Water Management

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ice | proceedings

Proceedings of the Institution of Civil Engineers

http://dx.doi.org/10.1680/jwama.15.00078
Paper 1500078
Received 13/08/2015 Accepted 17/02/2016
Keywords: failure/floods & floodworks/sustainability

ice Institution of Civil Engineers
publishing

Multifunctional urban flood resilience enhancement strategies

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Enhancing resilience in urban drainage systems (UDSs) can be achieved by implementing a range of strategies that minimise the magnitude and duration of flooding during or after the occurrence of unexpected system failures. Dual-purpose rainwater harvesting (RWH) systems provide a promising multifunctional resilience-enhancing strategy due to their associated multiple benefits such as water conservation and distributed control of storm water. However, their effectiveness in respect to minimisation of resulting flooding impacts and provision of alternative water supplies during unexpected system failures has not been explicitly investigated at a city district or catchment scale. This paper applies the global resilience analysis approach to investigate the effect of implementing a set of multifunctional RWH strategies on improvement of UDS resilience to random cumulative link (sewer) failure, using a case study of the Nakivubo system in Kampala, Uganda. The resulting water supply resilience enhancement benefits are also investigated. The study results reveal that catchment-scale implementation of suitably designed RWH systems provides an effective strategy that improves the system's global resilience to flooding by up to 25%, while simultaneously providing up to 30% of the household water supply requirements in the case study area.

Notation

A	area of collection (roof) surface (m^2)
D_N	5% of annual water demand (m^3)
D_t	demand in time period t
E_t	water saving efficiency
e	yield coefficient (%)
f_{D50}	number of days when required mains water use is greater than 50% of daily demand
h_f	hydraulic filter coefficient
M_t	volume of mains water top-up
n	Manning's roughness coefficient
n_p	number of persons per household
P_d	daily water requirement per person (l/person/d)
Q_t	rainwater runoff in current time interval
R_d	design rainstorm event depth (mm)
Res_o	structural resilience index
S	tank storage capacity (m^3)
V_D	water demand (retention) volume (l)
V_{SC}	storm water control (detention) volume (l)
V_t	volume of water stored in RWH tank in time interval t
V_{TS}	total storage volume (l)
Y_R	5% of annual rainfall yield (l)
Y_t	tank yield

1. Introduction

Globally, cities and urban areas are grappling with a multiplicity of emerging threats such as rapid urbanisation, climate change and variability that have increased urban flooding impacts and consequences (Butler *et al.*, 2014; Djordjević *et al.*, 2011; IPCC, 2014; UNPD, 2012). Furthermore, the challenge of urban flooding is further exacerbated by short-term (episodic) system failures such as sewer collapse, blockages or equipment malfunction or long-term (chronic) stresses such as asset ageing and deterioration (Barton *et al.*, 2007; Dawson *et al.*, 2008; Kellagher *et al.*, 2009; Mugume *et al.*, 2015a, 2015b; Ten Veldhuis and Clemens, 2011).

Consequently, the need to enhance the resilience of urban drainage systems (UDSs) is now well recognised as a key strategy to maintaining acceptable flood protection levels in cities, not only during normal operating conditions but also during

exceptional or unexpected loading conditions that lead to catastrophic system failures (Butler *et al.*, 2014; Mugume *et al.*, 2015a, 2015b). Conventional hydraulic reliability-based ('safe') approaches tend to focus on minimising the probability of hydraulic (functional) failures caused by rainfall of a given return period (Butler and Davies, 2011). In contrast, engineering system resilience-based approaches emphasise the need to ensure continuity and efficiency of system function during or after the occurrence of an unexpected system failure (Butler *et al.*, 2014; Mugume *et al.*, 2015a; Park *et al.*, 2013). In urban drainage and flood management systems, it is now recognised that urban flooding may result from a wide range of threats that not only include functional failures but also other causes such as internal system (structural) failures. Therefore, investigation of new resilience-based evaluation approaches that emphasise the need to improve a system's ability to minimise the magnitude and duration of flooding in the event of such unexpected failures is a subject of current research (Mugume *et al.*, 2015a, 2015b).

Furthermore, in order to operationalise resilience in real-world urban flood management, a number of recent studies have proposed a suite of potential intervention strategies (Cabinet Office, 2011; Ciria, 2014; McBain *et al.*, 2010; NIAC, 2009; Nie, 2015; Ofwat, 2012). These strategies generally seek to enhance inbuilt UDS properties or attributes such as redundancy and flexibility during design or rehabilitation so as to influence the ability of a whole system to minimise the resulting loss of system functionality during failure (Mugume *et al.*, 2015a). In contrast to a system-focused view, a paradigm focused on recipients (customers) seeks to enhance general resilience to flooding through the installation of equipment such as rainwater harvesting (RWH) systems (Burns *et al.*, 2015a; Campisano *et al.*, 2013; DeBusk *et al.*, 2012), property flood-proofing devices (Djordjević *et al.*, 2011; White *et al.*, 2013) and green infrastructure (Ahern, 2011, 2013; Strickland and Divall, 2015) in order to enhance customers' (i.e. tenants, home owners, landlords or businesses) preparedness for extreme events that could potentially reduce the acceptable flood protection service levels (Butler *et al.*, 2014; Tyler and Moench, 2012).

