UNIVERSIDADE DE LISBOA

INSTITUTO SUPERIOR TÉCNICO

Development of a resilience framework for urban stormwater services

João Pedro Lopes Barreiro

Supervisor: Doctor José Manuel de Saldanha Gonçalves Matos

Co-supervisor: Doctor Filipa Maria Santos Ferreira

Thesis approved in public session to obtain the PhD Degree in

Environmental Engineering

Jury final classification: **Pass with Distinction**

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"Paddle your own canoe; don't rely upon other people to row your boat."

Lord Baden-Powell
in Rovering to Success

ABSTRACT

The increasing challenge of managing urban stormwater systems under the exacerbated pressures of climate change and urbanization demands innovative solutions for adequately dealing with rainfall events and actively mitigating negative impacts on the cities. The concept of resilience allows a paradigm shift from conventional "fail-safe" to holistic "safe-to-fail" management, anticipating and planning for failure under exceptional conditions.

This thesis introduces "RESILISTORM," a resilience framework for stormwater services devised to assist utilities, researchers, and practitioners in assessing and enhancing urban stormwater services' response, adaptation, and transformation capacity. The framework includes a Strategic Dimension – emphasizing the system's organizational and planning capacity to reach the desired resilience objectives by assessing 43 question-oriented indicators - and a Performance Dimension - focusing on the service's ability to maintain core functions and minimize the impact of disturbances, namely, urban flooding, through assessment of context-dependent performance indicators. Besides providing segmented and overall resilience ratings, the framework presents a clear roadmap for identifying critical points that undermine the service's resilience. An open-source digital tool (RESILISTORM-tool) was developed alongside the framework elaboration, allowing expedited answering, data integration, and analysis of results.

A 1D/2D hydrodynamic simulation model was developed, integrating the open-source models EPA SWMM and MOHID Land. Thus, the developed 1D/2D model simulates the behavior of drainage systems and surface runoff in an integrated approach by accounting for the flow exchanges between them.

The usefulness and versatility of the framework were validated through its application to two critical drainage catchments in Lisbon: the Historical downtown catchment, crucial for its centrality in urban space, and the Alcântara catchment, the largest in Lisbon's drainage system. These applications not only proved the practicality of RESILISTORM but also highlighted its flexibility in adapting to the specific objectives of each case, significantly contributing to the city's overall resilience.

Keywords: Urban Resilience, Urban Stormwater Management, Resilience Framework, 1D/2D Simulation Model, Urban Flooding

RESUMO

Os desafios de gestão da drenagem urbana de águas pluviais, nomeadamente face à pressão dos efeitos das alterações climáticas e da urbanização e ocupação do solo, exigem soluções inovadoras para lidar adequadamente com eventos de precipitação e mitigar ativamente os seus impactos negativos nas cidades.

A presente tese introduz o "RESILISTORM", um quadro de resiliência para serviços de águas pluviais desenvolvido para auxiliar entidades gestoras, investigadores e profissionais na avaliação e melhoria da capacidade de resposta, adaptação e transformação dos serviços urbanos de águas pluviais. Este quadro inclui uma Dimensão Estratégica – enfatizando a capacidade organizacional e de planeamento do sistema para alcançar os objetivos de resiliência - e uma Dimensão de Desempenho - focada na capacidade do serviço em manter funções essenciais e minimizar o impacto das perturbações, nomeadamente, inundações urbanas. Além de fornecer classificações de resiliência segmentadas e globais, o quadro revela-se um processo útil para identificar pontos críticos que comprometem a resiliência do serviço. Foi desenvolvida uma ferramenta digital de código aberto (RESILISTORM-tool), permitindo responder aos indicadores, integrar dados e analisar os resultados de forma expedita.

Foi também desenvolvido um modelo de simulação hidrodinâmica 1D/2D, integrando os modelos de código aberto EPA SWMM e MOHID Land, que simula o comportamento dos sistemas de drenagem e do escoamento superficial de forma integrada.

O quadro desenvolvido foi validado através da sua aplicação a duas bacias de drenagem críticas da cidade de Lisboa: a bacia do centro histórico, crucial pela centralidade na cidade, e a bacia de Alcântara, a maior do sistema de drenagem de Lisboa. Os estudos de caso não só comprovaram o potencial de aplicação do RESILISTORM, mas também evidenciam a sua flexibilidade de adaptação a objetivos específicos de cada aplicação, e que podem contribuir para estratégias de melhora da resiliência global da cidade.

Palavras-chave: Resiliência Urbana, Gestão Urbana de Águas Pluviais, Quadro de Resiliência, Modelo de Simulação 1D/2D, Inundações Urbanas

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CC	Climate Change
CRF	City Resilience Framework
CRI	City Resilience Index
CRGP	City Resilience Global Programme
CRPP	City Resilience Profiling Programme
CRPT	City Resilience Profilin Tool
CSO	Combined Sewer Overflow
EDP-D	Energias de Portugal – Distribuição
EIVP	Ecole des Ingénieurs de la Ville de Paris
EU	European Union
FIC	Fundación para la Investigación del Clima
H2020	European Union’s Horizon 2020 Research and Innovation Programme
IRC	International Red Cross
IREC	Institut de Recerca en Energia de Catalunya
IPPC	Intergovernmental Panel on Climate Change
LNEC	Laboratório Nacioncal de Engenharia Civil
RT	Return Period
UN	United Nations
UNDRR	United Nations Office for Disaster Risk Reduction (former UNISDR)
UNISDR	United Nations International Strategy for Disaster Reduction
WMO	World Meteorological Organization

Chapter 1. INTRODUCTION

"Strategies for sustainability must take many forms.
There is no «one size fits all» approach to the future."

Walker et al., 2004

1.1. BACKGROUND

Urban floods usually result from intense rainfall events, concentrated in time and space, which result in runoffs higher than the design capacity of the drainage systems (Ramos, 2013; World Meteorological Organization and Global Water Partnership, 2017). IPCC (2022) reported that people are increasingly experiencing unfamiliar precipitation patterns, including extreme precipitation events. Climate change will not likely change the nature of intense rainfalls, but it will change their severity, frequency, and geographical range (Howard and Bartram, 2010). Moreover, the fast urban growth that has been ongoing since the last decades of the XXI century has led to profound changes in the pre-existing urban hydrologic cycle and posed existing infrastructures under stress. In 1950, 30% of the world's population lived in cities; in 2018, this fraction was 55%; in 2050, it is expected to rise to 68% (United Nations, 2018).

Conventional drainage systems are designed to get rid of runoff and convey it as fast as possible to an outfall (Matos, 2006). The discharge condition is a critical factor for the performance of drainage systems, especially on coastal systems subjected to sea tides. According to IPCC, the influence of tides on stormwater systems has been increasing due to climate change. It is certain that, in the near term (2021-2041), the continued and accelerating rise of the sea level will encroach on coastal settlements and infrastructure. If urbanization trends in exposed areas continue, the impacts on urban services will be exacerbated (IPCC, 2022). Additionally, meteorological-related events such as storm surges will pose higher pressures on stormwater discharges in coastal areas. This way, multiple factors interact, generating higher vulnerabilities to climate hazards and intensifying overall risk. Thus, future sea level rise, storm surge, and heavy rainfall will increase compound urban flood risks (IPCC, 2022).

There is always the residual risk of a structural failure or even the occurrence of a hydrological event greater than that of the assumed storm design. Disregarding the residual risk leads to a false sense of security, causing increased exposure to city hazards. Despite such growing concerns, flood events continue to cause extensive damage worldwide, even in developed countries with higher investment capacity. This situation indicates the need to change the strategy for urban flood management (Bertilsson et al., 2019a), and integrating the urban resilience concept is becoming relevant in this domain (Lhomme et al., 2010).

Resilience theory has become very popular in the last two decades (Meerow et al., 2016; Nunes et al., 2019), being applied in diverse fields - such as natural disasters, risk management, and climate change adaptation - and at different organizational levels, including academics, practitioners, and policymakers (Meerow et al., 2016; Nunes et al., 2019; Cinner and Barnes, 2019; Fourniere et al., 2017). Many organizations and stakeholders still poorly understand the resilience concept (Lhomme et al., 2010; Restemeyer et al., 2015; Balsells et al., 2015), making it difficult to transpose and implement at the level of urban services, such as the stormwater service. The fact that there is no closed resilience definition, although there is a tendency for stabilization (Nunes et al., 2019), and the complexity of urban systems and different players' responsibilities, objectives, and concerns creates confusion among stakeholders, making resilience-oriented management a challenging task (Balsells et al., 2015).

However, such a concept can better integrate water and flood risk management within urban planning and disaster preparedness (Serre, 2011), promote creative thinking and innovation, and focus on a dynamic, systemic, and integrated approach (Balsells et al., 2013). Nonetheless, it isn't common to find stormwater as an urban service on the urban management priorities. It is still often understood as a set of “static” infrastructures with low dynamic and contribution to urban development. Cardoso et al. (2020b) conducted a bibliographic review of 14 major urban resilience assessment programs and frameworks related to climate change focused on water. Of those, only two considered stormwater as an urban service/sector to include in such an assessment, which is a strong indicator of underrating this service, especially critical when considering the increasing tendencies of extreme rainfall events.

1.2. OBJECTIVES

The primary objective of this thesis is to contribute towards an improved integration of urban stormwater systems within cities, serving as a responsible entity for efficiently managing the flow rates generated by precipitation events and mitigating the resultant negative impacts, whether they be floods or the degradation of receiving environments. In this context, and given the increasing pressures faced by the management entities of these systems, both from the rising demands of the population and from the natural pressures exerted on the systems in a context of worsening meteorological variables due to climate change, the development of the present work aims to elucidate and provide utilities, practitioners, and researchers with a resilience framework for urban stormwater services (RESILISTORM).

