QUANTIFICATION OF THE HYDRAULIC DIMENSION OF STORMWATER MANAGEMENT SYSTEM RESILIENCE TO FLOODING

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ABSTRACT

Climate change, increasing urbanisation and a growing concern over existing stormwater management systems (SWMSs) has resulted in the development of various approaches to improve urban resilience to flooding and the performance of SWMSs. However, previous studies have focused on urban resilience and the hydraulic reliability of urban drainage systems, without considering all dimensions of a SWMS as the main urban flood control infrastructure. This paper presents an approach to quantify the resilience of the hydraulic dimension of primary SWMSs to flooding. Resilience was quantified based on the Hydraulic Performance Capacity (HPC), a new metric developed to represent the functionality of a SWMS over time using the temporal hydraulic characteristics across a catchment. The effect of network properties, catchment characteristics, and design storm events can be assessed through this approach based on the outputs of standard One Dimensional (1D) hydraulic modelling. The approach was applied to a case study urban catchment and was able to demonstrate the effect of different storm events and pipe material properties on resilience, robustness, and recovery. This framework can be used by decision makers to benchmark SWMS network resilience, optimise network capacity for design, and assess methods for reducing flood hazard in urban catchments.

Keywords

Stormwater management system, Resilience, Hydraulic Dimension, Flood Control, Hydraulic Performance, stormwater piped network

INTRODUCTION

With increasing urbanisation, growing population in cities, and the impacts of climate change, various approaches have been introduced to improve urban resilience to floods by implementing structural and non-structural strategies for SWMSs (Balsells et al. 2013; Balsells et al. 2015; Golz et al. 2013; Gupta 2007, Chang and Liou 2010; Jia et al. 2012). However, there is still a lack of robust approaches available to measure the resilience of urban SWMSs as the main urban flood control infrastructure, including all the main characteristics related to flooding.

Recently, some studies have attempted to define and quantify the concept of resilience for drainage systems in relation to flooding. Butler et al. (2014) defined the resilience of engineering systems for urban water management on the basis of "Safe & SuRe" as "the degree to which the system minimises level of service failure magnitude". Mugume et al (2015) introduced an index for evaluating flood resilience for drainage systems in urban areas on the basis of a functionality curve and the concept of severity (Hwang et al., 2015; Lansey, 2012). In this approach the overall resilience of a drainage system was evaluated under one dimension by considering the total flood volume within the catchment and the drainage systems affected by the flood. However, this approach did not consider the flooded area and the capacity of the system.

Mugume et al (2014) described a methodology that combined hydraulic performance assessment with utility performance functions to quantify the resilience of Urban Drainage Systems (UDSs) during flooding conditions. This approach relied on the theory of a functionality curve in the definition of resilience and existing flood depth-damage data for residential properties in the UK. Various rainfall return periods were used to evaluate UDS residual functionality and resilience to pluvial flooding. In this method, resilience was defined as the robustness and restorability of the system for extreme events. This approach did not consider the performance of stormwater infrastructure in terms of hydraulic characteristics and resilience of the system was only based on the proportion of flood depth.

Most of the previous quantitative studies related to SWMS resilience to flooding used a drainage-based approach, and the main focus was the hydraulic reliability of urban drainage systems. Therefore, the hydrological characteristics of the urban catchments, the structure of the network within the drainage system, the one dimensional (1D) hydraulic functionality of SWMSs , and the characteristics of floodplains and overland flow paths as the secondary SWMS have not been taken into account under an overarching framework.

Valizadeh et al. (2016) introduced a framework to quantify the resilience of SWMS s to floods and natural disasters, defining the resilience of SWMS as the ability of the system to minimize the disturbance of the system during floods, redistribute flows toward functional parts of the system, and minimize the time required for the system to recover to a normal operational state. Through this approach, the robustness capacity is associated with the capacity of natural hydrological processes and stormwater infrastructure to absorb the surface runoff produced in rainfall events. The recovery capacity is defined based on time it takes for the system to be restored back to pre-event functionality levels after an extreme event and this depends on the time of recovery of the system. In this framework, the hydraulic dimension of the resilience of a SWMS is quantified in terms of the hydraulic capacity of primary stormwater piped infrastructure and the hydraulic characteristics of overland flow paths as the secondary SWMS. In the hydrology dimension of this framework, the proposed approach quantifies the resilience of an urban catchment on the basis of the hydrological characteristics of the catchment. The network structure dimension quantifies the resilience of the network structure by focusing on the connectivity of the network components and the degree of redundancy.

