EVALUATING THE TECHNICAL RESILIENCE OF STORMWATER SYSTEMS TO FLOODING

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ABSTRACT

Continued urbanization and the effects of climate change have led to flooding events becoming the most common natural hazard experienced around the world. With greater numbers of people living in cities than ever before, the vulnerability of urban areas to flooding needs to be addressed. Urban stormwater management systems provide a crucial role in flood control, however, they typically overlook the complexities and interactions across the whole urban catchment and the unpredictability in quantifying flood risk. The concept of resilience is an emerging paradigm which is able to compare different stormwater management strategies to provide a more reliable and robust system. Within the literature, no frameworks quantify the resilience of urban stormwater management systems while considering both catchment attributes and the drainage network structure. This paper considers these points by presenting a methodology to evaluate the technical resilience of urban stormwater systems to flooding hazards. Three technical aspects in stormwater management; urban hydrological characteristics, hydraulic parameters, and network structures properties are considered. This allows the development of an indicator based model to quantify the temporal nature of system robustness and functionality in the conveyance of different extreme rainfall events. In applying this framework, a range of stormwater management solutions can be compared to assess the improvement to the overall resilience of a system.

KEYWORDS

Stormwater Resilience, Urban Flooding, Network Analysis, Technical Resilience

PRESENTER PROFILE

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1 INTRODUCTION

Water management in the 21st century has become increasingly challenging due to increased urbanization and the impacts of climate change. Natural drainage processes have seen severely impacted due to changes in population distributions meaning increased imperviousness and therefore storage (Brun & Band, 2000; Lhomme et al., 2013). In addition, others have linked the extreme and unpredictable rainfall events that damage technical infrastructure to climate change (Siekmann & Siekmann, 2015). On this basis, managing floods in urbanized area is a main concern in the reduction of flooding impacts.

Urban stormwater management systems control urban flooding by conveying surface runoff outside of the impervious developed areas. This is generally via piped-based stormwater management systems, which can ignore the complexity and unpredictability of flood risk when events exceed the design rainfall (Vis et al., 2003). Over time, stormwater infrastructure has been changing to more sustainable 'best management practice' (BMP) systems that imitate natural hydrological processes using both structural and non-structural components (Ahiablame et al., 2012; Chang & Liou, 2010; Semandeni-Davies et al., 2008). While such systems can show improvement in managing peak floods, they do not entirely eliminate the possibilities of flood risk. Today, it is accepted that floods are not able to be prevented completely; but, it is possible to reduce a systems vulnerability to adverse impacts (Balsells et al., 2013b). Recently, there has been growing interest in using the concept of resilience in flood management strategies to reduce flood vulnerability (Balsells et al. 2012; De Bruijn, 2004; Gersonius et al., 2012; Restemeyer et al., 2015; Siekmann & Siekmann, 2015). In the majority of these studies, the main concern was to evaluate urban resilience to flood events in accordance with social, economic and organizational dimensions (Gupta, 2007; Vis et al., 2003). In addition, the adopted definitions of flood resilience differ in the literature dependent of the study objectives. Examples include De Bruijn (2004) who defines resilience as the ability of the system to recover from a disruption and Balsells et al. (2013) who consider the ability of the system to cope with unexpected shocks over time. In comparison Lhomme et al. (2013) take a wider view suggesting resilience covers adaptation in a disruption event, operation in a degraded state, and the recovery of the system with disrupted components.

In the previous studies of flood resilience, the resilience of urban flood control infrastructure to extreme flood events has been largely neglected. Similarily, there is no robust framework to quantify the resilience of stormwater management systems in different extreme event conditions or measurement of resilience change by modifying the stormwater infrastructure networks using modern best management practices (BMPs) and/or low impact designs (LID). In addition, by developing urban water infrastructure into water sensitive cities as the most resilient system, quantifying the resilience of stormwater management system can provide better approach in improvement of water sensitive cities.

