A RESILIENCE BASED ASSESSMENT METHOD FOR PRIMARY STORMWATER MANAGEMENT SYSTEMS URBAN FLOOD CONTROL

N. Valizadeh (The University of Auckland), A. Y. Shamseldin (The University of Auckland), L.Wotherspoon (The University of Auckland)

ABSTRACT

Urbanization results in considerable land use changes in urban areas, increasing potential flood impacts. However, the majority of the main urban stormwater management systems are still pipe based systems, collecting excess water from urban sub-catchments and transferring it to outlets. This system is highly reliant on the structure of the piped drainage network and its capacity. In addition, stormwater drainage network structures are predominately acyclic systems that transfer load from sources to outlets by gravity. This type of network structure provides a minimum level of connectivity without alternative pathways between source nodes and destinations.

Water sensitive design (WSD) in stormwater is a new sustainable development approach that attempts to overcome the constraint of drained city systems and move toward a resilient system not only for flood control but also by protecting natural freshwater resources and ecosystems. To conduct WSD in stormwater, many approaches have been introduced to improve reducing peak flow and flood volume in the system. However, there is not a robust framework to quantify the change in the resilience of stormwater management systems using these approaches.

This paper introduces an index based methodology to quantify the resilience of primary stormwater management systems in terms of the network structure and hydraulic capacity dimensions. In the hydraulic capacity dimension, the degree of resilience for a primary stormwater system is quantified by accounting for the temporal nature of system robustness and functionality during the conveyance of different extreme rainfall events. To demonstrate this approach, a resilience-based approach is introduced to determine the best practicable option for a stormwater management plan within an urban catchment using WSD approaches by considering the two main objectives of WSD for flood quantity controls. These two aims are controlling flood volume and peak flow rate generated in an area in order to control the flow quantity downstream. These two objectives impact directly on hydraulic performance capacity (HPC) of the affected primary stormwater management system within the urban catchment by improving the robustness value and altering recovery and loss rates of the system.

KEYWORDS

Resilience based design, framework, Water Sensitive Design, WSD, stormwater network, hydraulic capacity

PRESENTER PROFILE

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1 INTRODUCTION

Due to increasing urbanization and growing populations in urban areas, flood risk has become increasingly challenging due to social, organizational and economic activities within urban areas (Pelling 2003). In addition, due to the impacts of climate change, the frequency and depth of rainfall events has become more unpredictable, increasing the uncertainties in flood control strategies. In the last decade, various contemporary approaches have been introduced to shift from drain based stormwater management system to a more resilient system (M Balsells et al. 2013a; Golz et al. 2013; Gupta 2007; Mireia Balsells et al. 2015). These approaches implement various structural and non-structural strategies to improve the resilience of urban stormwater management systems (C.-L. Chang and Liou 2010; Jia et al. 2012). However, there is currently no robust framework to quantify the technical resilience of stormwater systems of the main stormwater infrastructure within urban areas.

In general, an urban stormwater management system is categorized into primary and secondary stormwater management systems. The primary urban stormwater management system is used during shorter period events to manage runoff within urban sub-catchments by collecting and conveying runoff from the sub-catchment, mainly using the stormwater piped network. However, secondary stormwater management utilizes the natural and engineered overland flow paths to convey accumulated runoff from urban catchments. The stormwater piped network can be affected by hydraulic deterioration effects due to sediment and debris composition, erosion, and corrosion (Banasiak 2008; Barton et al. 2008; Guzmán et al. 2007; Marlow et al. 2010; Tran 2016). The impact of hydraulic deterioration on the functionality of the system and the resulting potential reduction in resilience is a significant issue for stormwater management systems. By altering storm frequency, the pattern of precipitation and temperature due to climate change, the functionality of urban primary stormwater infrastructure has been affected which causes decrease of stormwater infrastructure resilience by increasing system failure and forcing cities to invest in increasing the capacity of drainage systems (Neumann et al. 2015). In addition, although a range of approaches have been introduced to improve urban resilience to flooding, the technical resilience of stormwater management system has not been quantified in a holistic and robust approach.

