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RESEARCH ARTICLE

Evaluation of functional resilience in urban drainage and flood management systems using a global analysis approach

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ABSTRACT
Enhancing resilience in urban drainage systems (UDSs) requires new evaluation approaches that explicitly consider vital interactions between threats, system performance and resulting failure impacts during both normal and unexpected (exceptional) loading conditions. However, current reliability-based approaches only focus on prevention of functional (hydraulic) failures resulting from a specified design storm. In this study, the global resilience analysis (GRA) approach is further extended for evaluation of UDS performance when subject to a wide range of random functional failure scenarios (extreme rainfall) with varying magnitude, duration, and spatial distribution. The resulting loss of system functionality during the simulated failure scenarios is quantified using total flood volume and mean flood duration. System residual functionality for each considered rainfall block loading scenario is quantified using the functional resilience index. The developed approach has been successfully applied to test and characterise the functional resilience to extreme rainfall of an existing UDS in Kampala city, Uganda. The study concluded that: (1) UDS functional resilience is significantly influenced by both occurrence of short duration, high intensity rainfall events and spatial rainfall variation during extreme rainfall conditions and (2) future planning and design of resilience enhancement strategies should apply spatially distributed rainfall inputs to facilitate effective sizing of potential adaptation strategies.

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Global resilience analysis; hydraulic failures; pluvial flooding; spatial rainfall distribution

1. Introduction

The performance of existing urban drainage systems (UDSs) in various cities is increasingly threatened by multiple and uncertain threats such as climate change, rapid urbanisation and infrastructure failure that lead to catastrophic flooding impacts and consequences such as loss of lives or damage to property and critical infrastructure (Djordjević *et al*. 2011, IPCC 2014, Hammond *et al*. 2015). Conventional hydraulic reliability-based urban drainage design and rehabilitation approaches focus on minimising the probability of occurrence of hydraulic failures resulting from a given design rainstorm as a basis for determining the flood protection level of a given system (Thorndahl and Willems 2008, Butler and Davies 2011, Sun *et al*. 2011). However, in view of emerging threats, it is now recognized that UDSs should be designed not only to be reliable during normal (standard) conditions but also resilient to unexpected (exceptional) loading conditions (Park *et al*. 2013, Butler *et al*. 2014, Mugume *et al*. 2015).

The concept of *resilience* has been extensively developed in the field of ecology as a measure of a system's ability to maintain the system's basic structure and function (system integrity) under dynamic or non-equilibrium conditions (Holling 1996). In contrast to ecological resilience, engineering resilience seeks to ensure that a given system provides continuous or uninterrupted services to society during both normal and unexpected loading conditions in an efficient manner (Ahern 2011, Lansey 2012, Park *et al*. 2013, Butler *et al*. 2014). *Resilience* is formally defined as '*the degree to which the system minimises the level of service failure magnitude and duration over its design life when subject to exceptional conditions*' (Butler *et al*. 2014).

However, operationalization of resilience concepts in urban drainage and flood management systems has been constrained by lack guidelines, standards and suitable quantitative evaluation methods (Ofwat 2012, Park *et al*. 2013, Butler *et al*. 2014, Mugume *et al*. 2015). Consequently, development of new evaluation approaches that can enable systematic evaluation of resilience of urban drainage and flood management systems to extreme events (surprises) that lead to flooding is a subject of current research (Mugume *et al*. 2014, 2015).

In recent work, it is argued that effective characterisation of a given system's general resilience (i.e. state of system that enables it to limit failure magnitude and duration to any threat) requires explicit consideration of effects of all possible threats (causes) or combinations of threats on its performance (Kellagher *et al*. 2009, Hepworth 2015, Mugume and Butler 2015, Mugume *et al*. 2015). In addition, interactions between the *threats*, *system performance* (failed state) and the resulting *failure impacts* should be systematically evaluated (Kellagher *et al*. 2009, Ten Veldhuis

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2010, Butler *et al*. 2014, Mugume *et al*. 2015). Potential failures in UDSs are broadly categorised as: (a) functional failure which results from hydraulic overloading of the system for example due to occurrence of extreme rainfall, increased dry weather flows or excessive infiltration and (b) structural failure which results from malfunction of system components (Mugume *et al*. 2015).

In this research, the global resilience analysis (GRA) approach (Johansson 2010) is extended to investigate the effect of a wide range of functional failure scenarios resulting from extreme rainfall on the ability of an UDS to minimise the resulting loss of system functionality magnitude and duration (pluvial flooding). Pluvial flooding typically occurs when exceptional rainfall with intensity greater than 20–25 mm/hr occurs over very short durations (≤3 h) and leads to functional failure of an UDS due to exceedance of the flow conveyance capacity of the minor system or if the inlet capacity is insufficient to capture the surface runoff (Maksimović *et al*. 2009, Ten Veldhuis 2010, Houston *et al*. 2011). It can also occur following lower intensity rainfalls (~10 mm/hr) over longer durations, especially if the ground surface is highly impermeable (Houston *et al*. 2011).

In order to reliably and realistically evaluate the effect of a wide range of functional failure scenarios on the resulting magnitude and duration of surface flooding, a computationally efficient method of modelling the effect of spatial rainfall distribution (variation), which causes non-uniform system hydraulic loading mostly during convective rainstorms is required (Kellagher *et al*. 2009, Butler and Davies 2011, Chen and Djordjević 2012). However, most urban drainage design/modelling studies apply point rainfall as uniform input over the catchment or use areal reduction factors (ARFs) to account for the differences between point and catchment averaged rainfall volumes. Use of areally reduced point rainfall may lead to inaccurate quantification of the resulting flooding impacts particularly in large urban catchments where the effect of spatial rainfall variation is considered to be significant (Einfalt *et al*. 2004, Vaes *et al*. 2005, Achleitner *et al*. 2009, Kellagher *et al*. 2009, Butler and Davies 2011).