This paper presents an approach to quantify the resilience of the hydraulic dimension of primary SWMSs to flooding. This forms part of the framework developed by Valizadeh et al (2016) to evaluate the overall resilience of stormwater management systems to flooding. The approach to quantify the resilience of SWMSs to flooding is discussed, and the development of a metric to represent the functionality of a SWMS over time. Details of the parameters used to define this metric are presented, based on the outputs of 1D hydraulic modelling of a catchment. To demonstrate this approach, it is applied to a case study SWMS consisting of five urban sub-catchments. The effect of different design rainfall events and pipeline material roughness on the temporal functionality and the resilience, robustness and recovery characteristics of the system is presented.

RESILIENCE FRAMEWORK FOR THE HYDRAULIC DIMENSION

Urban SWMSs are highly dependent on the hydraulic capacity of stormwater piped networks within urban catchments. In a general, these networks collect stormwater runoff from contributing catchments and convey it to discharge points. The primary SWMS in an urban catchment consists of a set of stormwater network systems with associated sub-catchments collecting stormwater runoff via drainage networks and conveying them to natural water bodies such as streams, lakes, and the sea; or temporary storage areas such as ponds and wetlands.

Quantification of the resilience of the primary SWMSs in this study has been developed based on the analytical resilience concept presented by Bruneau et al. (2003). This concept of resilience is a multidisciplinary and multidimensional notion denoting strength and flexibility of a system during a disturbance. Bruneau et al (2003) introduced the framework based on the performance of the system to measure temporal functionality (Q) of the system, with resilience of the infrastructure equal to the area under this functionality curve. This framework has been applied in various infrastructure resilience studies to measure the resilience of the system in question (Ayyub 2014; Bocchini et al. 2013; Chang and Shinozuka 2004; Cimellaro, et al. 2010; Miles 2011; Ouyang et al. 2012).

To quantify the overall resilience (R) of a stormwater piped network of an urban catchment, the resilience of each sub-catchment is quantified and combined using:

$$R = \sum R_i W_i \qquad \text{Eq (1)}$$

where R_i is the resilience of each sub-catchment and W_i is the weighting applied to each sub-catchment resilience, based on the proportion of the runoff that is generated within each sub-catchment with respect to the overall catchment. This approach can be applied to different scales, from a small urban catchment with a simple stormwater network, through to a city scale urban catchment with various types of SWMSs. The components of this framework are described in more detail in the following sections.

Sub-catchment Network Functionality

To represent the functionality of each stormwater sub-catchment over time, a metric termed the Hydraulic Performance Capacity (HPC) of the stormwater system has been defined, analogous to the temporal functionality of Bruneau et al. The HPC is derived from the flow hydrograph of each pipe in the contributing catchment as well as temporal flow depth. The HPC curve represents the variation in HPC with time and is used to provide a measure of the overall degree of resilience of the system as well as the robustness, recovery time, and recovery rate for a rainfall event. To determine the HPC of the network within a sub-catchment over time, the sum of the unit performance of all pipes in each time step are divided by the total length of the stormwater pipes in the sub-catchment. The HPC of each sub-catchment network i ($HPC_i(t)$) at a particular time step t is equal to:

$$HPC_i(t) = 100\frac{\sum n_i(t)}{L_t} \qquad Eq(2)$$

where $n_i(t)$is the unit performance of each pipe in the sub-catchment and L_t is total length of the pipes within the sub-catchment.

The $HPC_i(t)$ of each sub-catchment is directly dependent on two main characteristics of each pipe within the sub-catchment, the remaining flow capacity of each pipe and the free depth of each pipe. If the flow rate within a pipe increases, the remaining flow capacity of the pipe decreases and results in a decrease in the functionality of the system. In storm events, backwaters due to blockages or pressurising of pipes can generate negative flow, causing the energy level of the pipes to exceed the maximum water level. Therefore, the free depth of the pipe has been used as an additional indicator of the temporal performance of the system. To determine the overall performance of a stormwater network, the performance of each pipe is weighted based on relative pipe length. By considering all these criteria the temporal unit performance of each pipe ($n_i(t)$) is equal to:

$$n_i(t) = \left[\frac{(Q - q_t)}{Q}\right]\left[\frac{(D - d_t)}{D}\right](L_i) \qquad \text{Eq(3)}$$

where Q is the maximum flow capacity of the pipe when the pipe is full, $q(t)$ is the flow rate of the pipe at time t in a rainfall event, $d(t)$ is remaining depth in the pipe at time t, and D is the total diameter (or depth) of the pipe.

The characteristics of the $HPC_i(t)$ over time defines the performance capacity curve of each stormwater sub-catchment, an example of which is presented in Figure 1. The performance capacity curve in each rainfall event is related to the flow hydrograph of the contributing catchment for each pipe, the flow capacity of the pipe and the physical proprieties of stormwater network. Using this curve, the total robustness of the system, the recovery time, and the resilience of a network can be defined. When a rainfall event starts, stormwater runoff is collected by the stormwater pipeline, reducing the hydraulic performance capacity of the system which is known as “Loss Phase” in a performance capacity curve. The minimum HPC_i of the system during a rainfall event is known as robustness value for the rainfall event. When there is a reduction in runoff within an urban catchment, the HPC_i of the system increases gradually to the point where it has recovered all the hydraulic capacity of the system, known as “Recovery Phase”.

