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A global analysis approach for investigating structural resilience in urban drainage systems

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ABSTRACT

Building resilience in urban drainage systems requires consideration of a wide range of threats that contribute to urban flooding. Existing hydraulic reliability based approaches have focused on quantifying functional failure caused by extreme rainfall or increase in dry weather flows that lead to hydraulic overloading of the system. Such approaches however, do not fully explore the full system failure scenario space due to exclusion of crucial threats such as equipment malfunction, pipe collapse and blockage that can also lead to urban flooding. In this research, a new analytical approach based on global resilience analysis is investigated and applied to systematically evaluate the performance of an urban drainage system when subjected to a wide range of structural failure scenarios resulting from random cumulative link failure. Link failure envelopes, which represent the resulting loss of system functionality (impacts) are determined by computing the upper and lower limits of the simulation results for total flood volume (failure magnitude) and average flood duration (failure duration) at each link failure level. A new resilience index that combines the failure magnitude and duration into a single metric is applied to quantify system residual functionality at each considered link failure level. With this approach, resilience has been tested and characterised for an existing urban drainage system in Kampala city, Uganda. In addition, the effectiveness of potential adaptation strategies in enhancing its resilience to cumulative link failure has been tested.

1. Introduction

Recent natural and manmade catastrophic events that have led to extreme flooding in various cities worldwide have underscored the need to build resilience into existing urban drainage and flood management systems as a key strategy to minimise the resulting flooding impacts and consequences (Djordjević et al., 2011; Park et al., 2013). Urban drainage system flooding is not only caused by *external* climate-related and urbanisation threats such as extreme rainfall and increasing urbanisation but also *internal* system threats for example equipment malfunction, sewer collapse and blockages (Kellagher et al., 2009; Mugume et al., 2014; Ryu and Butler, 2008; Ten Veldhuis, 2010). System or component failures can either be abrupt (unexpected) shocks for example pump or sensor failure or chronic pressures such as asset aging and long term asset decay or sewer sedimentation. The impact of such failures, either singly or in combination on existing urban drainage infrastructure could significantly reduce the expected flood protection service levels in cities and lead to negative consequences such as loss of lives, damage to properties and critical infrastructure (Djordjević et al., 2011; IPCC, 2014; Ryu and Butler, 2008; Ten Veldhuis, 2010).

Consequently, the need to build resilience in urban drainage systems (UDSs) is increasingly recognised as vital to enhance their ability to maintain acceptable flood protection service levels in cities that they serve and to minimise the resulting flooding consequences during unexpected or exceptional loading conditions that lead to system failure (Butler et al., 2014; Djordjević et al., 2011). Although the application of concept of ***resilience*** to infrastructure systems is a recent development, there is an extensive literature on definitions and interpretation of resilience, much of which has come from the ecological systems academic community (Butler et al., 2014; Park et al., 2013). Ecological system resilience is interpreted as a measure of *system integrity* and is defined as a system's ability to maintain its basic structure and patterns of behaviour (i.e. to persist) through absorbing shocks or disturbances under dynamic (non-equilibrium) conditions (Holling, 1996). In

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Nomenclature

rs_i	random link failure sequence
ns_i	random failure sequences for the existing system
cs_i	random failure sequences for the centralised storage strategy
ds_i	random failure sequences for the distributed storage strategy
N	total number of links
n	Manning's roughness coefficient
t_f	mean duration of nodal flooding
t_n	total elapsed (simulation) time
Res_o	Resilience index
P_f	Maximum system failure level
P_a	Accepteable system performance level
P_o	Original system performance level
Sev_i	Severity
Sev_p	Peak Severity
T	rainfall return period in years
V_{TF}	total flood volume
V_{TI}	total inflow volume
μ	mean
σ	standard deviation

contrast to ecological systems, engineering systems are product of intentional human invention and are designed to provide continued (uninterrupted) services to society in an efficient manner (Blackmore and Plant, 2008; Holling, 1996; Park et al., 2013). Engineering system resilience is therefore interpreted differently from ecological resilience and focuses on ensuring *continuity and efficiency of system function* during and after failure (Butler et al., 2014; Lansey, 2012).

In the context of urban drainage, current hydraulic reliability-based design and rehabilitation approaches tend to focus on prevention of hydraulic (functional) failures resulting from a specified design storm of a given frequency (i.e. return period). The design storm return period determines the flood protection level provided by the system (Butler and Davies, 2011). Hydraulic reliability-based approaches place significant emphasis on *identifying* and *quantifying* the probability of occurrence of extreme rainfall and *minimising* the probability of the resulting hydraulic failures i.e. *the fail-safe approach* (Ryu and Butler, 2008; Thorndahl and Willems, 2008). However, such approaches fail to consider other causes of failure for example structural or component failures (Table 1) which also lead to flooding (e.g. Kellagher et al., 2009; Mugume et al., 2014; Ten Veldhuis, 2010).

Furthermore, it is argued that the direct application of reliability-based approaches for evaluation of structural failures in UDSs could be insufficient mainly because causes and mechanisms of failure are largely unknown and difficult to quantify (Ana and Bauwens, 2010; Kellagher et al., 2009; Park et al., 2013; Ten Veldhuis, 2010). It is therefore important to develop new approaches that seek to ensure that UDSs are designed to not only be reliable during *normal* (standard) loading conditions but also to be resilient to *unexpected* (exceptional) conditions i.e. *the safe-fail approach* (Butler et al., 2014; Mugume et al., 2014). In this study, the definition and interpretation of resilience in engineering systems is pursued. Resilience is formally defined based on recent work on 'Safe and SuRe' Water Management as the "*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). Exceptional conditions refer to uncertain threats or disturbances that lead to system failure for example climate change induced extreme rainfall events, sewer collapse or blockage. Based on this definition, the goal of resilience is therefore to maintain acceptable functionality levels (by withstanding service failure) and to rapidly recover from failure once it occurs (Butler et al., 2014; Lansey, 2012; Park et al., 2013).

Resilience is further classified into two broad categories: a) *general (attribute-based) resilience* which refers to the state of the system that enables it to limit failure duration and magnitude to *any threat* (i.e. all hazards including unknowns) and b) *specified (performance-based)* resilience which refers to the agreed performance of the system in limiting failure magnitude and duration to a *given (known) threat* (Butler et al., 2014; Scholz et al., 2011). Reliability on the other hand is defined as the degree to which the system minimises the level of service failure frequency over its design life when subject to standard loading (Butler et al., 2014). Intuitively, it is argued that reliability and resilience are related with the latter extending and building on the former. It is consequently postulated that if resilience builds on reliability, by improving the former, the latter can also be improved (Butler et al., 2014).

