Quantifying the Resilience of Urban Drainage Systems Using a Hydraulic Performance Assessment Approach

Seith MUGUME[1*], Diego GOMEZ[1], David BUTLER[1]

[1]*Centre for Water Systems, College of Engineering, Mathematics and Physical Sciences, University of Exeter, Harrison Building, North Park Road, Exeter, EX4 4QF, United Kingdom; Tel: +44 (0)1392 723600, E-mail: snm205@exeter.ac.uk*

**Corresponding author's email: snm205@exeter.ac.uk*

ABSTRACT

Although considerable progress has been made towards achieving sustainable urban water management, urban drainage systems (UDSs) are increasingly threatened by multiple and uncertain drivers of future change. Building the resilience of UDSs to flooding is increasingly recognised as an imperative to promoting the long term sustainability of the urban areas they serve. This paper describes a methodology that combines the use of hydraulic performance assessment with utility performance functions to quantify the resilience of UDSs during flooding (exceedance) conditions. Utility performance functions, which relate the overall UDS performance to flood depths, are derived from existing flood depth-damage data for UK residential properties for various rainfall return periods and are used to estimate UDS residual functionality and hence resilience to pluvial flooding. The study shows that by introducing a storage tank for flow attenuation, the duration of nodal flooding and the flooded volume can be reduced by 6 to 10% and 18 to 38%, respectively and the overall system resilience to flooding can be increased by 8.0 to 9.5%.

KEYWORDS

Hydraulic performance assessment, resilience, restorability, robustness, urban flooding, utility performance functions

INTRODUCTION

Building resilience in urban drainage systems (UDSs) is increasingly recognized as being important to minimise flooding impacts and consequences under uncertain future climate change and urbanisation conditions (Blockley et al., 2012; Butler and Davies, 2011; Djordjević et al., 2011; Gersonius et al., 2013). The concept of resilience provides a paradigm shift from conventional 'fail-safe' approaches to a holistic 'safe-to-fail' view that accepts, anticipates and plans for failure under exceptional (non-design) conditions that could occur over the design life of the system (Ahern, 2011; Francis and Bekera, 2014).In the context of urban flood management, resilience can be defined as the robustness and restorability of the system over its design life when subjected to exceptional conditions. *Robustness* refers to the degree to which an UDS minimises the level of service failure *magnitude* over its design life when subject to exceptional conditions. *Restorability (recoverability)* on the other hand refers to the degree to which a system minimises level of service failure *duration* over its design life when subjected to exceptional conditions(Francis and Bekera, 2014; McDaniels et al., 2008).

In recent studies, significant progress has been made towards understanding and quantifying resilience in water distribution systems (Jung et al., 2013; Lansey, 2012). However, few studies have focused on developing suitable methodologies for quantitative assessment of resilience in UDSs. This paper therefore defines resilience in the context of UDSs and describes a methodology that combines hydrologic and hydrodynamic simulations with the use of derived utility performance functions to quantify the performance of UDSs and their resilience to flooding. Utility performance functions are mathematical models that relate a system performance attribute of interest to an index that ranges from 0 to 1; with zero given to the performance attribute valued least by the decision maker (Cardoso et al., 2004; Gharaibeh et al., 2006).

RESILIENCE OF URBAN DRAINAGE SYSTEMS

Urban drainage infrastructure projects are often large, capital intensive and with long design lives. These characteristics introduce uncertainties in the planning and design of an UDS to guarantee a given level of service over the system's design life (Djordjević et al., 2011; Mailhot and Duchesne, 2010). Building UDS resilience to extreme rainfall events is therefore vital to maintain acceptable flood protection levels in urban areas that they serve in view of anticipated future conditions. Resilience can either be focused on the level of service afforded to customers (and the environment) or on the systems, assets or networks that deliver the services (Mott MacDonald, 2012). From a review of resilience literature, three distinct interpretations of resilience can be identified: i) as a way of thinking - *epistemic* ii) as a quantifiable characteristic of a specific system in respect to a specific threat or known unknown - *specified resilience* and iii) as a system-wide state that determines the capacity to absorb threats of all kinds including unknown unknowns - *general resilience* (Carpenter et al., 2012, 2001; Cumming et al., 2005; Folke, 2006). This paper focuses on specified resilience of UDSs to extreme rainfall induced pluvial flooding. Resilience is interpreted as the *ability of the UDS system to minimize the magnitude and duration of flooding resulting from extreme rainfall events.*