A number of studies have investigated and quantified the benefits of RWH systems, which include reduction of stress on existing potable water distribution systems, provision of backup city water supplies, cost savings to customers and the provision of wider water resource conservation benefits (Aladenola and Adeboye, 2010; Burns *et al.*, 2015a; Campisano and Modica, 2012; Ward *et al.*, 2012). Furthermore, in recent works, a limited number of studies have demonstrated the uniqueness of multifunctional (dual-purpose) RWH systems; that is, their ability to simultaneously provide an alternative water supply and storm water control benefits in cities (Burns *et al.*, 2015a, 2015b; DeBusk *et al.*, 2012; Melville-Shreeve *et al.*, 2014; Sample *et al.*, 2012; van der Sterren *et al.*, 2012). With respect to urban drainage, dual-purpose RWH systems can provide spatially distributed detention storage within the catchment that could potentially reduce urban flooding by minimising storm water volumes and peak flow rates (Burns *et al.*, 2015a; DeBusk *et al.*, 2012).

However, most of these studies have investigated the effectiveness of implementing such innovative RWH systems on reduction of storm water inflows into existing UDSs and resulting flooding impacts at a site (plot) scale (Burns *et al.*, 2015a, 2015b; Kwak and Han, 2014; Mahmoud *et al.*, 2014; van der Sterren *et al.*, 2012). Consequently, the effect of implementing such innovative strategies in building the global resilience of an UDS to flooding at a city district or catchment scale requires further investigation. Furthermore, most of the previous studies take a narrow view of functional resilience by only investigating flooding caused by hydraulic overloading (functional failure) of UDSs and hence do not explicitly consider the effect of potential structural (system) failures that also contribute significantly to urban flooding (Barton *et al.*, 2007; Dawson *et al.*, 2008; Kellagher *et al.*, 2009; Mugume *et al.*, 2015b; Savić *et al.*, 2006). Further research aimed at evaluating the effect of widescale implementation of such innovative RWH strategies on minimisation of negative urban flooding impacts caused by unexpected sewer failures (such as blockages, collapse or bed load sediment deposition) and the provision of alternative water supplies in cities is required.

In this paper, the global resilience analysis (GRA) method (Mugume *et al.*, 2015b) is applied to investigate the effect of implementing a set of RWH strategies on enhancement of global UDS resilience to flooding when subject to a wide range of random cumulative link failure scenarios. The Nakivubo UDS in Kampala, Uganda is used as a case study. The resilience benefits of the tested RWH strategies with respect to provision of alternative water supplies in the case study area are also quantified. Finally, the results obtained by implementing proposed RWH strategies are compared with corresponding results obtained using more conventional strategies, that is the improved UDS operation and maintenance (O&M) and the centralised storage and distributed storage strategies recently investigated by Mugume *et al.* (2015b), and conclusions are drawn.

2. Case study and methods

2.1 Case study area

A case study of the Nakivubo UDS, which drains a highly urbanised catchment (central business district) in Kampala, forms the basis for the investigations carried out in this study. Kampala is the political and economic capital of Uganda, with a total population of 1·72 million and an estimated annual growth rate of 5·6% (UBOS, 2012). The current water demand in Kampala, which is estimated at 210 000 m^3/d (and projected to increase to 325 000 m^3/d by 2025), outstrips the

existing water production capacity of 183 000 m^3/d, leading to water supply interruptions and 'no water' (dry) zones in some parts of the distribution network (NWSC, 2015). The water supply situation is further compounded by abrupt failure of critical system components such as pipes and pumps, long-term asset decay and insufficient investments in rehabilitation and expansion of the water distribution network.

On the other hand, over the last decade, Kampala has experienced an increase in the number of pluvial flooding incidences with negative consequences such as property damage, traffic disruption, shallow groundwater contamination and so on (Lwasa, 2010; Sliuzas *et al.*, 2013; UN-Habitat, 2009). The number of catastrophic flooding events that occur during extreme convective rainfall events has doubled in the past 20 years, from an average of 5 in 1993 to 10 in 2014, with the later having an average duration of 2–4 h. The key threats (causes) that have contributed to the increased frequency and severity of urban flooding incidences in Kampala include extreme rainfall (caused by climate change and variability), rapid urbanisation, insufficient drainage infrastructure, inadequate system cleaning and maintenance, and insufficient solid waste management in the city (Mugume and Butler, 2015).

A hydrologic and hydraulic model of the Nakivubo UDS (Figure 1) was built in the storm water management model SWMM v5·1 (Rossman, 2010). The hydraulic model of the system consists of 81 links (network length of 22·8 km), 81 nodes and one outfall, and drains a total catchment area of 2793 ha delineated into 31 sub-catchments (Mugume *et al.*, 2015b).

2.2 Tested adaptation strategies

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 properties. This paper investigates the effect of implementing multifunctional RWH systems at an urban catchment scale on the enhancement of global UDS resilience to unexpected structural failures and the provision of alternative water supplies. In addition, the tested RWH strategies are compared with corresponding results obtained by the implementation of more conventional strategies – the improved system O&M strategy and centralised storage and distributed storage strategies (Mugume *et al.*, 2015b) – and conclusions are drawn. A description of the modelled adaptation strategies is presented in Table 1.