To contribute to this gap in the literature, this paper presents a novel framework to quantify the resilience of urban stormwater infrastructure to flooding. The first part of the paper explains the theory of resilience and analytical definition of resilience properties. The concept of resilience in stormwater infrastructure is then discussed and followed by a methodology for quantifying flooding resilience properties of the infrastructure based on hydrologic characteristics, hydraulic factors of the infrastructure, and network structure characteristics.

2 DEFINING THE CONCEPT OF RESILIENCE

Depending on severity of the disruption, under an extreme event, the functionality of a system can be expected be affected. To reduce this loss of the system functionality, the adaptability and redundancies within the system are important. Returning back to pre-disruption levels is then directly associated with the resources available in the system (Bruneau et al., 2003).

The concept of resilience is characterized by four properties namely; robustness, rapidity, redundancy, and resourcefulness (Bocchini et al., 2013). Bruneau et al. (2003) provides widely cited definitions for these properties. Here we generalise these as; robustness being the proportion of system functionality that can withstand against external shocks without suffering degradation, redundancy is the alternate means within the system to provide some continuing minimum level of system's service, resourcefulness as the ability of the system to commit the right resources in the correct manner in response to a catastrophic event, and rapidity is the speed of which the system recovers. These four properties are related to each other; in which, redundancy and resourcefulness of the infrastructure have direct effect on the robustness and rapidity capacity as shown in Figure 1.

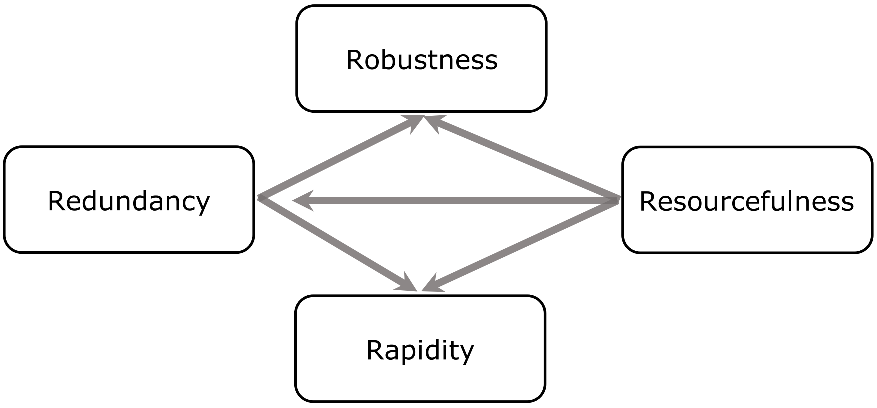

Figure 1: The Relationship of Resilience Properties

The concept of resilience can be conceptualized over time as shown in Figure 2.

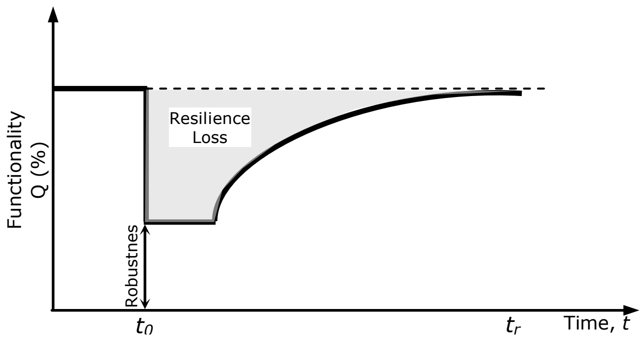

Figure 2: Schematic of Resilience Concept

Disturbing the system due to an extreme event at time t_0 causes the loss of functionality equal to 1 – *Robustness* (Figure 2). By restoring the system, functionality recovers gradually to return to the normal serviceability at time t_r. The area above this curve throughout the time period of interest represents the resilience loss R_L (Bocchini et al., 2013) and is defined by Eq. (1), where Q is the functionality (as a percentage), and t is time.

$$R_L = \int_{t_0}^{t_r} [100 - Q(t)]dt \qquad (1)$$

The integration of the functionality curve can be separated into two different categories namely robustness and recovery to quantify the resilience of infrastructure.