Beyond the intrinsic concept of evaluation through indicators, this framework intends to serve as a roadmap for identifying critical points that undermine these services' response, adaptation, and transformation capacity. It is aimed that this framework possesses comprehensiveness concerning the varying maturity levels of urban stormwater utilities. This inclusiveness is reinforced through the publication of the current work and scientific articles and the development of open-source tools that facilitate its application. Examples include the coupling of the MOHID Land hydrodynamic model (MARETEC, 2020) with the EPA-SWMM model (Rossman, 2015), the development of the RESILISTORM-tool, and tools that allow for a practical calculation of indicators.

The application of the framework to two critical drainage catchments in the city of Lisbon, the Historic downtown catchment (critical for its centrality in the urban space) and the Alcântara catchment (the largest of Lisbon's drainage system) allows, on the one hand, to validate its utility and practice, and on the other, to guide future applications by demonstrating its flexibility in the face of objectives set for different cases.

1.3. THESIS STRUCTURE

The work carried out during the doctoral research led to the publication of a significant number of articles in peer-reviewed journals, serving as the main author, specifically:

- Barreiro, J., Lopes, R., Ferreira, F., Brito, R., Telhado, M. J., Matos, J. S., & Matos, R. S. (2020). **Assessing Urban Resilience in Complex and Dynamic Systems: The RESCCUE Project Approach in Lisbon Research Site.** Sustainability, 12(21), 8931. https://doi.org/10.3390/su12218931
- Barreiro, J., Lopes, R., Ferreira, F., & Matos, J. S. (2021). **Index-based Approach to Evaluate City Resilience in Flooding Scenarios.** Civil Engineering Journal, 7(2), 197–207. https://doi.org/10.28991/cej-2021-03091647
- Barreiro, J., Santos, F., Ferreira, F., Neves, R., & Matos, J. S. (2022). **Development of a 1D/2D Urban Flood Model Using the Open-Source Models SWMM and MOHID Land**. *Sustainability*, *15*(1), 707. https://doi.org/10.3390/su15010707
- Barreiro, J., Ferreira, F., Brito, R., & Matos, J. S. (2024). **Development of Resilience Framework and Respective Tool for Urban Stormwater Services**. Sustainability, 16(13), 1316

The author is also preparing the following manuscript:

- Barreiro, J., Ferreira, F., & Matos, J. S. (2024). **Resilience Assessment of Urban Stormwater Services: Case Studies in Lisbon, Portugal** *(in preparation)*.

Furthermore, during the research period, the author of this work contributed to three publications in peer-reviewed journals, serving as co-author. Such publications are listed below:

- Almeida, M. do C., Telhado, M. J., Morais, M., & Barreiro, J. (2021). **Multisector Risk Identification to Assess Resilience to Flooding. Climate**, 9(5), 73. https://doi.org/10.3390/cli9050073
- Almeida, M. do C., Telhado, M. J., Morais, M., Barreiro, J., & Lopes, R. (2020). **Urban Resilience to Flooding: Triangulation of Methods for Hazard Identification in Urban Areas**. Sustainability, 12(6), 2227. https://doi.org/10.3390/su12062227
- Cardoso, M. A., Telhado, M. J., Almeida, M. do C., Brito, R. S., Pereira, C., Barreiro, J., & Morais, M. (**2020). Following a Step by Step Development of a Resilience Action Plan.** *Sustainability*, *12*(21), 9017. https://doi.org/10.3390/su12219017

This work has greatly benefited from RESCCUE - Resilience to Cope with Climate Change in Urban Areas, a large-scale EU Research project involving various stakeholders in Portugal, Spain, and the United Kingdom. The candidate was deeply involved in tasks such as urban drainage modeling and hazard assessment for urban services operation, holistic resilience assessment with a dedicated software tool, and application of the Resilience Assessment Framework and consequent development of the Lisbon Resilience Action Plan. These tasks were developed in constant partnership with the project partners, namely the Portuguese: HIDRA, LNEC, CML, AdTA, and EDP-D, which strongly enriched perspectives, concepts, and methodologies related to the thesis.

Considering such background and publications, the current thesis is structured in seven chapters and three annexes.

Following the current introductory chapter, the thesis adopts a narrowing structure concerning the accomplishment of its objectives. Chapters 2 and 3 correspond to literature reviews that provide the proper context between resilience (as a concept and approach) and urban stormwater systems as an urban service.

Chapter 2 presents a literature review on resilience and its application to cities. It starts by identifying the main resilience-thinking systems and their essential properties. From this, it evolves to exploring existing large-scale projects and initiatives that frame the potential for applying the resilience concept to urban stormwater services.

Chapter 3 moves profoundly in the scope of the work, starting by exploring the main tendencies regarding urban stormwater management and infrastructures. From this point, the aim is to adopt a paradigm shift by considering urban stormwater management as an urban service and not merely as a set of infrastructures that perform a given role. This sets up the ideal circumstances to analyze how this service interacts with the city and its contributions to a livable city. Therefore, Chapter 3 follows with a literature review to determine the current situation regarding the resilience assessment of urban stormwater services and identify the main shortcomings and development opportunities.

Chapter 4 presents a parallel work on 1D/2D hydrodynamic modeling of urban drainage systems. This type of modeling allows for assessing the performance of drainage infrastructures and the behavior of surface runoff. Thus, this chapter presents an integrated 1D/2D modeling approach developed based on two open-source models: the EPA-SWMM (Rossman, 2015) and the MOHID Land (MARETEC, 2020). By enabling dual simulation, with results for underground infrastructure and surface flow, this innovative type of modeling provides a tool of great interest for making better-informed decisions about the consequences of urban drainage system performance.

In Chapter 5, a resilience assessment framework for urban stormwater services is proposed, following the conclusions withdrawn from Chapter 3. For this, resilience objectives, criteria, and indicators are presented. To complement the framework and ease its application, an open-source digital tool (RESILISTORM-tool) is also introduced to expedite answering, data integration, and visual analysis of results.

After establishing the framework, Chapter 6 follows its application to two critical catchments regarding urban floods in Lisbon, Portugal. This application aims to test and validate the pertinence of such a framework and respective tool. By assessing the resilience of these case studies, management and operational aspects undermining the system resilience are identified, allowing us to infer recommendations and assemble critical information to establish a resilience roadmap for the stormwater service and, therefore, for the city's resilience.

The thesis ends with Chapter 7, presenting a summary of the main conclusions and findings of the work and providing guide steps for future developments.

Chapter 2. URBAN RESILIENCE: A REVIEW

"One does not need the precise capacity to predict the future, but a broad capacity to invent systems that can accommodate unexpected events, both in magnitude as in type."

C. S. Holling, 1973

2.1. INITIAL CONSIDERATIONS

The main objectives of the initial chapter of this thesis are to understand the concept of resilience, its evolution over time, and how it is translated into the urban field. Such purposes allow for identifying urban resilience aspects that shall be translated into stormwater services, the core of this thesis.

To reach such objectives, Subchapter 2.2 starts by presenting the concept of resilience and the central thinking systems and resilience characteristics associated with it. From such understanding, Subchapter 2.3 transitions between the theoretical resilience concept and its application in urban fields. Subchapter 2.3.1 follows with a presentation of urban resilience large-scale initiatives. The current chapter ends with some discussion and conclusions on Subchapter 2.4.

2.2. RESILIENCE CONCEPT AND EVOLUTION

2.2.1. RESILIENCE THINKING SYSTEMS

The word resilience has its etymological origin from the Latin word «resiliens» or «resilire,» obtained from the joining of the terms «re,» which means back, and «salire,» which means to jump or leap (MaoningTech, 2019). Thus, its literal meaning refers to the "act of rebounding or springing back." This meaning is often referred to as a property of a given system, service, individual, etc., that allows them to cope with a given disruption by recovering from it and returning to a previous normal functioning state.

The term "resilience" has various applications in many subjects, such as engineering, anthropology, psychology, physics, and risk management (Folke, 2006; Meerow et al., 2016). The work of the ecologist Holling (1973) is frequently cited as the origin of the modern resilience theory and a starting point for the adaptation and application of the concept in such fields.

In his work, Holling proposes that the behavior of ecological systems can be defined by two distinct properties: resilience and stability. From an ecologist's perspective, resilience is characterized as a property of the system that "determines the persistence of relationships within a system and is a measure of the ability of these systems to absorb changes of state variables, driving variables and parameters, and persist.". On the other hand, stability is "the ability of a system to return to an equilibrium state after a temporary disturbance. The more rapidly it returns, and with the least fluctuation, the more stable it is.". From these definitions, Holling states that the result from resilience is the "persistence or probability of extinction," while the result from stability is the "degree of fluctuation around specific states."

In this sense, Holling presented a new paradigm to analyze ecologic systems where, instead of focusing on their stability around an equilibrium state and on the maintenance of a predictable world (from a typical stability approach), the focus is made on the capacity of the system to endure and keep its relationships, in what is called a "basin of attraction," and to keep options open.

A "basin of attraction" is a region in state space where the system tends to remain. The "state space" is defined by the state variables that constitute the system; it is the n-dimensional space of all combinations of the n-state variables. So, at a given time, the system's state is set by the value of each state variable. Suppose the system tends to a given state space, i.e., an equilibrium state. In that case, that state is called an "attractor." The basin of attraction comprises all the initial conditions that will tend toward that equilibrium state. In reality, it is usual for systems not to tend to an attractor but to move around this state due to continuous disturbances and decisions of actors, i.e., to be dynamic (Walker et al., 2004).

According to Holling's theory, a system can be resilient and unstable or vice versa. From the ecological point of view, "the balance between resilience and stability is a product of the evolutionary history of the systems in the face of the range of random fluctuations they have experienced" (Holling, 1973). This means that the capacity of a given system to react to external changes is highly dependent on previous experiences and accumulated knowledge and memory. When a system is exposed to frequent or variable external changes, it will retain mechanisms that improve its survivability in the future and allow it to capitalize on chance opportunities for better recuperation. In contrast, the more homogeneous the environment is in space and time, the more likely the system is to have low fluctuations (high stability) and low resilience. With this approach, Holling shifts the existing paradigm of studying ecological systems by emphasizing «the need to keep options open, the need to view events in a regional rather than a local context, and the need to emphasize heterogeneity. Flowing from this would be not the presumption of sufficient knowledge but the recognition of our ignorance, not the assumption that future events are expected but that they will be unexpected. The resilience framework can accommodate this shift of perspective, for it does not require a precise capacity to predict the future, but only a qualitative capacity to devise systems that can absorb and accommodate future events in whatever unexpected form they may take.» (Holling, 1973).