In a limited number of recent urban drainage modelling studies, the effect of spatial rainfall distribution on the resulting flooding impacts has been investigated using two main approaches: (a) use of radar rainfall data and (b) stochastic rainfall models (Einfalt *et al*. 2004, Achleitner *et al*. 2009, Kellagher *et al*. 2009, Blanc *et al*. 2012, Chen and Djordjević 2012). On the one hand, widespread use of radar rainfall data in real-world applications is still constrained by insufficient (i.e. short) observed radar rainfall data sets, uncertainties or biases in radar estimates of extreme rainfall, heterogeneities in recorded radar data sets (due to continuous improvements in data processing algorithms) and other organisational constraints (Einfalt *et al*. 2004, Svensson and Jones 2010). On the other hand, although arguably more promising when compared to radar data, the direct use of stochastic rainfall model data (continuous spatial rainfall data) in urban flood modelling studies has also been constrained by significant computational burden (time/resources) required to run the simulations, need for additional pre-processing of the generated rainfall data to identify/filter significant events and unresolved inaccuracies in mathematical modelling of non-stationary local convective rainstorms patterns (Kellagher *et al*. 2009, Chen and Djordjević 2012, Willems *et al*. 2012). Consequently, new and computationally efficient approaches that enable the practical use of spatially varying rainfall in real-world UDS resilience evaluation are required.

In this study, the developed GRA method applies rainfall blocks derived from observed extreme rainfall data (Intensity-Duration-Frequency curves) to evaluate the effect of spatial rainfall distribution on UDS performance during extreme rainfall loading conditions. Using the developed methodology, the following key research questions are investigated:

(a) What is the effect of a change in the functional loading *magnitude* on the ability of the UDS to maintain its functionality?
(b) What is the effect of a change in the functional loading *rate* on the ability of the UDS to minimise the resulting flooding impacts?
(c) How does the *spatial rainfall distribution* affect the performance behaviour of an UDS during extreme rainfall events?

To address these research questions, rainfall blocks with varying magnitudes and intensity derived from a set of Intensity-Duration-Frequency (IDF) curves are used to represent the functional loading scenarios at various return periods. To model the effect of spatial rainfall distribution over the catchment, individual sub-catchments are randomly and increasingly loaded (i.e. 'failed') with the selected rainfall blocks until all the sub catchments in the case study have 'failed'. The process of random and cumulative extreme rainfall loading of the sub-catchments simply represents the stochastic and distributed nature of rain cell arrivals over the catchment. It also models the effect of storm movement across the catchment (e.g. due to changes in wind direction in a convective storm) on the performance of the UDS (Vaes *et al*. 2005).

The developed GRA method is applied to quantify the effect of a large number of random cumulative functional failure scenarios on UDS performance. System performance (loss of functionality) is quantified at each sub-catchment 'failure' level using two key performance indicators that is: total flood volume and mean nodal flood duration. Based on the results of the analysis, sub-catchment failure envelopes which represent the resulting loss of system functionality (impacts) at each sub-catchment 'failure' level are determined by computing the upper and lower limits of the model solutions obtained from simulations involving a total of 51,200 sub catchment failure scenarios derived from 1600 random cumulative sub catchment failure sequences, rs_i. Finally, the resilience index, Res_f, which quantifies system residual functionality (hence the level of functional resilience) as a function of the failure magnitude and duration, is computed for each considered rainfall block loading scenario (Mugume *et al*. 2015). The computed resilience indices can be compared with the existing UDS's design functional resilience index to determine whether occurrence of each considered rainfall block loading scenario leads to exceedance of its design flood protection level of service.

2. Methods

A case study of the Nakivubo UDS that drains the Nakivubo catchment, a highly urbanised central business district in Kampala, Uganda is used in this research (Mugume *et al*. 2015). A model of the existing system (Figure 1) has been built using the Storm Water Management Model (SWMMv5.1) and is described in detail in Mugume *et al*. (2015).

The hydraulic model of the system consists of 81 links, 81 nodes and one outfall, with a total conduit length of 22,782 m (Figure 1). The modelled system drains a total catchment area of 2793 hectares, delineated into 31 sub catchments and drains into the Nakivubo wetland and finally into Lake Victoria. The computed areas for the respective sub catchments range from 10.4 ha to 424.4 ha while the percentage imperviousness levels for the respective sub catchments range from 52.3 to 85.7.

The system was designed for a flooding return period of 10 yrs (KCC 2002). However, during the last 10 years, the frequency, magnitude and duration of flooding incidences during extreme convective rainfall events have increased and led to negative consequences such as property damage, traffic disruption, shallow ground water contamination and structural failure of the existing paved road network (UN-Habitat 2009, Lwasa 2010).

2.1. IDF curves and design storms

In this research, rainfall frequency analysis for Kampala city, Uganda is carried using the Annual Maximum Series (AMS) method (Butler and Davies 2011). The total number of available daily rainfall observation years for the considered rain gauge stations is as follows: Makerere University (19), City Hall (30) and Kampala municipality (51). Because the observations have been recorded over a relatively short period of time (≤51 years) for reliable estimation of extreme rainfall with higher return periods (e.g. $T = 25$, 50 and 100 yrs), using the available data sets, the AMS method was applied to determine the $T = 2$ yr rainfall depths where the prediction accuracy is high. Thereafter, a generalised Gumbel equation is applied to determine the 24 h point rainfall for $T = 5$, 10, 25, 50 and 100 yrs. Temporal disaggregation is carried out to determine rainfall depths and intensities for $t = 15$ min, 30 min, 1 h, 2 h, 4 h, 6 h and 12 h using existing rainfall depth-duration relationships for Kampala (Equations (1) and (2)) which relate the average rainfall intensity, I_R (mm/hr) to the duration, t (hr) for a given return period for Kampala (Fiddes *et al*. 1974, MoWT 2010). The rainfall depth-duration relationships were developed in comprehensive study that was aimed at developing simplified methods for prediction of rainstorms for design of drainage structures in East Africa including Kampala city (Fiddes *et al*. 1974, MoWT 2010).

$$I_R = \frac{a}{(t+b)^c} \tag{1}$$

Where a, b and c are constants, with $b = 0.33$ and $c = 0.95$ (Fiddes *et al*. 1974).