According to the general definition of the functionality curve and characteristics of stormwater drainage system, increased flow within the system reduces the residual capacity of the system, resulting in a reduction of the resilience of the system. This approach is able to evaluate the change in resilience of the system for a wide range of rainfall events, the effect of system degradation and the effect of disturbances to the system (such as blockages and damage due to other natural hazard events).

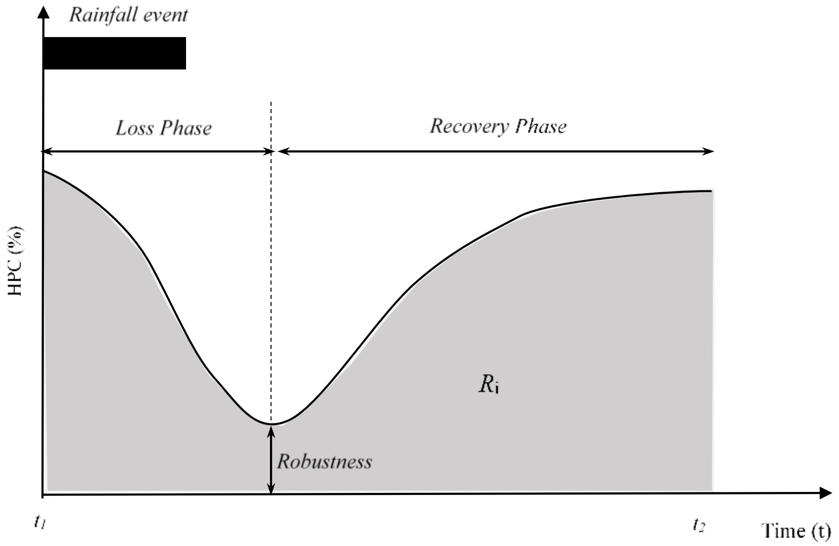

Figure 1: Schematic of a Hydraulic Performance Capacity curve of a primary stormwater management system sub-catchment and associated metrics. The shaded area under the HPC_i curve is the resilience (R_i), and the robustness is the minimum HPC_i value.

The sum of weighted HPC$_i(t)$ for all contributing catchments within the study area identifies overall Hydraulic Performance Capacity ($HPC(t)$) of the stormwater piped network for an urban catchment as shown in following formula:

$$HPC(t) = \sum (HPC_i(t))(W_i) \qquad Eq(4)$$

Sub-catchment Resilience

According to the analytical definition of resilience, the total area under the HPC curve from the start of an extreme event to the point of recovery the system can be used to define the resilience of the network (Figure 1). The resilience of stormwater sub-catchment network *i* in the hydraulic dimension (R_i) is equal to:

$$R_i = \int_{t_1}^{t_2} [100 - HPC_i(t)]dt \qquad Eq(5)$$

where t_1 is the start time of the rainfall event and t_2 is the network recovery time, representing when the network has returned to its full capacity after a rainfall event . It should be noted that since the resilience value is based on temporal performance of system, the total value of resilience does not reach to zero as it represents the functionality of the system through the loss and recovery phases.

In this approach, the time to discharge all stormwater runoff for normal and blocked pipelines will be different, resulting in an inconsistency between the durations and normalised resilience. In order to assess different scenarios, a fixed definition of t_2 was required.

It is difficult to determine an explicit time for t_2 that is applicable for all scenarios. Here we have used a fixed time that has been defined based on the design hydrograph for the catchment. In general, the flood hydrograph will change in different rainfall events according to the relationship between peak time from origin (t_p), defining the time with the greatest rainfall intensity, and horizontal distance of the centroid (c) of the flood hydrograph (t_c) from the origin. The three main shapes of flood hydrographs are “prior peak shape” where $t_p<t_c$, “mid-peak shape” where $t_p=t_c$, and “posterior-peak shape” where $t_p>t_c$ (Yue et al. 2002).

The network recovery time (t_2) of the HPC curve has been defined based on a positively skewed prior peak shape hydrograph considering all possible hydrograph scenarios. According to a review of unit hydrographs, the Soil Conservation Service (SCS) recommended that the time of recession is approximately 1.67t_p as shown in Figure 2 (Te Chow 1988). To evaluate the HPC curve of urban catchments, the total time taken into account is from the start of a rainfall event and extends to 2.0t_p after the last peak of the rainfall event. This method provides a consistent metric for different scenarios, particularly when the recovery time differs for each scenario. A sensitivity study conducted confirmed that this duration was able to adequately represent the resilience properties of the system. In some studies, t_2 includes the time for repair of damage/blockages (Lansey, 2012), but this is not accounted for here.