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 capacity is reached, 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 to show how a system can resist a certain magnitude of disturbance until a certain point with instantaneous functionality loss (dark line), and how a resilient system (dashed line) may lose functionality at lower magnitude disturbances, however, does not see any abrupt increases in functionality loss.

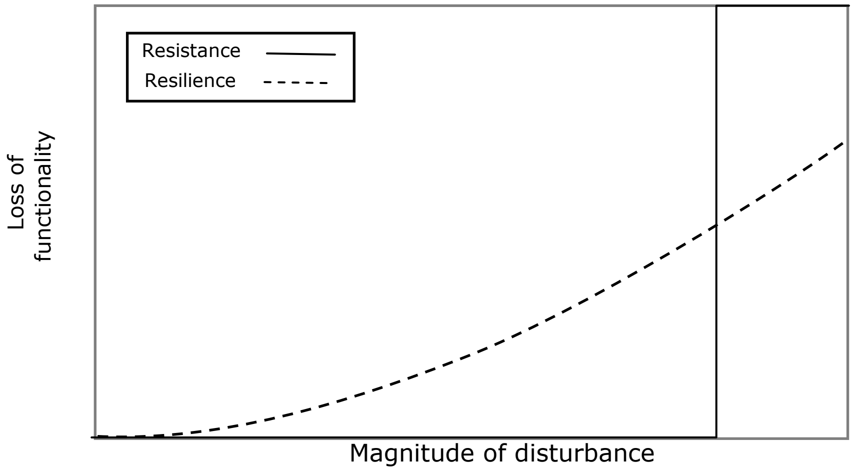

Figure 3: The relationship between Disturbance and Amplitude in Resilience and Resistance Systems (De Bruijn, 2004)

3 RESILIENCE OF STORMWATER MANAGEMENT SYSTEMS

Although stormwater infrastructure can be highly reliable for the most part, the relatively wide spatial areas covered and design limitations for conveyance capacities can mean failures become more frequent during flood events. To cope with the vulnerability such in significantly large events, quantifying possible improvements of a stormwater infrastructure's resilience is advised.

In this study the resilience of stormwater infrastructure is defined as the ability of stormwater management system to minimize the disturbance of the system during floods, redistribute flows toward functional parts of the system and minimize the time required to recover the system to the normal operation. Thus, the concept of two significant properties of resilience being robustness and recovery capacities are taken into account to evaluate the resilience of the infrastructure to flood events. In either robustness or recovery capacities, the hydrological, hydraulic and network structure characteristics of urban flood management would impact the resiliency of the system (Figure 4).