By eliminating a, Equation (1) can be simplified into Equation (2).

$$R_T = \frac{t}{24}\left(\frac{24+b}{b+t}\right)^c \times R_d \tag{2}$$

Where R_T is the rainfall depth for any duration, t, R_d is the 24 h rainfall.

Based on the analysis results, IDF curves are derived by plotting a graph of rainfall intensity, I_R against duration, t for the respective return periods (Figure 2).

2.2. Functional loading scenarios

In contrast to application of uniform spatial rainfall loading over the whole catchment, *rainfall blocks* are applied randomly and progressively to the sub-catchments using the GRA method that is described in detail in Section 2.3. The rainfall blocks have a constant intensity over their duration, t that is greater than or equal to the time of concentration, t_c, and are consequently chosen for subsequent resilience analysis. For a given duration and return period, each block rainstorm represents an engineering 'worst case' functional loading scenario (Butler and Davies 2011). Consequently, it is argued that using rainfall blocks for UDS model simulations enables assessment of maximum loss of system functionality (i.e. hydraulic overloading) for a given return period and duration. The main steps taken to derive the

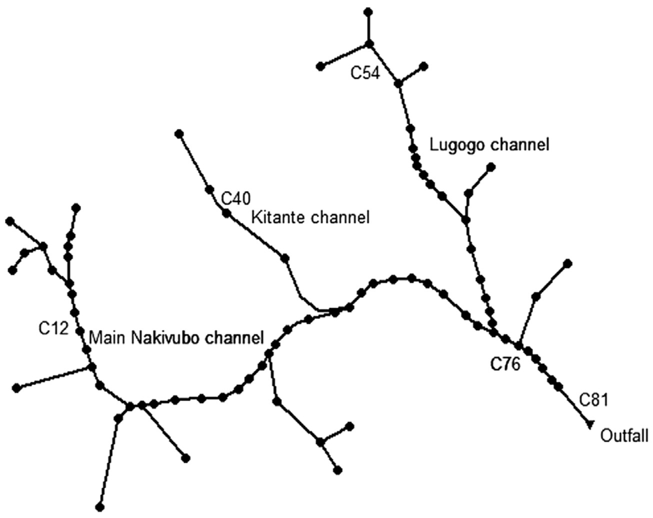

Figure 1. Layout of the modelled Nakivubo urban drainage network.

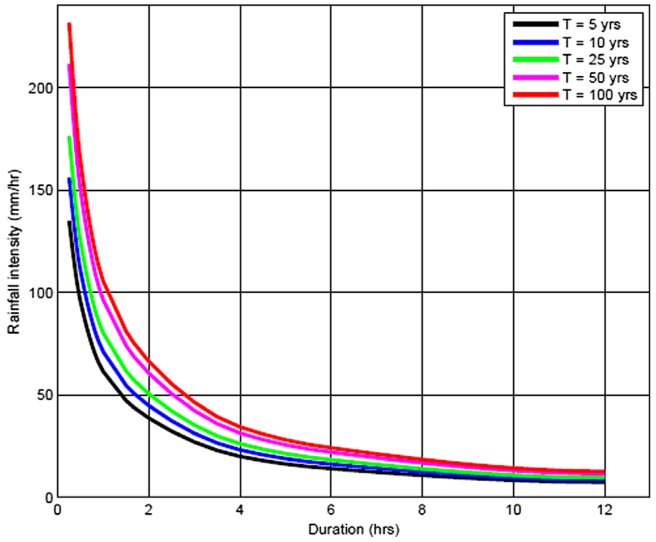

Figure 2. Derived intensity-duration-frequency curves for Kampala.

rainfall blocks include: (a) computation of the time of concentration, t_c, and (b) derivation of rainfall blocks as a function of constant rainfall intensities (read off the IDF curves) and time $t : t > t_c$.

2.2.1. Computation of time of concentration, t_c for Nakivubo UDS

The time of concentration, t_c is defined as the time required for run-off to travel from the most hydraulically distant point in the catchment to point under consideration (NRCS 1986, Butler and Davies 2011). The time of concentration therefore represents the critical storm duration above which the catchment to operate at steady state (equilibrium) conditions and consequently to generate maximum flows (Butler and Davies 2011). In this study, the t_c is estimated using the TR-55 method, which is recommended for large urban catchments (NRCS 1986). A detailed description of the main steps taken in the computation of t_c is provided in Supplementary information Section 1.2.

The time of entry and average time of flow are computed as 13.1 min and 52.1 min respectively (i.e. t_c = 65.2 min). It is however noted that the computed value of t_c for the Nakivubo catchment is rather short considering a total contributing area of 2793 ha. However, this is attributed to the steep sub catchment slopes, high imperviousness levels (52.3–85.7%) and urbanisation effects that have increased channelization of the previously natural drainage system leading to high channel flow velocities (Sliuzas *et al*. 2013). Based on these results, a duration of 70 min is taken as the critical storm duration for subsequent functional resilience analysis.

2.2.2. Derivation of rainfall blocks

Two sets of rainfall blocks graphically illustrated in Figure 3 are chosen that is: $t = 2t_c$ (140 min) and $t = t_c$ (70 min). The rainfall blocks are derived by reading off corresponding intensities, I_R from the IDF curves at t = 140 min and t = 70 min respectively for various rainfall return periods T = 5, 25, 50 and 100 yrs. The rainfall block durations, t are chosen such that $t \geq t_c$ to ensure that UDS performance is assessed at steady state (equilibrium) conditions (Butler and Davies 2011). The derived 70 min rainfall blocks have higher rainfall intensities (63%) but slightly lower total rainfall depths (19%) when compared to the 140 min block rainstorms.

2.3. GRA and convergence analysis

2.3.1. GRA implementation

Global resilience analysis is applied to characterise the performance of an existing UDS when subject to a wide range of functional failure scenarios resulting from extreme rainfall.