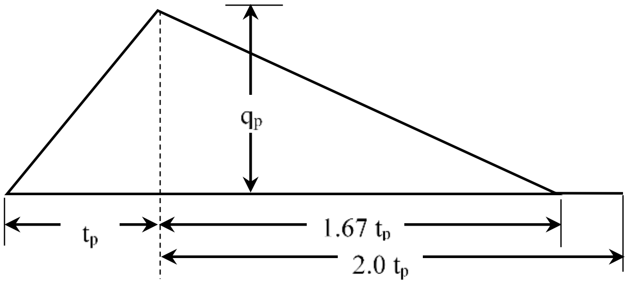

Figure 2: Triangular unit hydrograph recommended by Soil Conservation Service (SCS) and the recommended durations to use in the development of HPC curves.

CASE STUDY APPLICATION

The approach described in the previous section is able to be applied to any drainage-based urban SWMSs across a range of network sizes and stormwater management system characteristics, as it is based on the temporal hydraulic characteristics of the system from typical hydraulic modelling software. To demonstrate the framework, it was applied to a case study catchment within the urban suburb of Takanini in Auckland, New Zealand (Figure 3). The Takanini catchment was used because the area had recently been developed and there was reliable data available to constrain the development of the catchment model. This suburb has a separated SWMS collecting stormwater runoff from residential lots and public impervious areas. The total contributing catchment of the study area is 60ha, with over 1200 residential lots located in predominately flat topography. According to the Auckland Council Unitary Plan (Auckland Council 2017), the maximum allowable impervious area for this catchment is 60%.

Stormwater management of this area is comprised of five separated sub-catchments with individual stormwater piped network systems. The stormwater piped network for this study area was designed for 5- and 10-year Annual Recurrence Intervals (ARI) storm runoff, aligning to the recent change in design criteria for primary stormwater network design in Auckland. The characteristics of these five sub-catchments have been summarised in Table 1.

Table1: Sub-catchment and stormwater pipe network characteristics

	Sub-catchment 1	**Sub-catchment 2**	**Sub-catchment 3**	**Sub-catchment 4**	**Sub-catchment 5**
Catchment area (ha)	23.75	6.3	4.78	3.56	22.58
Total pipe length (m)	6003	1403	946	678	5075
Minimum pipe size (mm)	225	225	225	225	225
Maximum pipe size (mm)	1800	825	900	750	1200
Number of connections (manholes)	150	40	21	19	131
Pipe density (m/100m^2)	2.53	2.23	1.98	1.90	2.25

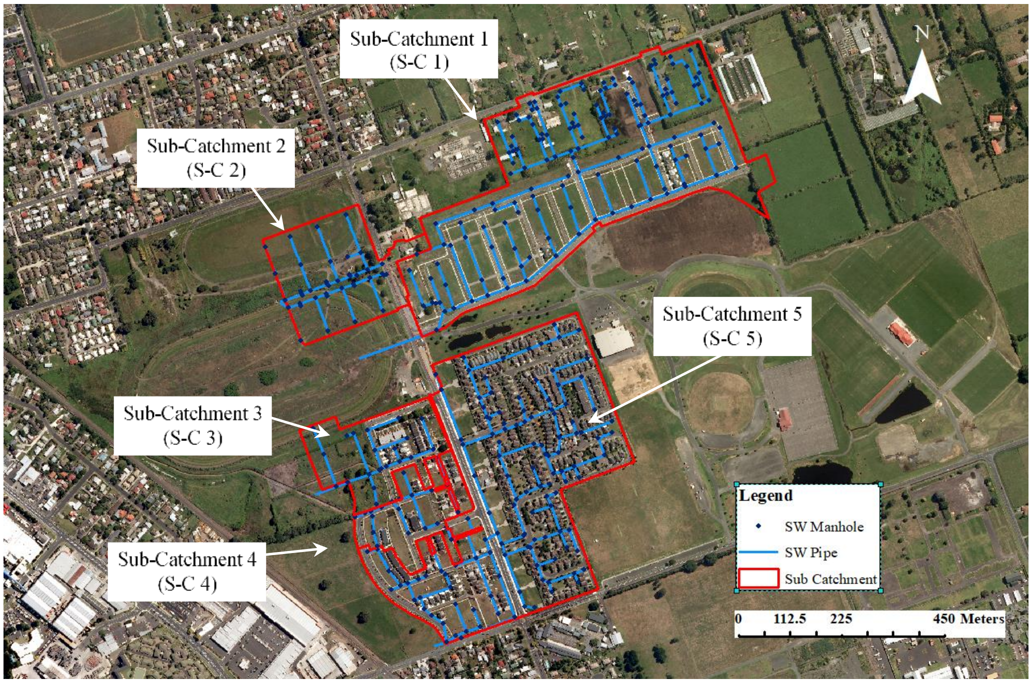

Figure 3: Plan of the stormwater network and sub-catchments of the study area.