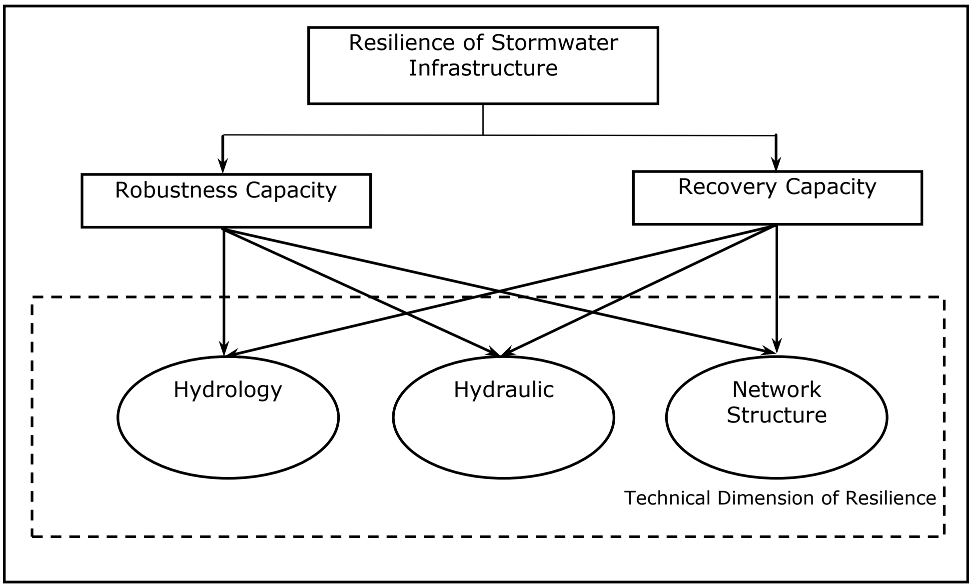

Figure 4: Technical Resilience Dimensions of Stormwater Management System

3.1 EVALUATING THE ROBUSTNESS OF STORMWATER MANAGEMENT SYSTEMS

The robustness capacity in urban flood control systems are associated with the capacity for the stormwater infrastructure to absorb the surface runoff produced in rainfall events. In a rainfall event the functionality of the system would decrease gradually due to decreasing the natural hydrologic capacity of the system before starting runoff. This is the initial loss of available functionality as presented in Figure 5. When capacity is reached and overflow from the system begins, the secondary loss mode starts. This continues to reach the minimum functionality of the system in the extreme event. In evaluating the secondary loss mode of the system functionality, the capacity of the stormwater infrastructure and the flooded area are the two critical factors of interest. Where the initial and secondary loss phases of stormwater system functionality are shown in Figure 5, the gradient of secondary loss is apparently greater than initial loss because secondary loss mode starts when overflow from the system affects a wider urban area by decreasing the infrastructure capacity and increasing flooded area.

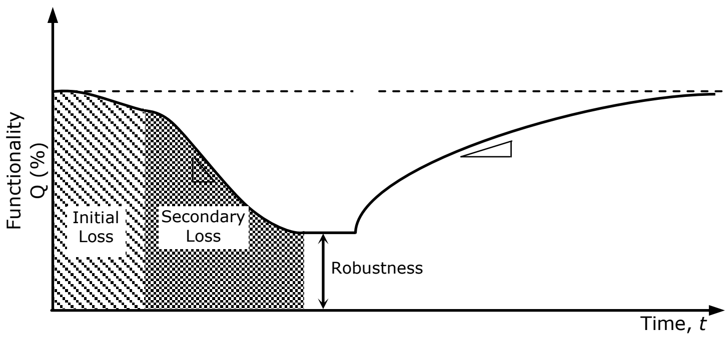

Figure 5: Loss Functionality phases in Stormwater management system

In the initial loss phase, the significant technical factor to withstand against starting runoff in rainfall events is the absorbing the rainwater in surface and subsurface layers. The significant hydrologic factors affecting the initial loss capacity are surface and subsurface hydrological abstraction capacities such as infiltration, interception, and depression capacities which are associated with the level of imperviousness and land use of the area (Cheng & Wang, 2002). Thus, by increasing urbanised area the robustness capacity of the system decreases considerably due to decreasing the capacity of absorption in the natural hydrological process. Moreover, the catchment characteristics have a direct impact on the runoff production (Merz & Blöschl, 2009).

In the secondary loss phase, the functionality of the system decreases further by the higher gradient of loss in the resilience curve (Figure 5) because this phase starts as surface runoff produced in rainfall events. The secondary loss phase consists of two parts. The first part is the surface runoff collected by stormwater infrastructure which depends upon the hydraulic properties of the infrastructure such as flow rate, drain capacity and underlying geology. Stormwater infrastructure with higher capacities to convey and store the surface runoff decrease the probability of flood prone areas with higher rainfall depths. The second part of the secondary loss phase of the system takes place when the capacity of the infrastructure is exceeded and surface runoff floods the surrounding urban area, or through component failure leading to upstream flooding from the system.

However, for design limitations and economic reasons, a compromise is typically sought.

Equation (2) shows the analytical definition of the loss of functionality in a stormwater management system including initial and secondary loss capacities between t_s (starting initial loss) and t_l, when the maximum functionality degradation takes place.

$$Loss = \frac{\int_{t_l}^{t_s} Q_L(t)dt}{(t_l - t_s)} \quad (2)$$

Where ($Q_L(t)$) is loss function of the system over time.