Taking the UK water sector as an example, recent studies have proposed range of strategies or options for building resilience in UDSs (Cabinet Office, 2011; CIRIA, 2014; Mcbain et al., 2010). These strategies generally seek to enhance inbuilt system properties or attributes such as *redundancy* and *flexibility* during design, retrofit or rehabilitation so as to influence the ability of the system to withstand the level of service failure and to rapidly recover from failure once it occurs (Hassler and Kohler, 2014; Vugrin et al., 2011). Redundancy is defined as the degree of overlapping function in a system that permits the system to change in order to allow vital functions to continue while formerly redundant elements take on new functions (Hassler and Kohler, 2014). In UDSs, redundancy is enhanced by introducing multiple elements (components) providing similar functions for example storage tanks or parallel pipes, in order to minimise failure propagation through the system or to enable operations to be diverted to alternative parts of the system during exceptional loading conditions (Cabinet Office, 2011; Mugume et al., 2014). Flexibility on the other hand is defined as the inbuilt system capability to adjust or reconfigure so as to maintain acceptable performance levels when subject to multiple (varying) loading conditions (Gersonius et al., 2013; Vugrin et al., 2011). It can be achieved in UDSs, for example, by designing in future proofing options (Gersonius et al., 2013), use of distributed (decentralised) or modular elements for example distributed storage tanks, rainwater harvesting systems, roof disconnection and use of

Table 1
Failure modes in urban drainage systems.

Failure mode	Description	Examples/Causes
Functional failure	Hydraulic overloading due to changes in inflows leading to failure e.g. overflow operation, surcharging and surface flooding	Increase in dry weather flows, extreme rainfall events, excessive infiltration
Structural failure	Malfunctioning of single or multiple components in the system such as pumps, tanks or pipes leading to the inability of the failed component to deliver its desired function in full or in part	Pipe collapse, blockages, sediment deposition, solid waste, pump failure, rising main failure

designed multifunctional urban spaces such as car parks, playgrounds or roads (Mugume et al., 2014).

However, the operationalisation of resilience in urban drainage and flood management is still constrained by lack of guidelines, standards, and suitable quantitative evaluation methods (Butler et al., 2014; Ofwat, 2012; Park et al., 2013). In water distribution systems, a number of recent studies have investigated both *component (structural)* and *hydraulic* reliability when subject to stresses such as demand variations, single pipe failure and changes in pipe roughness (Atkinson et al., 2014; Trifunovic, 2012). In urban drainage systems however, most quantitative studies tend to focus on investigating *hydraulic reliability* which only considers *functional failures* such as occurrence of extreme rainfall or increasing dry weather flows (Sun et al., 2011; Thorndahl and Willems, 2008). The main short coming of such approaches is that the full system failure scenario space that includes other causes of surface flooding such as equipment failure, sewer collapse and blockage is not explored.

It is recognised that different threats or combinations of threats such as extreme rainfall or sewer failure could lead to the same failed state (i.e. surface flooding). Therefore, by only considering a narrow range of hydraulic failures, current approaches take a limited view of *functional resilience* with no due consideration given to *structural resilience*. Further research is needed to develop new quantitative approaches that explicitly consider all possible failure scenarios in order to holistically evaluate resilience in UDSs (Butler et al., 2014; Kellagher et al., 2009; Ofwat, 2012; Ten Veldhuis, 2010).

In this study, a new Global Resilience Analysis (GRA) approach is developed, that shifts the object of analysis from the threats themselves to explicit consideration of system performance (i.e. failed states) when subject to large number of failure scenarios (Johansson, 2010). Global Resilience Analysis has been carried out by evaluating the effect of a wide range of progressive structural failure scenarios in various systems such as water distribution systems and electrical power systems (Johansson, 2010). The GRA methodology is extended to investigate the effect of random cumulative link (sewer) failure scenarios on the performance of an UDS. The methodology is then applied to test the effect of implementing two potential adaptation strategies that is; introducing a large centralised detention pond or use of spatially distributed storage tanks on minimising loss of functionality during the considered structural failure scenarios.

The key strengths of the developed GRA method is that emphasis is shifted from accurate quantification of the probability of occurrence of sewer failures (e.g. Egger et al., 2013), to evaluating the effect of different sewer failures modes and extent, irrespective of their occurrence probability, on the ability of an UDS to minimise the resulting flooding impacts (e.g. Kellagher et al., 2009).

Link failure envelopes, which show the upper and lower limits (bounds) of the resulting loss of functionality for each considered link failure level are determined based on the hydraulic simulation results from 49,200 scenarios. The failure envelopes reflect vital system resilience properties that determine the resulting loss of functionality when the system is subjected to increasing failure levels. Finally, a new resilience index, Res_0 that quantifies system residual functionality as a function of failure magnitude and duration is computed at each failure level for both the existing system and for the tested adaptation strategies.

2. Methods

2.1. Global Resilience Analysis (GRA) approach

Global Resilience Analysis is applied to characterise the performance of an existing UDS when subject to a wide range of structural failure scenarios involving random cumulative link failure. Structural failure in an UDS can be modelled by removal of components for example sewers (links), storage tanks or pumps in the system to represent the inability of the removed component to deliver its prescribed function. In this study, links in an UDS are randomly and cumulatively failed and the resulting impacts on the global performance of the system are investigated at each failure level, until all the links in the system have been failed. This process of cumulative link failure is used to represent structural failure modes such as sewer collapse, blockages and sediment deposition in closed systems and blockage resulting from deposition of solid waste and washed-in sediments in open channel systems. The approach of failing links randomly ensures that all links, N in the system have an equal probability of being removed (Johansson and Hassel, 2012). In addition, a step by step increase in sewer failure levels enables the exploration of the full sewer failure scenario space that ranges from *predictable* or commonly occurring failure scenarios such as single component ($N - 1$), or two component ($N - 2$) failure modes but also other *unexpected* scenarios involving simultaneous failure of a large number of components (e.g. Johansson, 2010; Park et al., 2013).

To fully explore the extent of the failure scenario space in global resilience analysis, a very large number of model of simulations involving different failure scenarios would be required to capture the resulting flooding impacts (e.g. Kellagher et al., 2009). In addition, different possible sewer (link) states for example non-failed (good condition), partial or complete failure need to be evaluated (Ana and Bauwens, 2010; Kellagher et al., 2009). Taking an UDS with 81 links as an example, and assuming only two link states (non-failed or completely failed), the total number of link failure scenarios within the full failure scenario space would be 2.4×10^{24}. To reduce the computational time, a convergence analysis (Trelea, 2003) is carried out to determine the minimum number of random cumulative link failure sequences, rs_x that are required to achieve consistent results (refer to Supplementary information Section 1.1). Given the significant computational burden of GRA, a simple 1D approach to modelling of surface flooding (of the minor system) is proposed rather than using more complex 2D overland flow models (Digman et al., 2014; Maksimović et al., 2009).

2.2. GRA implementation

The GRA method is implemented in the MATLAB environment linked to the Storm Water Management Model, SWMMv.5.1; a physically based discrete time hydrological and hydraulic model that can be used for single event and continuous simulation of runoff quantity and quality, primarily built for urban areas (Rossman, 2010). Link failure can be modelled in SWMMv5.1 by either significantly reducing pipe diameters in the model (e.g. Mugume et al., 2014) or increasing the Manning's roughness coefficient, n to a very high value. In this study, link failure is modelled by increasing the Manning's n *from its initial (non-failed) state value* ($n = 0.020$) to a very high value ($n = 100$). The high value of n was chosen because it significantly curtails the conveyance of flows in each failed link and hence enables modelling of *complete failure* of each link.