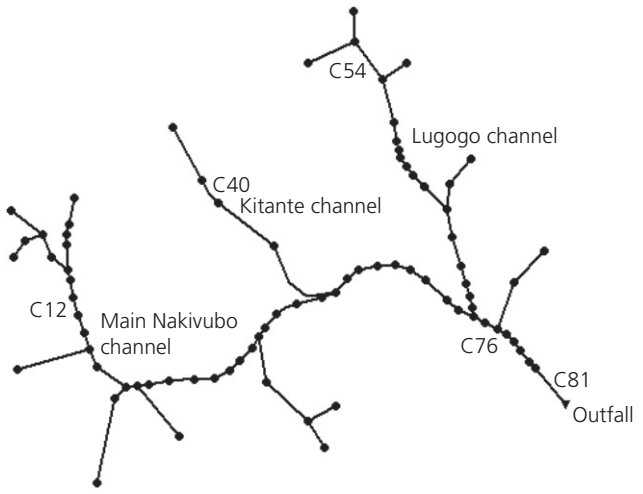

Figure 1. Layout of modelled Nakivubo urban drainage network (Mugume *et al.*, 2015b)

2.3 Design of RWH systems

Two key objectives guided the design of the RWH systems in this study – first, the reduction of storm water inflows into the UDS through detention of roof runoff and, second, the provision of alternative water supplies to households. To achieve these objectives, the 'intermediate' approach recommended by the British Standard for RWH systems (BSI, 2013) was used for sizing the RWH systems (Equation 1). In contrast to the 'simplified' approach, which uses UK-based rainfall data for RWH tank design, the intermediate approach allows for the use of local design rainstorm events and hence provides a more accurate and flexible methodology for sizing of the storm water control volume of RWH tanks in non-UK locations.

$$1.\quad V_{TS} = \begin{cases} V_{SC} + Y_R & \text{when } D_N - 3Y_R < 0 \\ R_d \times A & \text{when } D_N - 3Y_R > 0 \end{cases}$$

where

$$2.\quad Y_R = A \times e \times \text{AAR} \times h_f \times 0{\cdot}05$$

$$3.\quad D_N = P_d \times n_p \times 365 \times 0{\cdot}05$$

$$4.\quad V_{SC} = R_d \times A - [(D_N - Y_R) \times 0{\cdot}5]$$

in which V_{TS} is the total storage for storm water control and alternative water supply (l), V_{SC} is the additional tank volume needed for storm water control (l), V_D is the water demand volume (l), Y_R is 5% of the annual rainfall yield (l), D_N is 5% of the annual water demand (l), R_d is the design rainstorm event depth (mm), A is the area of the collection surface (m^2), e is the yield coefficient (%), AAR is the annual average rainfall depth for the location (mm), h_f is the hydraulic filter coefficient, P_d is the daily water requirement per person (l/person/d) and n_p the number of persons per household.

The methodology was applied to the Nakivubo UDS in Kampala, which drains a large urbanised catchment with a

total area of 2793 ha (Mugume *et al.*, 2015b) and an estimated population of 376 855 (NWSC, 2014). The average annual rainfall for Kampala is 1292 mm (Figure 2) and this value was used to determine the yield (Y_R) using Equation 2. The recently updated standard on RWH systems (BSI, 2013) recommends use of a 100 year, 6 h design storm for sizing of dual-purpose RWH systems in the UK. However, due to the convective nature of rainfall in Kampala, direct use of a 100 year, 6 h design storm may lead to oversized and hence costly RWH systems. In this research, therefore, the storm water control volume (V_{SC}) of the RWH tank was designed considering a 2 year, 6 h design storm for Kampala, with a total depth of 56·1 mm (Equation 4). Two RWH tank sizing scenarios were considered – medium-demand, two-bedroomed house and high-demand, three-bedroomed house (Table 2).

The per capita water demand used in this study was based on analysis of available water demand data for Kampala for the period July 2011 to June 2012 (NWSC, 2014), in which customer water demand patterns were classified into five demand categories (Table 3). As noted earlier, this study considered the medium (63·7 l/person/d) and high (81·5 l/person/d) per capita water demand categories. The average household sizes used to compute the water demand volume (D_N) were in the range

Strategy	Description	General resilience attribute influenced
Centralised storage	Introduce a large downstream centralised detention pond with a total storage volume of $3{\cdot}15 \times 10^5$ m^3	Redundancy
Distributed storage	Introduce 28 spatially distributed upstream storage tanks with the same total storage capacity as the centralised storage strategy	Flexibility
Improved asset management (O&M)	Improve system cleaning and maintenance (asset management) so as to maintain its as-built hydraulic capacity and to improve flow conditions in the individual links	Redundancy
Multifunctional RWH	Implement multifunctional RWH systems at a catchment scale with the same total storage capacity as the distributed storage strategy	Flexibility

Table 1. Modelled adaptation strategies

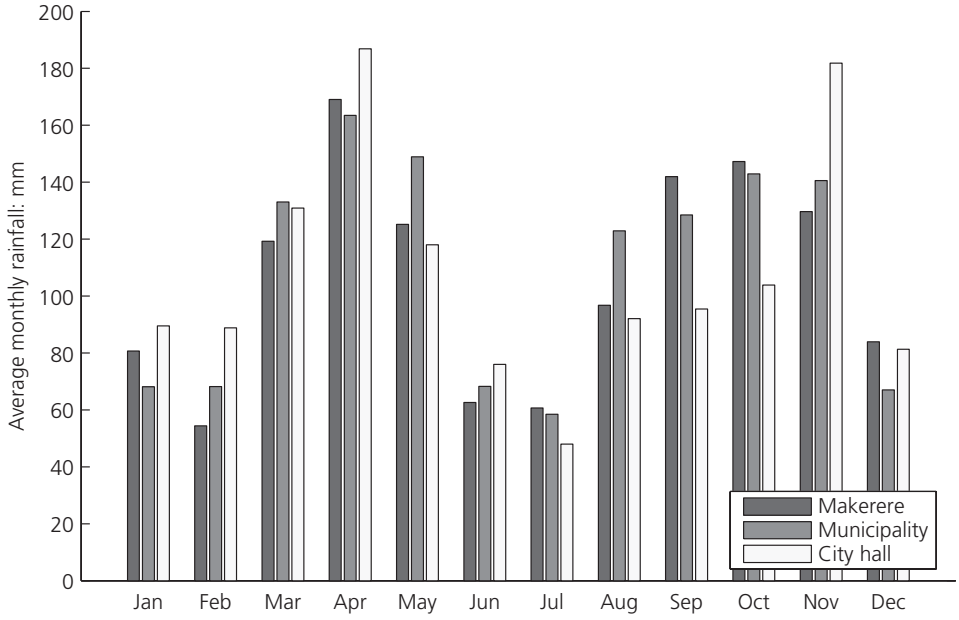

Figure 2. Average monthly rainfall for Kampala city from three rain gauge stations – Makerere University (1991–2009), municipality (1942–1993) and city hall (1963–1992)