Water Sensitive Design (WSD) is the latest approach in stormwater management, from a combined sewers system to the multidisciplinary approach of WSD to managing urban stormwater, seeking to minimize the impacts arising from changes in catchment hydrology due to urbanization (Fenelon and Hellberg 2015). In terms of water quantity control, the main objectives of WSD are to reduce runoff volume and peak flows, minimizing the adverse effect of land use changes on natural freshwater systems (Lewis et al. 2015). A range of stormwater devices can be utilized to provide a retention volume prior conveying the generated runoff from impervious areas of development areas to the primary and secondary stormwater management systems. This reduces the impact of development on the stormwater management system and reduces the volume added to downstream system during storm events. In addition, by reducing the stormwater peak flows, the volume and flows can be attenuated over a longer period of time, which can reduce the flow entering primary stormwater management systems.

Valizadeh et al. (2016) introduced a framework to quantify the resilience of stormwater management systems to floods and natural disasters (Valizadeh, Zorn, and Shamseldin 2016). In this approach the resilience of stormwater management system is defined as the ability of the system to minimize the disturbance 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, recovery capacity and adaptability of the system are characterised as the main resilience properties to evaluate the stormwater system resilience. On this basis, three dimensions, hydrology, hydraulic and network structures were considered to evaluate the resilience of the system. (Figure 1).

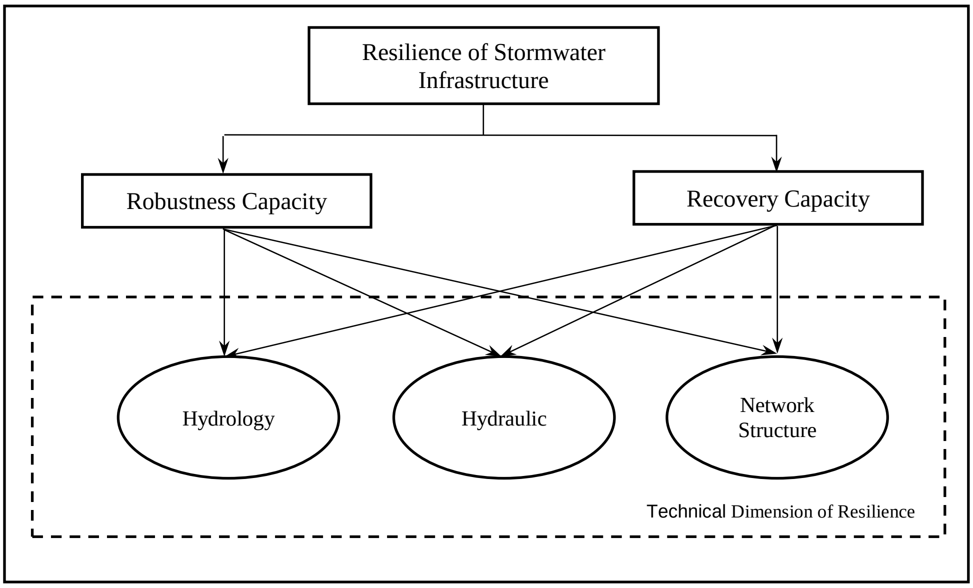


Figure 1: Technical Resilience Dimension of Stormwater management System

In this framework, the hydraulic dimension of the resilience of a stormwater management system is quantified in terms of the hydraulic criteria of the system. This dimension has been categorised according to the hydraulic capacity of primary stormwater piped infrastructure and the hydraulic characteristics of overland flow paths as the secondary stormwater management system. 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, which can be conducted in stormwater design. 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 of stormwater infrastructure.

This paper presents the framework to evaluate the resilience of stormwater management systems in term of the hydraulic dimension for a primary stormwater management system. The first part of the paper explains the approach to define a metric termed Hydraulic Performance Capacity (HPC) of a primary stormwater system, based on the theory of resilience and analytical definition of resilience properties. A methodology is introduced to quantify the HPC of a primary stormwater system and evaluate the degree of resilience of primary stormwater system in terms of the 1D hydraulic dimension. To demonstrate this methodology, the impact of retention and detention basins as the main components of water sensitive urban design components were analysed using the HPC and the degree of resilience of the systems quantified.