Functional failure is modelled by random and cumulative loading of the sub catchments with the derived rainfall blocks to represent system hydraulic overloading that leads to surface flooding. The adopted approach of random and cumulative 'failure' of sub catchments models the effect of spatial rainfall distribution (variation) over the catchment, which leads to spatially

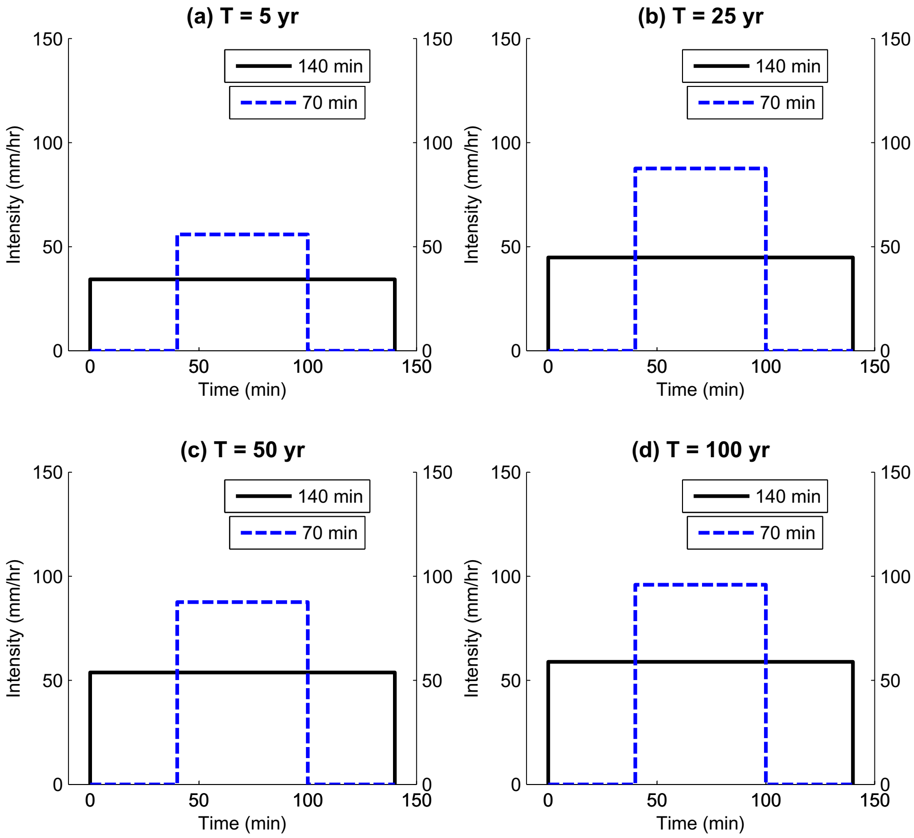

Figure 3. 140 min rainfall blocks derived from rainfall intensities corresponding to various rainfall return periods, T = 5, 25, 50 and 100 years (derived from an IDF curve for Kampala). The dashed lines show the corresponding rainfall blocks derived from the IDF curves at t = 70 min.

non-uniform hydraulic loading in the UDS. For each sub catchment, two system states are considered:

(a) Non-failure: The sub catchment is loaded with an insignificant (dummy) rainfall block (constant I_R = 6 mm/hr, t = 100 min) that does not cause flooding at any of the nodes in the UDS.
(b) Failure: The sub catchment is loaded ('failed') with a specified rainfall block (Figure 3) that leads to hydraulic overloading of the links and flooding in parts of UDS.

Given the significant computational burden involved in simulating such a large number of scenarios, the minimum number of sub catchment failure sequences, rs_x necessary to achieve consistent GRA results is determined using convergence analysis (Trelea 2003, Mugume *et al*. 2015). In addition, a simple 1D modelling of surface flooding (i.e. nodal flooding of the minor system) is applied to enhance computational efficiency of GRA, rather than using more complex 2D overland flow models which require immense computational resources (simulation time and computer power).

Model simulations are carried out in a MATLAB environment linked to the Storm Water Management Model (SWMM v5.1) to quantify the UDS performance at each failure level, using total flood volume and mean nodal flood duration as system performance indicators. A time period of 7 h is used for the wet weather simulation to ensure that the maximum flows and consequently the maximum total flood volume and duration resulting from the respective rainfall blocks is quantified. Surface flooding is 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 system when the capacity allows (Rossman 2010). The main steps taken in applying the GRA approach include:

(a) A simulation is run to quantify the initial state performance of the UDS i.e. with all sub catchments in a non-failure state.
(b) A randomly selected sub-catchment, $S_w : w = 1, 2, 3 \ldots S_w$ is 'failed' and a simulation is run to quantify the UDS performance, where S_w is the total number of sub catchments.
(c) In the next iteration, two randomly selected sub-catchments are 'failed' and a second simulation is run.
(d) The procedure is repeated by running simulations at each failure level until all the sub-catchments, S_N in the catchment area have been failed.
(e) Convergence analysis is carried out by repeating the procedure in (a)–(d) for a range of random sub-catchment failure sequences rs_i for i = 1, 2, 3 … m; where m is the minimum number of rs_i that should be evaluated to achieve consistent GRA results. The study results suggest that at least 200 random failure sequences are sufficient (Refer to Section 2.3.2).
(f) The minimum, mean and maximum values of all model solutions (total flood volume and mean nodal flood duration) are computed at each considered sub catchment failure level and used to derive the resulting sub catchment failure envelopes. The envelopes represent the upper and lower limits of the resulting loss of functionality.
(g) The procedure described in (a)–(d) and (f) is then carried out for other rainfall blocks calculated for rainfall return periods of T = 5, 25, 50 and 100 years.

In addition, the GRA results are compared with simulation results obtained by applying an areal reduction factor (ARF) computed for the Nakivubo catchment to the derived design storm profiles for each return period (Figure S1). In this study, an ARF factor of 0.9 for the Nakivubo catchment is applied. The ARF is computed using Equation (3) specified in the 'Wallingford Procedure' (Butler and Davies (2011).

$$ARF = 1 - f_1 D^{-f_2} \tag{3}$$

Where:

$$f_1 = 0.0394A^{0.354}$$

$$f_2 = 0.040 - 0.0208 \ln(4.6 - \ln A)$$

And A is the catchment area in km^2 and D the storm duration.