Scenario	Design parameters			Computed tank sizes		
	Average household size (number of persons)	Average water demand: l/person/d	Contributing roof area: m^2	Water demand volume, V_D	Storm water control volume, V_{SC}: m^3	Design tank volume, V_T: m^3
High demand	4·02	81·5	99·8	6·0	5·6	11·0
Medium demand	3·78	63·7	79·9	4·4	4·5	9·0

Table 2. RWH tank design scenarios for Kampala

Water demand category	Connected population (2013)	Proportion of population connected (2013): %	Average water demand: l/person/d
Very low	181 486	8·9	30·8
Low	641 632	31·6	38·0
Medium	364 355	18·0	63·7
High	477 507	23·5	81·5
Very high	364 503	18·0	114·1
	2 029 482	100	

Table 3. Water demand categories for Kampala (based on NWSC, 2014)

3·28–4·27 persons per household (UBOS, 2014). In this work, it was assumed that collected rainwater could be used for potable water uses through treatment using low-cost processes (Naddeo *et al.*, 2013; WHO, 2011). Collected rainwater can also be used directly for non-potable uses such as toilet flushing, washing or urban gardening purposes, without the need for treatment (Aladenola and Adeboye, 2010; Awuah *et al.*, 2014).

2.4 Modelling single RWH tank units

The single (unit) RWH tanks designed (Section 2.3) were modelled in SWMM v5·1, using the 'rain barrel' option in the 'low impact development' (LID) control editor. The single units were replicated across all the sub-catchments in the case study area, effectively displacing an equal amount of non-LID area from each sub-catchment (Rossman, 2010). This modelling approach distributes the total installed RWH storage volume proportionately across the catchment and hence represents a decentralised adaptation option implemented at a large catchment (city district) scale.

In this research, to simplify the modelling and subsequent GRA simulations, it was assumed that the RWH tank is emptied before the onset of a rainfall event. This could be achieved in practice through implementing passive or active control systems for regulation of the flow of stored rainwater into the UDS. In passive control systems, flow regulation is achieved through temporary capture and storm water is released between subsequent rainfall events (DeBusk *et al.*, 2012; Herrmann and Schmida, 2000; Melville-Shreeve *et al.*, 2014). It could also be achieved through the effect of increased household demand patterns (for example resulting from connecting toilet flushing, laundry and outdoor use devices to the RWH tank), consequently increasing the available total storage volume between storm events. Figure 3 provides an example of a multifunctional RWH system.

2.5 Catchment-scale modelling of RWH strategies

The modelled RWH tank units were replicated across all sub-catchments in the study area to represent a multifunctional adaptation strategy aimed at enhancing global UDS resilience to flooding while simultaneously providing alternative water supply benefits. For the catchment-scale modelling, three RWH sub-strategies (referred to as RWH options 1, 2 and 3) were considered for further investigation (Table 4).

In option 1, a total of 28 636 units with a total storage volume (V_{TS}) of 315 000 m^3 are represented in the SWMM model. The modelled total RWH tank storage volume is the same as that of the centralised storage and distributed storage strategies. The modelled RWH tanks collect runoff from a combined contributing roof area of 228·7 ha, which represents 20% of the total roof area in the catchment (i.e. one in five houses has a RWH tank installed). RWH options 2 and 3, in which V_{TS} is reduced by 25% and 50%, respectively (Table 4), are used to investigate if comparable performance could be achieved with smaller volumes with a higher level of spatial distribution of control strategies. Details of the catchment-scale RWH model parameters are provided in Table S1 in the Supplementary Material.

2.6 Global resilience to structural failures

Global resilience analysis was carried out in a Matlab environment linked to SWMM v5·1. This involves carrying out a large number of model simulations to quantify whole (global) system performance (loss of system functionality) during a wide range of random and cumulative link failure scenarios. In this research, links in the UDS were randomly and progressively failed and the resulting loss of functionality for each failure level quantified until all the links in the system had

been failed (Mugume *et al*., 2015b). Link failure is modelled by increasing the Manning's roughness coefficient (n) of each link (open channel section) from its initial value to a very high value of 100 (Mugume *et al*., 2015b).

The main steps involved in carrying out GRA are described in detail by Mugume *et al*. (2015a, 2015b) and include the following.

(a) A simulation is run to assess UDS performance in its initial (non-failed) state using a given single extreme rainfall event as a functional loading input.
(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 a 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) A minimum number of random failure sequences, rs_x is determined and run to generate consistent GRA results.