Model simulations are carried out at each randomly generated link failure level and system performance is quantified using the total flood volume and mean duration of nodal flooding as key performance indicators. Surface flooding is simply modelled using the ponding option inbuilt in SWMM which allows exceedance flows to be stored atop of the nodes and to subsequently re-enter the UDS when the capacity allows (Rossman, 2010). The flooding extent at each node is modelled using an assumed ponded area of

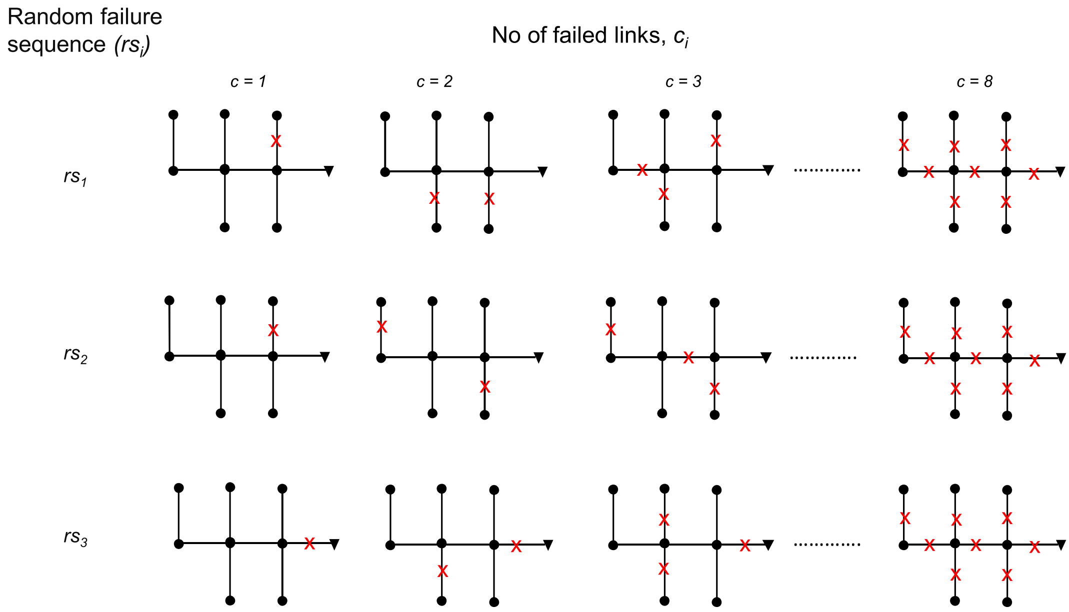

Fig. 1. Modelling framework for random cumulative link failure in a simplified urban drainage system with 8 links, 8 nodes and 1 outfall illustrating (a) random and increasing link failure levels c_1, c_2, c_3 … c_N and (b) three potential random failure sequences rs_1, rs_2 and rs_3.

7500 m^2. Fig. 1 further illustrates the adopted modelling framework. The main steps in implementing the GRA include:

a) A simulation is run to assess UDS performance in its initial (non-failed) state using the considered extreme rainfall loading
b) A randomly selected single link c_i: $i = 1, 2, 3, \ldots N$, in the UDS is failed and a simulation is run using the same extreme rainfall loading. This step represents single link failure mode and is denoted as $N - 1$.
c) Two randomly selected links, in the UDS are failed (denoted as $N - 2$ *failure mode*) and the simulation is repeated
d) The procedure is repeated for all $N - i$: $i = 1, 2, 3, \ldots N$ failure modes until all the links in the system have been failed.
e) The procedure in (a)–(d) is repeated to determine the minimum number of random failure sequences rs_x that ensures *convergence* of results. A detailed description of convergence analysis in GRA is presented in the Supplementary information Section 1.1).
f) Using the determined rs_x, the procedure in (a)–(d) above is repeated to investigate the effect of the proposed adaptation strategies on minimising the loss of system functionality resulting from the considered cumulative link failure scenarios.

2.3. Determination of link failure envelopes

The use of average values in reliability and resilience analysis simplifies results interpretation but can potentially hide key information about the range of possible failure impacts and consequences (Trifunovic, 2012). The process of determining failure envelopes provides a means of graphically illustrating the range of failure impacts at each considered failure level (e.g. Church and Scaparra, 2007). In this study, link failure envelopes are determined by computing the minimum and maximum values of all model solutions (total flood volume and mean duration of nodal flooding) obtained at each considered link failure level for the existing UDS and for the considered adaptation strategies. The resulting envelopes represent the upper and lower limits of the resulting loss of system functionality (impacts) that therefore provide vital information about the resilience properties of the system being tested. If the resulting envelope covers solutions with lower impacts at all link failure levels, then the resulting loss of system functionality is minimised during the considered failure scenarios. If the resulting envelope covers solutions with higher impacts and with a larger range between the minimum and maximum values, the tested system exhibits higher loss of system functionality during the considered failure scenarios (e.g. O'Kelly and Kim, 2007).

2.4. Computation of the flood resilience index

The resilience index, Res_o, is used to link the resulting loss of functionality to the system's residual functionality and hence the level of resilience at each link failure level. The resulting loss of

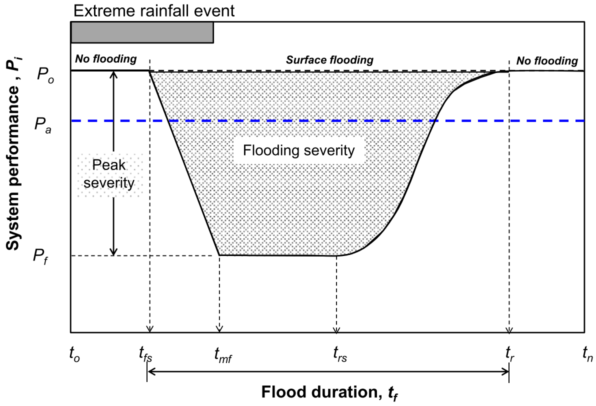

Fig. 2. Theoretical system performance curve for an urban drainage system. The black solid horizontal line, P_o represents the original (design) performance level of service. The blue dotted line, Pa represents a lower but acceptable level of service. P_f represents the maximum system failure level resulting from the considered threat. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

system functionality is estimated using the concept of *severity*, Sev_i (Hwang et al., 2015; Lansey, 2012). Severity is interpreted as a function of maximum failure magnitude (peak severity) and failure duration (Fig. 2). Fig. 2 illustrates the theoretical response of an UDS (in which one or more links have been failed) to a single extreme rainfall loading scenario. In Fig. 2, severity can be estimated as the (shaded) area between the original system performance level, P_o and the actual system performance curve, $P_i(t)$, at any time t after occurrence of a given threat that lead to system failure (Equation (1)).

$$Sev_i = f\left[Sev_p,\ t_f\right] = \frac{1}{P_o}\int_{t_o}^{t_n}(P_o - P_i(t))dt \tag{1}$$

Where t_f is the failure duration, t_o the time of occurrence of the threat, and t_n the total elapse time. Equation (1) above is further simplified by assuming that the system failure and recovery curve is rectangular (Equation (2))

$$Sev_i = \frac{V_{TF}}{V_{TI}} \times \frac{t_r - t_{fs}}{t_n - t_o} = \frac{V_{TF}}{V_{TI}} \times \frac{t_f}{t_n} \tag{2}$$

The resilience index, Res_o, which is a measure of system residual functionality, is estimated as one minus the computed volumetric severity and is computed at each link failure level (Equation (3)).

$$Res_o = 1 - Sev_i = 1 - \frac{V_{TF}}{V_{TI}} \times \frac{t_f}{t_n} \tag{3}$$

Where V_{TF} is the total flood volume, V_{TI} the total inflow into the system, t_f the mean duration of nodal flooding and t_n the total elapsed (simulation) time.