Quantifying resilience in urban drainage systems

Developing suitable quantitative resilience assessment methodologies can enable characterization and testing of the performance behavior of UDSs during flooding conditions. With improved understanding of system behavior, potential mitigation and adaptation strategies aimed at providing appropriate customer service levels can be tested and prioritised.Figure 1~~Figure 1~~ presents a theoretical system performance curve in which *robustness* and *failure* are represented as *time independent* functions of *system performance*, P_i, while *response* and *recovery* are represented as both *system performance* and *time dependent* functions.

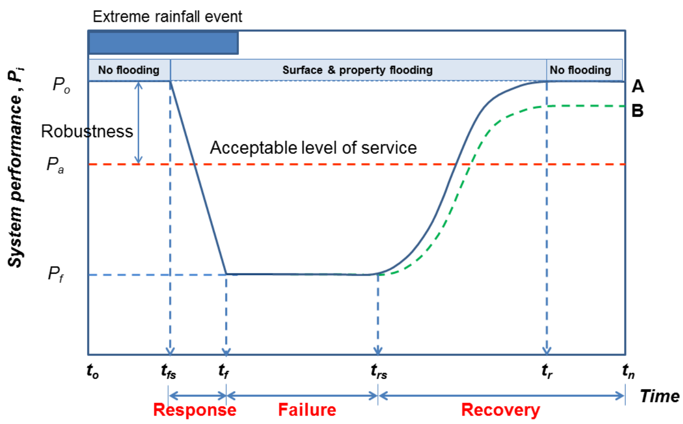

Figure 1: Theoretical system performance curve for an UDS (Adapted from Henry and Ramirez-Marquez, 2012; McDaniels et al., 2008; Mens et al., 2011).

Robustness is dependent on in built multiple 'fail-safe' mechanisms (e.g. parallel pipes, storage tanks or flood retention basins) that enable the system to maintain system functionality or to minimise failure magnitude when subjected to exceptional loading (Jung et al., 2013; Lansey, 2012; NIAC, 2009). In Figure 1, the theoretical system robustness, $Rob_i = f[P_o - P_a]$; where P_o is the original (stable state) performance level *before system surcharging and onset of surface flooding* and P_a is the minimum acceptable system performance level which corresponds to *no property flooding*. In utility theoretic terminology, it can be postulated that robustness is maximized if flooding depth is minimized. A robust UDS, which conveniently conveys runoff generated by a given extreme rainfall event with minimal flooding is highly preferred by the decision maker and would consequently be allocated a higher utility performance value compared to one that leads to higher flood depths.
Response refers to the system's ability to buffer shocks so as to enable graceful as opposed to rapid degradation of system functionality when subjected to exceptional conditions. The gradient of the 'response' part of the system performance curve is an indicator of the sensitivity of the UDS functionality (Lansey, 2012). It is given by $f[(P_f - P_o)/(t_f - t_{fs})]$; where P_f is system failure which corresponds to flood depths, $0.6 < x < 3.0$ m, t_{fs} the time to start of system performance degradation and t_f the time to failure.
Restorability can be expressed as a function of the return time to original (or lower but acceptable) system functionality following failure. It is mainly dependent on available human and capital resources, efficient contingency planning, and competent emergency response operations among others (McDaniels et al., 2008; NIAC, 2009). In Figure 1, system restorability, $Restore_i = f[t_r - t_f]$; where t_r is the return time to original system functionality. In utility theoretic terms, restorability can be maximized by minimizing the return time to original performance levels. A highly restorable system that quickly recovers to original functionality after failure is most preferred by the decision maker and can consequently be allocated a higher utility performance value.

