enhancing resilience in UDSs is well understood and supported by a suite of promising adaptation strategies (Cabinet Office, 2011; CIRIA, 2014; Hepworth, 2015; Mcbain et al., 2010; Ofwat, 2012). However still, there is limited clarity on how each strategy actually enhances UDS resilience to unexpected failures and this can be attributed to a range of factors: lack of clear and consistent guidelines and standards; lack of suitable quantitative evaluation methods and computational complexity inherent in considering ‘all possible threats’ or ‘combination of threats’ (Mugume et al., 2015b).

This paper builds on recent work on *Safe & SuRe* Water Management that seeks to ensure that urban drainage systems are designed or retrofitted not only for safe (reliable) provision of services during *normal* conditions but also to be more resilient to extreme (exceptional) loading conditions that could lead to unexpected system failures (Butler et al., 2014; Mugume et al., 2015a, 2015b). In this work, engineering (infrastructure) system resilience is interpreted as an emergent system property that provides a measure of the system’s ability to ensure continuity and efficiency of function during or after occurrence of system failure (Butler et al., 2014; Mugume et al., 2015a; Park et al., 2013). The definition emphasizes the notion that resilient systems possess a number of desirable properties (*general resilience attributes*) for example redundancy, flexibility, connectedness or resourcefulness that could enhance their ability to minimise resulting loss of functionality when subject to given threats (*specified resilience*) (Butler et al., 2014; Hassler and Kohler, 2014; Mugume et al., 2015a, 2015b).

This paper presents a new and computationally efficient Global Resilience Analysis (GRA) approach that shifts emphasis from accurate quantification of threat occurrence probabilities to evaluation of UDS performance under a wide range of possible failure scenarios (Mugume et al., 2015b). The paper further describes the *Safe & SuRe* framework and presents results of work where the developed GRA method has been successfully applied to evaluate the effect of both *structural* (sewer failure) and *functional* (extreme rainfall) failures on the ability of an existing UDS in Kampala, Uganda to minimise the magnitude and duration of flooding and to investigate the effectiveness of implementing a set of promising adaptation strategies in enhancing global UDS resilience to flooding.

2. Methods

2.1 Safe & SuRe framework

The *Safe & SuRe* framework has been developed to provide a means of linking emerging threats such as climate change, urbanisation and long term asset degradation to urban water systems (UWSs) through to their impacts and consequences (Figure 1). The framework further underscores the role and place for intervention strategies, namely mitigation, adaptation, coping and learning in building the resilience of UWSs to specific threats (Butler et al., 2014). In this work, the focus is placed on adaptation as an intervention strategy for enhancing UDS resilience to flooding. Adaptation is

interpreted in this research as local responses to increasing threats for example modification of vital (general resilience) attributes of a given system so as to enhance its ability to minimize the resulting loss of functionality (failure) magnitude and duration when impacted upon by both normal and extreme loading conditions (Mugume et al., 2015a).