From the introduction of Holling's resilience concept for ecological systems analysis, the resilience concept has been adapted depending on the subject to which it has been applied (Meerow et al., 2016; Fourniere et al., 2017; Nunes et al., 2019). Three mainstream resilience thinking systems are found in the literature (Fourniere et al., 2017; Nunes et al., 2019), addressed in the following paragraphs and synthesized in Table 2-1.

Table 2-1. Resilience systems thinking main characteristics (adapted from Fourniere et al., 2017)

System thinking	Engineering resilience	Ecological resilience	Socio-ecological resilience
Temporal scale	short-term	medium-term	long-term
Number of equilibriums	one	multiple (stability landscape)	none, continuously changing through system feedback and cross-scale dynamic interaction
Main response	recovery	adaptation	transformability, learning, and innovation
Measure of resilience	speed of return to the single equilibrium	magnitude of shocks that can be absorbed before the threshold to enter a new equilibrium is crossed degree of self-organization and capacity for learning	magnitude of shocks and stresses that are continuously absorbed degree of self-organization and capacity for learning by social-ecological systems (human agency)
Nature of disturbances	predictable external shocks	predictable and unpredictable external shocks	predictable and unpredictable internal and external shocks and stresses
System qualities	resistance and recovery efficiency, predictability	persistence adaptability, flexibility resourcefulness, efficiency, diversity	persistence adaptability, flexibility human potential to transform its surroundings

The first resilience system thinking is mainly connected to its literal meaning, that is, the capacity of the system to return to a previous single steady state after a disturbance. In this sense, the sooner the steady state is reinstated, the more resilient the system is. Due to its practical purpose, it is named engineering resilience, and this approach is typical of subjects like risk management, psychology, or the economy (Fourniere et al., 2017).

A second approach moves from this notion of a single steady state to which the system must return after a disturbance. Based on Holling's work, this approach is called ecological or systems resilience (McClymont et al., 2020). The focus of the system behavior analysis is shifted to its capacity to absorb disturbances and persist, i.e., to keep its core functionalities, but not necessarily to remain the same. Thus, the higher the magnitude of the disturbance that the system can absorb before being forced to change to a new steady state (not necessarily the previous one), the more resilient the system is. It implies that a disturbance can force the system over the current steady-state threshold, shifting it to a new "basin of attraction," i.e., to a new steady state (Folke et al., 2010).

However, resilience also embraces the capacity to capitalize on disturbances (and their consequences) as opportunities to recombine structures and processes to renew and create new trajectories. Thus, resilience is also about influencing continuous development as a dynamic interplay between sustaining (and keeping the status quo) and developing towards more sustainable trajectories (Folke, 2006). Additionally, the thinking systems mentioned above rely mainly on the occurrence of shocks, i.e., punctual disturbances. In dynamic and complex systems, continuous disturbances on time also occur, i.e., stresses, with a slow and long-term impact. Considering this and that a system can be constantly changing even if not threatened by disturbing events (denying the existence of steady states), a third approach considers resilience as an evolutive process that transforms challenges into opportunities, named socio-ecological resilience or complex adaptive systems resilience (McClymont et al., 2020). Its use is highly related to social sciences, where the relation and interconnectivity between people and nature are interdependent systems (Folke et al., 2010; Cinner and Barnes, 2019). Therefore, it relies on people's behavior as individuals, as a community (social change), and even as humanity. This approach expands the ecological theory, including people as a significant actor in resilience, with a high capacity to influence the trajectory of a system through self-organization (versus lack of organization or organization forced by external factors) and learning and adaptation capacity (Folke, 2006).

Chelleri et al. (2015) associate two critical definitions to these resilience systems thinking: the temporal scale and main response property (Figure 2-1). Engineering resilience is related to short-term resilience, and recovery ("bouncing back") is its main response. It is important to understand that although recovery is mainly associated with shocks, long-term transitions can result from a reconstruction process when medium/long-term measures are taken due to a given shock.

Ecological resilience is considered a medium-term adaptation process since it relies on the capacity of the system to adapt to changes and their consequences by shifting regime thresholds to make the system persist within a given basin of attraction as much as possible. This process is based on adaptability as the capacity of the system to combine experience and knowledge, adjust its responses to external drivers and internal processes, and continue developing within the current stability domain (Berkes et al., as cited in Folke et al., 2010).

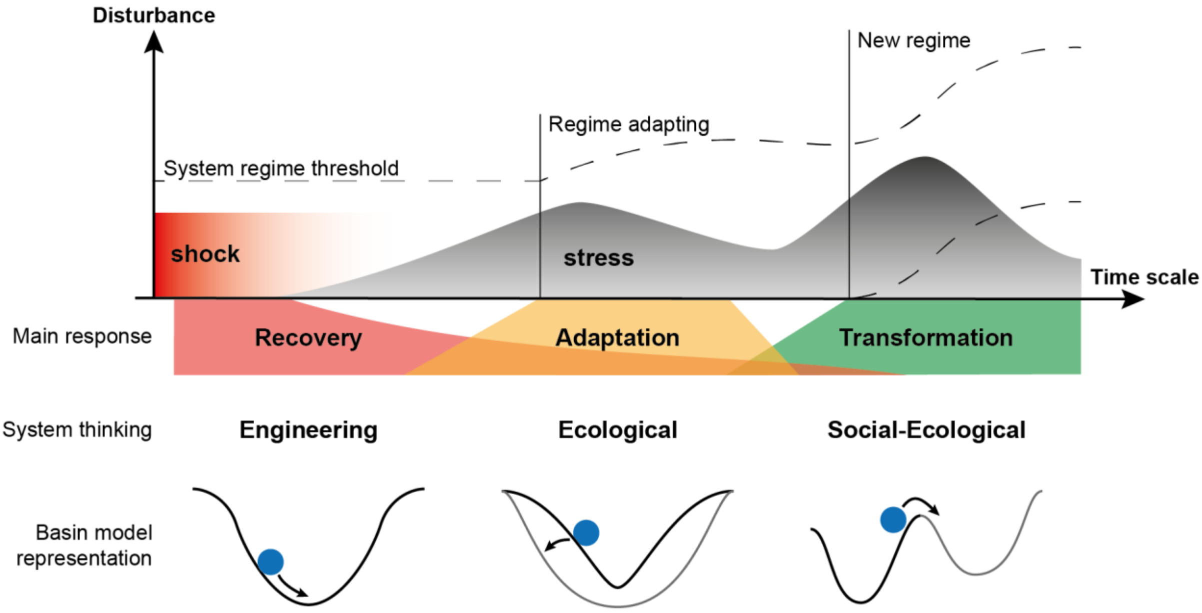


Figure 2-1. Resilience thinking systems (adapted from Chelleri et al., 2015)

Socio-ecological resilience is considered a long-term structural transformation, resulting in a response through transition. In this sense, transformability is seen as the capacity to create a new system when ecological, economic, or social structures make the existing system untenable (Walker et al., 2004). Thus, transformability is about redefining the system status quo, i.e., introducing new state variables or removing existing ones, which might result in a change of identity. The process can be deliberated, i.e., intentionally promoted by people as a human agency or forced by changing environmental or socioeconomic conditions. The first is typically initiated at multiple scales and gradually, while the latter usually occurs faster and at scales larger than the management focus and beyond the influence of local actors (Folke et al., 2010).

Despite differences between concepts, engineering and ecological resilience are not mutually exclusive (Angeler et al., 2018), nor is socio-ecological resilience. This is a consequence of the study and application of the concepts not only in different fields but also by different agents and through time, triggering conceptual evolutions, as expected. This rapid and extensive evolution of the resilience domain is challenging when engaging the literature since conceptual clarity and practical relevance are in danger (Brand and Jax (2007) as cited in Wilkinson, 2012).

For instance, Meyer (2015) emphasizes that although the ecological resilience vision of Holling neglects the return time for characterizing resilience, this property is essential to determine resilience to repeated disturbances when they are considered over the entire basin of attraction and not only when the system is near or at the equilibrium state. Conversely, interpreting resilience literally from the engineering perspective might lead to constraints regarding innovation and transitions to new trajectories, leading to a contradiction between resilience and evolution (Folk et al., 2010). Thus, Meyer (2015) suggests that instead of considering only one definition for resilience, it is crucial to consider the full spectrum of resilience thinking systems and remember that context is critical in a real-case approach to determine which indicators matter the most. In other words, the specific system context will determine which thinking system or systems might be more relevant and, consequently, which resilience characteristics might be more suitable to characterize the system's resilience. In the same way, strategies for resilience must depend on the context and will tend to change over time due to the intrinsic dynamic of the systems (Walker et al., 2004).

2.2.2. RESILIENCE PROPERTIES

Considering the basin of attraction model, Walker et al. (2004) propose four components of resilience: Latitude, Resistance, Precariousness, and Panarchy (Figure 2-2). Latitude refers to the admissible range the state variable can endure before the system loses its ability to recover, i.e., before reaching a threshold from which it is very difficult or impossible to recover (recovery threshold). Resistance is the amount of opposition the system offers before reaching such thresholds. Precariousness is the closest distance of the system's current state to the recovery threshold. Panarchy is the influence of the cross-scale interactions and dynamics of systems at different scales on the previous three components, simultaneously an extrinsic and intrinsic system characteristic.