2.3.2. Convergence analysis

To fully explore the sub-catchment failure scenario space, a large number of simulations is required. For the Nakivubo catchment, which is delineated into 31 sub catchments, and assuming the two system states above, the full failure scenario space would be $2^{31} = 2.15 \times 10^9$ failure combinations.

Given the significant computational burden involved in simulating such a large number of scenarios (i.e. considering all sub catchment failure scenarios), the minimum number of sub catchment failure sequences, rs_x necessary to achieve consistent GRA results is determined using convergence analysis (Mugume *et al*. 2015). Convergence analysis is carried out by implementing the following key steps.

(a) GRA is carried out using 5 random sequences (i.e. 5(N+1) failure scenarios) and the mean values of the total flood volume are determined.
(b) The procedure is repeated for 10, 25, 50, 100, 150 and 200 random failure sequences that is: 10(N+1)*;* 25(N+1)*;* 50(N+1)*;* 100(N+1)*;* 150(N+1) *and* 200(N+1) failure scenarios respectively.
(c) The percentage deviation, PD between the computed mean values is computed for each step-wise increase in rs_i, for i: i = {5, 10}; {10, 25}; {25, 50}, {50, 100}, {100, 150} and {150, 200}. If PD reduces to less than 5%, after the specified maximum number of random failure sequences (i.e. 200 in this case), then the GRA results are considered to have converged. If this is not the case, then rs_x is increased and the procedure is repeated. The study results suggest that at least 200 random sub catchment failure sequences, i.e. 200 x 32 = 6400 sub catchment failure scenarios should be simulated for each block rainfall event (Figure 4).

In this research, it is considered that the quick reduction in the percentage deviation of the mean values to less than 5% (with increasing number of random failure scenarios considered) indicates convergence of the distribution (e.g. Trelea 2003). Further research is recommended further validate this assertion using multiple case studies with varying sub catchment parameters.

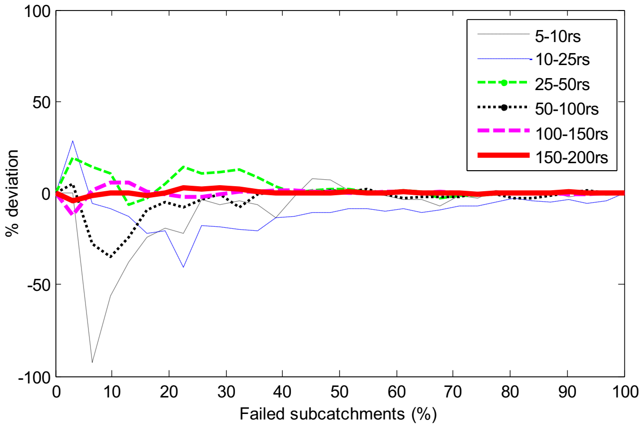

Figure 4. Convergence of GRA results after 200 random cumulative sub catchment failure sequences.

In addition, further research using multiple case studies is recommended to establish the adequacy of the number of random failure scenarios required to adequately represent the respective distributions.

2.4. Computation of functional resilience index

The functional resilience index, Res_f is used to link the resulting loss of functionality to the system's residual functionality and hence the level of resilience during the considered rainfall block loading scenarios. The resulting loss of system functionality is estimated using the concept of volumetric severity, Sev_y which provides a measure of the level of consequences (e.g. injury, property or system damage) that could result the simulated failure impacts (e.g. Hwang *et al*. 2015). In this study, Sev_y (Equation (4)) is estimated as a function of maximum surface flooding *magnitude* and *duration* which effectively assumes that the system failure and recovery curve is rectangular (Mugume *et al*. 2015).

$$Sev_y = \frac{V_{TF}}{V_{TI}} \times \frac{t_{fn}}{t_{mf}} \tag{4}$$

Where V_{TF} is the total flood volume; V_{TI} the total inflow into the system; t_{fn} the mean duration of nodal flooding (computed for all flooded nodes in the system) and t_{mf} the maximum nodal flood duration (maximum duration of flooding that occurs at any node in the system). It however noted that the ratio between mean flooding duration and maximum nodal duration fails to distinguish the contribution of different flood durations to the computed volumetric severity for example; the same severity effects on the duration part will result from the following two cases that is: (i) one node in the network flooding for 10 h flooding; while on average all nodes in the network flood for a duration of 5 h and (ii) one node in the network flooding for a duration of 1 h, while on average all nodes in the network flood for a duration of 0.5 h. It is therefore recommended that in future work, further development of the severity index should be carried out to adequately take into account the contribution of flood duration to the computed volumetric severity.

However, it is noted that using the simulated surface flood duration (obtained using the 1D surface flood model), does not consider the duration of flooding that occurs in the major system (i.e. overland flow paths such as roads, paths and grass ways) during extreme events which could lead to underestimation of the mean flood duration. In addition, it is noted that the simulated surface flood duration represents the 'failure impact' time and does not include other factors that affect system recovery time such as 'system repair' time and the 'failure consequence' e.g. time taken to repair a property affected by flooding (Mugume *et al*. 2015).

The functional resilience index, Res_f, is estimated using Equation (5) and ranges from 0 to 1; with 0 indicating the lowest level of functional resilience and 1 the highest level functional resilience to the considered extreme rainfall loading scenarios (Mugume *et al*. 2015). It is computed at 100% (full) sub catchment failure level and hence represents the most severe functional loading scenario that leads to the maximum loss of system functionality ($Sev_{\max}$) for each considered rainfall block.

$$Res_f = 1 - Sev_{\max} = 1 - \frac{V_{TF}}{V_{TI}} \times \frac{t_{fn}}{t_{mf}} \tag{5}$$

In addition, Equation (4) is used to compute the design functional resilience, $Res_{f,d}$ for the Nakivubo UDS (designed for a 10 yr flooding return period). For the computation, it is assumed that the 10 year design flooding return period corresponds to a 2 yr design rainstorm. Consequently, $Res_{f,d}$ is computed by simulating the effect of the 2 yr design rainstorm on the resulting loss of system functionality.