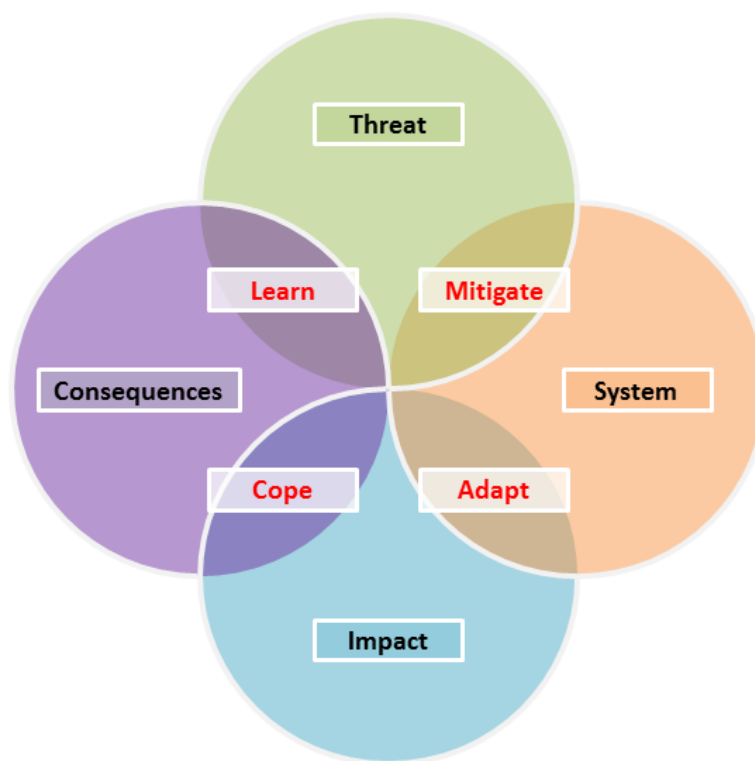


Figure 1: Safe & SuRe intervention framework (Butler et al., 2014)

2.2 Middle-state based Global Resilience Analysis

The Global Resilience Analysis (GRA) method is applied in the study. GRA is implemented by carrying out a large number of model simulations to quantify the global performance of the system during potential failure conditions or so-called middle states (Mugume et al., 2015a, 2015b). Based on the simulation results, systems are characterised as less resilient if a small fraction of stresses (sewer failure or extreme rainfall increase) leads to disproportionately large impacts of loss of functionality (strains) or more resilient if a significantly large fraction of stresses leads to minimal impacts (Butler et al., 2014; Mugume et al., 2015b). GRA shifts the object of analysis from a focus on precise quantification of the probability of occurrence of given threats (e.g. extreme rainfall or sewer failures), to explicit consideration UDS performance when subject to a wide range and number of possible failure scenarios (Mugume et al., 2015b). Using the GRA method enables the effect of different failure modes and extent (middle states) on UDS performance to be quantified without the need to quantify the probability of occurrence of the threats/causes (Kellagher et al., 2009; Mugume et al., 2015a, 2015b). A middle (failed) state refers to a point in the phase plane of a system (e.g. surface flooding) that may result from different threats (Johansson, 2010). Table 2 provides examples of middle states and key level of service indicators for UDSs.

Table 1: Examples of middle states and level of service (impact) indicators

Middle States	Impacts /Levels of service indicators
Stress (functional): <ul style="list-style-type: none"> x% rainfall increase y% DWF increase 	Strain: <ul style="list-style-type: none"> Surface flood volume (m³) Surface flood duration (hrs) Flood extent (no. of flooded nodes) Flood extent (no. of flooded properties)
Stress (structural): <ul style="list-style-type: none"> z% sewers (links) failed t% pumps failed 	

The developed GRA method is applied to investigate the effect of a wide range of functional and sewer (structural) failure scenarios on global UDS performance and to investigate the effect of implementing a set of adaptation strategies on enhancement of both functional and structural resilience in UDSs. Application of the GRA method is particularly beneficial for evaluation of the effect of unexpected (unpredictable) failures such as occurrence of extreme rainfall or sewer failures on resulting flooding impacts in cities which lack extensive data sets on the physical condition of existing sewer networks. Surface flooding is quantified using a set of level of service indicators that include total flood volume and mean nodal flood duration.