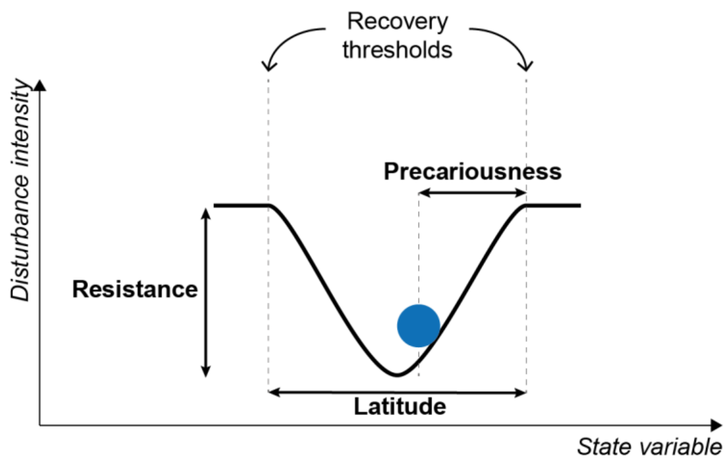


Figure 2-2. Resilience components, according to Walker et al. (2004)

There is ambiguity in how Walker et al. (2004) define resistance since it is mentioned as the depth of the basin of attraction and simultaneously as the "slope" of the attraction basin (Depth/Latitude). The work of de Bruijn (2004) disrupts this approach since it considers resistance and resilience distinct properties (Figure 2-3). Bruijn states that if the system is resistant to a given disturbance up to a certain threshold, then its resilience, as property, is only "activated" when that threshold is exceeded. This approach directs resilience to a property that deals only with the recovery phase of the system and not with the early stages of absorption and response to disturbances.

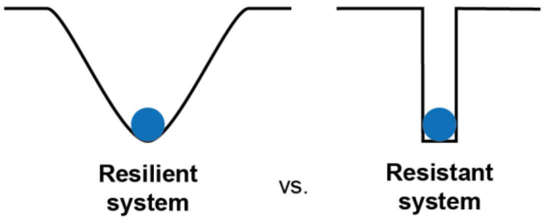


Figure 2-3. Resilient and resistant systems, according to de Bruijn (2004)

However, if one merges both approaches, the resistance concept presented by de Bruijn (2004) can be translated as the slope of the attraction basin - as vaguely hinted at by Walker et al. (2004). If the system is highly resistant, the slope of the basin is high, and the system does not react to the disturbance (its state variables do not vary). A new concept needs to be introduced herein: Robustness. Robustness is the inverse of the system's reaction sensitivity to disturbances. Since this reaction is related to the continued functions of the system, this concept is related to resilience (Anderies et al., 2013). If the system is less robust, i.e., more sensible, a more minor disturbance can easily remove the system from its actual basin of attraction. Consequently, Resistance can be defined as Robustness/Latitude (Figure 2-4), i.e., how hard it is to push the system away from its attractor.

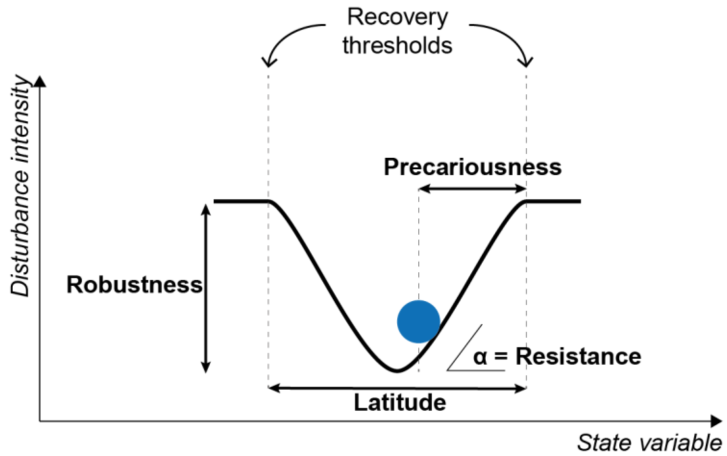


Figure 2-4. Resilience components and the basin of attraction model

Still, the definition of resistance is not consensual among researchers. As Meyer (2015) stresses out, state variables do not necessarily influence reaction and recovery in the same way, i.e., the slope that controls the shift of the state due to a disturbance (reaction) might not be the same as the return (recovery).

The basin of attraction model helps understand and interpret the changes in the mentioned resilience properties. Adaptability can be seen as the collective capacity of the system's human actors to manage or influence resilience (Walker et al., 2004). Thus, adaptability refers to the change in the mentioned resilience’s components, namely, by enlarging (increasing Latitude, i.e., moving thresholds away) or deepening (increasing Robustness) the basins of attraction, or shrinking undesirable basins; by moving the current state of the system deeper into a desirable basin or closer to the thresholds of an undesirable basin (affecting Precariousness); by managing cross-scale interactions to decrease or increase resilience (affecting Panarchy); or even by creating favorable or eliminating undesirable basins of attraction (changing the stability landscape). When considering transformability, as mentioned above, a whole new status quo is defined, changing the way the system is defined, its state variables, and even the scale at which it is defined. Thus, the transformability process results in a whole new stability landscape.

As mentioned above, Resistance, Robustness, Latitude, and Precariousness are highly intrinsic resilience properties of a system. Panarchy - the bidirectional influence of different time and space scales – brings a strongly extrinsic component to the system resilience analysis. There are always larger and thinner scales than the ones being analyzed. This is also mentioned as multiscale resilience, and it is crucial to understand the interplay between persistence and change, as well as adaptability and transformability (Folke et al., 2010).

To better explore Panarchy, the adaptive renewal cycle concept (Pendall et al., 2010), an ecological resilience-based model of adjustment to internal and external forces, is introduced and illustrated in Figure 2-5.

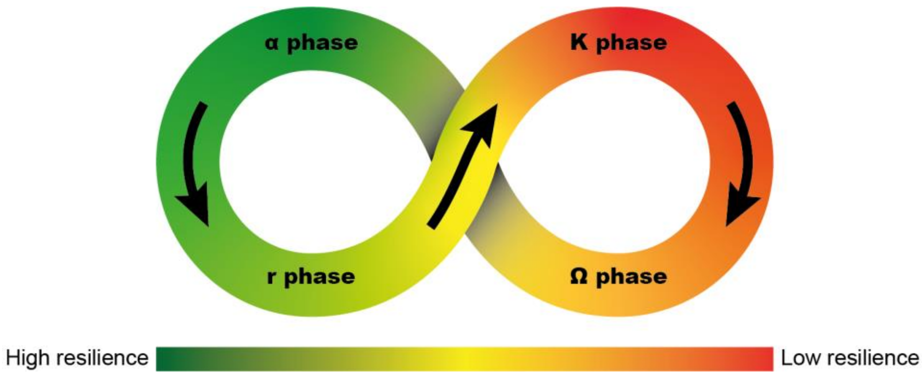


Figure 2-5. Adaptive renewal cycle (adapted from Pendall et al., 2010)

Each cycle phase is related to a resilience level reflecting the system's vulnerability to disturbances. Being a cycle, the system continuously changes (slower or faster), meaning resilience is not a fixed property. Instead, resilience, as property, varies with the system status. The adaptive cycle model attributes greater resilience when the system presents more significant fluxes and flexibility (Pendall et al., 2010). This cycle is composed of four phases (Folke, 2006; Pendall et al., 2010):

- **Exploitation phase - r phase:** Period of growth and change triggered by the appearance of key opportunities and promising resources. This is a phase of high but decreasing resilience.
- **Conservation phase - K phase:** Along the exploitation phase, the conditions that withstand the fluxes mature over time, resources are accumulated, and practices are solidified. As the growth stagnates and stability is reached, the system has greater rigidity, increasing the vulnerability to external and internal disruptions. Thus, the system has low resilience, and minor disturbances can trigger intense changes.
- **Release phase - Ω phase:** When a disturbance occurs, instabilities in the critical system's foundations are triggered, resources are lost, and relations are broken. Also called the "creative destruction" phase, it is a period of uncertainty and low but increasing resilience due to the system's incapacity to respond to new incoming disturbances.
- **Reorganization phase - α phase:** After the collapsing of the system, this is a period of change and reorganization, with the emergence of new regimes and relationships (innovation). Although this phase poses high uncertainty on the system due to the many possibilities for the future, the capacity to deal with such uncertainty provides the system with high resilience. The system is now positioned for a new adaptive cycle.

The adaptive cycle is a sequence of gradual changes followed by rapid changes triggered by disturbances. This way, instabilities organize the behaviors as much as do stabilities. In other words, disturbances are part of development, and periods of gradual change and rapid transition coexist and complement each other (Folke, 2006).

Panarchy can now be explained by considering not only one adaptive cycle but a series of nested adaptive cycles operating and interacting at different scales and periodicities (Figure 2-6), moving the adaptive cycle from theory to a more realistic and practical demonstration of the functioning of real complex systems (Pendall et al., 2010). Each level of the nested system operates at its speed, embedded in slower and larger levels but invigorated by faster and smaller ones (Folke, 2006), emphasizing the importance of cross-scale interactions.