2 DEFINING THE CONCEPT OF RESILIENCE

The approach to quantify the 1D hydraulic resilience of a stormwater system in an urban catchment is based on the analytical concept of resilience introduced by Bruneau et al. (2003). This concept is a multidisciplinary and multidimensional notion indicating strength and flexibility of the system during a disturbance. Bruneau et al. introduced a framework relying on the performance of the system to evaluate functionality (Q) of the system over time and is conceptualised as the functionality curve in Figure 2. According to this approach, the resilience of an infrastructure in extreme events is the area under the functionality curve. This framework has been applied in various infrastructure resilience studies to measure the resilience of the system in question (Ouyang, Dueñas-Osorio, and Min 2012; Cimellaro, Reinhorn, and Bruneau 2010; Bocchini et al. 2013; Ayyub 2014; Miles 2011; S. E. Chang and Shinozuka 2004).

The integration of the functionality curve can be separated into two significant properties of resilience, namely robustness and recovery, to quantify the resilience of infrastructure. The concept of robustness is defined as a proportion of the functionality curve that can withstand external shocks without suffering degradation; whereas, the recovery is the rate at which the system recovers to full functionality.

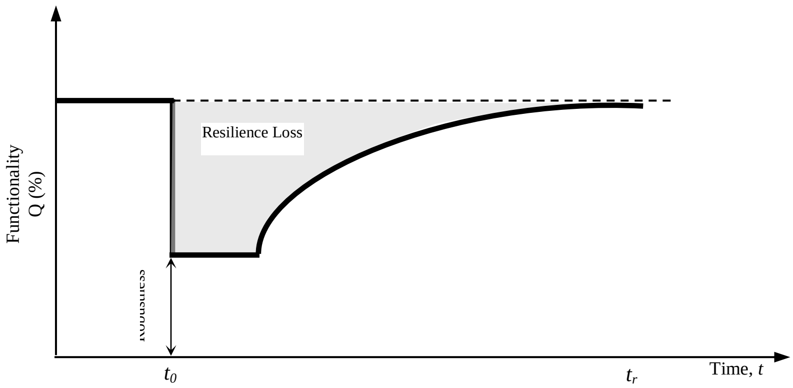


Figure 2: Conceptual definition of measuring resilience (Bruneau et al. 2003)

In practice, the loss of functionality in extreme events is more complicated, with the loss not necessarily taking place abruptly. While some systems may see no change in functionality over time until a failure occurs, adaptable systems can be more flexible to disturbances with reductions in functionality being much more gradual (De Bruijn, 2004). This is illustrated in Figure 3, with a system that can resist a certain magnitude of disturbance until a point where instantaneous functionality loss occurs (solid line), and how a resilient system (dashed line) may lose some functionality at lower magnitude disturbances, however, does not see any abrupt reduction in functionality.

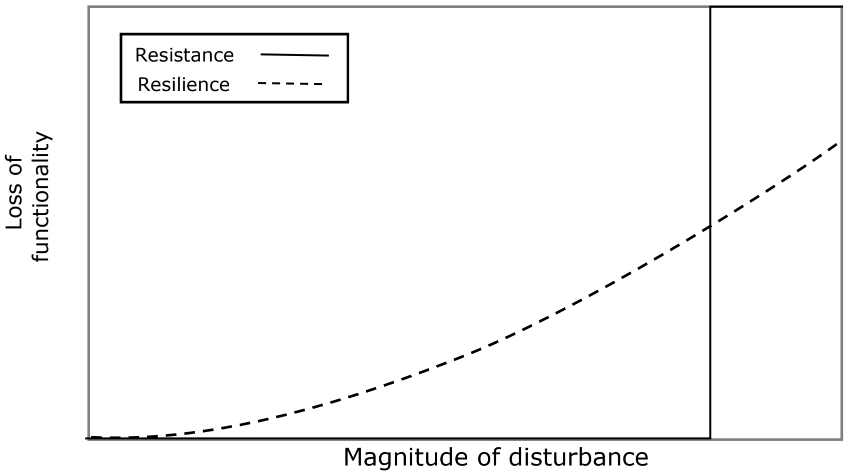


Figure 3: The relationship between Disturbance and Amplitude in Resilient and Resistant Systems (De Bruijn 2004)

3 RESILIENCE FRAMEWORK FOR THE 1D HYDRAULIC DIMENSION

In storm events, the capacity of a stormwater piped network of the primary stormwater management system reduces gradually due to reducing flow capacity and increased flow depths within the piped network. On this basis, to represent the functionality curve of a stormwater piped network in an urban catchment over time, a metric termed the Hydraulic Performance Capacity (HPC) of the stormwater system has been defined. The HPC is based on the temporal flow rates and flow depths within the pipes in an urban sub-catchment. To determine the overall HPC of the network within a sub-catchment, the sum of the unit performance of all pipes are divided by the total length of the stormwater piped network in the sub-catchment (Valizadeh et al. 2018).