For a given threat (i.e. percentage of failed links), the proposed index quantifies the residual functionality of the UDS as function of both the failure magnitude (total flood volume) and duration (mean nodal flood duration). Res_o ranges from 0 to 1; with 0 indicating the lowest level of resilience and 1 the highest level resilience to the considered link failure scenarios. Resilience envelopes are then derived by plotting the minimum and maximum values of Res_o computed at each failure against the percentage of failed links. The resulting envelopes graphically illustrate the system residual functionality at each considered link failure level. A detailed description the theoretical behaviour of an UDS during failure conditions and the derivation of the Res_o is provided in Supplementary information Section 1.3.

3. Urban drainage system description and modelling results

3.1. Case study UDS

A case study of the existing urban drainage system in the Nakivubo catchment, a highly urbanised part of Kampala city, Uganda is used in this work. The system requires rehabilitation to minimise the frequency, magnitude and duration of flooding during extreme convective rainfall events (Sliuzas et al., 2013). A model of the existing system is built in SWMMv5.1. The full dynamic wave model in SWMM is used to route flows through the modelled UDS. The data needed to build the model has been obtained from a Digital Elevation Model (DEM) for Kampala (2 m horizontal resolution), a 2011 satellite image for Kampala (0.5 m horizontal resolution), as-built drawings and from existing reports (e.g. KCC, 2002). A single, non-areally adjusted extreme event was used to represent a worst functional loading case in the GRA. This event used was recorded on 25th June 2012 at 10 min resolution with a 100 min duration and depth of 66.2 mm (Sliuzas et al., 2013).

The existing primary and secondary conveyance system consists of trapezoidal open channel sections constructed using reinforced concrete in upstream sections and gabion walls in the downstream sections. The resulting hydraulic model of the system consists of 81 links, 81 nodes and 1 outfall, and with a total conduit length of 22,782 m. The system drains into the Nakivubo wetland and finally into Lake Victoria. The gradients of the open channel sections range from 0.001 to 0.0124. The modelled system drains a total area of 2793 ha delineated into 31 sub-catchments (Fig. 3). The computed average sub catchment slopes and percentage imperviousness values range from 0.034 to 0.172 (Fig. A.1) and 52.3–85.7 (Table A.1) respectively. The existing system is not always clean in a 'business as usual' case. This was reflected in the SWMM model by taking the initial value of *Manning's n* as 0.020 which is the upper limit of the recommended range (i.e. 0.010–0.020) for concrete lined channels.

3.2. Modelling the effect of adaptation strategies on UDS performance

Enhancing the resilience of an UDS during design or retrofit can be achieved by altering its configuration in order to enhance its redundancy and flexibility. ***Redundancy*** could be increased by introducing extra elements such additional storage tanks, temporary storage areas or increasing spare capacity in critical links (Butler and Davies, 2011; Cabinet Office, 2011; CIRIA, 2014). ***Flexibility*** on the other hand can be increased, for example, by designing in future proofing options, use of distributed elements and provision of back-up capacity (e.g. Gersonius et al., 2013). In this study, two adaptation strategies are modelled and tested using the GRA methodology namely, addition of one large centralised detention pond (*centralised storage strategy*) and several, spatially distributed storage tanks (*distributed storage strategy*) respectively (Fig. A.2).

In the *centralised storage* (CS) strategy, a large centralised detention pond with a total storage volume of 3.15×10^5 m^3 is introduced upstream of link C47 (Fig. A.2a) to enhance system redundancy. In choosing the possible location of the centralised storage tank, two main criteria were used; land availability and flow rates in the downstream links in the primary Nakivubo channel. In the *distributed storage (DS) strategy*, 28 spatially distributed upstream storage tanks with a combined total storage volume of 3.15×10^5 m^3 are introduced at the outlets of the sub

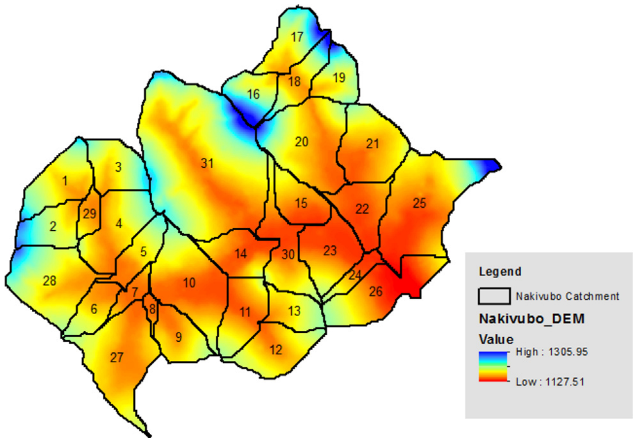

Fig. 3. Digital elevation model and delineated sub catchments in the Nakivubo catchment.

catchments to enhance flexibility in crucial points in the network (Fig. A.2b). The DS strategy models upstream distributed source control.

3.3. Simulation and performance assessment of the existing UDS

In order to test the performance of the modelled existing UDS, simulations were carried out and flows were investigated at selected links in the system (Fig. 4). The hydraulic data on the selected open channel cross sections is presented in Table A.2.

Lower peak flow rates, are simulated in most upstream links. The flow rates increase along the system leading to very high peaks in downstream links, for example flows of 297.4 m^3/s and 318.2 m^3/s are simulated at downstream links C76 and C81 respectively after an elapsed time of 75 min (Fig. A.3). Globally, 57 links (70.4%) in the system experience hydraulic overloading that consequently leads to surface flooding. Hydraulic overloading in links occurs when: (i) the upstream ends of the link run at full capacity and (ii) when the slope of the hydraulic grade line exceeds the slope of the link (Butler and Davies, 2011). The most severe hydraulic overloading is simulated in 26 links (32%), with the duration of hydraulic overloading ranging from 13 to 54 min.

The results of the simulation also indicate the system experiences flooding at a total of 57 nodes, representing a flood extent of 70.7%, with a total volume of flooding of 706, 045 m^3 and mean nodal flood duration of 48 ± 4 min.

3.4. Global Resilience Analysis of the existing UDS

The proposed GRA methodology described in section 2 is applied to characterise the performance of existing UDS. The overall performance of the system is quantified by simulating total flood volume and mean duration of flooding resulting from 16,400 link failure scenarios generated from 200 random link failure sequences (Fig. A.4). The average values of the total flood volume and duration of nodal flooding are computed for all the considered link failure scenarios and are presented in Fig. 5. The GRA results indicate that failure of just 10% of links leads to a disproportionately large increase of 91% in total flood volume (Fig. 5a). Thereafter, further increase in the percentage of failed links leads to comparatively small increases in the total flood volume.