3. Results

3.1. Effect of spatial rainfall distribution on flooding

3.1.1. Effect on total flood volume

The results obtained by carrying out model simulations using the 140 min rainfall blocks indicate the effect of increasing spatial rainfall distribution on UDS's ability to minimise the resulting loss of system functionality is less pronounced for rainfall blocks derived from rainfall intensities with lower return periods (e.g. $T = 5$ yrs) but increases with increasing rainfall return periods. This can be observed in Figures 5b, c and d where the simulated total flood volume at higher sub-catchment failure levels significantly increases with increasing rainfall return periods, implying that increased spatial loading of the sub catchments leads to disproportionately high loss of system functionality magnitude.

Secondly, the results show that applying uniform, areally reduced rainfall over the catchment (i.e. use of ARFs) over estimates the total flood volume at spatial rainfall loading levels less than 70% and that the overestimation increases with increasing T (Figure 5). On the other hand, the results also indicate that use of ARFs could lead to underestimation of the total flood volume at higher spatial rainfall loading levels; for example, for rainfall blocks derived from higher T (i.e. $T > 25$ yrs) the total flood volume at a spatial rainfall loading level of 90% (which corresponds to the applied ARF factor of 0.9) underestimates the total flood volume by 16–34%.

3.1.2. Effect on mean flood duration

The results generally suggest that for all rainfall return periods, 'failure' of about 20% of the sub- catchments results in

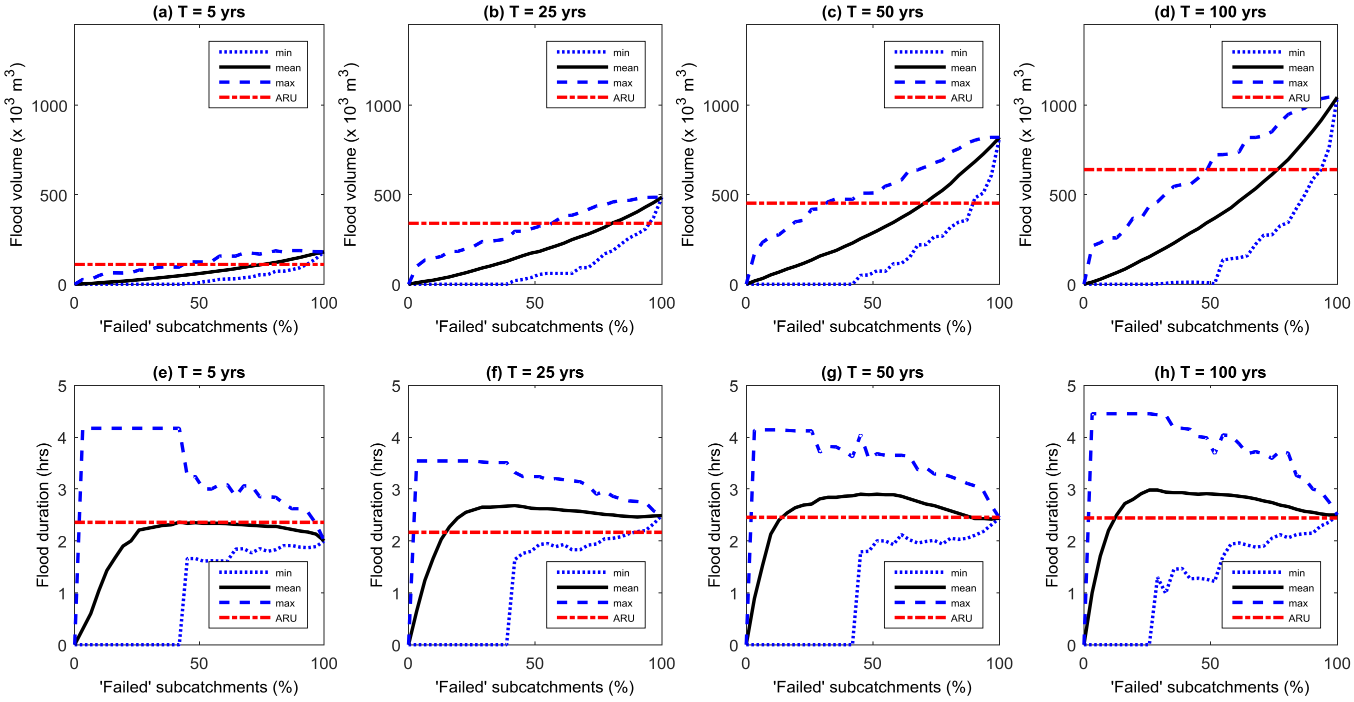

Figure 5. Generated UDS failure envelopes showing the effect of spatial rainfall distribution on total flood volume (a-d) and mean nodal flood duration (e-h) for 140 min rainfall blocks derived from rainfall intensities corresponding to various rainfall return periods. The red dashed dot horizontal line (ARU) shows computed values of total flood volume and mean nodal flood duration using corresponding areally reduced uniform rainfall (Design storms with an ARF of 0.9 applied).

the highest increase in the mean flood duration. When the sub catchment 'failure' exceeds 20%, minimal variation in the mean flood duration is observed for all considered *T* (Figure 5). A slight reduction in the mean flood duration is observed at higher sub catchment 'failure' levels, which is due to the effect of 'averaging' i.e. the number of flooded nodes increases with increasing total flood volume. Subsequently, the effect of 'averaging' leads to more stable results and in some instances lower mean values of the flood duration. The results also suggest for higher *T* (i.e. 25, 50 and 100 years), that use of ARFs (with the assumption of uniform loading) slightly underestimates the mean flood duration (by 3.4–10.1%) when sub catchment 'failure' levels exceed 15%.

3.2. Effect of a rapid increase in rainfall intensity on flooding

3.2.1. Effect on total flood volume

To model the effect of a rapid increase in rainfall intensity, the GRA is carried out using the 70 min rainfall blocks as functional loading inputs. The GRA results indicate that when compared to the 140 min rainfall blocks, the 70 min rainfall blocks result in higher loss of system functionality magnitude at all considered rainfall return periods (Figure 6). The effect on total flood volume is more pronounced for when the spatial rainfall loading exceeds 40%. The results indicate that the 70 min rainfall blocks result in a significant increase of 41–135% in the simulated total flood volume (at 90% sub catchment 'failure' level) when compared to the 140 min rainfall blocks for all considered *T*.