The characteristics of the HPC over time defines the performance capacity curve of each stormwater sub-catchment, an example of which is presented in Figure 4. The performance capacity curve in each rainfall event is directly related to the flow hydrograph of the contributing catchment for each pipe and the physical stormwater network. Using this curve, the total robustness of the system, the recovery time, and the resilience of a network can be defined. During storm events, the HPC of the network degrades gradually to reach the minimum robustness in each rainfall event, representing the minimum capacity of the hydraulic dimension of the stormwater system during the storm event.

The stormwater management system 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 discharge points. 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 full recovery the system can be used to define the resilience of the network (Figure 4). Therefore, the resilience of stormwater sub-catchment network *i* in the hydraulic dimension (R_i) is equal to:

$$R_i = \int_{t_2}^{t_i} [100 - HPC_i(t)]dt$$

Where R_i is the degree of the resilience for each sub-catchment; $HPC_i(t)$ is the hydraulic performance capacity at time t, t_1 is the initial time of starting the storm event and t_2 is the final time when the system is recovered and ready for the next storm event.

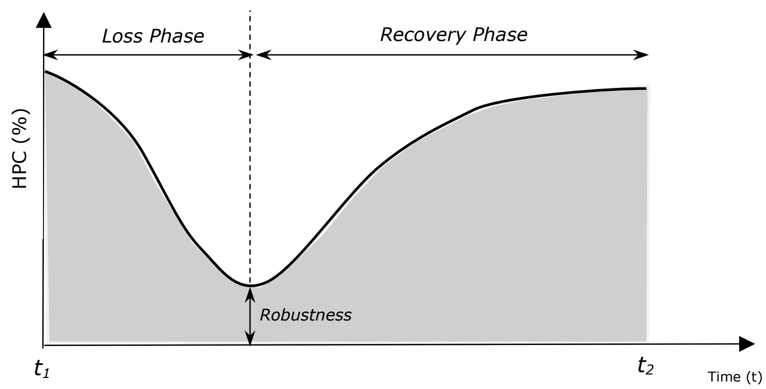


Figure 4: Schematic of a Hydraulic Performance Capacity curve of a primary stormwater management system and associated metrics. The shaded area under the HPC curve is the resilience (Ri), and the robustness is the minimum HPC value.

To quantify the HPC and degree of resilience of the overall stormwater piped network of an urban catchment, the weighted HPC and degree of resilience of each sub-catchment within urban catchments are combined. This concept is presented in Figure 5. In Figure 5, R_i is the degree of resilience for each catchment; HPC_i is the Hydraulic performance capacity of each catchment; W_i is the normalizing weight of each sub catchment within the framework on the basis of catchment area; R and HPC are the total degree of resilience and Hydraulic Performance Capacity for all the urban catchment area respectively. This approach is able to be implemented at scales ranging from a small urban catchment with a stormwater network, through to a city scale urban catchment with various types of stormwater management systems.