SYSTEM PERFORMANCE EVALUATION

System configuration and simulation options

A synthetic urban drainage system (UDS) consisting of 9 nodes and 9 links with diameters ranging from 400 mm to 800 mm and draining five 4-hectare sub catchments with an average slope of 0.5% was used for used for hydrologic and hydrodynamic simulations using the Storm Water Management Model (SWMM) v.5.0 (Figure 2~~Figure 2~~). SWMM is a physically based discrete time hydrological and hydrodynamic model that can be used for single event and continuous simulation of run-off quantity and quality primarily built for urban areas. SWWM utilizes both the kinematic wave and the full dynamic wave models (St. Venant equations) to route flows through a network of pipes, open channels, storage or treatment units and diversion structures and can model various flow regimes such as backwater, surcharging, reverse flow and surface ponding (Rossman, 2010). The ponding option in SWMM allows exceedance flows either to be lost or to be stored atop of the nodes and to subsequently re-enter the UDS when the capacity allows.

Two UDS configurations were compared: i) configuration 1 - without storage and ii) configuration 2 - with a storage tank with a maximum volume of 4,933 m^3 (maximum depth = 3m; surface area = 5,000 m^2, ponded area = 5,000 m^2). The storage tank performs the function of flood peak attenuation to enhance the robustness and restorability of the UDS (Figure 2~~Figure 2~~). In UDS configuration 2, the diameter of link C5 (inlet into the tank) was increased from 600 mm to 800 mm to improve the hydraulic conditions during filling and draining of the tank (e.g. Kim et al., 2013). The outlet from the tank was modelled as bottom type orifice with a height of 1 m, width of 0.5 m and an inlet offset of 0.5 m. Infiltration was modelled using the Green-Ampt model and flow routing was modelled using dynamic wave model with ponding was allowed atop of each node.

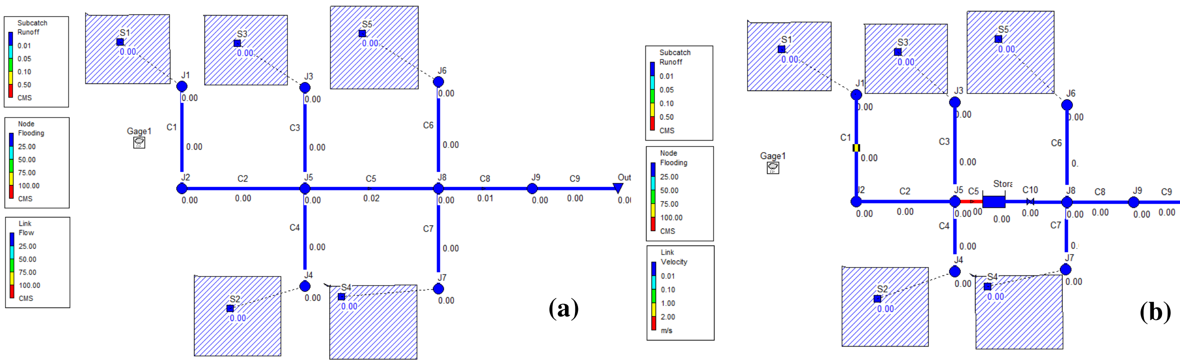

Figure 2(a) UDS without storage **(b)** UDS with a storage tank for flood peak attenuation

Event based rainfall data

Model simulations were carried out to investigate the performance of the synthetic UDS in respect to extreme rainfall induced pluvial flooding. For the simulations, an observed 2 year, 100 minute convective rainfall event for Kampala, Uganda with a resolution of 10 minutes and a total rainfall depth of 66.2 mm was used in the study (Mhonda, 2013). To account for the effect of increasing intensity of extreme rainfall events resulting from climate change, rainfall depths for events with higher return periods, *T* of 5, 10, 25, 50 and 100 years were estimated based on the observed rainfall event characteristics using a generalized rainfall-duration frequency relationship (Shaw 1994) for short duration tropical convective rainstorms (Equation 1).