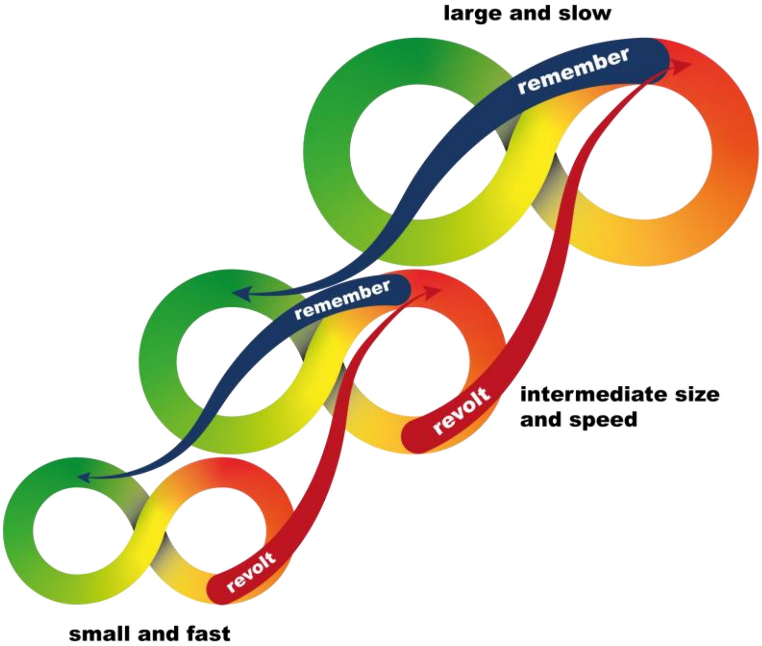


Figure 2-6. Nested adaptive cycles with cross-scale interactions as an illustration of Panarchy (adapted from Folke, 2006; Pendall et al., 2010)

The smaller scales interfere with larger scales through a “revolt” function. Each step in that cascade of events moves the disturbance to a larger and slower level. The inverse interaction, from larger to smaller scales, is made through a “remember” function, which is of utmost importance in times of change, renewal, and re-organization. Remembering often mitigates revolts that would otherwise cascade upward through the multi-scale system. Through its higher-level feedback loop, remembering stabilizes the sub-systems (Pendall et al., 2010). If “revolts” are frequent, the response may become routinized, and the capacity to deal with moderately or slowly changing variables might be affected. This threat of routinization highlights the importance of multi-scale and independent “remember” functions (Pendall et al., 2010). Memory is the accumulated experience and history of the system, and it provides context and sources for renewal, recombination, innovation, novelty, and self-organization following disturbance (Folke, 2006).

The Panarchy property, however, raises an interesting issue regarding resilience: What are the boundaries of a system and its resilience? Ultimately and absurdly, system resilience studying can go from the smallest scales, such as the molecular level, to the largest scales, like the universe. Resilience scholars and theoretical responses have addressed this issue and have stabilized around the definitions of specific or specified resilience and general resilience.

It is common to find resilience studies applied to issues related to particular aspects or parts of a system, usually due to the threat of specific and known shocks. Those studies refer to specified resilience, which is the resilience of a part of a system, specific issue, or set of problems (Folke et al., 2010). Specified resilience is often related to the question: "The resilience of what to what?" (Carpenter et al., 2001). It requires a clear system definition regarding the variables that describe the state and the nature of internal/external disturbances (Pendall et al., 2010). However, a danger emerges when one is too focused on specified resilience because the system might become resiliently uncompensated; some parts of the system might be very resilient to specific threats while other parts of the system have low resilience. In extreme cases, the increase of specific resilience might trigger the loss of resilience in other components or threats not considered or expected. In contrast, the focus might be spread on all kinds of disturbances, including new and unpredictable ones. In this case, one refers to general resilience. Thus, general resilience does not define the part of the system that might cross a threshold or the kinds of disturbances the system has to endure, coping with uncertainty in all ways (Folke et al., 2010).

2.3. URBAN RESILIENCE TRENDS

Although the resilience theory has been highly developed regarding social-ecological systems, it has been widely applied in diverse fields - as natural disasters and risk management, climate change adaptation, and energy systems, among others - and also at different organizational levels, including academics, practitioners and policymakers (Cinner and Barnes, 2019; Nunes et al., 2019).

Resilience approaches regarding cities have become very popular in recent years (Meerow et al., 2016; Nunes et al., 2019), both in academic and policy discourse. The social-ecological system thinking - assuming that systems are constantly changing and aiming at dealing with uncertain future disturbances - provides a favorable theoretical background for cities to deal with future uncertainties, such as climate change (Meerow et al., 2016).

Nunes et al. (2019) performed an academic literature review on urban-centric resilience works dated between 1984 and February 2018 from the Thompson Reuters Web of Science database. These authors have considered six urban research fields to trace the evolution of publications regarding the number of publications, the thematic focus (research fields), the research focus (general vs. specific resilience), and the conceptual focus (resilience thinking system).

The evolution of the urban-centric resilience publications (Figure 2-7) shows a notorious growth since the beginning of the XXI century, with about 88% of the total publications dated between 2009 and 2018 (Nunes et al., 2019).

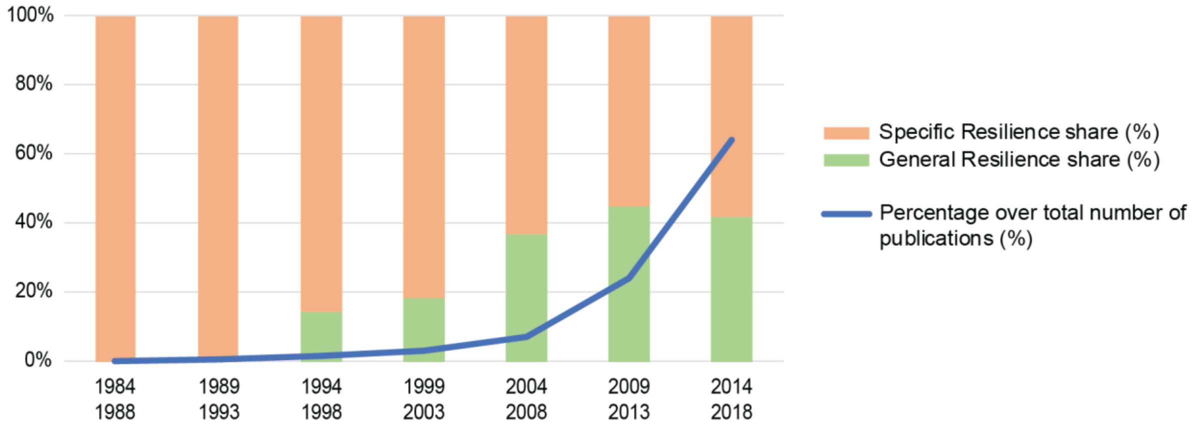


Figure 2-7. Share between general and specific resilience and the percentage over the total number of publications at each time interval (Nunes et al., 2019)

The Social Sciences field has played a significant role in developing urban-centric resilience, being the research field with the most significant share of publications in all the analyzed periods. However, the heterogeneity growth regarding the research field's involvement in urban-centric resilience is evident, mainly since the beginning of the XXI century. With this spread of resilience thinking among the research fields, the resilience research focus concerning general resilience also tended to increase (Figure 2-7). Naturally, with the increase of contributions from different research fields, more comprehensive approaches regarding urban resilience are arising, emphasizing the importance of multidisciplinary collaborations. That is critical when addressing societal changes since the view of different fields allows a better understanding, recognition, and appliance of different solutions across different scales (Cinner and Barnes, 2019).

While the Social Sciences dominate the publication’s research field, the Environmental and Biosciences field played a vital role in widening the urban-centric resilience research focus, shifting the predominance of specific resilience to a similar share with general resilience by considering the complexity and adaptability of urban systems, and thus evolving from engineering resilience to ecological and social-ecological resilience systems thinking (Nunes et al., 2019).

In summary, each research field has started to work on urban-centric resilience from the engineering and specified resilience view, dealing with the specific issues of each field. With the evolution and deepening of the works, each research field tends to broaden the topics and domains of investigation, evolving to more comprehensive and complex works within each research field, deepening internal concerns and exploring relations with outer scales.

It is notorious that different resilience approaches tend to the coexistence of the three resilience thinking systems in all research fields, suggesting that their use is not exclusive but mutually reinforcing (Nunes et al., 2019). The research focus has tended to a stabilization around equal shares between specific and general resilience. As urban resilience progressively focuses on more complex and adaptive systems, more general approaches are expected to emerge. Nevertheless, different research fields will focus on their specific issues, thus contributing to general approaches. This represents, in part, the reinforcement of the different conceptual focuses and the trend to multi-scalar resilience approaches, with contributions from both top-down (general to specific) and bottom-up (specific to general) approaches. While the overlap of the several resilience systems thinking grants some malleability and adaptability of the resilience approach to adopt in a particular context, this can also create some confusion and vagueness in the approach (Nunes et al., 2019), making it difficult to plan, operationalize, and measure (Meerow et al., 2016).

Meerow et al. (2016) also realized a theoretical bibliographic review around the definition of urban resilience, analyzing Elsevier's Scopus and Thompson Reuters Web of Science publications dated between 1973 (the publication year of the work of Holling) and 2013. These authors have defined six conceptual tensions that are critical to allow a proper application of resilience-oriented approaches, namely:

1. **Characterization of "urban"** – The physical domain of urban resilience, i.e., what a city is, is often vaguely defined, and there is not a consensual characterization in those who define it. Additionally, globalization has interconnected cities with more or less distant places, creating strong interdependencies and making it difficult to delineate the boundaries of cities or urban systems.
2. **Notions of equilibrium** - This conceptual tension is related to the conceptual focus of the urban resilience thinking systems. The definitions are distributed among the adoption of a single equilibrium state (engineering resilience), multiple-state equilibrium (ecological resilience), and dynamic non-equilibrium (social-ecological resilience).
3. **Resilience as a positive concept** - The view of resilience as a desirable attribute is consensual in the definitions, aiming at allowing the cities to maintain their normal functions and improve over time. There are, however, some issues with the positivity

of resilience when the reinstatement of the pre-disturbance state might not be desirable, as in dictatorships, poverty, or fossil fuel dependence. These situations tend to be undesirable for some but highly resilient by self-reinforcing through social and behavioral feedback (Cinner and Barnes, 2019).

4. **Pathways to urban resilience** - These relate to how each resilience thinking system achieves resilience through persistence, adaptation (or transition), and transformation. Most definitions focus on persistence, and the majority neglect any mechanism for change (transition or transformation). Although some definitions identify the need to foster changes and promote adaptation, there are different notions of whether this should be achieved through incremental changes (transition/adaptation) or by more substantial changes on the status quo (transformation).
5. **Understanding of adaptation** - This conceptual tension is related to the distinction between specific adaptation (to known issues or threats) and more comprehensive adaptability, i.e., between specific and general resilience. It is frequently argued that focusing on particular issues might compromise the system's reaction and response as a whole. In the same way, focusing on short-term adaptation will narrow the adaptation possibilities, leading to specific adaptation and potentially lowering the adaptability capacity for the future. Resilience approaches should be comprehensive, fostering general resilience to unexpected threats and specific resilience to known disturbances.
6. **Timescale of action** - The definitions of urban resilience are consensual regarding the need to recover rapidly after a disturbance but unclear regarding the definition of “rapidly.” Engineering-based approaches define “recovery speed” as a measure of resilience, although the remaining conceptual approaches are less clear on defining the importance of timescale for adaptation or transformation.