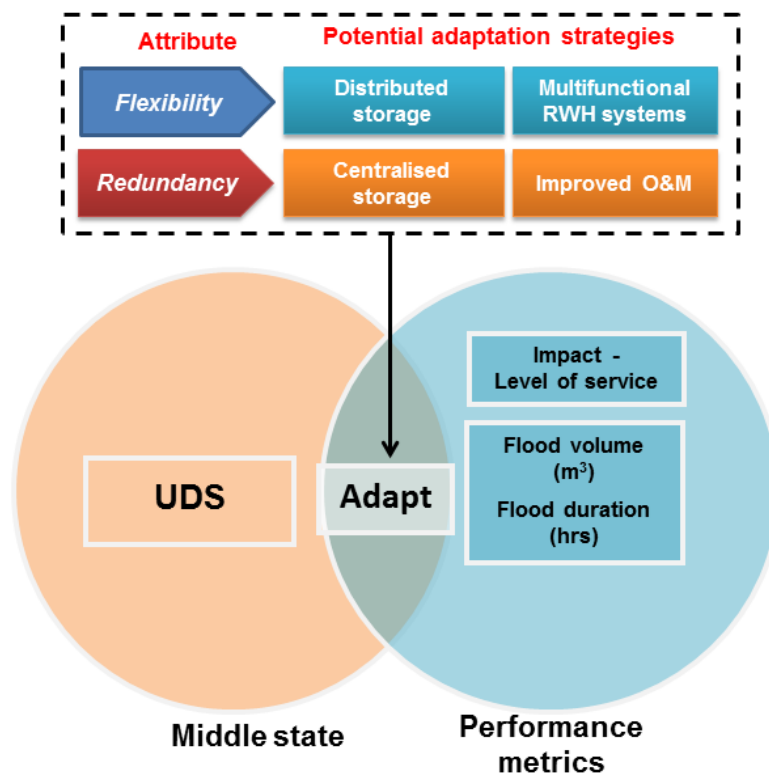


Figure 2: Middle-state based global resilience analysis of UDSs

2.3 Case study and UDS modelling approach

A case study of the Nakivubo UDS that drains a highly urbanised catchment (central business district) in Kampala city, Uganda forms the basis for the investigations carried out in this study. Kampala is the political and economic capital of Uganda with total population of 1.72 million and an estimated annual growth rate of 5.6% (UBOS, 2012). Over the last decade, Kampala has experienced an increase in the number of pluvial flooding incidences with negative consequences such as property damage, traffic disruption and shallow ground water contamination among others (Lwasa, 2010; Sliuzas et al., 2013; UN-Habitat, 2009). The number of catastrophic flooding events that occur during extreme convective rainfall events has doubled; from an average of 5 in 1993 to 10 in 2014, with the later having an average duration of 2 – 4 hours. Key threats (causes) that have contributed to increased frequency and severity of urban flooding incidences in Kampala include: extreme rainfall (caused by climate change and variability), rapid urbanisation, insufficient drainage infrastructure, inadequate system cleaning and maintenance and insufficient solid waste management in the city (Mugume and Butler, 2015a).

A hydrologic and hydraulic model of the Nakivubo UDS (Figure 3) has been built in the Storm Water Management Model, SWMM v5.1 (Rossman, 2010). The hydraulic model of the system consists of a 81 links (network length of 22.8 km), 81 nodes and 1 outfall and drains a total catchment area of 2,793 ha delineated into 31 sub catchments (Mugume et al., 2015b).

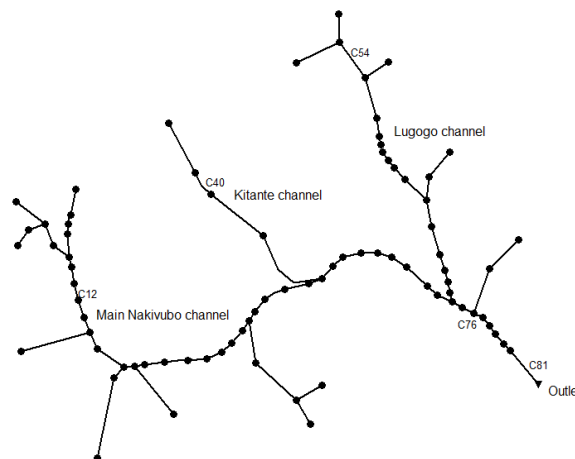


Figure 3: Layout of the modelled Nakivubo urban drainage network (Mugume et al., 2015b)