$$R_T^t = (0.35lnT + 0.76)(0.54t^{0.25} - 0.50)R_2^{60} \quad (1)$$

for $2 \leq T \leq 100$ years and $5 \leq t \leq 120$ minutes; where *R* is the rainfall depth (mm), *t* is rainfall duration (min). Two key assumptions that formed the basis for applying this approach are: i) that the recurrence interval of extreme rainfall events changes under future conditions (for example a 1 in 10 year event becomes a 1 in 2 year event), (ii) that temporal characteristics of the rainfall events remain unchanged under anticipated future conditions (Mugume et al., 2013). Based on these assumptions, the rainfall depths (in mm) and corresponding climate change factors (in brackets) were estimated for *T* = 5, 10, 25, 50 and 100 years as87.9 (1.33), 104.0 (1.57), 125.3 (1.89), 141.4 (2.14) and 157.5 (2.38) respectively (Figure 3Figure 3).

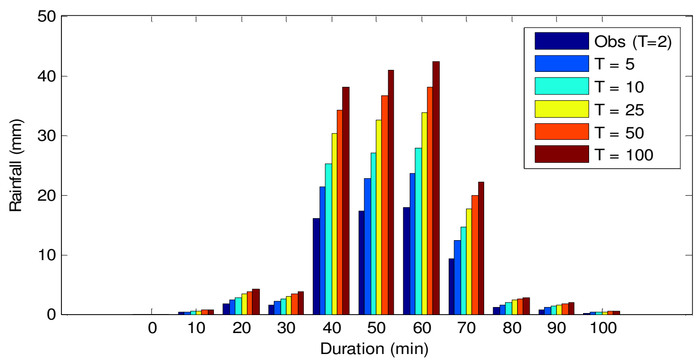

Figure 3: Observed extreme rainfall event on 25th June 2012 for Kampala (Obs) and estimated future extreme rainfall events with return periods, *T*= 5, 10, 25, 50 and 100 years.

Developing flood depth-based utility performance functions

Existing depth-damage data for UK residential properties (Penning-Rowsell et al., 2010)for various flood depths thresholds, x and return periods, T was used to derive utility performance functions $u(x)_T$ for an UDS during failure conditions. The functions relate overall performance of an UDS to flood depths; with the most preferred system performance level by the decision maker (no flooding, $u(x=0)$) and the least preferred system performance level by the decision maker (flood depths greater than or equal to3 m, $u(x\geq 3.0)$) being allocated utility performance values of 1 and 0 respectively. Equation 2 was applied to estimate utility performance values, $u(x)_T$ for $x = 0.1$, 0.3, 0.6, 0.9 and 1.2 m.

$$u(x_i)_T = 1 - \frac{D_x}{D_{max}} \qquad (2)$$

Where D_x is the flood damage attributed to a flood depth x, occurring after an elapsed time i, and D_{max} is the maximum flood damage for a particularly rainfall return period, T.Figure 4(a) shows the depth-damage curves for UK residential properties and Figure 4(b) shows the derived utility performance functions for the respective return periods.