Considering the mentioned conceptual tensions, these authors formulated a set of questions that should be considered when addressing urban resilience (Table 2-2), helping contextualize and address the correct issues when aiming for a resilience approach. Resilience approaches can vary in many aspects, which is not a problem if those are adequately exposed when defining or addressing resilience boundaries (Nunes et al., 2019).

Table 2-2. The five Ws for addressing urban resilience (Meerow et al., 2016)

Questions to consider	
Who?	Who determines what is desirable for an urban system? Whose resilience is prioritized? Who is included (and excluded) from the urban system
What?	What perturbation should the urban system be resilient to? What networks and sectors are included in the urban system? Is the focus generic or specific resilience?
When?	Is the focus on rapid-onset disturbances or slow-onset changes? Is the focus on short-term resilience or long-term resilience? Is the focus on the resilience of present or future generations?
Where?	Where are the spatial boundaries of the urban system? Is the resilience of some areas prioritized over others? Does building resilience in some areas affect resilience elsewhere?
Why?	What is the goal of building urban resilience? What are the underlying motivations for building urban resilience? Is the focus on process or outcome?

Such questions are indirectly addressed by Chen et al. (2017), who aimed to relate resilience with sustainability. These authors present a conceptual framework based on two axes, "Passive-Active" and "Rational-Irrational" (Figure 2-8).

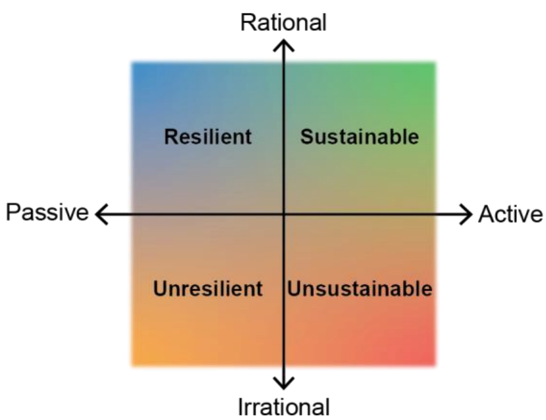


Figure 2-8. Rational-Irrational vs Passive-Active urban development (adapted from Chen et al., 2017)

Resilience is placed on the passive/rationale quadrant, while sustainability is on the active/rationale quadrant. If the development is not resilient or unsustainable, it is irrational. Irrational development is convergent, leading to the destruction of the urban environment. Although these authors place resilience and sustainability on opposite sides of the Passive-Active axis, this does not represent a divergence between these concepts. This must be viewed from the perspective that rational urban development can only be achieved through a balance between resilience and sustainability (Marchese et al., 2018), and complementary approaches that enhance cities' capacity to endure future uncertainties and promote sustainable urban development should be considered (Anderies et al., 2013; Zhang and Li, 2018). Such is also imprinted in the UN's 11th Sustainable Development Goal, which aims to make cities and human settlements inclusive, safe, resilient, and sustainable and reinforces the need to deepen the relationship between urban resilience and urban sustainability (Zeng et al., 2022)

2.3.1. URBAN RESILIENCE LARGE-SCALE INITIATIVES

Fourniere et al. (2017) mapped the main stakeholders participating in urban resilience-related activities, exploring their interconnectivity (Figure 2-9 and Table 2-3). As a result of such interconnectivities analysis, the authors categorize the stakeholders around four clusters: 1. United Nations and the European Union (in blue); 2. The Rockefeller Foundation and the 100 Resilient Cities Network (in red); 3. The United Kingdom Department for International Development Network (in yellow); and 4. De-linked Actors (in grey).

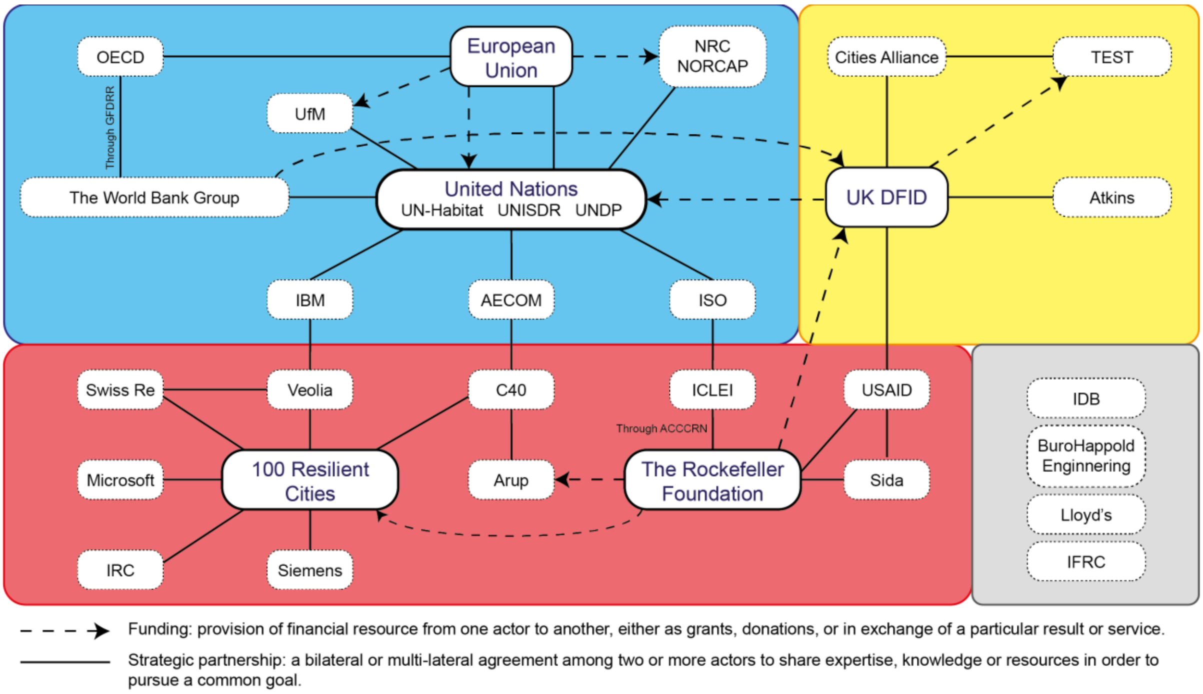


Figure 2-9. Global network of actors for urban resilience (adapted from Fourniere et al., 2017)

The presented network of actors comprises governmental, inter-governmental, and non-governmental organizations and a diverse range of private actors, philanthropic foundations, and academic and research institutes. Many are involved in different approaches, projects, teams, and alliances, leading to several crosses between their works. A frequent issue these activities address are climate-related threats, namely, natural hazards and climate change, to which resilience thinking fits by addressing its inherent uncertainties.

The next subchapters present four main large-scale urban resilience projects.

Table 2-3. Acronyms in Figure 2-9 and respective meanings

Acronym	Designation
AECOM	AECOM Technology Corporation
IBM	International Business Machines Corporation
ICLEI	Local Governments for Sustainability
IDB	Inter-American Development Bank
IFRC	International Federation of Red Cross
ISO	International Organization for Standardization
NRC/ NORCAP	Norwegian Refugee Council / Norwegian Capacity
OECD	Organization for Economic Co-operation and Development
Sida	Swedish International Development Cooperation Agency
TEST	The Ecological Sequestration Trust
UfM	Union for the Mediterranean
UK DFID	United Kingdom Department for International Development Network
UNDP	United Nations Development Programme
USAID	United States Agency for International Development

2.3.1.1. MAKING CITIES RESILIENT CAMPAIGN

In 2010, UNISDR launched the Making Cities Resilient Campaign in a pioneering effort to include resilience on its agenda. The campaign addresses the main issues of this agency's core, namely local governance and urban risks (UNISDR, 2010). The campaign was mainly an effort to raise awareness of local authorities and governments on disaster risk governance, urban risk, and resilience and to support them in implementing the Hyogo Framework for Action 2005-2015: Building the Resilience of Nations and Communities to Disasters (United Nations Specialized Conferences, 2005). In 2016, the Campaign was working with more than 3400 global cities, with a high diversity in characteristics. This led to a network of cities engaging on the same goals, even with different contexts, promoting learning exchanges and cooperation (UNDRR, 2019a). The campaign was based on three main tools to help local leaders assess, monitor, document, and improve on disaster risk and resilience, namely, the "Ten Essentials for Making Cities Resilient," the Local Government Self-Assessment Tool and the Handbook for Local Government Leaders on How to Make Cities Resilient.

In 2015, a new UN framework entered into force, the Sendai Framework for Disaster Risk Reduction 2015-2030 (United Nations Specialized Conferences, 2015), and other 2030 agendas were developed, such as the Sustainable Development Goals and the New Urban Agenda. Thus, the Campaign enters a new phase, up to 2020, shifting its focus from advocacy to implementation support, partner engagement, investment-cooperation opportunities, local action planning, and monitoring of progress (UNDRR, 2019a). In 2015, the Ten Essentials for Making Cities Resilient were updated (Figure 2-10), and in 2017, an updated Handbook for

Local Government Leaders on How to Make Cities Resilient was published along with a new tool, the Disaster Resilience Scorecard for Cities.