2.4 Tested adaptation strategies

The GRA method has been previously been applied to investigate the effectiveness of implementing centralised and distributed storage strategies in enhancing UDS structural resilience using the Kampala case study (Mugume et al., 2015b). The study concluded that occurrence of sewer failures significantly reduces the effectiveness of adaptation strategies such as centralised storage which aim at enhancing system redundancy at single (critical) locations in an urban drainage network, while use of upstream source control strategies such as distributed storage which reduce the flow rates and

volume of stormwater that enters the UDS significantly enhances the ability of the whole system to maintain higher residual functionality levels during unexpected sewer failures. Building on this work, this paper further investigates the effectiveness of improved asset management and catchment scale multifunctional rainwater harvesting (RWH) systems (Figure 4) on enhancement of global UDS resilience when subject to unexpected functional and structural failures.

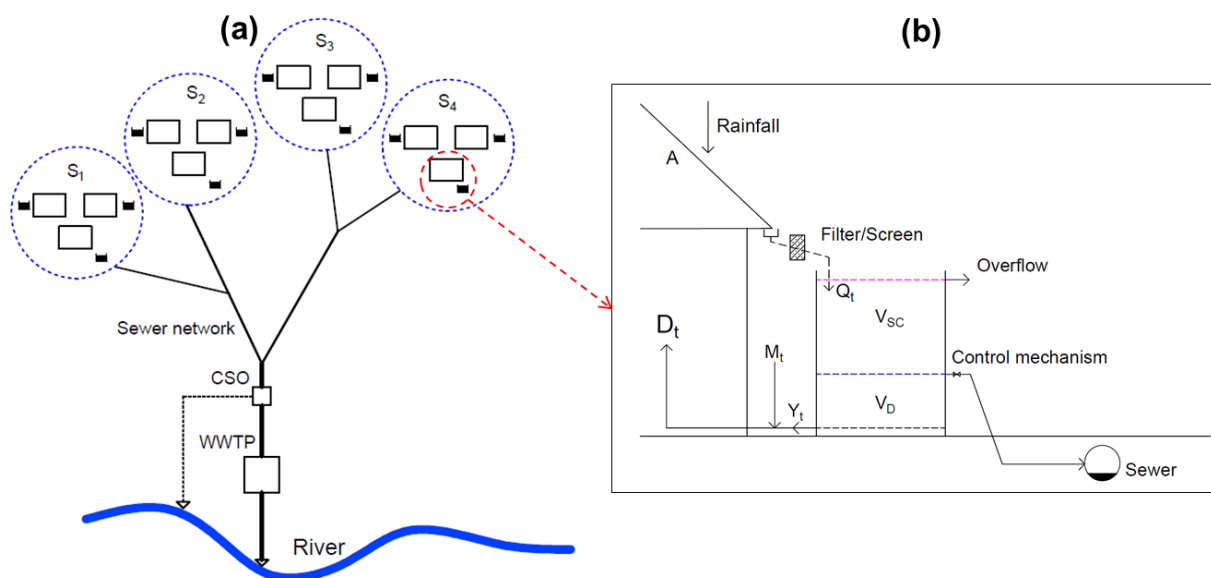


Figure 4: (a) Example of an UDS in which multifunctional (dual purpose) RWH systems with active or passive control devices are implemented at a catchment scale (b) Dual-purpose RWH system configuration (Mugume et al., 2015c)

Furthermore, the study further compares and contrasts the effect of two different failed states on surface flooding, that is hydraulic overloading caused by extreme rainfall and occurrence of sewer failures on resulting loss of functionality magnitude and duration. Finally the effectiveness of implementing a set of interventions on enhancement of functional and structural resilience respectively is investigated (Table 2).