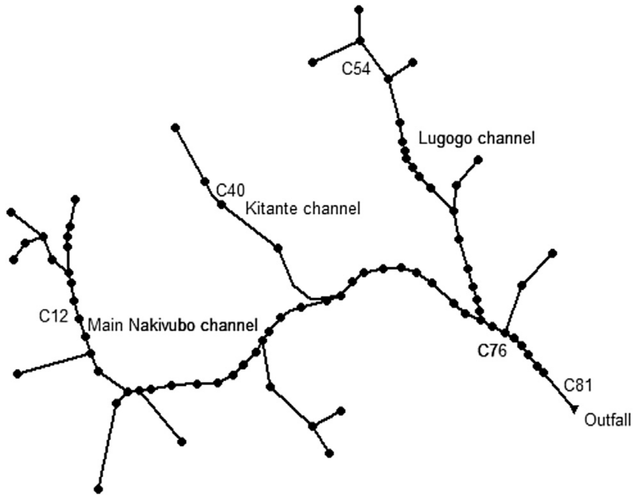

Fig. 4. Layout of the modelled Nakivubo urban drainage network.

The situation is very different for nodal flood duration, where results show failure of 10% of links leads to just a 6% increase (Fig. 5b). Globally, the results indicate that the failure duration increases from 41 min to 56 min representing an increase of 36.2% when all the links in the system are failed.

3.5. Effect of adaptation strategies on system performance

The GRA methodology is applied to test each of the proposed UDS adaptation strategies. An additional 16,400 link failure scenarios are simulated for the CS and DS strategies respectively that is, a total of 32,800 generated from a total of 400 random link failure sequences (Fig. A.4). The effect of the CS strategy is a slight reduction of flood volume which occurs at lower link failure levels (less than 60%) with very little impact on flood duration at all failure levels. Globally, it results in a 3.4% reduction of total flood volume and a 1.1% increase in mean duration of flooding (Fig. 5).

On the other hand, the DS strategy results in a significant reduction of the total flood volume (32%) at all considered link failure levels. At link failure levels greater than 20% any additional increase in link failure levels leads to minimal increase in total flood volume. The strategy also reduces the mean nodal flooding duration from 48 min to 35 min giving a reduction of 27% for all considered link failure scenarios. Table 2 details the key statistics of the GRA results for the existing system and for the considered resilience strategies.

3.6. Link failure envelopes

The resulting link failure envelopes which represent the range of model solutions from the lowest to the highest flooding impacts computed at each link failure level are presented in Fig. 6. For the existing UDS and considering the flood volume, a large range of deviation between the computed failure envelopes and the mean values (27–87%) is observed at lower link failure levels (<20%). A convergence of both failure envelopes is observed at higher link failure levels. The results from the nodal flood duration are different, and indicate a narrow range of deviation (<26.3%) between resulting failure envelopes and the mean values at all link failure levels. Rather similar ranges of deviation between the resulting flood volume and flood duration failure envelopes and the respective mean values are observed for the CS and DS strategies respectively.

In order to evaluate the effectiveness of the considered adaptation strategies, the generated link failure envelopes are plotted into one graph to map out the failure space common to all (Fig. 7). Comparing the results of the CS strategy to those of the existing system, a slight downward shift of both the maximum and minimum flood volume failure envelopes is observed at lower link failure levels (<40%), which represents the effect of the strategy in minimising the magnitude of flooding. However, there is no significant effect at higher link failure levels. Also, the results suggest that the CS strategy has minimal effect on the flood duration failure envelopes.

For the DS strategy, a significant downward shift in the flood volume failure envelope (i.e. a reduction in the magnitude of flooding) is observed at all cumulative link failure levels. The strategy limits further increase in flood volume when link failure levels exceed 33% (i.e. a flattening of the flood volume failure envelope is observed at higher link failure levels). The strategy also shifts the flood duration failure envelopes downwards (i.e. reduces the failure duration) for all considered link failure levels when compared the existing UDS.

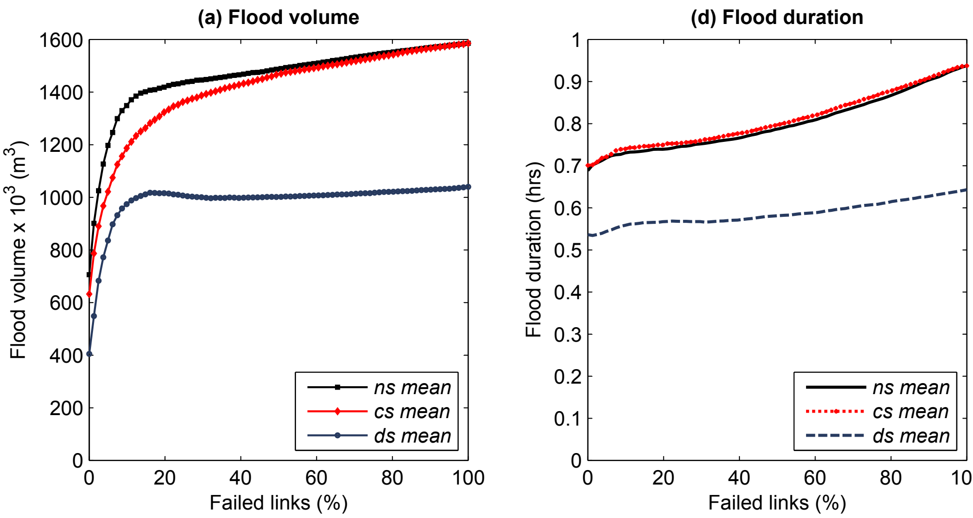

Fig. 5. Effect of cumulative link failure on (a) total flood volume (b) mean duration of nodal flooding for the existing UDS (*ns mean*), for the centralised storage strategy (*cs mean*) and for the distributed storage strategy (*ds mean*).

Table 2
Mean values of GRA results for all considered link failure scenarios. The values in the square brackets indicate the reduction range computed by considering 1 standard deviation of the mean.

Strategy	Flood volume (x10^3 m^3)			Mean nodal flood duration (hrs)		
	Mean, μ	Standard deviation, σ	% Reduction	Mean, μ	Standard deviation, σ	% Reduction
Existing system	1457.5	143.6		0.80	0.07	
Centralised storage	1408.8	183.4	3.3 [1.0–5.1]	0.81	0.07	−1.1 [−2.3 to −0.2]
Distributed storage	986.1	96.3	32.3 [29.9–34.1]	0.59	0.03	26.8 [25.6–28.4]