This approach can be applied based on the outputs of different hydraulic software platforms available in industry to calculate the temporal hydraulic characteristics of the system. For this case study the hydrology and the hydraulic modelling was performed using MIKE URBAN (Hénonin et al. 2010). The total area of each sub-catchments was delineated based on the contributing catchment of each pipe to determine the incremental flow hydrograph of each pipe. In the hydraulic model, the design flow hydrographs associated with each pipe have been loaded at the upstream end of each pipe. The approach was applied in two studies to assess the effect of different parameters on the HPC curves and the resilience of the study area.

Firstly, the effect of different design rainfall events was assessed. An urban stormwater catchment is designed for a prescribed maximum design rainfall event. However, during its lifetime, it will be exposed to different rainfall events, and these can reach longer ARI than the designed system. This will also be affected by climate change, both in terms of the total rainfall depth and the rainfall intensity. The ARIs for the rainfall events were varied between 1.58 years and 50 year to determine the performance of the system for rainfalls smaller and larger than the design rainfall events shown in Figure..4 The design rainfalls were extracted from the High Intensity Rainfall System V3 (HIRDS) (NIWA 2017) and the rainfall temporal pattern recommended by Guidelines for Stormwater Runoff Modelling in the Auckland Region (TP108) was used to be consistent with Auckland design criteria (TP108, 1999). Since the time of concentration of the all catchments was less than 1 hour, a 1 hour rainfall duration was considered for this study as shown in Figure 4.

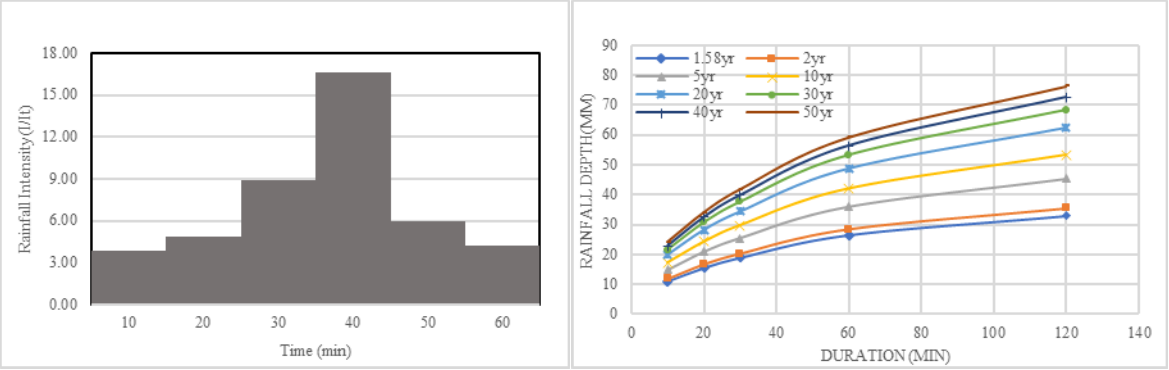

Figure 4: a) Depth Duration Frequency of rainfall for study Area (NIWA 2017); (b) 1 hour Chicago method temporal pattern

The second variable assessed was the influence of pipeline roughness on the degree of resilience of the system. Different pipeline materials and increasing pipeline roughness due to aging will both affect the capacity of stormwater management system to convey flow and therefore change the resilience of the system. To assess the impact of pipe roughness five different Manning's roughness values were applied to all the pipes within the system.

RESULTS AND DISCUSSION

Effect of Storm ARI on Resilience

Figure 5 summarises the HPC of all sub-catchments for ARIs from 1.58 years to 50 years, with total rainfall depth increasing from 26.5 mm to 59.1 mm respectively. As expected, the robustness value of the HPC curves decreased with increasing ARI, demonstrating the change in the overall remaining capacity of the SWMS. However, during the loss phase, the total time of reduction of the HPC value across all ARI values did not change significantly. In the 10 year ARI design rainfall event , the minimum robustness of sub-catchments 2, 4 and 5 were close to 0%, indicating that all the pipes within these sub-catchments had reached their maximum capacity, linked to the fact that the piped network in these sub-catchments were designed mainly for storm events between a 5 year and 10 year ARI. When the HPC has reduced to 0%, all the pipelines within the catchment do not have the capacity to collect more flow, meaning the flow must accumulate in these urban sub-catchments and increases the potential for flooding. When the ARI increases further, the HPC of the sub-catchments remains at 0% for a longer period of time, until the rainfall intensity reduces and the HPC transfers from the loss phase to the recovery phase. In the recovery phase of the HPC curves, the recovery rate and recovery time of each sub-catchment is directly dependent on the characteristics of the stormwater infrastructure of each sub-catchment.