Table 2: Modelled adaptation strategies

Strategy	Description	General resilience attribute influenced
Centralised storage (CS)	Introduce a large downstream centralised detention pond with a total storage volume of $3.15 \times 10^5 \text{ m}^3$	Redundancy
Distributed storage (DS)	Introduce 28 spatially distributed upstream storage tanks with the same total storage capacity as the CS strategy	Flexibility
Improved asset management (O&M)	Improve system cleaning and maintenance (asset management) so as to maintain its as-built hydraulic capacity and to improve flow conditions in the individual links	Redundancy
Multifunctional rainwater harvesting (RWH)	Implement multifunctional rainwater harvesting (RWH) systems at a catchment scale with the same total storage capacity as the DS strategy	Flexibility

2.5 Effect of extreme rainfall

In order to evaluate the functional resilience of the UDS to extreme rainfall, a single non-areally reduced extreme rainfall event recorded at Makerere University rain gauge station and which occurred on 25th June 2012, with a duration of 100 minutes of total depth of 66.2 mm is used for the simulations (Sliuzas et al., 2013). In addition, the effect of climate change on UDS performance is investigated by running model simulations using upscale events i.e. climate change factors are applied to the observed single event to obtain more extreme events (Figure 5). The single rainfall events are applied uniformly over the catchment so as to represent ‘worst case’ UDS functional loading scenarios. A total of 25 model simulations is carried out in SWMM v5.1 for the existing UDS in its initial state and for the considered adaptation strategies.

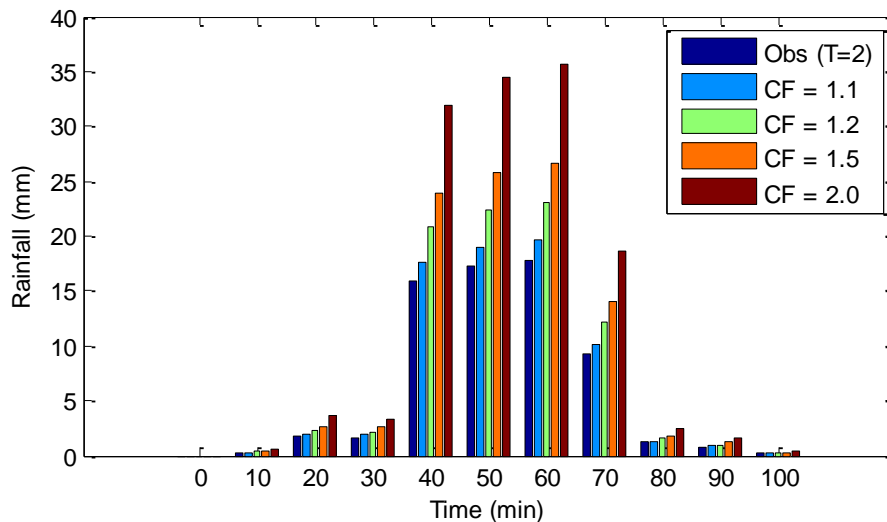


Figure 5: Observed extreme rainfall event on 25th June 2012 for Kampala (Obs) and estimated future extreme rainfall events with climate change factors (CFs) of 1.1, 1.2, 1.5 & 2.0 applied.

2.6 Effect of sewer failures

The GRA method is applied to investigate the performance of existing UDS when subject to a wide range of random cumulative link failure scenarios (i.e. to quantify its structural resilience). Links in the case study UDS are randomly and cumulatively failed and resulting impacts on global performance of the UDS are quantified at each link failure level, until all the links in the UDS have failed (Mugume et al., 2015b). Link failure is modelled in SWMM by increasing the Manning’s roughness coefficient, n from its initial (non-failed) state value ($n = 0.02$) to a very high value ($n = 100$) in order to significantly curtail flow conveyance in each link. This approach enables representation of complete failure of a given link in the UDS that could result from collapse, blockage, or sediment deposition (in closed systems) or deposition of solid waste and washed in sediments in open channel systems (Mugume et al., 2015b). Inherent computational complexity associated with the need to simulate all possible link failure scenarios is minimised by applying a *convergence analysis* technique that enables determination of the minimum number of random link

failure sequences that should be simulated to achieve consistent GRA results (Mugume et al., 2015b).