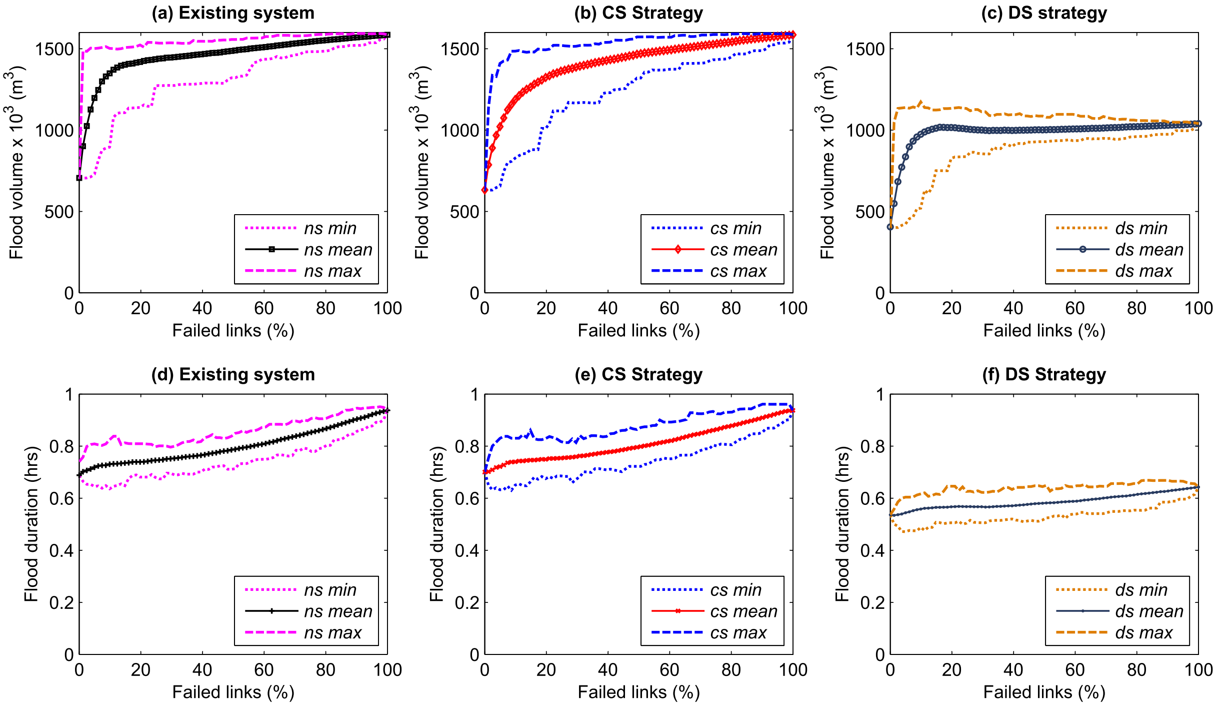

Fig. 6. Results of generated link failure envelopes for total flood volume (a)–(c) and for mean duration of nodal flooding (e)–(f) for the existing UDS and for the CS and DS strategies.

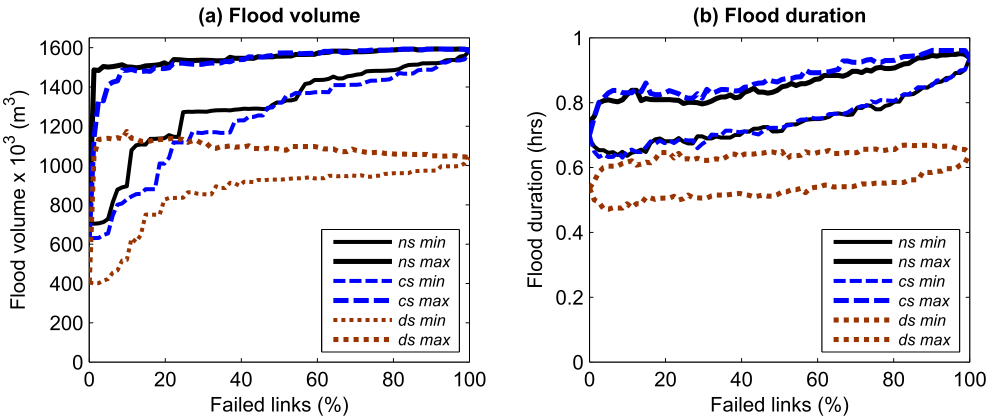

Fig. 7. Intersection of cumulative link failure envelopes for the existing system and for the CS and DS strategies.

3.7. *Resilience index*

The resilience index (Res_o) is computed using Equation (3). Based on the computed indices, resilience envelopes which represent the residual functionality of the whole UDS as a function of both the failure magnitude and duration are determined by computing the minimum and maximum values of Res_o at each link failure level for the existing system for the tested adaptation strategies (Fig. 8). To facilitate comparison of the performance of the tested strategies, an assumed acceptable level of resilience threshold of 0.7 is plotted on each of the graphs, as an example of the minimum acceptable flood protection level of service (for example no property flooding) that needs to be achieved by the considered adaptation strategies.

The figure reveals large variations in Res_o for the existing system and for the tested strategies at lower link failure levels (<20%) with a convergence of the results occurring with increasing link failure levels. For the existing UDS, the computed mean values of Res_o range from 0.54 to 0.66. When compared to the resilience threshold, the results indicate that the existing system crosses this threshold when link failure levels in system exceed 6.2%.

Considering the CS strategy, a slight improvement in Res_o of 1.2–2.3% is observed. The results indicate that resilience index falls below the threshold value when link failure levels exceed 8.6%. When the distributed storage strategy is considered, higher mean values of Res_o are computed (0.76–0.84). The results also indicate that for the DS strategy, the resilience threshold is not crossed at all link failure levels. Overall, the DS strategy leads to significant improvement in the Res_o of 27.5–41.4%.

4. Discussion of results

4.1. *Existing system*

Considering the existing system, random failure of less than 20% of the links leads to disproportionately high degradation of system functionality magnitude (i.e. total flood volume). The disproportionately high loss of system functionality suggests that failure of a small fraction of links rapidly reduces the global hydraulic conveyance capacity of the (minor) system. This result is also confirmed by critical component analysis (Johansson and Hassel, 2012) involving targeted failure of single (individual) links in the UDS (Refer to Supplementary information Section 1.1, Fig. S2) This therefore suggests that the existing UDS exhibits low levels of resilience to sewer failures. This could be attributed to the already insufficient hydraulic capacity of the system (due to use of an extreme rainstorm for modelling purposes) but could also be attributed to other key factors such as its dendritic network topology and limitations of using 1D modelling approach which excludes the contribution of the major system (i.e. effect of additional redundancies) in conveying surface flows to downstream parts of the system during extreme events.

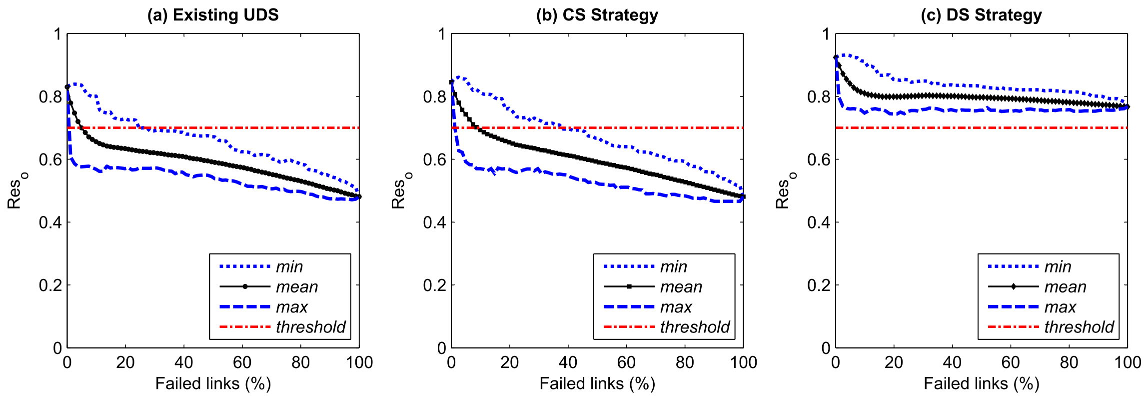

Fig. 8. Resilience envelopes showing maximum, mean, minimum values of Res_o computed at each link failure level for (a) existing UDS, (b) CS strategy and (c) DS strategy. The red dashed dot horizontal line is an assumed minimum acceptable resilience level of service threshold of 0.7. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

In contrast to the total flood volume, random cumulative link failure has a limited effect on mean nodal flood duration. This could be attributed to use of a single short duration rainfall event for the simulations as opposed to using multiple events. Similarly, this could also be attributed limitations of using a simplified above ground flood model. By using a simplified above-ground flood model, surface flooding which occurs in the major system (i.e. overland flood pathways such as roads, paths or grass ways) during extreme events and which may also cause substantial damage to property and infrastructure is not considered, which could also lead to inaccurate estimation of the mean flood duration (e.g. Digman et al., 2014; Maksimović et al., 2009).