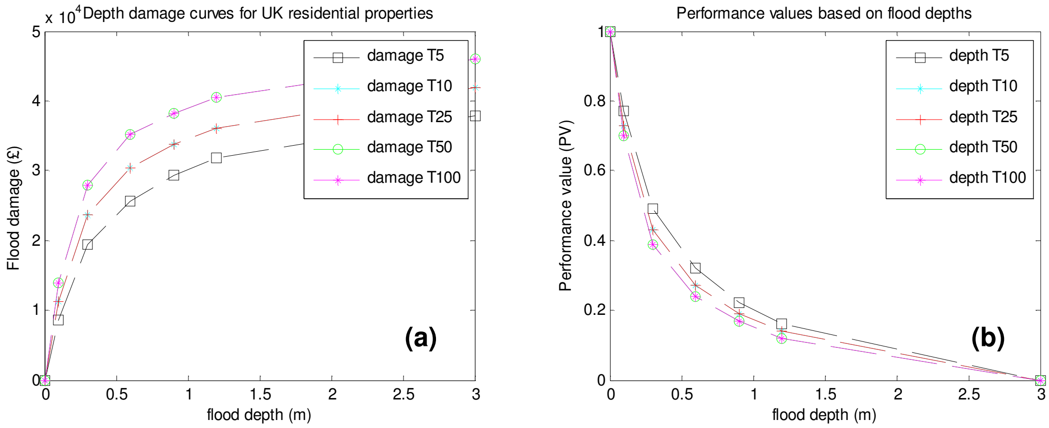

Figure 4 (a): Depth-damage curves for single UK residential properties **(b)** Computed flood depth based utility performance functions

Estimation of UDS resilience

The derived utility performance functions, $u(x_i)_T$, are used to estimate the system's residual functionality by assigning utility performance values, $u(t)$ to the system based on the simulated flood depths at each 5 minute time step . A higher utility performance value (close to 1) represents a higher proportion of system functionality retained after a flooding event and consequently a high level of system performance. Conversely, a low utility performance value (close to 0) implies that a lower residual functionality is retained by the system after a flooding event. Therefore, a system with a high average performance value over all simulation time steps can be considered to be more resilient compared to one with a lower average performance value because it has higher residual functionality. This therefore implies that a highly resilient system maintains higher residual functionality levels relative to original or pre-event levels after a flooding event. A surrogate measure of overall UDS resilience, Res_i, which combines *robustness* and *restorability,* can therefore be estimated by $Res_i = \frac{1}{t_n}\int_{t_0}^{t_n} u(t)dt$, where t_o is the start time of the simulation and t_n is the total elapsed time at the end of the simulation as represented in Figure 1~~Figure 1~~.

RESULTS AND DISCUSSION

Derived utility performance functions

The derived utility performance functions indicate that system performance is negatively correlated to increasing flood depths. The 5-year extreme rainfall event that results in flood depths of up to 0.6 m degrades the system hydraulic performance by 84%. Beyond flood depths of 0.6 m, the marginal degradation in hydraulic performance decreases significantly. This is explained by the steep slope of depth-damage curves up to flood depths of 0.6 m, which indicate that maximum damage to residential property occurs between flood depths of 0 - 0.6 m. Secondly, the effect of duration of flooding also affects the nature of the derived utility performance functions. Higher rainfall return periods result into higher flood durations and hence higher degradation of UDS performance. At very higher return periods (e.g. T = 50 or 100), the shape of the derived utility performance functions is almost identical.

Hydrological and hydrodynamic simulation results

Simulation results for UDS configuration 1 result in a maximum flood duration of 0.79 hours and flood volume of 14,319 m^3 for the 25 year rainfall event. The maximum flood depth of 1.24 m occurred after an elapsed time, t = 70 minutes. The effect of addition of a storage tank reduces the average duration of nodal flooding and the flood volume to 0.72 hours and 8,486 m^3 respectively for the 25 year rainfall event, with a maximum flood depth of 1.07m occurring after an elapsed time, t = 70 minutes. Figure 5~~Figure 5~~ provides a plot of computed average flood depths against elapsed time for the both UDS configurations. The effect of introduction of a storage tank is reflected in the downward shift of the peak flood depths for T = 5, 10 and 25 years. However, the effect is minimal for high magnitude events i.e. T = 50 and 100 years.