To determine the rate of change in system functionality, the slope of loss function is calculated as shown in Equation (3). The greater value of the slope indicates the severity of loss that might occur due to a sudden structural failure (the slope is vertical). Whereas, lower values of the slope can be identified as the main factors to improve the resilience of the system to flooding because it decreases the area above the resilience curve making the system more resilient. Additionally the loss in the system would be more gradual and the time required to reach the maximum loss increased.

$$SL = -\frac{dQ_L}{dt} \quad (3)$$

To quantify the robustness of stormwater management system to floods, it is required to evaluate all three of the above mentioned technical dimension factors of stormwater resilience (hydrologic characteristics, hydraulic factors of the infrastructure, and network structure characteristics) separately to determine the maximum robustness capacity of the system in flood events using indicators evaluating the robustness of each factor.

Figure 6 presents an index based approach to quantify the robustness of stormwater systems over time, after a storm event has occured. The characteristics of each dimension are calculated to determine the minimum robustness capacity of the system and the gradient of loss functionality over time. By evaluating the robustness of a system, the minimum functionality of the system in different extreme events can be quantified, which is essential in urban hazard management. Moreover, it shows the trend of losing functionality of the system helping to improve the resiliency by optimizing the network structure and stormwater components capacity and their locations.

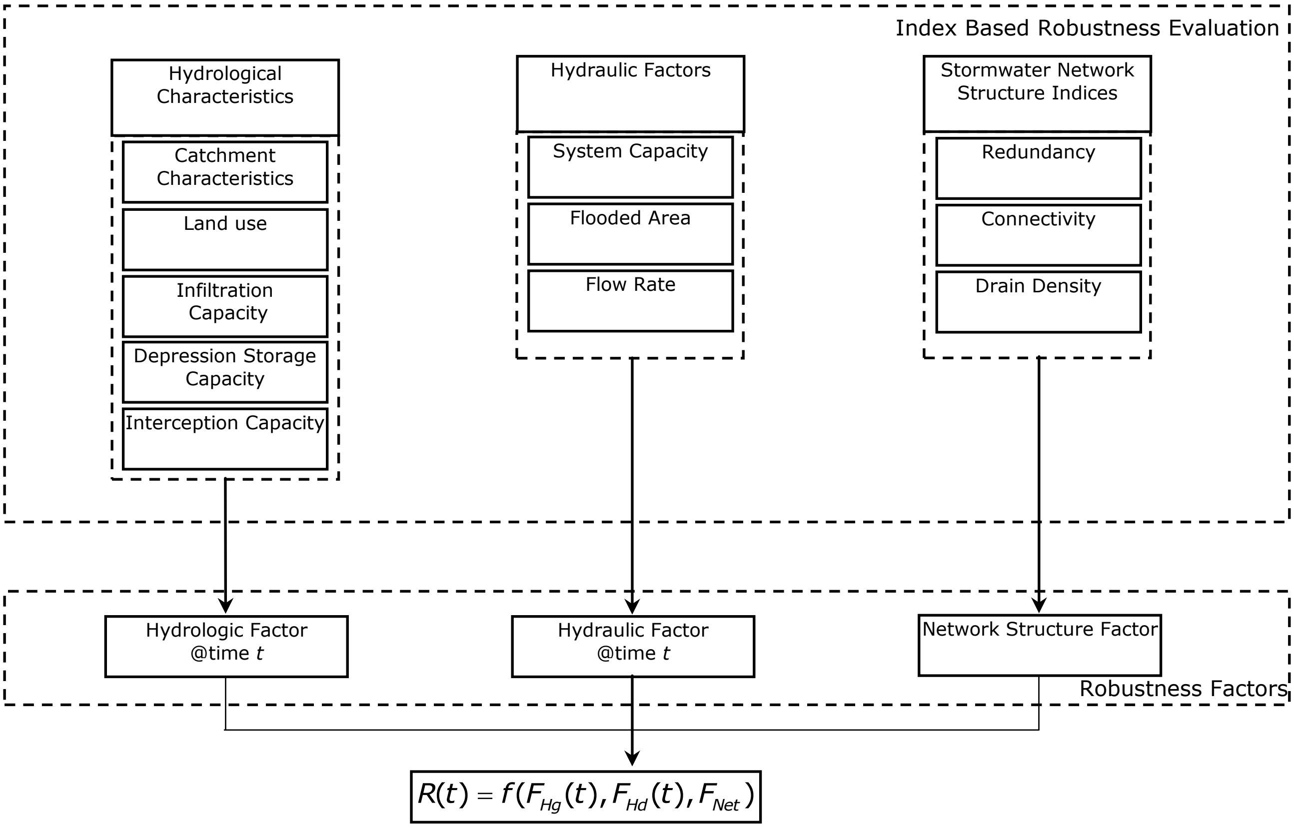