The Disaster Resilience Scorecard, an evolution of the Local Government Self-Assessment Tool, aids local governments in monitoring and reviewing the progress of implementing the Sendai Framework, supporting the development of disaster risk reduction and resilience strategies. This tool is now divided into two levels (UNDRR, 2021a):

- **Preliminary level** – aiming for key Sendai Framework targets and indicators, also posing some critical sub-questions. It is suggested that it be answered through a multistakeholder workshop of 1 or 2 days. It comprises 47 questions to be scored between 0 and 3.
- **Detailed assessment** – a deepening of the previous level, comprising a multistakeholder exercise intended to take 1 to 4 months and serve as the basis for developing a city resilience action plan. It includes 117 indicators, each to be scored between 0 and 5.

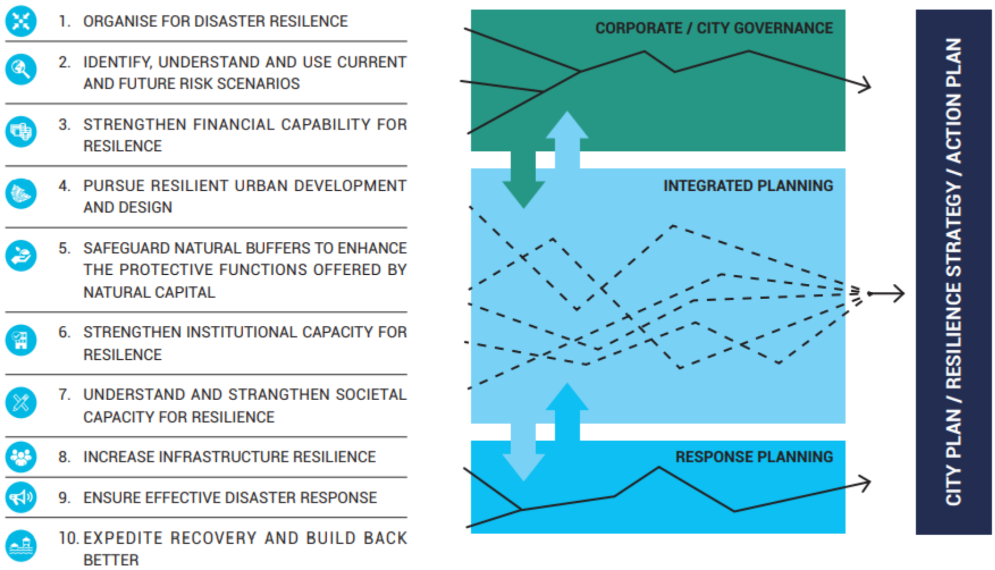


Figure 2-10. Ten Essentials for Making Cities Resilient (Amaratunga et al., 2019a)

In 2019, the UN published a report regarding the results of 214 cities that engaged in the Disaster Resilience Scorecard between 2017 and 2018, excluding European cities (Amaratunga et al., 2019a). The main conclusion withdrawn is that the overall performance at the preliminary level is very incipient in all the Resilience Essentials, as shown in Figure 2-11.

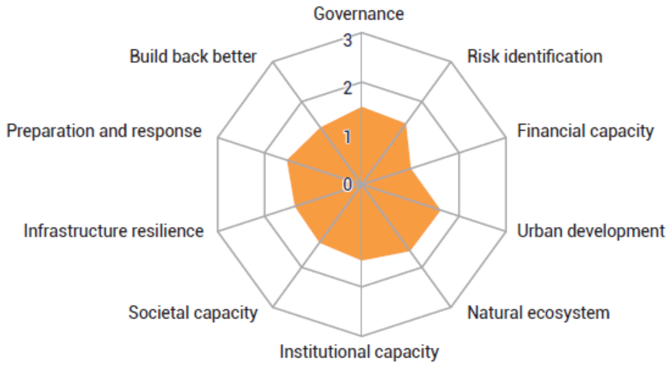


Figure 2-11. Overall performance of local governments in disaster resilience and risk reduction (Amaratunga et al., 2019a)

A parallel survey was done on cities regarding their progress in disaster risk reduction and implementing the Sendai Framework, including cities that are not part of the MCR Campaign (Amaratunga et al., 2019b). The risks identified by inquired cities are mostly climate-related - floods (65%), landslides (37%), drought (22%), and earthquakes (22%). The cities participating in the MCR Campaign are more advanced in developing spatial analysis of vulnerability, exposure, hazards, and risks. From all the inquiries, only 53% translated their analysis on specific strategies or plans, while 30% were developing strategies, and the remaining 17% had no strategy or plans. When passing from theory to practice, only 27% of the cities with disaster risk strategies have fully implemented them, around 53% have only implemented some measures, and around 20% have not started implementing the plans. Lack of financial resources, followed by changes in government priorities and lack of political interest, are the critical barriers pointed out by governments.

In 2020, the Campaign entered its actual phase with the Making Cities Resilient 2030 (MCR2030). The objectives of the MCR2030 are to improve cities' understanding of risk and secure their commitment to local disaster risk reduction and resilience, to strengthen cities' capacity to develop local strategies/plans to enhance resilience, and to support cities to implement local strategies/plans to strengthen resilience. In this phase, the roadmap for resilience has been updated, being more precise and better adjusted to each city stage. The roadmap is now divided into three stages (A, B, and C) that relate to each campaign objective, and local governments must take specific actions to go through each phase (UNDRR, 2021b).

By December 2021, 617 cities had joined the campaign, corresponding to about 434 million inhabitants. From these, 149 cities are in Stage A, 164 are in Stage B, and 304 are in Stage C (UNDRR, 2021c).

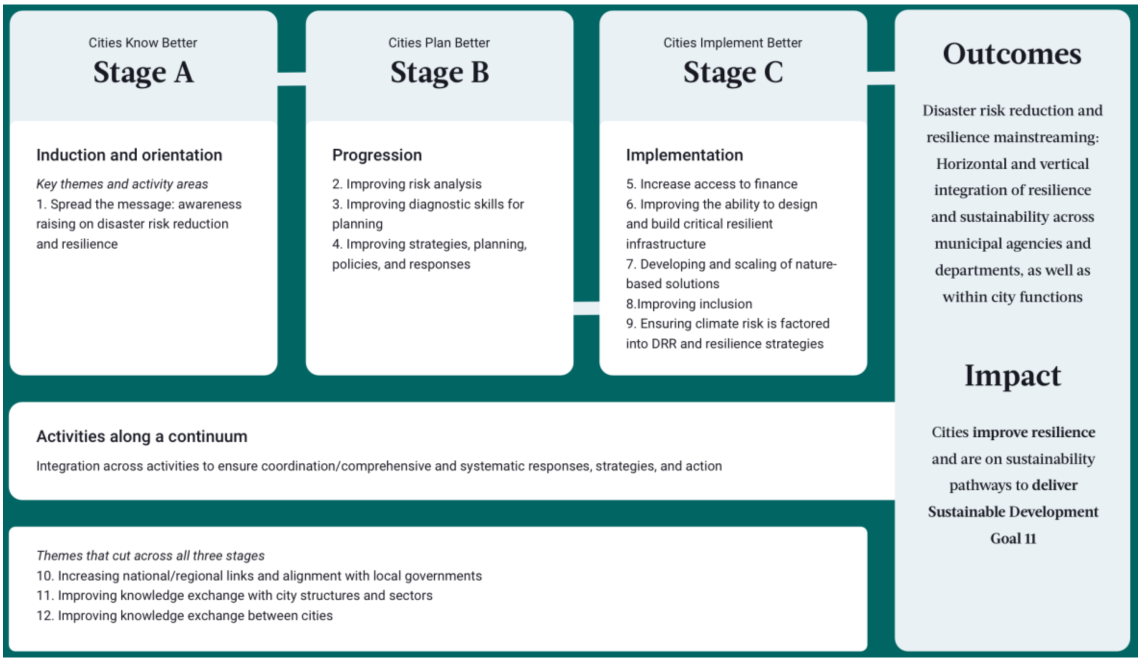


Figure 2-12. MCR2030 roadmap for resilience (UNDRR, 2019b)

Figure 2-13. Worldwide distribution of cities enrolled in MCR2030 Campaign (UNDRR, 2021c)

2.3.1.2. 100 Resilient Cities

The 100 Resilient Cities was launched in 2013, pioneered by The Rockefeller Foundation. Governments received this project with great expectation due to its high potential to improve physical, social, and economic resilience. The foundation has committed $100 million to build resilience in 100 cities worldwide, which had to apply and be selected. When selected, cities would have access to a set of benefits, namely (The Rockefeller Foundation, 2013):

1. Membership in the 100 Resilient Cities Network with support, knowledge, and resilience best practices sharing by fostering new connections and partnerships.

2. Support the hiring or funding of a Chief Resilience Officer (CRO), a new role in the city government that helps ensure resilience building and coordination, being responsible for developing a resilience plan for the city. The CRO will be part of a learning network of other CROs representing the 100 Resilient Cities Network.
3. Support creating a resilience plan that reflects each city's needs.
4. Access to an innovative platform of solutions, services providers, and partners from the private, public, and NGO sectors to provide tools and resources for the implementation of the plan, focused on four areas: innovative finance, innovative technology, infrastructure, and land use, and community and social resilience.

The cities were selected in three rounds: 30 in 2013, 33 in 2014, and 37 in 2016 (Figure 2-14). Up to 2020, more than 80 CROs were hired and trained, and more than 50 resilience plans were created, translating into more than 1800 concrete actions or initiatives, $230 million of pledged support from the platform partners, and more than $655 million leveraged from national, philanthropic, and private sources (The Rockefeller Foundation, 2020).

Figure 2-14. 100 Resilient Cities Network (Saurabh Gaidhani, 2016)

The City Resilience Framework (CRF), which comprehends an assessment tool, the City Resilience Index (CRI), was developed with the support of Arup, a 100RC partner. The CRF is presented as a "holistic framework that combines the physical aspects of cities with the less tangible aspects associated with human behavior; that is relevant in the context of economic, physical and social disruption; and that applies at the city scale rather than to individual systems within a city." (ARUP, 2015, p. 4).