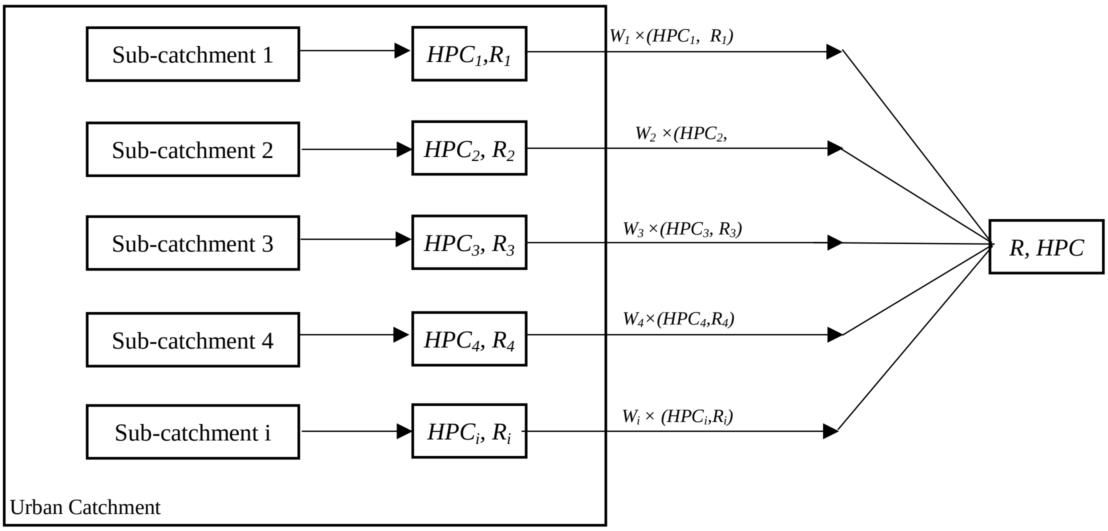


Figure 5: Schematic of the approach used to quantify the resilience of an urban catchment

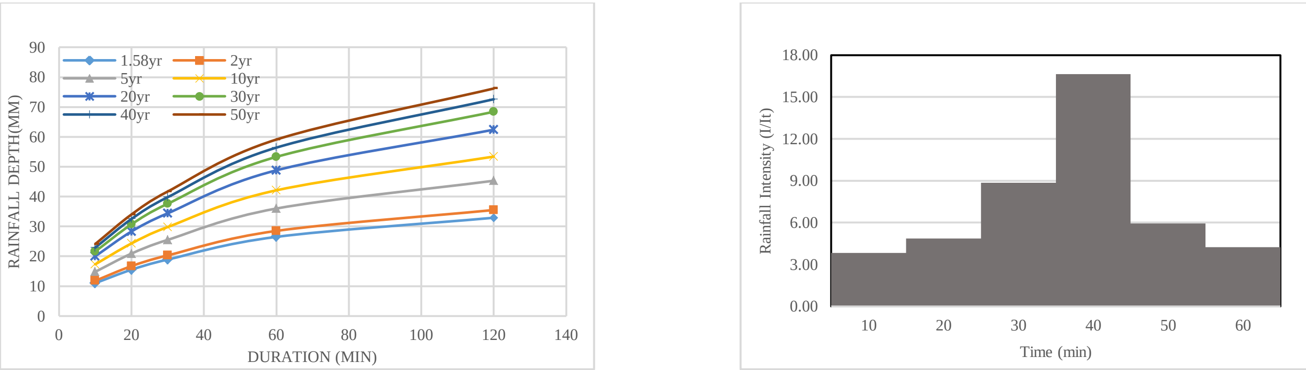
4 CASE STUDY APPLICATION

The proposed framework described in the previous section is applied to a case study catchment in an urban suburb of Auckland, New Zealand (Figure 6). This suburb has a separated stormwater management system collecting stormwater runoff from residential lots and public impervious areas. According to the Auckland Council Unitary Plan (The Auckland Unitary Plan, Operative in Part (AUP (OiP)) 2017), this area is located in a mixed housing suburban zone with maximum allowable impervious areas of 60% (AUP(OiP)).

The stormwater piped network of the study area has a total of 146 main pipes with diameters of 225mm to 1800mm collecting stormwater runoff from the site and discharging it downstream. This stormwater piped networks eventually conveys to the Manukau Harbour. The stormwater piped network has been 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.

For this case study, the hydrology and the hydraulic modelling has been performed using MIKE URBAN software (Hénonin et al. 2010). The total area of the catchment has been 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.

Figure 6: Study area (red line) and stormwater piped network (green lines) within the site



(a) (b)

Figure 7: a) Depth Duration Frequency of rainfall for study Area (NIWA v3); (b) 1 hour Chicago method temporal pattern

To determine the impact of WSD approaches to control volume and peak flows on HPC and overall degree of resilience, two scenarios were assessed. In the both scenarios, the results were compared to the piped network without any control methods.