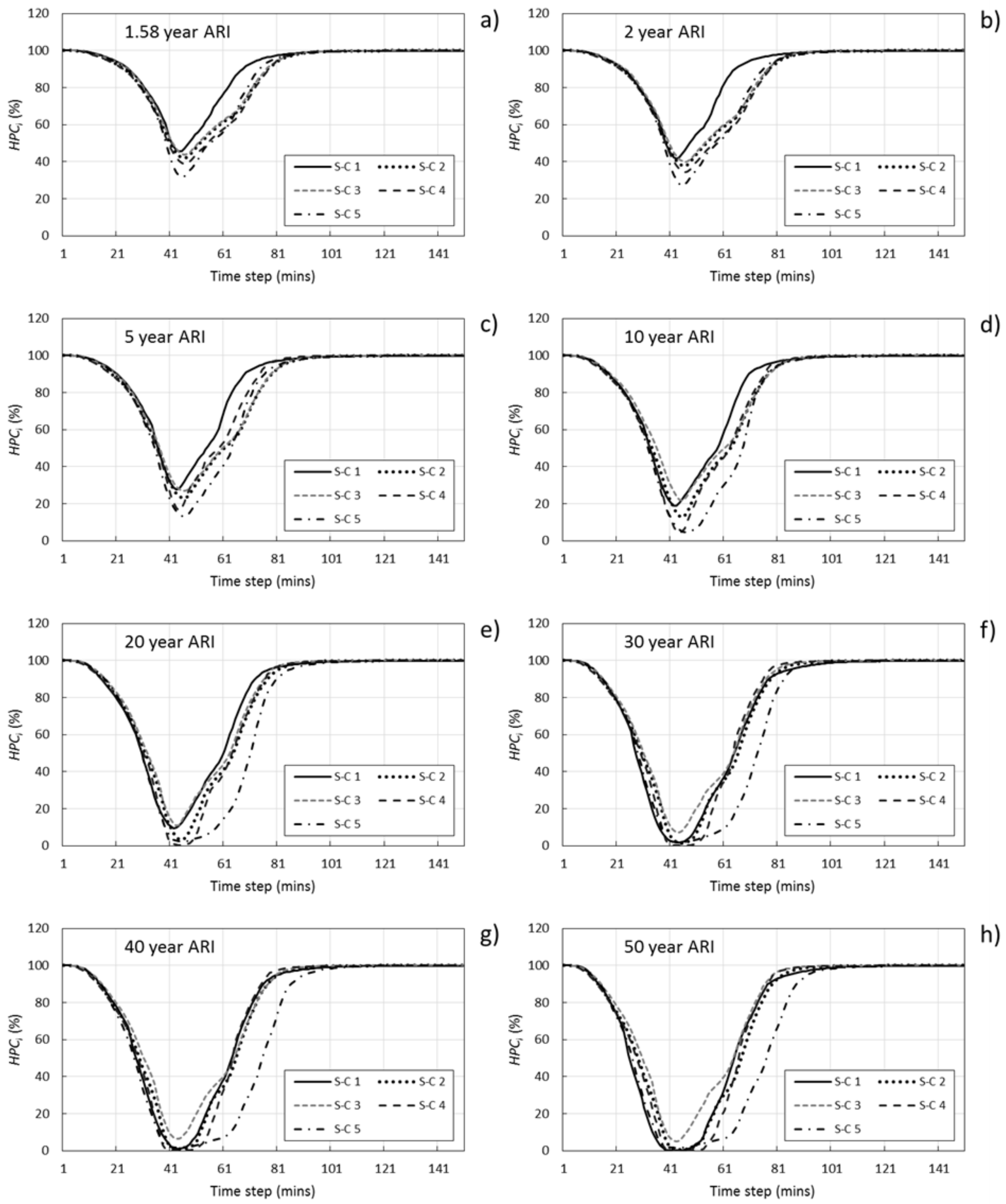

Figure 5: Hydraulic performance capacity (HPC) curves of each sub-catchment for different annual recurrence interval (ARI) design rainfall events

The HPC curve of the overall catchment in Figure 6 shows the overall robustness value and HPC characteristics in the loss and recovery phases during different design rainfall events. The robustness value varies between 40% and 0% as the ARIs increase, representing the reduction in the minimum residual capacity of the stormwater infrastructure during each storm event. In addition, by increasing the ARIs, the recovery duration and the gradient of the loss portion of the HPC curve both increased, reducing the area under the HPC curve of the catchment and decreasing the resilience of the catchment.