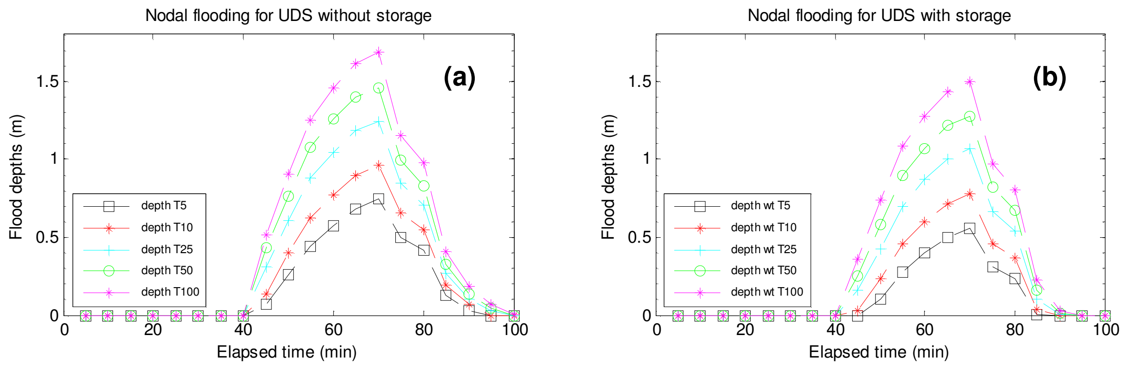

Figure 5 **(a)** Nodal flooding for UDS without storage **(b)** Nodal flooding for UDS with storage

Overall, the addition of a storage tank reduces the average duration of nodal flooding and the flooded volumes by 6 – 21% and 18 - 58% respectively (Figure 6~~Figure 6~~).

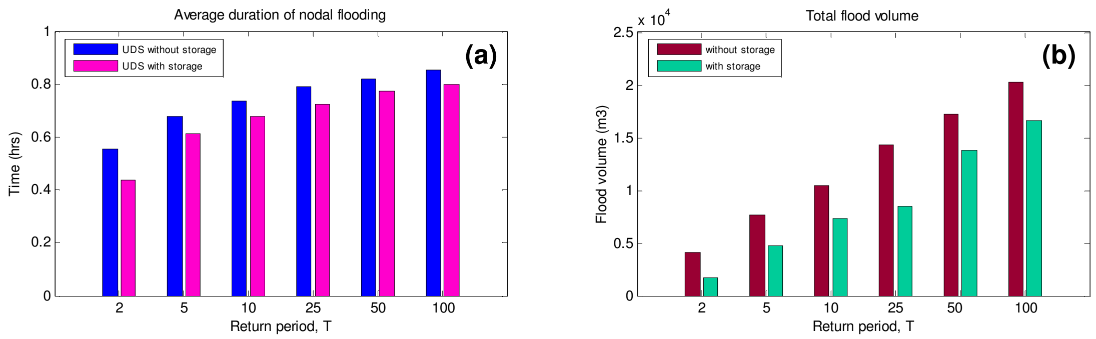

Figure 6: **(a)** Duration of flooding and **(b)** total flood volume for various extreme rainfall event return periods

Computed UDS resilience

The overall system resilience ranges from 0.76 (T = 5) to 0.59 (T = 100) for UDS configuration 1 (Table 1~~Table 1~~). The effect of the addition of a storage tank increases system resilience to 0.83 (T = 5) and 0.64 (T = 100). System resilience is therefore increased by 8.0 – 9.5% and the hydraulic performance of the UDS is restored to its original level before the end of the simulation period for all rainfall return periods (Figure 7~~Figure 7~~).