In the first scenario of this study, the impact of runoff volume control on the resilience of primary stormwater network during different storm events was quantified. Here it was assumed that the first 5 mm of runoff generated in all impervious areas of the study area were able to be retained using stormwater devices such as raingardens, residential raintanks, green roofs, and infiltration trenches prior to collection by the primary stormwater management system. Therefore, the initial abstractions of sub-catchments were adopted to calculate the temporal hydrographs after retaining the initial 5mm from impervious areas prior loading the flow to the networks. The study was conducted for various rainfall events between 1.58 ARI and 50 rainfall ARI as shown in Figure 7 (HIRDS, V3. NIWA). The Chicago method for 1 hour temporal design rainfall was used (Figure 8) (Akan and Houghtalen 2003), with all the design rainfalls considered in this study using a 1 hour temporal pattern with identical start and end times. The rainfall depth of a 1 hour design rainfall increased from 26.5 mm in a 1.5 year ARI to 59.1mm in a 50 year ARI

The second scenario quantified the influence of peak flow control for residential lots on the primary stormwater network. Controlling the peak flow of the development area can decrease the flash flood probability by controlling the peak flows discharging from new development areas, and it directly affects the hydraulic capacity of the downstream piped network. To model the effect of peak flow control, the MIKE URBAN model for the study area was modified by adding detention tanks for residential lots including orifices to attenuate the peak flows to 90%, 80% and 60% of the fully developed area during a 10 year ARI rainfall event.

5 RESULTS AND DISCUSSION

5.1 EFFECT OF RUNOFF VOLUME CONTROL ON RESILIENCE

Figure 8 summarises the HPC of the study area with and without runoff volume control for events between 1.58 year ARI and 50 year ARI. As expected the robustness value of the HPC curves, equal to the minimum HPC value over time, decreased as the ARI increased. Figure 8 shows that the HPC curves for networks with runoff volume control are skewed slightly to the right for all storm events. This represents the decrease in the rate of degradation of robustness slightly, and the time of minimum robustness was delayed slightly compared to collecting the networks without any stormwater control. However, in the recovery phase, the two models were approximately identical for all the studied storm events.

The results indicate that apart for the 50 year ARI, the runoff volume control measures resulted in slightly larger robustness values. During the 50 year ARI, the minimum robustness values of both models were 0%, indicating that all the pipes were at their maximum hydraulic capacity.

Figure 9 summaries the degree of resilience for the 1D hydraulic dimension of the study area with and without runoff volume control. In the two models, the degree of resilience decreases in a same pattern with increasing storm ARI. Although the overall degree of resilience for the two models were approximately similar in storm events with an ARI less than 5 years, above a 5 year ARI, the degree of resilience in the model with a retention system increases by approximately 1% compared with the model without a retention system. Therefore, retaining the volume of generated runoff in this case study only had a small effect on both the robustness and resilience of the primary stormwater network.