4.2. *Effect of adaptation strategies*

It is argued that an effective adaptation strategy should result in a downward shift (i.e. towards the origin) of the failure envelope of the existing system. By doing this, the failure magnitude and duration is minimised across the considered failure scenarios. The derived link failure envelopes suggest that CS strategy has a very limited effect on minimising the total flood volume, with the reduction being achieved at lower link failure levels. More so, no significant effect on flood duration is observed at all considered link failure levels. As a consequence, the CS strategy only minimally improves the residual functionality of the existing system during the considered link failure scenarios. This therefore suggests that sewer failures could significantly limit the effectiveness of adaptation strategies involving enhancement of redundancy at a single location in the UDS. This also suggests that other preventive asset management strategies for example improved cleaning and maintenance practices may be more effective for resilience enhancement, because they in increase spare capacity in the links themselves and minimise structural failure in existing systems (e.g. Ten Veldhuis, 2010).

In contrast to the CS strategy, the study results suggest that the DS strategy is more effective in minimising the resulting loss of functionality at all link failure levels. This could be attributed to the effect of increased the spatial distribution of control strategies (i.e. smaller decentralised upstream storage tanks with the same total storage volume as the CS strategy) results in optimal use of the total storage volume for reduction both the storm water volume and the inflow rates before entry into UDS. Reducing the storm water inflows into the system in turn enables the degraded UDS to continue functioning with minimal impacts. It could also be due to a reduction in propagation of hydraulic failures from one part of the UDS to another, which suggests that the DS strategy improves the flexibility properties of the whole (minor) system. Using this argument, it could be suggested that adaptation strategies that increase the spatial distribution of control strategies in upstream parts of the catchment for example implementation of multifunctional (dual-purpose) rainwater harvesting (DeBusk, 2013) at a city district or catchment scale could significantly increase the resilience UDSs to sewer failures.

4.3. *Outlook*

The developed global resilience analysis approach presents a promising quantitative tool which opens up new opportunities for holistic and systematic evaluation of the effect of a wide range of threats that have not been considered in conventional hydraulic reliability based urban drainage design and rehabilitation approaches. Future research will compare the results obtained by the presented GRA method with those obtained by using dual-drainage (1D–1D) or 2D rapid flood spreading models (e.g. Blanc et al., 2012; Maksimović et al., 2009) in GRA to account for the effect of the major system in providing additional system redundancies during flooding conditions.

Additionally, the following areas are recommended for further research.

- Investigation of the influence of inherent/inbuilt UDS characteristics for example network structure, network size (number of links), pipe diameters, pipe gradients on resilience to structural failures.
- Investigation of the effect of other types of component failures (e.g. pump failures) on global resilience in UDSs.
- Investigation of the linkages and interdependences between UDS failure (flooding) and unexpected failures in interconnected systems such as electrical power systems.
- Further investigation aimed at linking the computed resilience indices to new resilience-based flood protection level of service standards that are based on minimisation of the magnitude and duration flooding as opposed to use of design return periods.

5. Conclusions

This research has tested and extended the global resilience analysis (GRA) methodology to systematically evaluate UDS system resilience to random cumulative link (sewer) failure. The GRA method presents a new and promising approach for performance evaluation of UDSs that shifts emphasis from prediction of the probability of occurrence of key threats that lead to flooding (*the fail-safe approach*) to evaluating the effects of a wide range of failure scenarios that not only includes functional failures but also structural or component failures which also contribute to flooding in cities (*the safe-fail approach*).

In this study, the effect of a wide range of random and progressive link failure scenarios on the ability of existing and adapted UDSs to minimise the resulting loss of functionality has been investigated. Link failure envelopes have been determined by computing the minimum and maximum values of the total flood volume and mean nodal flood duration results generated by simulating a large number of random cumulative link failure scenarios. A new resilience index has been developed and used to link the resulting loss of functionality to the system's residual functionality at each link failure level. Based on the results of the study, the following conclusions are drawn.

- The presented global resilience analysis approach provides a promising quantitative evaluation tool that enables consideration of wide range of possible sewer failure scenarios ranging from *normal* to *unexpected* with reduced computational complexity.
- The use of convergence analysis enables determination of the minimum number of random cumulative link failure sequences require to achieve consistent GRA results, which in turn enhances that practicability of resilience assessment by significantly reducing the computational complexity involved in simulating all possible sewer failure combinations.
- Building resilience in UDSs to unexpected failures necessitates explicit consideration of the contribution of different failure modes, effect of interactions between different failures modes for example interdependences between sewer failures and hydraulic overloading in UDS design or performance evaluation of existing systems.
- Building resilience in UDSs should not only be addressed through capital investments aimed at enhancing inherent UDS properties such as redundancy and flexibility but should also consider investments in asset management strategies such as improved cleaning and maintenance of existing UDSs.

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Appendix A. Supplementary data

Supplementary data related to this article can be found at http://dx.doi.org/10.1016/j.watres.2015.05.030.

Appendix

Table A.1
Sub catchment area and computed percentage imperviousness.

Sub catchment ID	Sub catchment area (ha)	Imperviousness (%)
S1	83.6	69.9
S2	59.5	71.3
S3	69.0	67.2
S4	97.2	84.1
S5	52.0	81.1
S6	46.1	76.6
S7	23.8	82.7
S8	10.2	66.2
S9	60.0	72.4
S10	144.4	72.0
S11	76.1	71.5
S12	81.4	71.1
S13	50.0	79.6
S14	67.3	75.3
S15	57.4	70.7
S16	55.4	52.3
S17	67.9	61.5
S18	52.9	56.6
S19	52.3	66.7
S20	158.8	61.5
S21	108.5	71.6
S22	71.0	78.2
S23	89.1	82.1
S24	25.4	85.7
S25	199.9	68.1
S26	115.7	62.7
S27	147.5	80.7
S28	134.4	75.8
S29	23.1	81.1
S30	88.7	69.1
S31	424.4	73.0
Total Area	2,793.2	

Table A.3
Distributed storage tank volumes.