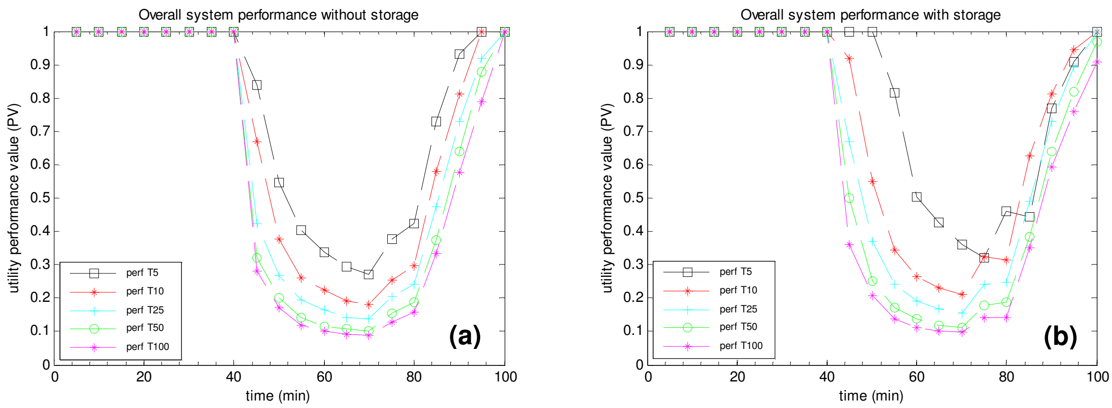

Figure 7: Urban drainage system performance curves **(a)** without storage **(b)** with storage

However, the introduction of additional storage does not completely eliminate nodal flooding. This could be attributed to the capacity and positioning of the storage tank, the sewer network configuration or the characteristics of inlet and outlet control devices (Kim et al., 2013). To achieve considerable improvements in system performance and hence resilience to flooding a number of strategies require further investigation (i) effect of changing the drainage network configuration (including the positioning of the storage tank) and ii) implementation of sustainable drainage systems (SuDs) in the upstream catchments.

Table 1: Overall system resilience for various return periods

Return period, T	5	10	25	50	100
System resilience (without storage)	0.76	0.69	0.65	0.61	0.59
System resilience (with storage)	0.83	0.76	0.70	0.66	0.64
% Increase in system resilience	**8.9%**	**9.5%**	**8.9%**	**8.4%**	**8.0%**

CONCLUSIONS

Resilience is defined as the ability of an UDS to minimize the magnitude and duration of flooding. Utility performance functions derived from depth-damage data for UK residential properties are applied to estimate the residual functionality (and hence resilience) of an UDS by assigning utility performance values to the system based on SWMM v.5.0 model simulation results. The proposed methodology provides a promising approach for quantifying resilience of UDSs. It can also be applied to evaluate and prioritize potential, cost effective mitigation and adaptation strategies aimed at providing appropriate customer service levels. Further work will focus on developing separate performance metrics for system robustness and restorability and investigating the effect of different failure modes i.e. pipe failure and sediment deposition on UDS resilience.

ACKNOWLEDGEMENTS
This work is financially supported by the UK Department for International Development (DFID) through a Commonwealth PhD scholarship awarded to the first author. This work has also been supported through the ESPRC funded Safe & SuRe Project fellowship (EP/K006924/1) awarded to the last author.

REFERENCES
Ahern, J.F. (2011). From fail-safe to safe-to-fail: sustainability and resilience in the new urban world. Landscape 100, 341–343.

Blockley, D., Agarwal, J., Godfrey, P. (2012). Infrastructure resilience for high-impact low-chance risks, in: Proceedings of the Institution of Civil Engineers, Civil Engineering Special Issue 165, Issue CE6. ICE Publishing, pp. 13–19.

Butler, D., Davies, J.W. (2011). Urban Drainage, 3rd ed. Spon Press, Taylor and Francis Group, London and New York.

Cardoso, M., Coelho, S., Matos, R., Alegre, H. (2004). Performance assessment of water supply and wastewater systems. *Urban Water J*. 1, 55–67.

Carpenter, S., Arrow, K., Barrett, S., Biggs, R., Brock, W., Crépin, A.-S., Engström, G., Folke, C., Hughes, T., Kautsky, N., Li, C.-Z., McCarney, G., Meng, K., Mäler, K.-G., Polasky, S., Scheffer, M., Shogren, J., Sterner, T., Vincent, J., Walker, B., Xepapadeas, A., Zeeuw, A. (2012). General Resilience to Cope with Extreme Events. *Sustainability* 4, 3248–3259.