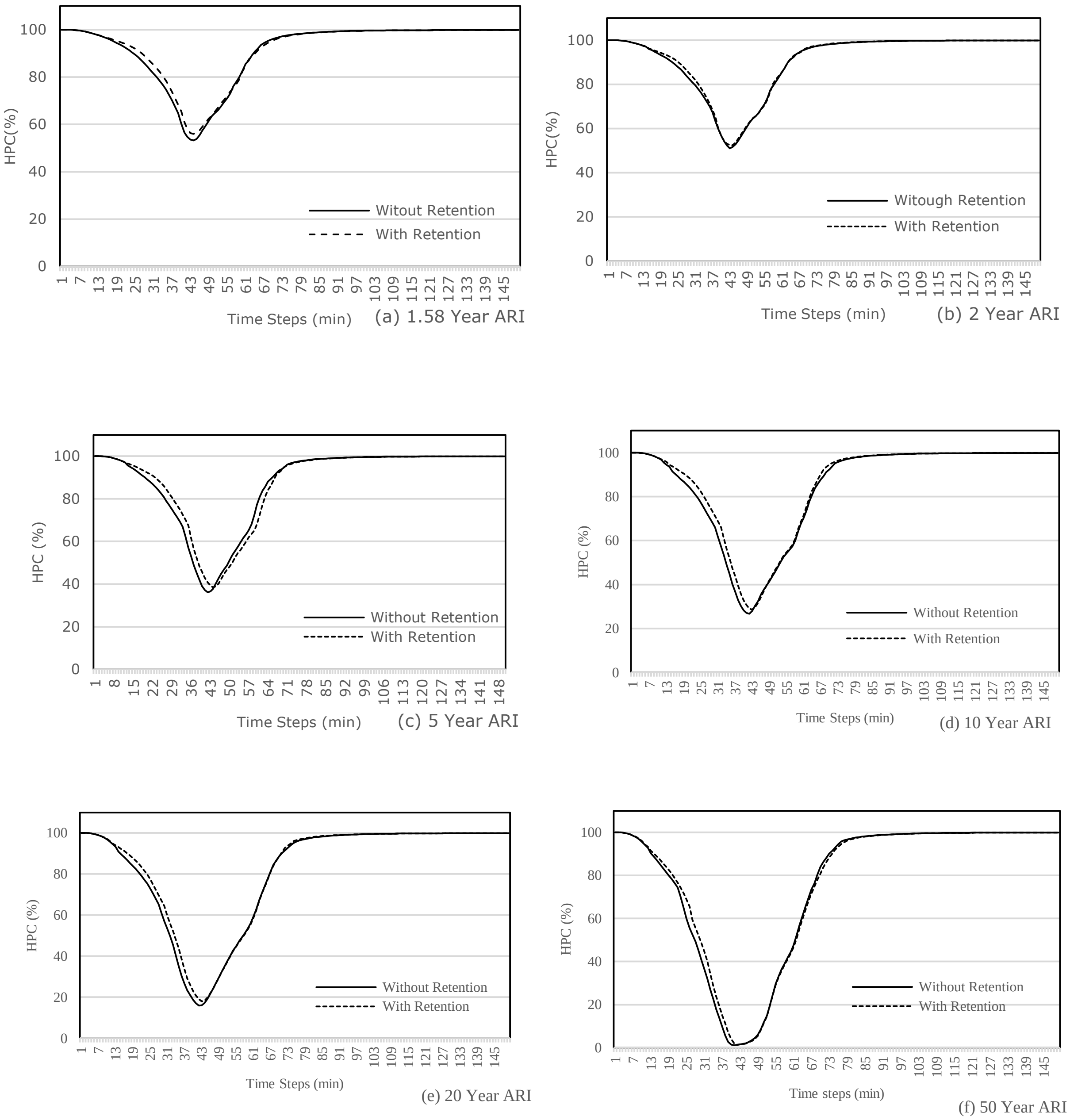


Figure 8: Hydraulic performance capacity (HPC) for the scenarios of direct runoff and volume control under different annual recurrence interval (ARI) design storm events

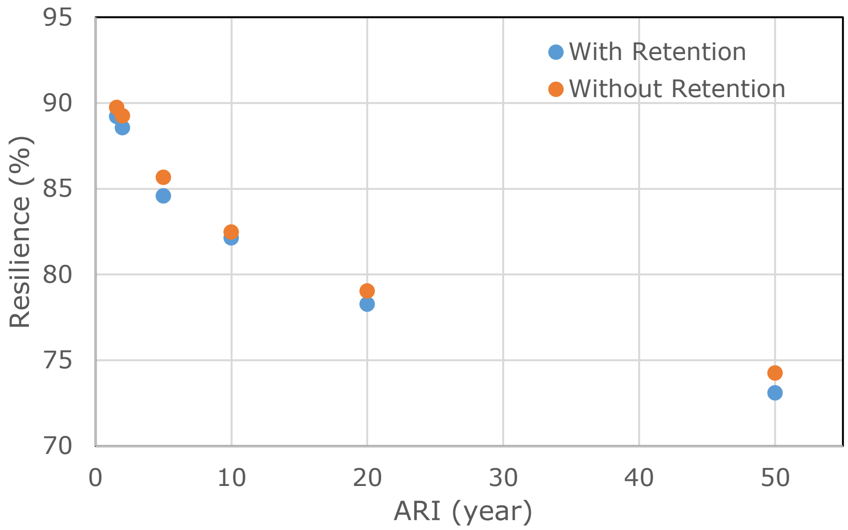


Figure 9: Weighted resilience of the overall catchment for a range of ARI design storm events for the scenarios of direct runoff and runoff volume control.