Finally, the GRA method is applied to test each of the proposed UDS adaptation strategies. Overall, a total of 82,000 failure scenarios involving 1000 random cumulative link failure sequences are simulated to evaluate their resulting effect on performance of the existing and adapted UDSs. The main findings are summarised in this paper. A detailed description of the GRA and convergence analysis methods is provided in Mugume et al., (2015b) and detailed modelling and analysis of effectiveness of multifunctional rainwater harvesting strategies in building resilience in UDSs when subject to unexpected sewer failures is provided in Mugume et al., (2015c).

3. Results and discussions

3.1 Effect on enhancement of functional resilience

GRA results indicate that for the existing system, increase in extreme rainfall loading leads to disproportionate (doubling) increase in total flood volume. For example a 20% increase in rainfall leads to a 40% in total flood volume, while a 50% increase in extreme rainfall loading leads to a 106% increase in the simulated total flood volume. This is attributed to high imperviousness levels in the catchment resulting from rapid urban development and insufficient hydraulic conveyance capacity in the existing system. On the other hand, increase in extreme rainfall leads to slightly lower impacts on mean flood duration (Figure 6). However, it is noted that the simulated flood duration only quantifies the ‘failure impact’ duration of the 1D minor system and excludes the duration of failure that could occurs in the major system during exceedance flows (Mugume et al., 2015b)

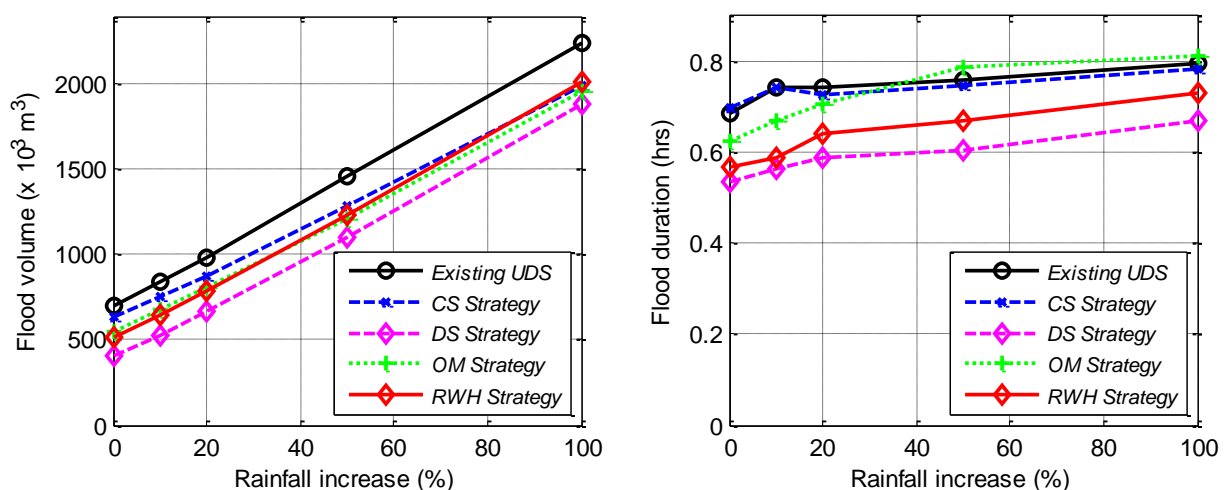


Figure 6: Effect of increase in extreme rainfall on (a) total flood volume and (b) mean flood duration for the existing UDS and for the tested intervention strategies

The results indicate that the DS strategy is the most effective in terms of a 16 – 43% reduction in the total flood volume and a reduction in mean flood duration of 16 – 24%. The O&M and RWH

strategies result in comparable reductions in total flood volume that range from 13 – 23% and 10 – 27% respectively. However, the RWH strategy is more effective in reducing the mean flood duration (9 – 21%) when compared the O&M strategy which leads to increase in mean flood duration when the increase in rainfall exceeds 40%. In contrast, the CS strategy is the least effective and results in a reduction of the total flood volume and mean flood duration of 10 – 12% and up to 2% respectively. These results suggest that increased spatial distribution of control options in upstream parts of the catchment is the most effective for minimising resulting loss of functionality during unexpected system failures.