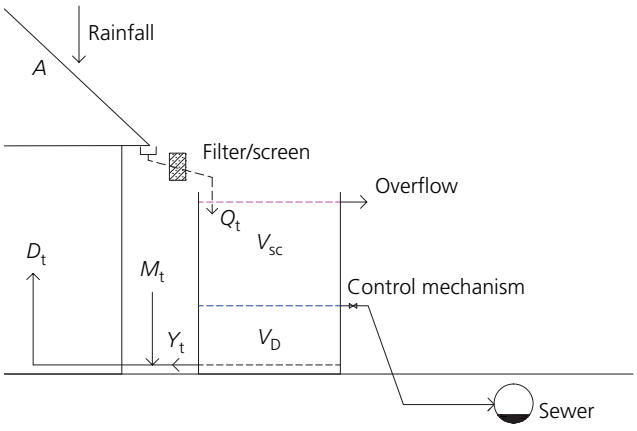

Figure 3. Example of a multifunctional RWH configuration with orifice-type control for passive release of storm water (adapted from Fewkes (2000) and Herrmann and Schmida (2000))

(f) Using the determined rs_x, ($rs_x = 200$ in this case) the procedure in steps (a)–(e) 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.

A total of 16 400 link failure scenarios was simulated for each of the three RWH options (i.e. a combined total of 49 200 cumulative link failure scenarios generated from 600 random link failure sequences was simulated). To enable comparison with the effect of improved sewer asset management, an additional 16 400 simulations were also carried out to quantify the effect of improved UDS O&M. The minimum, mean and maximum values of all model solutions obtained at each considered link failure level were computed using total flood volume and mean duration of nodal flooding system performance indicators, and represent the resulting loss of system functionality resulting from the simulated failure scenarios.

In addition, resilience envelopes were derived by computing the minimum and maximum values of the structural resilience index (Res_o) at each link failure level for each of the tested RWH strategies. 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 failure level (Mugume *et al*., 2015b). For each simulated failure scenario (i.e. percentage of failed links), Res_o quantifies the residual functionality of the UDS as a function of both the failure magnitude (total flood volume) and duration (mean nodal flood duration). Res_o values range from 0 to 1, with 0 indicating the lowest level of resilience and 1 the highest level resilience to the considered failure scenarios. Resilience envelopes were then derived by plotting the minimum and maximum values of Res_o computed at each failure level against the percentage of failed links. The resulting envelopes graphically illustrate the system residual functionality at each considered failure level (Mugume *et al*., 2015b).

2.7 Effect on improvement of water supply resilience

Resilience assessments were carried out to evaluate the performance of the proposed RWH strategies with respect to water savings and reduction of the magnitude and duration of centralised (mains) water use in the case study area caused by

Adaptation strategy	Single RWH tank size: m^3	Number of units	Total storage volume: m^3	Contributing roof area: %	Remarks
RWH option 1 (base case)	11	28 636	315 000	20	Same total volume (V_{TS}) as centralised storage and distributed storage strategies
RWH option 2	9	26 250	236 250	15	$0{\cdot}75V_{TS}$ (25% reduction)
RWH option 3	9	17 500	157 500	10	$0{\cdot}50V_{TS}$ (50% reduction)

Table 4. RWH sub-strategies

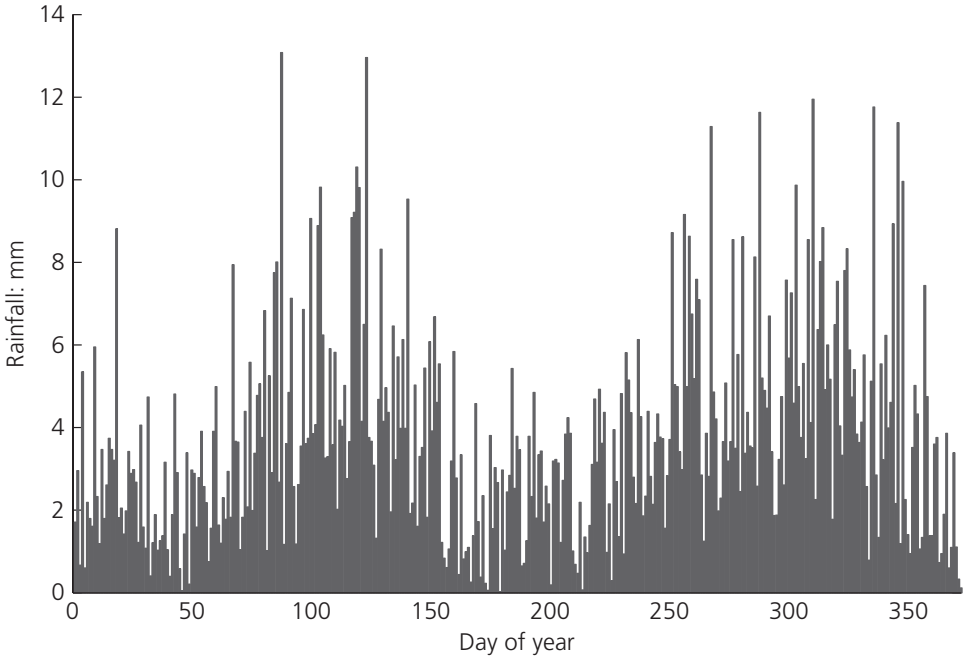

Figure 4. Average daily rainfall for Makerere University rain gauge station for the period 1991–2009

volumetric failure of the proposed RWH strategies. Volumetric failure of RWH systems may result from inadequate sizing of storage tanks, extended periods of low or no rainfall, or high demands connected to the system (Wang and Blackmore, 2012). Water balance modelling was carried out using an 18-year (1991–2009) average daily rainfall dataset for Makerere University rain gauge station (Figure 4). The performance of the RWH system was investigated using the 'yield after spill' (YAS) operating rule (Fewkes, 2000).