In Figure 6, it is noted that for both the 70 min and 140 min rainfall blocks, the computed mean flood duration for whole system at lower percentage of failed sub catchments (i.e. <50%) is initially higher and reduces with increasing percentage of failed sub catchments. It is also noted that this effect is more pronounced for simulation results obtained using rainfall blocks corresponding to higher return periods (i.e. *T* = 50 and 100 yrs). This is attributed to the effect of 'averaging' of the simulated nodal flood durations. At lower sub catchment failure levels, fewer nodes are flooded and slightly higher durations leading higher values of the computed mean flood duration. With increasing sub catchment failure loading, the number of flooded nodes increases but the average values of the computed flood duration for the whole system is slightly reduced.

3.2.2. Effect on mean flood duration

In contrast to the flood volume results, the 70 min rainfall blocks result in slightly lower mean flood duration values when compared to corresponding 140 min rainfall blocks. The effect is pronounced when sub catchment 'failure' levels exceed 10% (Figure 6). The results show that the 70 min rainfall blocks result in a reduction of 25–40.8% in the simulated mean flood duration (at 90% sub catchment 'failure' level) when compared to the 140 min rainfall blocks for all considered *T*.

3.3. Functional resilience index

The computed functional resilience indices for the considered rainfall block loading scenarios are presented in Figure 7. The computed design functional resilience index (0.91) represents the design flood protection level of service delivered by the existing UDS. The results also indicate that occurrence of shorter duration, high intensity rainstorms with higher return periods, significantly reduces the residual functionality of the UDS and hence it's functional resilience to extreme rainfall. For example occurrence of the 50 yr 70 min and 100 yr 70 min rainfall blocks

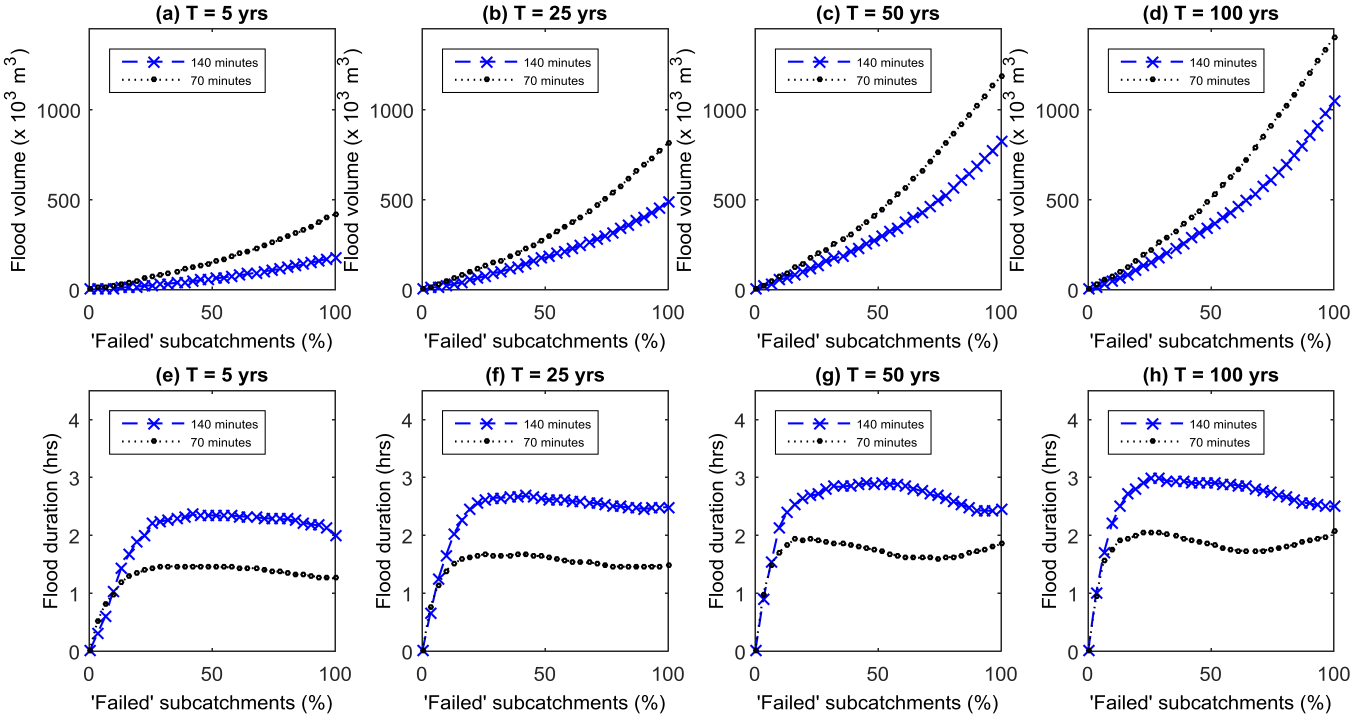

Figure 6. Mean values of GRA results obtained using 140 min and 70 min rainfall blocks derived from rainfall intensities corresponding to various rainfall return periods showing the effect of increased rainfall intensity on total flood volume (a-d) and mean duration of nodal flooding (e-h) for various rainfall return periods.