Figure 6: The approach to evaluate stormwater system robustness

3.2 EVALUATING THE RECOVERY OF STORMWATER MANAGEMENT SYSTEMS

The speed of restoration following a recovery is an important technical dimension of resilience depending on the redundancies and resourcefulness available for system recovery (Figure 1). The area above the recovery curve (Figure 2) provides an indication of the resources required to return the normal operation. As can be seen in Figure 7, the recovery of a system can take many shapes, however, for recovery to a constant level over an identical time period, it can be seen that the total area above the curves can vary significantly. When the initial rate of restoring a system is greater due to higher adaptability and redundancy, the area over the recovery curve is smaller which implies the resources required to recover the system could be reduced.

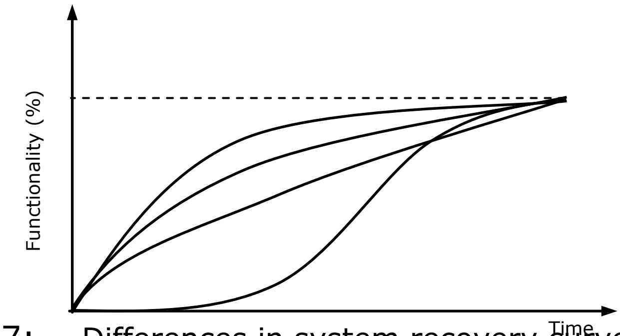

Figure 7: Differences in system recovery curves

While functionality state and recovery is dependent on a wide range of technical parameters, system recovery can be separated into of two phases namely initial recovery system, and secondary recovery system (Figure 8). In the initial recovery phase, surface runoff accumulated in the urban catchment area is conveyed through the infrastructure network and discharged from outlets. As stormwater is released from the system, the availability for absorbing further runoff is increased and thus increases functionality. Secondary recovery capacity is associated with restoring hydrologic capacity of the system and the discharge rate from temporary storage. By combining these two recovery capacities, the total recovery capacity of the stormwater system can be determined.