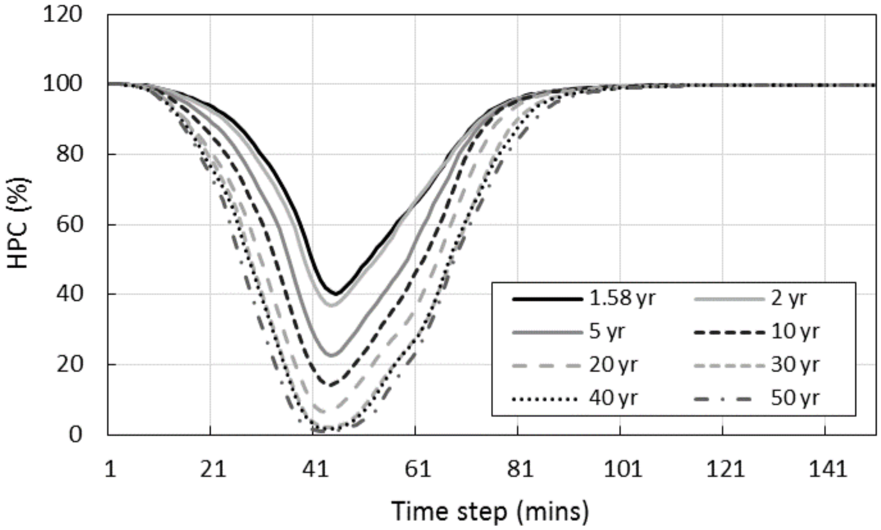

Figure 6: Performance capacity of the overall catchment for different Annual Recurrence Interval (ARI) design storm events.

Figure 7 summarises the overall resilience of the sub-catchments within the study area (R_iW_i) for different rainfall events. By increasing the ARI of the rainfall events, the total resilience of the catchment reduces from 88% to 72%. The rate of reduction of resilience for rainfall events with a less than 10 year ARI is higher than the rate for rainfall events higher than 10 ARI, generating an inflection point in 10 year ARI. This inflection point represents the approximate design capacity of the stormwater management system for the rainfall event. As the stormwater system does not have the capacity to accommodate the peak flow of a larger design rainfall event, the minimum robustness remains zero for a longer period of time which reduces the area under the HPC curve. In this condition the system does not have further capacity to accommodate the additional excess flow. The total resilience of a system is still greater than 0% for all these events because the system has residual capacity during the loss and recovery phases. These results show how the system is affected by different design rainfall events and how this affects the degree of resilience. These results could help stakeholders and decision makers develop strategies to optimize the system using different contemporary approaches.

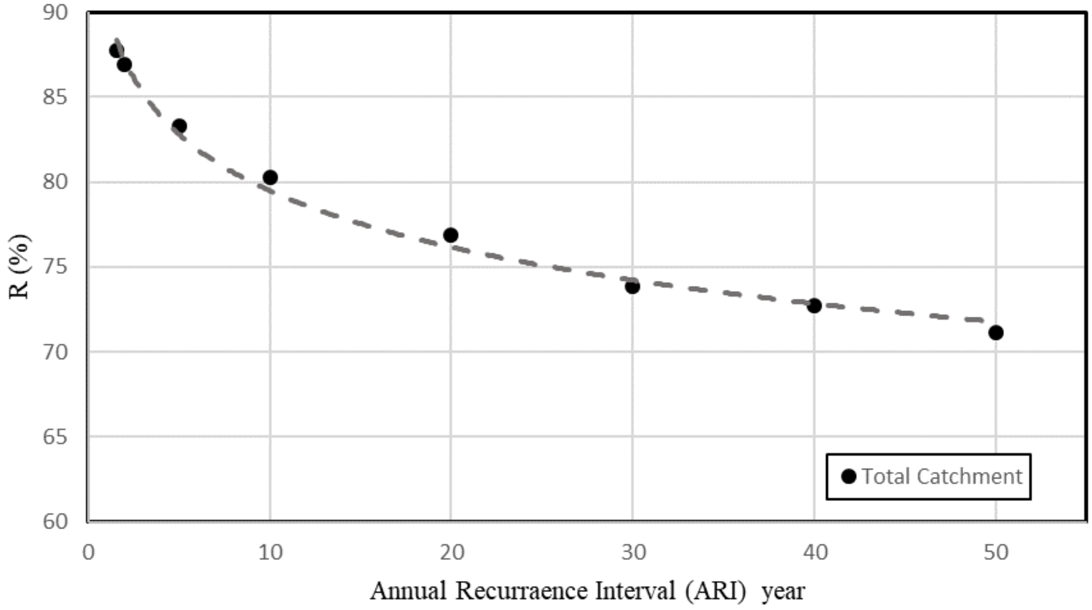

Figure 7: Weighted resilience of each sub-catchments and the overall resilience of the catchment for a range of ARI design storm events.

Impact of roughness on 1D hydraulic resilience

To assess the effect of roughness of the stormwater piped network on the resilience of the system, all the pipes within the catchment were assigned a Manning's roughness ranging from 0.011, for a smooth concrete material, through to 0.019 for a rough surface. As the majority of the sub-catchment networks within the study area were designed for a 10 year ARI event, all the models were assessed using a 10 year ARI design storm event.