It is further noted that these results have been obtained by carrying out model simulations in which uniform spatial rainfall inputs are applied over the entire catchment. However, most pluvial flooding events tend to result from occurrence of short duration high intensity convective rainfall events which are characterised by high spatial variability particularly in large urban catchments (Butler and Davies, 2011; Einfalt et al., 2004; Kellagher et al., 2009). It is therefore suggested that in future work, additional functional resilience enhancement benefits that could be achieved by the tested adaptation strategies should be investigated by carrying out a large number of model simulations using spatially distributed rainfall inputs (e.g. Mugume and Butler, 2015a, 2015b).

3.2 Effect on enhancement of structural resilience

GRA results are presented in Figures 7 and 8 for when the system is subjected to a wide range of structural failures. The results indicate that for the existing UDS, failure of a small proportion (10%) of links in the UDS lead to disproportionately high increase (91%) in the total flood volume but only a 6% increase in mean flood duration respectively. The results also indicate that the CS strategy leads to minimal reduction of the total flood volume (1 – 5%), which occurs at lower link failure levels (< 20%) and almost no effect on mean flood duration. The results therefore suggest that occurrence of sewer failures significantly limits the effectiveness of adaptation strategies that enhance system redundancy at a single location in the UDS.

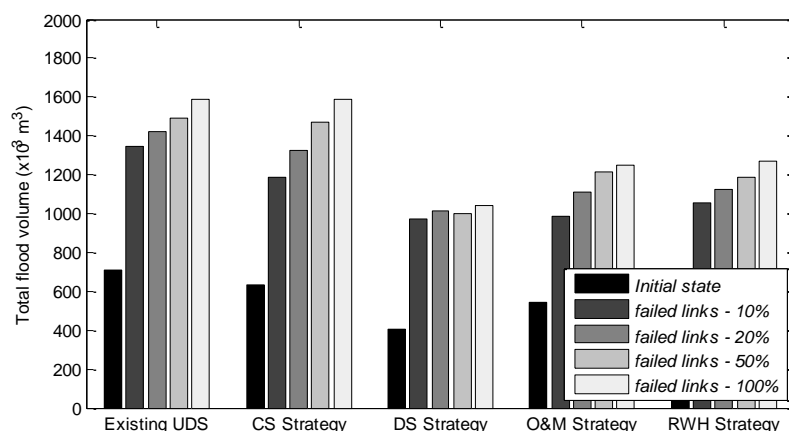


Figure 7: Effect of random cumulative link failure on (a) total flood volume for the existing UDS and for the tested intervention strategies

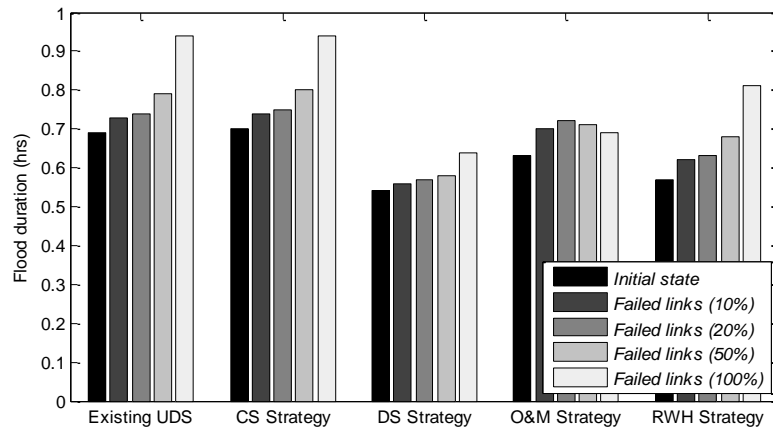


Figure 8: Effect of random cumulative link failure on mean flood duration for the existing UDS and for the tested intervention strategies