The YAS operating rule assigns the RWH tank yield (Y_t) during time interval t, as the minimum value of either the volume of rainwater in storage from the preceding time interval or the demand in the current time interval (Equation 5). To obtain the final volume of water stored in the RWH tank (V_t), the rainwater runoff in the current time interval (Q_t) is added to the volume of rainwater in the storage tank from the preceding time interval, and then Y_t is subtracted (Equation 6). The YAS algorithm is preferred because it gives a conservative estimate of system performance irrespective of the model time interval (Fewkes, 2000).

5. $$Y_t = \min\begin{cases} D_t \\ V_{t-1} \end{cases}$$

6. $$V_t = \min\begin{cases} V_{t-1} + Q_t - Y_t \\ S - Y_t \end{cases}$$

The water saving efficiency E_t is computed as the ratio of the demand D_t to the yield Y_t using Equation 7 (Ward *et al.*, 2012). To assess the resilience of the proposed strategies with respect to minimisation of volumetric failure magnitude and duration, two performance metrics were investigated at a daily time step for a range of water demand and total installed tank volume scenarios. The volume of mains water top-up (M_t) provides a measure of the failure magnitude over the considered modelling period (Equation 8). The number of days in a year when M_t exceeds 50% of the average daily demand (f_{D50}) provides a measure of the RWH system failure duration (Equation 9).

7. $$E_t = \frac{Y_t}{D_t} \times 100$$

8. $$M_t = D_t - Y_t$$

9. $$f_{D50} = \text{number of days } M_t > 0{\cdot}5D_t$$

3. Results

3.1 Initial state system performance assessment

Model simulations were carried out for each of the proposed RWH adaptation options in their respective initial states

Adaptation strategy	Flood volume		Flood duration	
	Volume: 10^3 m^3	Change: %	Duration: h	Change: %
Existing UDS	706·0	—	0·69	—
RWH option 1	514·6	–27·1	0·57	–17·0
RWH option 2	580·7	–17·7	0·59	–13·9
RWH option 3	639·0	–9·5	0·63	–9·1

Table 5. Initial system state performance for the existing UDS and tested RWH adaptation strategies

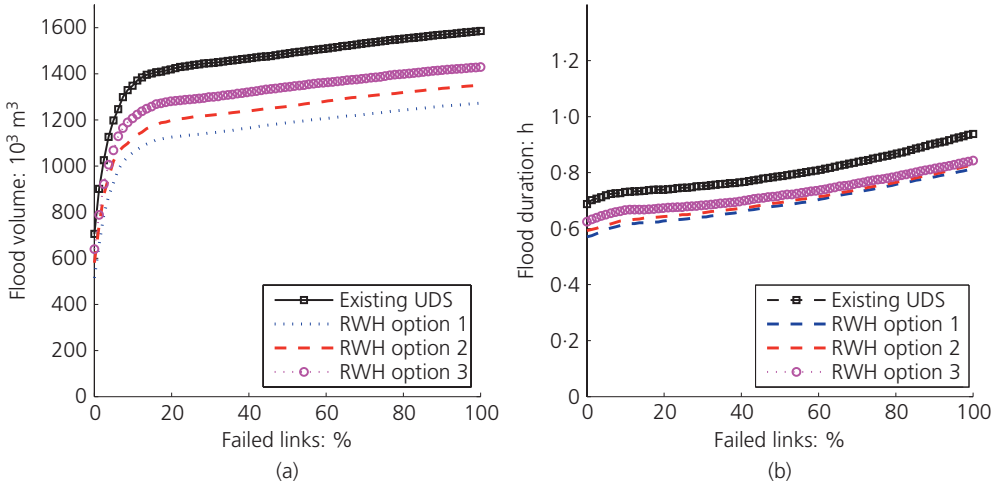

Figure 5. Results of GRA for existing UDS and RWH adaptation options 1, 2 and 3 showing the effect of cumulative link failure on (a) total flood volume and (b) mean nodal flood duration

(i.e. before the UDS was subjected to sewer failure). The global performance of the whole (minor) system was then quantified. As shown in Table 5, implementing option 1 reduces the total flood volume and mean nodal flood duration by 27·1% and 17·7%, respectively. Implementing option 2 leads to more modest reductions in total flood volume (17·7%) and mean flood duration (13·9%). Implementing option 3 results in minimal reductions of the total flood volume and mean flood duration of 9·5% and 9·1%, respectively.

3.2 GRA results

The GRA results for option 1–3 are compared with those obtained by simulating the performance of the existing UDS (business-as-usual strategy) in Figure 5. The effect of implementing option 1 is a considerable reduction in the total flood volume, in the range 19·7–20·5%, for all considered link failure levels (Figure 5(a)). Option 1 also leads to a modest reduction in the mean nodal flood duration (11·6–16·6%), with the reduction being achieved at all link failure levels (Figure 5(b)).

Implementing option 2 results in a slightly lower reduction in total flood volume (14·6–17·7%) and mean flood duration (11·7–13·8%), at all link failure levels. Implementing option 3 leads to the lowest reductions in both total flood volume and mean nodal flood duration of 9·4–10·0% and 8·7–10·2%, respectively. The results also indicate that for all the tested RWH strategies, progressive increases in link failure levels beyond 20% lead to minimal increases in total flood volume.