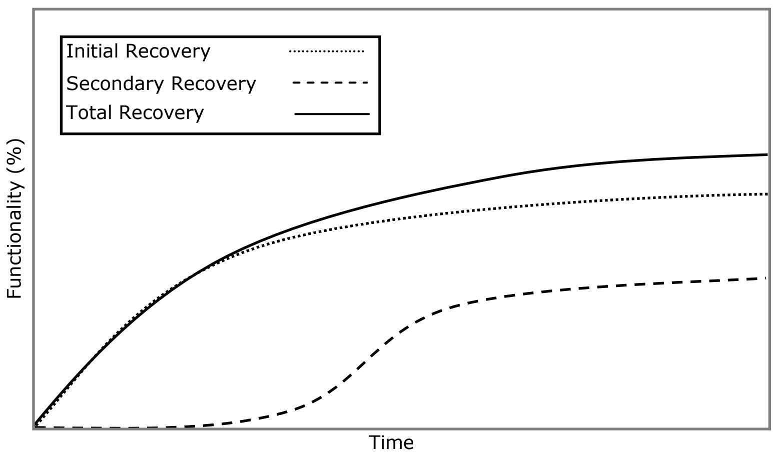

Figure 8: Recovery Phases of Stormwater management system

Technical resilience of stormwater management systems is directly associated with the rainfall pattern, although the initial recovery phase generally starts after the peak discharge and it depends on the time of concentration of the urban catchment and network structure characteristics. To evaluate the total recovery factors of the system, the initial and secondary recovery phases are taken into account to determine the total recovery time and the rate or of restoring the system functionality for each phase. In the initial recovery phase, the main concern is to discharge excess water from surface area and stormwater network infrastructure, while, after draining the stormwater network, the secondary recovery phase has greater influence in restoring the system by recovering the storage and hydrologic abstractions in the system. The combination of these two recovery phases throughout time determine the total recovery phase. Both of these two phases are started simultaneously with different recovery rates. Figure 9 illustrates the indices affecting the technical dimension evaluation of system recovery, and the approach to quantify the recovery time and total recovery rate of the system.

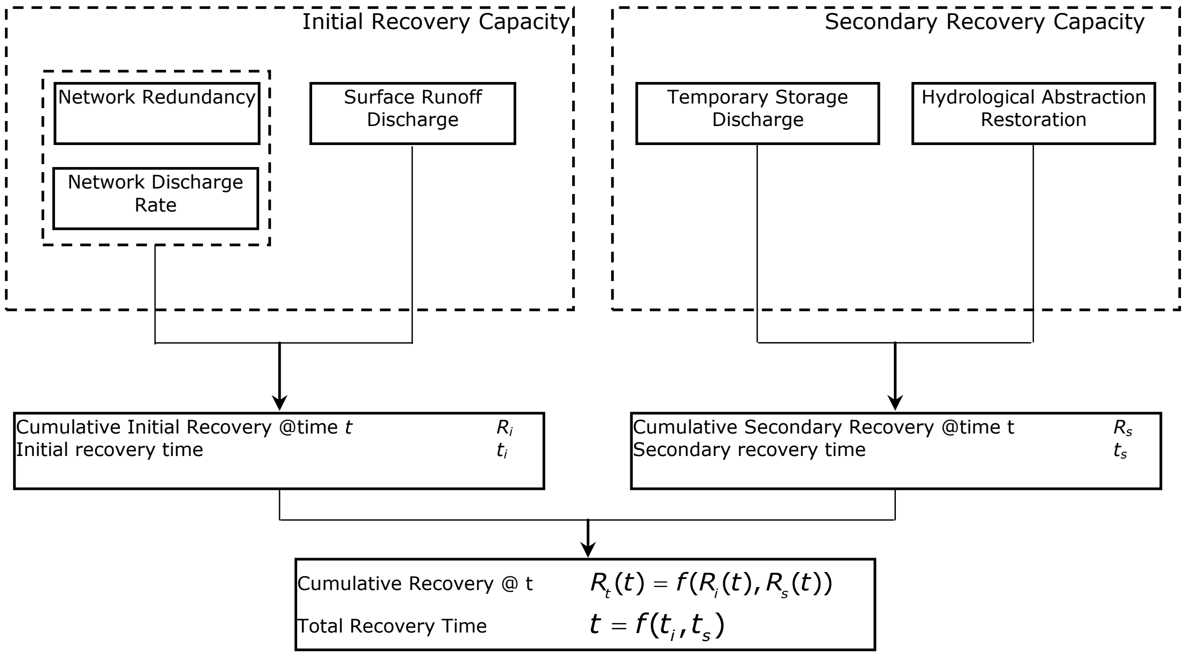

Figure 9: The approach to Evaluate Stormwater system Recovery

4 CONCLUSIONS

This study represents a framework to quantify the technical resilience of stormwater management systems to floods through considering the robustness and recovery properties of resilience. The framework relies on minimizing the impact of a disturbance on the system during an extreme event and decreasing the time of system recovery to return to normal and dry conditions. The methodology for quantifying robustness and rapidity of the system considers hydrologic characteristics, hydraulic factors and network structure characteristics of a stormwater management system to indicate the change of system resilience over time. This provides a unique robust approach to measure resilience properties of stormwater infrastructures on the basis of engineering aspects. The technical dimension of stormwater infrastructure resilience is a cornerstone of urban flood resilience influencing directly on social, organization, and economic dimensions of urban resilience. Moreover, this makes it possible to carry out comparative studies of resiliency improvement of stormwater management system using low impact design (LID) strategies and various sustainable approaches employing best management practices (BMPs).