5.2 EFFECT OF PEAK FLOW CONTROL ON RESILIENCE

Figure 10 shows the temporal HPC of the study areas with and without runoff flow control during a 10 year ARI event. As can be seen in this figure, in the loss phase the degradation rate for the four scenarios were similar, indicating that the HPC for the four models reduced at same rate. As expected, the minimum robustness value increased as the peak flow reduction from residential areas increased. This was due to an increase in the available hydraulic capacity within the piped network over time. However, the minimum robustness for all the models occurred at the same time, meaning the duration of the loss phase did not reduce.

In the recovery phase, attenuation of the peak flow decreases the rate at which the HPC increases. As a result, although the robustness of the system increases with an increase in flow reduction, the degree of resilience of the system is fairly similar across all models.

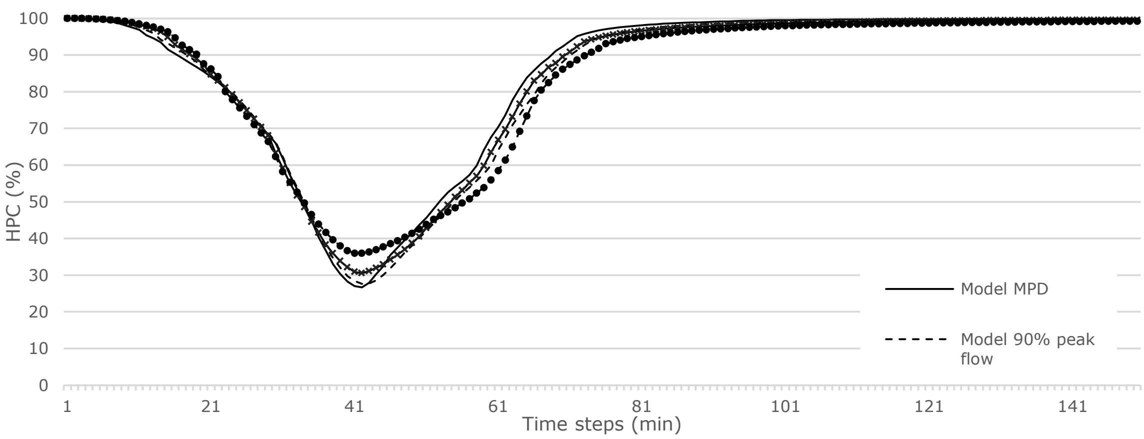


Figure 10: Hydraulic performance capacity different peak flow control models

6 CONCLUSIONS

This paper has presented a framework to quantify the resilience of urban stormwater management systems in terms of the hydraulic dimension for a primary stormwater system using the analytical concept of a functionality curve. Temporal characterisation of the remaining capacity and flow depth of each pipe has been used to evaluate remaining hydraulic performance capacity (HPC) of the stormwater network over time, which in-turn defines the resilience, minimum robustness of the system, and recovery time of the system. This framework is able to determine the 1D hydraulic resilience of all types of urban catchments, from very small catchments with a piped network system, through to a complicated large scale urban catchment with various sub-catchments and stormwater systems. The applicability of this approach was demonstrated using a case study newly developed urban catchment area in Auckland. The change in resilience has been assessed for two scenarios to determine the impact of water sensitive design approaches for flood quantity control.

This proof of concept shows that 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 optimizing stormwater management systems for reducing flood hazard in urban catchments. By changing the capacity of the system using the degradation of pipe properties, the change in resilience of the system over time can be estimated. In addition, this framework could be used to estimate the change of resilience following other natural hazard that may reduce the functionality of the stormwater network, such as earthquake induced liquefaction and ashfall from volcanic eruptions.

ACKNOWLEDGEMENTS

We acknowledge Auckland Council for providing the details of the case study catchment stormwater network. This research was supported by MIKE by DHI by providing MIKE software packages for this research. This research was funded by the Resilience to Nature's Challenges National Science Challenge.

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