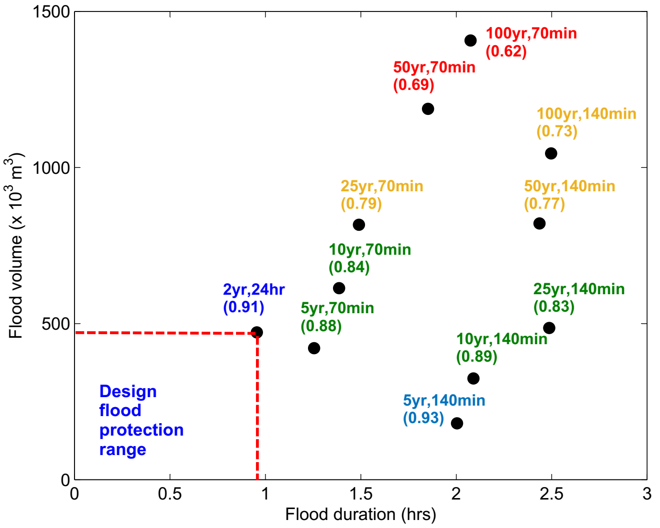

Figure 7. Computed functional resilience indices for the existing UDS at various rainfall block loading scenarios.

result in a reduction of functional resilience of 24% and 32% respectively when compared to the UDS's design functional resilience.

4. Discussion of results

The developed GRA method enables systematic evaluation of functional resilience in UDSs with reduced computational complexity. Specifically, the results of the study suggest that the resulting loss of functionality of the existing UDS increases with increasing rainfall block magnitudes. In addition, the study results indicate that the loss of system functionality is more sensitive to functional loading resulting from the short duration, high intensity rainfall blocks when compared to corresponding lower intensity rainfall blocks and that this sensitivity is higher when the spatial rainfall loading extent exceeds 40%. This therefore suggests that the existing UDS exhibits low levels of resilience to extreme rainfall that could result from anticipated future climate change or climate variability.

Secondly, the study results also suggest that current approaches which use uniform rainfall loading inputs (with ARFs applied) may lead to overestimation of the magnitude of flooding resulting from a given rainfall event when the spatial rainfall loading is less than 70%. However, for rainfall events that cover that entire catchment, use of uniform spatial rainfall loading underestimates the resulting magnitude of flooding. These results suggest that effective design (or sizing) of catchment scale resilience enhancement strategies such as distributed storage or rainwater harvesting systems should apply spatially distributed rainfall inputs to achieve accurate results.

Thirdly, the generated sub catchment 'failure' envelopes suggest that in addition to the areal rainfall extent, storm movement, which may result from a change of wind direction (e.g. Vaes *et al*. 2005) during a given extreme rainfall event affects UDS performance and hence its functional resilience. To validate this assertion, a total of 62 simulations in which targeted 'failure' of sub catchments starting from the most upstream one down to the most downstream sub catchment (and vice versa) were carried out. The effect of increasing spatial rainfall loading from upstream to downstream parts of the catchment results in higher failure impacts. On the other hand, random and increasing spatial rainfall loading from downstream to upstream parts of the catchment resulting in lower flooding impacts. These results are attributed to the non-uniform system hydraulic loading during non-stationary rainstorms. As the spatial rainfall loading is gradually extended to cover downstream parts of the catchment, the generated flows from upstream parts of the catchment reach downstream links just when the local (downstream) storm run-offs are entering the UDS leading to higher flooding impacts.

5. Conclusions

The global resilience analysis (GRA) method has been developed and applied to evaluate the functional resilience of an existing UDS in Kampala, Uganda when subject to a wide range of extreme rainfall loading conditions. The developed methodology facilitates improved understanding of the hydraulic performance behaviour of existing UDSs during unexpected extreme events. It also enables the effect of spatial rainfall distribution to be explicitly considered in UDS resilience evaluation with reduced computational complexity.

From the study, the following conclusions specific to the Kampala city are drawn:

- Occurrence of short duration, high intensity rainfall events leads to significant loss of system functionality magnitude but has less effect on failure duration when compared to corresponding lower intensity rainfall events. Globally, it is concluded that short duration, high intensity rainfall events (i.e. 70 min rainfall block) result in more significant reduction (24–32%) of the existing UDS's functional resilience.
- Because the short duration events lead to higher loss of functionality magnitude but less effect of duration, it is suggested that implementation of multifunctional infrastructure for example intentional design of specific road network sections (major system) to enable safe conveyance of exceedance flows during extreme rainfall events could provide a promising option for enhancement of the system's functional resilience. Other promising strategies that focus on upstream source control of storm water inflows into the UDS for example distributed storage and dual purpose rainwater harvesting are recommended for further investigation.
- Use of areal reduction factors can lead to overestimation of the magnitude of flooding resulting from extreme rainfall events with higher return periods (T > 25 yrs) when the actual spatial rainfall extent is less than 70% of the total catchment area. This suggests that future planning of resilience enhancement strategies should apply spatially distributed rainfall inputs to enable effective design/sizing of potential adaptation strategies and therefore to minimise erroneous and costly adaptation decision-making (e.g. Gersonius *et al*. 2013).

Furthermore, the following general conclusions on evaluation of functional resilience in UDSs are drawn:

- For large urban catchments, the effect of spatial rainfall variation can lead to spatially non-uniform system hydraulic loading, which significantly influences the hydraulic performance behaviour and hence functional resilience of UDSs during extreme (convective) rainfall conditions.
- The developed GRA approach provides a realistic, practical and computationally efficient method that can be applied by water utilities/companies for diagnostic assessment of functional resilience in existing or planned UDSs.
- The developed approach can be applied to inform decision-making processes for example during prioritisation of investments in capital or asset management interventions that are required to build resilience in UDSs in view of emerging climate related and urbanisation threats.

Nomenclature

aA	catchment area (km^2)
ba	depth-duration constant
cb	depth-duration constant
dc	depth-duration constant
eD	storm duration (hrs)
fI_R	rainfall intensity
gN	total number of sub catchments in case study area
hR_d	24 h rainfall
$iRes_f$	functional resilience index
jrs_i	random sub catchment failure sequence
kR_T	rainfall depth for any duration
$lSev_{\mathbf{max}}$	maximum volumetric severity
$mSev_y$	volumetric severity
nS_N	andomly selected sub catchment
ot	rainfall duration
pT	rainfall return period in years
qt_c	time of concentration
rt_e	time of entry
st_f	time of flow
tt_{fn}	failure duration
ut_{mf}	maximum nodal flood duration
vt_n	elapsed (simulation) time
wV_{TF}	total flood volume
xV_{TI}	total inflow volume
yX	minimum number of random sub catchment failure sequences required to generate consistent GRA results

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