REFERENCES

Ahiablame, L. M., Engel, B. A., & Chaubey, I. (2012). Effectiveness of low impact development practices: literature review and suggestions for future research. *Water,* *Air, & Soil Pollution*, *223*(7), 4253–4273.

Balsells, M., Barroca, B., Amdal, J. R., Diab, Y., Becue, V., & Serre, D. (2013a). Analysing urban resilience through alternative stormwater management options: application of the conceptual Spatial Decision Support System model at the neighbourhood scale. *Water Science and Technology : A Journal of the International Association on Water Pollution Research*, *68*(11), 2448–57. doi:10.2166/wst.2013.527

Balsells, M., Barroca, B., Amdal, J. R., Diab, Y., Becue, V., & Serre, D. (2013b). Analysing urban resilience through the alternative stormwater management options: application of the conceptual DS3 model at the neighbourhood scale.

Birgani, Y. T., & Yazdandoost, F. (2015). Resilience in urban drainage risk management systems.

Bocchini, P., Frangopol, D. M., Ummenhofer, T., & Zinke, T. (2013). Resilience and sustainability of civil infrastructure: Toward a unified approach. *Journal of Infrastructure Systems*, *20*(2).

Brun, S. E., & Band, L. E. (2000). Simulating runoff behavior in an urbanizing watershed. *Computers, Environment and Urban Systems*, *24*(1), 5–22.

Bruneau, M., Chang, S. E., Eguchi, R. T., Lee, G. C., O'Rourke, T. D., Reinhorn, A. M., … von Winterfeldt, D. (2003). A framework to quantitatively assess and enhance the seismic resilience of communities. *Earthquake Spectra*, *19*(4), 733–752.

Chang, C.-L., & Liou, T.-Y. (2010). The placement strategies of structural best management practices for different moving rainstorms. *Environmental Monitoring and Assessment*, *166*(1-4), 495–502.

Cheng, S., & Wang, R. (2002). An approach for evaluating the hydrological effects of urbanization and its application. *Hydrological Processes*, *16*(7), 1403–1418.

De Bruijn, K. M. (2004). Resilience and flood risk management. *Water Policy*, *6*(1), 53–66.

Gersonius, B., Ashley, R., Pathirana, A., & Zevenbergen, C. (2012). Adaptation of flood risk nfrastructure to climate resilience. In *Proceedings of the ICE-Civil Engineering* (Vol. 165, pp. 40–45). Thomas Telford.

Gupta, K. (2007). Urban flood resilience planning and management and lessons for the future: a case study of Mumbai, India. *Urban Water Journal*, *4*(3), 183–194.

Lhomme, S., Serre, D., Diab, Y., & Laganier, R. (2013). Analyzing resilience of urban networks: a preliminary step towards more flood resilient cities. *Natural Hazards and Earth System Science*, *13*(2), 221–230.

Merz, R., & Blöschl, G. (2009). A regional analysis of event runoff coefficients with respect to climate and catchment characteristics in Austria. *Water Resources Research*, *45*(1).

Restemeyer, B., Woltjer, J., & van den Brink, M. (2015). A strategy-based framework for assessing the flood resilience of cities–A Hamburg case study. *Planning Theory & Practice*, *16*(1), 45–62.

Semadeni-Davies, A., Hernebring, C., Svensson, G., & Gustafsson, L.-G. (2008). The impacts of climate change and urbanisation on drainage in Helsingborg, Sweden: Suburban stormwater. *Journal of Hydrology*, *350*(1), 114–125.

Siekmann, T., & Siekmann, M. (2015). Resilient urban drainage – Options of an optimized area-management. *Urban Water Journal*, *12*(1), 44–51. doi:10.1080/1573062X.2013.851711

Vis, M., Klijn, F., De Bruijn, K. M., & Van Buuren, M. (2003). Resilience strategies for flood risk management in the Netherlands. *International Journal of River Basin Management*, *1*(1), 33–40.