3.3 Resilience envelopes

The resulting resilience envelopes are presented in Figure 6 for the existing UDS and for all the tested RWH adaptation strategies. To facilitate comparison of the performance of the tested strategies, a resilience threshold of 0·7 is plotted on each of the graphs. The figure shows that implementing option 1 leads to a considerable improvement in computed Res_o values, ranging from 17·3% to 24·9% when compared with the existing system. In addition, the computed Res_o values are higher than the threshold until 26% of the links have failed. Option 2 results in a slightly lower increase in Res_o (17·7–20·0%) when compared with option 1. In addition, the computed Res_o

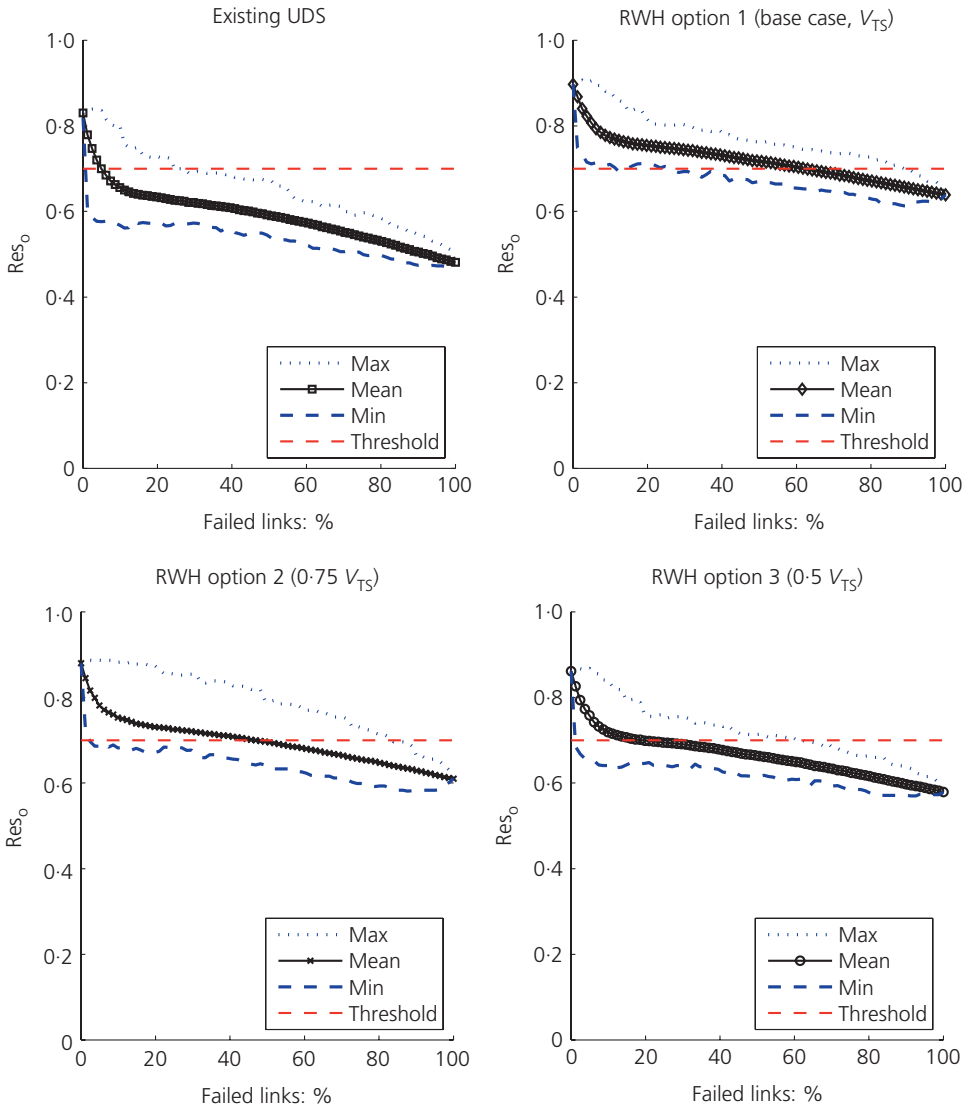

Figure 6. Resilience envelopes showing maximum, mean and minimum values of computed Res_o for the existing UDS and the tested RWH strategies. The plots also show the Res_o values relative to a threshold of 0·7

values for option 2 rapidly fall below the resilience threshold after random failure of a single link in the UDS. In contrast, option 3 leads to a slight increase in Res_o, in the range 9·7–14·9%. Similar to option 2, the computed Res_o values rapidly fall below the threshold value with increasing link failure levels.

3.4 Water supply resilience enhancement benefits

The study results indicate that RWH option 1 results in a considerable water saving efficiency (E_t) of 30·2%. RWH options 2 and 3 result in slightly lower but significant E_t values of 22·7% and 15·1%, respectively (Table 6).

The study results also indicate that, for a constant total installed RWH tank capacity and contributing roof area, reducing the water demand volumes connected to the RWH tanks to less than 35 l/person/d significantly increases E_t and consequently reduces the required volume of mains water use (M_t) and the number of days when the required mains water use is greater than 50% of the daily demand (f_{D50}) (Figure 7).

4. Discussion

4.1 Effect on global UDS resilience to flooding

In RWH option 1, every one in five properties in the catchment area is installed with an 11 m^3 RWH tank. This strategy

Adaptation strategy	Water demand, D_t: m^3/d	Tank yield, Y_t: m^3/d	Water saving efficiency, E_t	Mains top-up ratio	Days $M_t > 0{\cdot}5D_t$, f_{D50}: %
RWH option 1	30 714	8990	30·2	70·3	90·7
RWH option 2	24 004	5444	22·7	77·3	92·9
RWH option 3	24 004	3629	15·1	84·9	98·6

Table 6. Water saving efficiency considering connected RHW water demand of 63·7 l/person/d