In contrast, the DS strategy is the most effective strategy and results in a reduction in the total flood volume and mean nodal flood duration of 30 – 34% and 26 - 28% respectively. The results further confirm that increased spatial distribution of control options in upstream parts of the catchment results in better use of the total installed storage for reduction of storm water inflow rates and volumes in the UDS, which in turn enables the degraded UDS to continue functioning with minimal impacts. The improved asset management (O&M) strategy, which maintains the as built hydraulic capacity in the links (and which minimises the future rate of system degradation), results in a significant reduction in total flood volume (17 – 25%) and mean flood duration (10 – 13%). The RWH strategy also results in a substantial reduction of total flood volume (20 – 21%) and a reduction of the mean flood duration of 12 – 17%. These results suggest that catchment scale implementation of multifunctional RWH systems gives a comparable reduction of the loss of system functionality (and hence improvement of global UDS resilience to cumulative link failure) as the improved asset management strategy. However, the RWH strategy is slightly less effective when compared to use of DS strategies from a flood resilience perspective alone which could be attributed possible over flow of RWH tanks during extreme events. Based on this, it is argued that for a given UDS, there exists an optimum size and spatial distribution of storage controls that leads to the highest reduction of the magnitude and duration of flooding during extreme events.

4. Conclusions

Building resilience in urban drainage systems requires consideration of all possible threats such as sewer failure, existing network capacity constraints and occurrence of extreme rainfall. In this paper, an unconventional and computationally efficient GRA method, which provides a systematic approach to evaluating whole system resilience, has been described and applied to investigate the effectiveness of a set of intervention strategies in building global (UDS) resilience to a wide range of unexpected functional and structural failure scenarios. Based on the results of the study, the following conclusions are drawn for the Kampala case study:

- Global UDS resilience to flooding is significantly influenced by occurrence of extreme rainfall (caused by climate change or variability) as well as occurrence of unexpected system failures (link collapse, blockages, sediments or equipment malfunction) that are caused by both abrupt shocks and long term asset deterioration.
- Enhancing urban drainage system flexibility properties through increased spatial distribution of control options in upstream parts of the catchment provides the most promising strategy for enhancing the global UDS resilience to flooding.
- Asset management interventions aimed at maintaining as built hydraulic conveyance capacity in existing systems are more effective when compared to more costly interventions that aim at increasing system redundancy in single locations (e.g. use of larger centralised storage tanks).
- Wide scale implementation of multifunctional rainwater harvesting (RWH) strategies is slightly less effective when compared to use of large distributed storage tanks and improved asset management from a flood resilience perspective alone but should still be pursued due to their ability to provide alternative city water supplies during unexpected water supply system failures.
- A combination of RWH strategies and improved asset management provides the most promising option for enhancing both urban flood and water supply resilience and thereby contributing to more sustainable urban water management in the long term.

More general conclusions are that:

- System resilience can be assessed without needing to know the probability of the cause (threat) of the impact;
- The developed GRA method enables specified resilience to be derived for various failure states (functional and structural) allowing a picture of general resilience of a given UDS to be built up;
- GRA provides a way of quantifying the impact of interventions on system resilience either absolutely or against agreed standards;

Acknowledgement

This research is financially supported through a UK Commonwealth PhD scholarship awarded to the first author. The work is also supported through the UK Engineering & Physical Sciences Research Council (EPSRC) funded Safe & SuRe research fellowship (EP/K006924/1) awarded to the second author. Acknowledgement is given to the National Water and Sewerage Corporation (NWSC) the Kampala Capital City Authority (KCCA), the Water Resources Management Department, Ministry of Water and Environment, Uganda for providing datasets used in the study.

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