Storage tank ID	Volume (m^3)
ds1	9,433
ds2	6,711
ds3	7,782
ds4	10,956
ds567	13,743
ds8	1,151
ds9	6,770
ds10	16,287
ds11	8,582
ds12	9,181
ds13	5,639
ds14	7,591
ds16	6,243
ds17	13,623
ds19	5,899
ds20	17,906
ds21	12,239
ds22	8,011
ds23	10,052
ds24	2,859
ds25	22,547
ds26	13,051
ds31	47,864
ds30	10,000
ds29	2,609
ds28	15,160
ds27	16,636
ds15	6,474

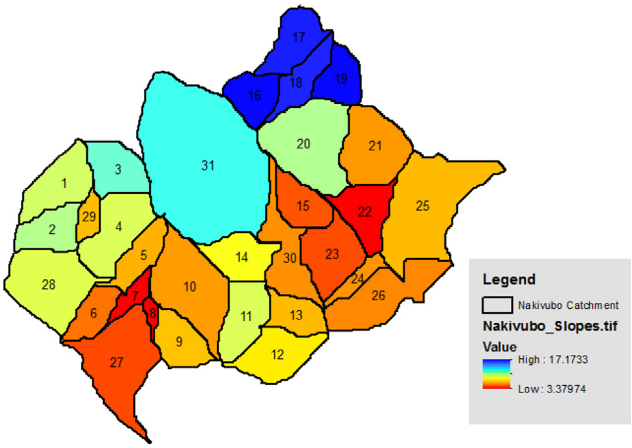

Fig. A.1. Computed Nakivubo sub catchment slopes.

Table A.2
Hydraulic data of selected trapezoidal open channel sections in the Nakivubo UDS. The slope values represent ratios of horizontal to vertical distance.

Link	Length (m)	Depth, d (m)	Bottom width, b (m)	Left slope	Right slope	Equivalent pipe diameter, D_e (m)
C12	100.0	1.8	4.3	0.743	0.743	3.5
C40	290.0	2.5	1.0	1.000	1.000	3.3
C54	512.6	1.5	1.0	0.667	0.667	2.0
C76	400.0	4.3	17.4	0.040	0.040	9.8
C81	400.0	2.0	26.0	1.375	1.375	8.6

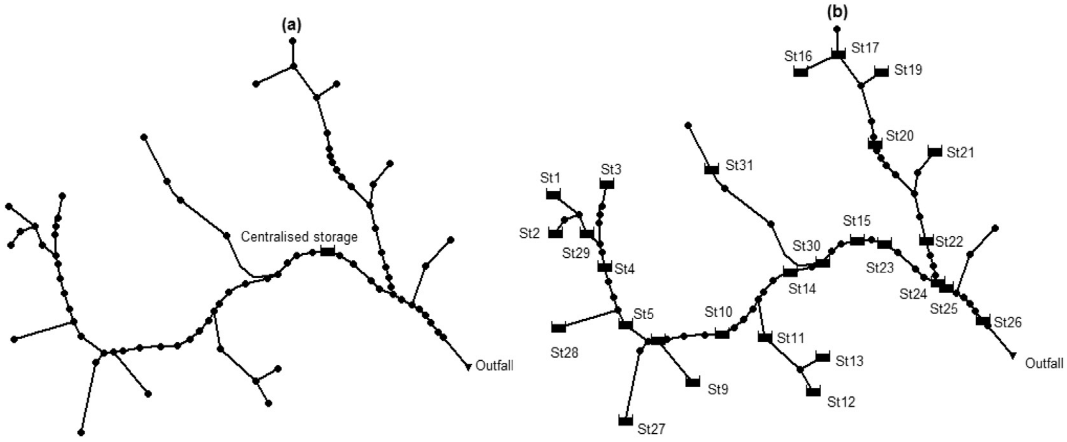

Fig. A.2. Layout of adapted UDS (a) centralised storage (CS) and (b) upstream distributed storage (DS) strategy.3

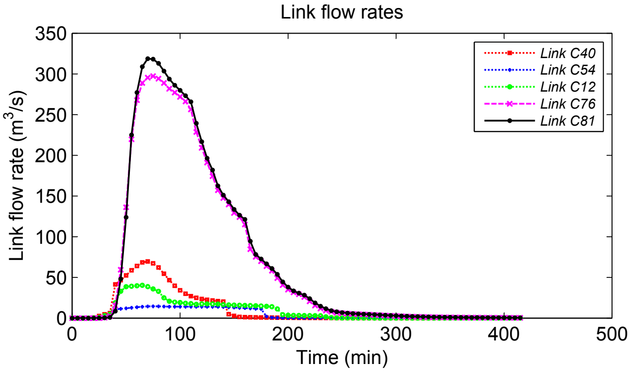

Fig. A.3. Simulated flows in the Nakivubo UDS for upstream links C12, C40, C54 and downstream links C76 and C81.4

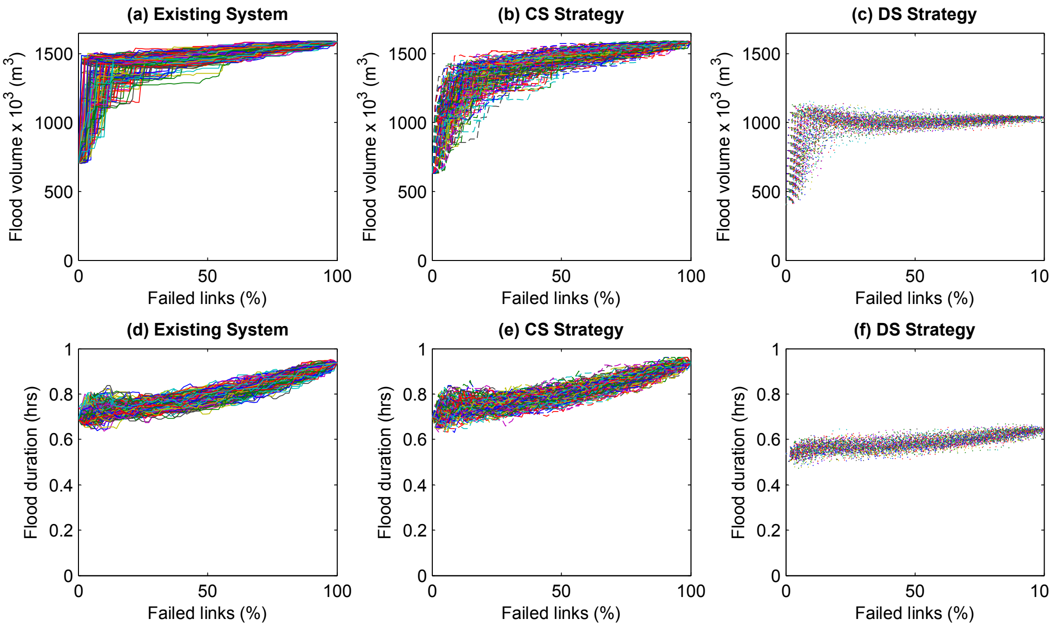

Fig. A.4. Effect of random cumulative link failure on total flood volume (a–c) and mean nodal flood duration (d–f). 200 random link failure sequences (16,400 random link failure scenarios) are simulated for the existing UDS (ns_i: $i = 1,2,3 \ldots 200$), for the CS Strategy (cs_i: $i = 1,2,3 \ldots 200$) and for the DS Strategy (ds_i: $i = 1,2,3 \ldots 200$). In total, 49,200 link failure scenarios are simulated.

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