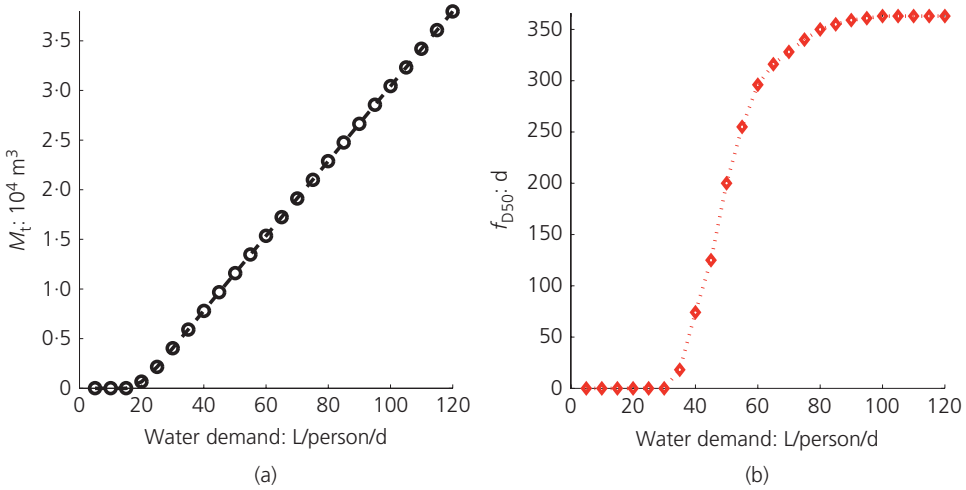

Figure 7. Water supply resilience analysis results for RWH option 1showing the effect of changes in connected (RWH tank) water demand levels on (a) required mains top-up volume (M_t) and (b) number of days when mains top-up exceeds 50% of the daily water demand (f_{D50})

leads to a significant reduction of the total flood volume during the considered link failure scenarios when compared with the existing UDS. However, the strategy is slightly less effective when compared with both the distributed storage and O&M strategies when link failure levels exceed 60%. This could be attributed to the fact the RWH tanks may over flow during extreme events. The results could also suggest that there is an optimum storage tank capacity and distribution of storage controls that result in the highest reductions of flooding magnitude and duration during extreme events.

Considering RWH option 2, the total storage volume is reduced by 25% (i.e. a 9 m^3 RWH tank is installed in approximately one in seven properties). Despite the reduction in total storage volume, the strategy is still more effective in maintaining higher global system residual functionality and also results in higher net benefits when compared with the centralised storage strategy. Implementing option 3 reduces the total storage volume by 50% (one in every ten properties is installed with a 9 m^3 RWH tank). However, the strategy is relatively less effective in maintaining higher global system residual functionality when link failure levels exceed 20%.

The study results suggest that the use of household RWH systems solely for enhancement of flood resilience is slightly less effective when compared with the use of relatively larger sub-catchment-scale DS tanks or investments in improved sewer asset management (e.g. Kwak and Han, 2014; Mugume *et al.*, 2015b; Ten Veldhuis and Clemens, 2011). These results suggest that the spatial scale of control strategies may be crucial for achieving optimal improvements in global resilience to flooding. Based on this study, it is suggested that there is an optimal spatial scale (i.e. distribution of RWH units) and size of storage tanks that delivers the maximum improvement in global UDS resilience to flooding during unexpected sewer failures while minimising upfront capital costs. It is further noted that strategy combinations, for example through implementing multifunctional RWH strategies and improvements in sewer asset management, simultaneously provide the most promising option for enhancing both urban flood resilience and water supply resilience in the case study area.

4.2 Effect on enhancement of water supply resilience

It should be noted that although all the tested RWH strategies are relatively less effective when compared with both

distributed storage and improved O&M strategies from a flood resilience perspective, their ability to provide alternative and renewable water supply in cities is very important, particularly in most developing-country cities where centralised water supplies and distribution system resilience to unexpected system failures (e.g. pipe, pump or interconnected electrical power system failures) are considerably lacking (e.g. Aladenola and Adeboye, 2010; Yazdani *et al.*, 2011).

Based on this premise, it is argued that large-scale implementation of multifunctional RWH systems would improve the resilience of water service provision to individual households through enhancing user flexibility (the ability to switch from mains water to rainwater in unexpected water distribution system failures for example) and preparedness for exceptional failures by providing back-up water storage to augment water supplies until centralised mains water services are restored.

5. Conclusions

The global resilience analysis method has been applied to investigate the effect of widescale implementation of multifunctional rainwater harvesting (RWH) systems on the enhancement of structural resilience to flooding of the Nakivubo urban drainage system (UDS) in Kampala, Uganda, and the improvement of water supply resilience in the case study area. The following conclusions are drawn based on the results of this study.

- Widescale implementation of dual-purpose RWH systems in the case study catchment enhances the global resilience of the UDS to random cumulative link failure by up to 25% while simultaneously providing alternative water supplies that meet approximately 30% of the domestic water supply requirements.
- When compared with conventional approaches such as improved sewer asset management that focus on a single objective of reducing urban flooding impacts, implementation of multifunctional RWH systems at a catchment scale provides a more effective approach for enhancing both urban flood resilience and balancing water demand in urban water networks with failures.
- Water regulatory authorities, utilities and local councils should pursue implementation of multifunctional RWH systems so as to achieve more sustainable water management in the long term, particularly in tropical developing cities where annual rainfall is relatively evenly distributed and where water supply system resilience is low. This should be operationalised in practice by developing new policies promoting the installation of RWH systems on all new residential builds or during retrofit of large-scale commercial or institutional buildings.
- Strategy combinations such as combining RWH strategies with improved sewer asset management provide the most promising results for enhancing urban flood and water supply resilience in the case study area.

Acknowledgement

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

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