The effect of increased roughness on the HPC curve was similar to the effect of the increasing ARI, reducing the robustness and shifting the HPC curve to a lower trend. Figure 8 indicates the overall resilience of the study area for different roughness values, providing a measure of the sensitivity of the stormwater network resilience to the roughness of the pipelines. Across all sub-catchments there is a fairly consistent reduction in resilience with increasing roughness as the same roughness values have been used, and if these varied across catchments these effects would different from one sub-catchment to the other.This outcome could be used to determine the sensitivity of the resilience of the system to pipeline aging effects and identify the best pipe material for new development areas to reduce the impact of deterioration and sedimentation.

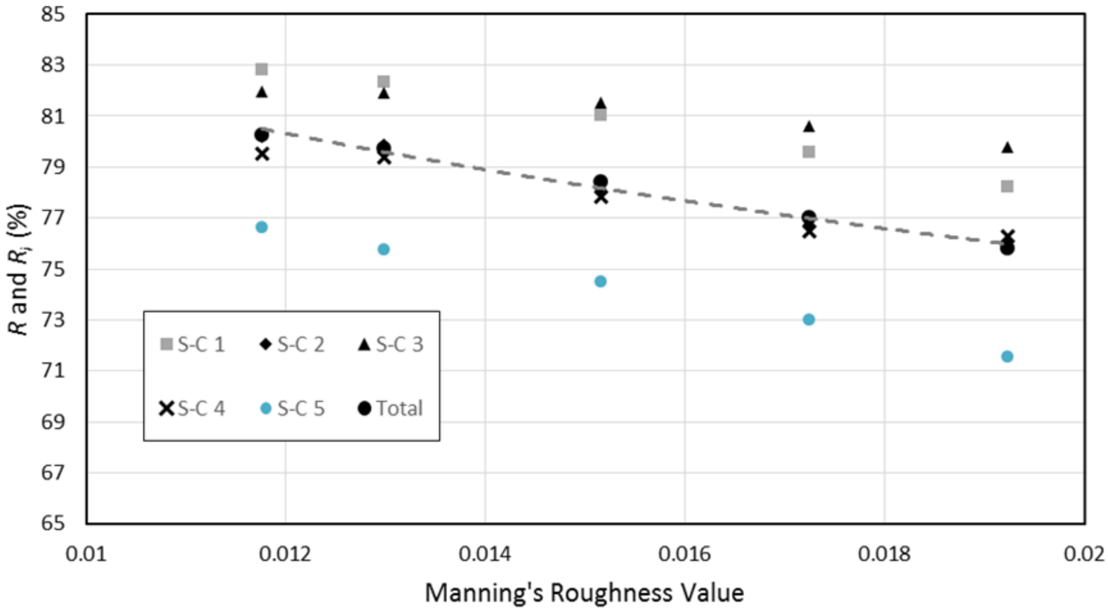

Figure 8: Resilience of sub-catchments and the overall resilience for a range of roughness values.

CONCLUSIONS

This paper has presented a framework to quantify the resilience of urban SWMS s in terms of the hydraulic dimension for primary stormwater system using the analytical concept of a functionality curve. A temporal representation of the remaining capacity and flow depth of each pipe has been used to evaluate the hydraulic perormance capacity (HPC) of the stormater network network over time, which represents the resilience, minimum robustness of the system, and recovery time of the system. This can be assessed based on the outputs of standard One Dimensional (1D) hydraulic modelling A case study application to an urban catchment showed that at ARI rainfalls events above the design ARI, almost all of the pipes within the system were not able to collect further runoff, degrading the network robustness to nearly zero and reducing the resilience. The sensivity of resilience to the degradation of the network was assessed by altering the pipe roughness characteristics, suggesting that resilience would reduce in an approximately linear trend as the roughness increased.

This framework can be used by decision makers to benchmark stormwater network resilience, improve the network system for an optimum capacity design, as well as optimising stormwater management systems for reducing flood hazards in urban catchments. By changing of capacity of the system using the degradation of pipe properties, the resilience of the system over time can be estimated. In addition, this framework can be used to estimate the change of resilience following other natural hazards that may reduce the functionality of the stormwater network, such as earthquake induced liquefaction and ashfall from volcanic eruptions.

Further research will focus on the implementation of this framework to different scenarios such as assessing the influence of stormwater Best Management Practice (BMP) approaches, water sensitive approaches and pipeline deterioration. The approach presented in this paper is limited to the hydraulic characteristics of primary SWMS, and is a part of a wider study for quantifying the resilience of SWMS to flooding under network, hydraulic and hydrology dimensions.

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COMPLIANCE WITH ETHICAL STANDARDS

Conflict of Interest: None

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