Carpenter, S., Walker, B., Anderies, J.M., Abel, N. (2001). From metaphor to measurement: Resilience of what to what? Ecosystems 4, 765–781.

Cumming, G.S., Barnes, G., Perz, S., Schmink, M., Sieving, K.E., Southworth, J., Binford, M., Holt, R.D., Stickler, C., Holt, T., 2005. An Exploratory Framework for the Empirical Measurement of Resilience. *Ecosystems* 8, 975–987.

Djordjević, S., Butler, D., Gourbesville, P., Mark, O., Pasche, E. (2011). New policies to deal with climate change and other drivers impacting on resilience to flooding in urban areas: the CORFU approach. *Environ. Sci. Policy* 14, 864–873.

Folke, C. (2006). Resilience: The emergence of a perspective for social-ecological systems analyses. Glob. *Environ. Chang*. 16, 253–267.

Francis, R., Bekera, B. (2014). A metric and frameworks for resilience analysis of engineered and infrastructure systems. *Reliab. Eng. Syst. Saf.* 121, 90–103.

Gersonius, B., Ashley, R., Pathirana, A., Zevenbergen, C. (2013). Climate change uncertainty: building flexibility into water and flood risk infrastructure. *Clim. Chang*. 116, 411–423.

Gharaibeh, N.G., Asce, M., Chiu, Y., Gurian, P.L. (2006). Decision methodology for allocating funds across transportation infrastructure assets. *J. Infrastruct. Syst*. 12, 1–9.

Henry, D., Ramirez-Marquez, J.E. (2012). Generic metrics and quantitative approaches for system resilience as a function of time. *Reliab. Eng. Syst. Saf.* 99, 114–122.

Jung, D., Kang, D., Kim, J.H., Lansey, K. (2013). Robustness-based design of water distribution systems. *J. Water Resour. Plan. Manag*.

Kim, B., Kim, Y., Sanders, B.F., Famiglietti, J.S., Han, K. (2013). Calibration of stormwater management model using flood extent data. Proc. Inst. Civ. Eng. Water Manag. 167, 17–29.

Lansey, K. (2012). Sustainable, robust, resilient, water distribution systems, in: 14th Water Distribution Systems Analysis Conference. Engineers Australia, pp. 1–18.

Mailhot, A., Duchesne, S. (2010). Design Criteria of Urban Drainage Infrastructures under Climate Change. *Water Resour. Plan. Manag*. *136*, 201–208.

McDaniels, T., Chang, S., Cole, D., Mikawoz, J., Longstaff, H. (2008). Fostering resilience to extreme events within infrastructure systems: Characterizing decision contexts for mitigation and adaptation. *Glob. Environ. Chang*. *18*, 310–318.

Mens, M.J.P., Klijn, F., de Bruijn, K.M., van Beek, E. (2011). The meaning of system robustness for flood risk management. *Environ. Sci. Policy14*, 1121–1131.

Mhonda, A. (2013). Evaluating flash flood risk reduction strategies in built-up environment in Kampala. University of Twente.

Mott MacDonald (2012). Resilience - outcomes focused regulation. Principles for resilience planning. Birmingham.

Mugume, S., Gomez, D., Butler, D. (2013). Statistical methods for climate change impact assessment on urban rainfall extremes for cities in tropical developing countries – A review, in: Butler, D., Chen, A.S., Djordjevic, S., Hammond, M.J. (Eds.), International Conference on Flood Resilience: Experiences in Asia and Europe. University of Exeter, Exeter, United Kingdom.

NIAC (2009). Critical infrastructure resilience - Final report and recommendations.

Penning-Rowsell, E., Viavattene, C., Pardoe, J., Chatterton, J., Parker, D., Morris, J. (2010). The benefits of flood and coastal risk management: A handbook of assessment techniques - 2010. London.
Rossman, L. (2010). Storm Water Management Model - User's Manual Version 5.0. Cincinnati, Ohio.
Shaw, E.., 1994. Hydrology in Practice, 3rd Editio. ed. Van Nostrond Reinhold.