The CRF has 12 goals divided into four dimensions of city resilience (Table 2-4), built around seven qualities of resilient systems: flexibility, redundancy, robustness, resourcefulness, reflectiveness, inclusiveness, and integration. This framework is presented as a layered approach that cities can use to engage stakeholders and build a shared understanding of city resilience, identify critical aspects to target actions and investments, and find knowledge gaps where further analysis is required (ARUP, 2015). The objective is not to compare cities' performance or rank cities by their resilience status but to provide a common basis for understanding and assessing urban resilience, fostering dialogue, and change experiences between local governments (ARUP and Rockefeller Foundation, 2017).

Table 2-4. City Resilience Framework (adapted from ARUP, 2015)

Dimensions	Goals
Leadership and strategy	Effective leadership and management
	Empowered stakeholders
	Integrated development planning
Health and wellbeing	Minimal human vulnerability
	Diverse livelihoods and employment
	Effective safeguards to human health and life
Economy and society	Collective identity and mutual support
	Comprehensive security and rule of law
	Sustainable economy
Infrastructures and ecosystems	Reduced exposure and fragility
	Effective provision of critical services
	Reliable mobility and communications

The CRI deepens the CRF by adding one more layer corresponding to the indicators layer, with 52 indicators distributed along the 12 goals. The 52 indicators are assessed by a double approach, comprising 156 qualitative and 156 quantitative prompt questions. The qualitative questions intend to evaluate the adequacy of the mechanisms and processes of the city to achieve the outcome of the indicator and are scored on a scale from 1 to 5, considering a "worst case" and "best case" scenario, respectively. The quantitative questions pretend to identify metrics that can be used as proxies for past and future performance in attending to the respective indicators and are translated in a scale from 1 to 5 based on standardized performance scales (ARUP and Rockefeller Foundation, 2017).

Practical outcomes of the CRI result in graphical results that ease the communication with stakeholders (Figure 2-15), mainly the resilience qualities profile (a) presenting the status of the city about the seven resilience qualities; the qualitative (b) and quantitative (c) resilience profiles – presenting the status of the city at the qualitative and quantitative sub-indicators level, respectively; and completeness profile (d) – presenting the extent of quantitative sub-indicators answered by the city.

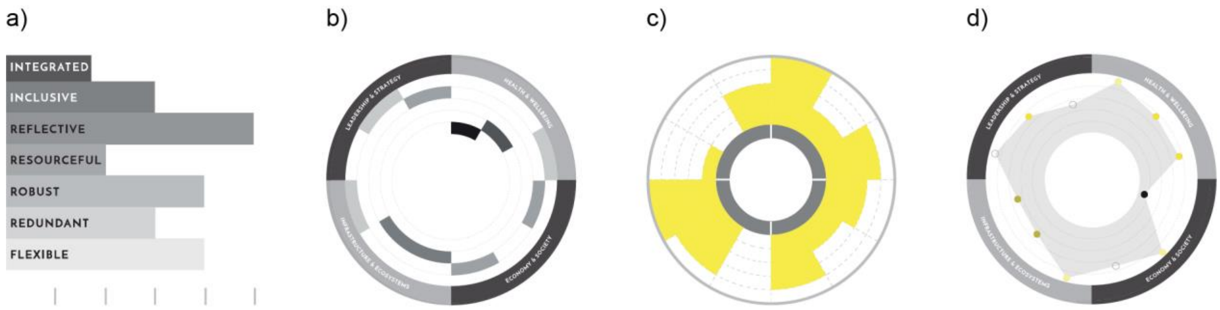


Figure 2-15. City Resilience Index graphical results (adapted from ARUP and Rockefeller Foundation, 2017)

In April 2019, The Rockefeller Foundation president announced that the 100RC project would be shut down by the end of July of the same year. The first consequence of this action was the dismissal of around 86 City Resilience Officers. However, in July 2019, the foundation announced a $8 million commitment to continue the support of the CROs at the member cities of the 100RC Network (The Rockefeller Foundation, 2020). It is not clear why this decision was made. However, it is pointed out that the change of the Rockefeller Foundation presidency in 2017 has increased the pressure on the 100RC members to prove "marketable " impacts of the project, and budget issues have also been critical (UNEP, 2020).

Due to the 100RC shutdown, the 100RC board members started two distinct new organizations, the Global Resilient Cities Network (GRCN) and the Resilient Cities Catalyst (RCC). Both these organizations claim to be a consequence of the 100RC, taking advantage of the strengths and experience acquired. However, it is unclear why two paths were created instead of merging efforts for the same goals.

The Global Resilient Cities Network, presented in February 2020 (Sanchez, 2020), has many similarities with the 100 Resilient Cities Network, being a natural successor of this project composed of 97 member cities of the 100RC (Figure 2-16) and still having The Rockefeller Foundation as funding partner (R-Cities, 2021). The GRCN has spread its thematic priorities. While the 100RC focused on climate and disaster risk resilience, the GRCN has three thematic priorities: Climate Resilient Cities, Circular Cities, and Equitable Cities (R-Cities, 2021). This leads to a new approach to urban resilience, bringing more flexibility to each city and allowing the development of more city-oriented programs with the support of the network partners.

Figure 2-16. Member cities of the GRCN (Resilient Cities Network, 2022)

The Resilient Cities Catalyst, announced in January 2020 (Resilient Cities Catalyst, 2020), follows a different approach from the 100RC and GRCN projects. It is based on a consulting business model. The RCC offers three programs to address urban resilience: Regional Resilience Partnerships, Project Preparation Program, and Resilient Neighborhoods Program (Resilient Cities Catalyst, 2021). From the available online information, this project is significantly narrowed and oriented to the USA market.

2.3.1.3. City Resilience Profiling Programme

In 2012, UN-Habitat launched the City Resilience Profiling Programme (CRPP), a program to provide national and local governments with tools for measuring and increasing resilience to multi-hazard impacts, including those related to climate change, with a predicted investment of $8 million (UN-Habitat, 2012). The project was launched with global competition for cities to apply to be a Partner City, and the winners were announced in April 2013: Balangoda, Sri Lanka; Barcelona, Spain; Beirut, Lebanon; Dagupan, Philippines; Dar es Salaam, Tanzania; Lokoja, Nigeria; Portmore, Jamaica; Cocepción/Talchuano, Chile; Tehran, Iran; Wellington, New Zeeland (Figure 2-17).

As the ultimate goal, the program developed a new UN-Habitat normative framework for global monitoring of urban systems' resilience (UN-Habitat, 2013), translated into the City Resilience Profiling Tool (CRPT).

After 2016, the CRPP evolved from a research program to a technical and operational cooperation program aiming at helping urban settlements apply the CRPT and improve their resilience. The CRPT is built over an urban system model composed of five interdependent dimensions common to all human settlements: spatial attributes, organizational attributes, physical attributes, functional attributes, and time. The last phase resulted in a new UN-Habitat approach to urban resilience, the City Resilience Global Programme: a team of technical partners that help cities increase their resilience by diagnosing the state of their urban system, driving actions, sharing, and building knowledge for policy making.

Figure 2-17. Partner cities of the CRPP (UN-Habitat, 2013)

The UN-Habitat approach to urban resilience considers three characteristics of being resilient - persistence, adaptability, and inclusion - and three characteristics of achieving resilience - integration, reflexibility, and transformability (UN-Habitat, 2018). The implementation steps of the tool are presented in Figure 2-18 and are described below.

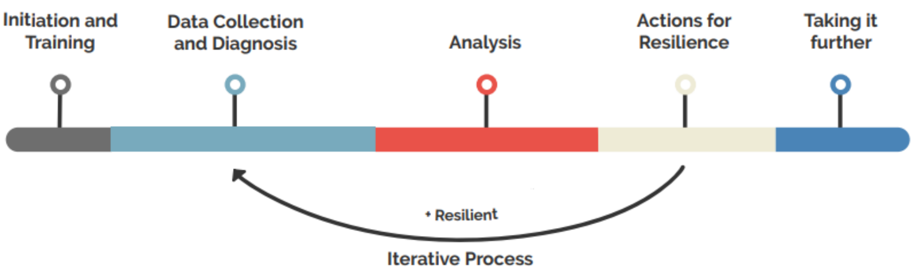


Figure 2-18. City Resilience Profiling Tool implementation process (UN-Habitat, 2018)

The Initiation process is made by an initial contact between the local government and the UN-Habitat, resulting in a formal agreement among these entities that can include other key city partners. The initial Training process is conducted during a workshop to introduce the tool to the local government and identify the main stakeholders that must be involved first.

The second phase - Data Collection - and the third phase - Diagnosis and Analysis - require inputs from local government, other levels of government, and city partners (NGOs, private sector, etc.) to create a resilience profile of the city and guide the actions for resilience.

Data collection is divided into four main sets:

- **Set 1. City ID -** Pretends to contextualize and characterize the city's identity by gathering data regarding its historical and spatial context, governance model, population, economy, and hazards and challenges. Through this initial characterization, it is possible to identify some probable hazards and challenges.
- **Set 2. Local governments and stakeholders -** Intends to allow proper preparation for actions for resilience by focusing on the governance and institutional relations within the city. While the remaining data sets focus on gathering more data-related elements, this data set pretends to analyze how the city can foster actions for resilience by analyzing three main pillars: local government instruments and capacity to enforce decision-making (political structure), decision-implementation (executive structure), financial planning (fiscality and funds allocation), and statuary planning (strategic planning and government plans).
- **Set 3. Shocks, stresses, and challenges -** Aims to address the city's critical problems (identified in Set 1) and assess the city's performance and risk reduction due to implementing actions for resilience. Shocks are addressed as events that shift the city from a normal state to a state of disturbance, and actions must be taken to anticipate, mitigate, or prepare for better response (mentioned as "risk reduction measures"). Stresses are defined as chronic dynamic pressures originating from within the urban system, which undermine the city's capacity for sustainability and resilience, fostering its fragilities and vulnerabilities. Challenges are seen as long-term contextual changes or pressures originating outside the urban system, such as climate change. They must be addressed due to their long-term effects and potential to aggravate shocks and stresses impacts. Stresses and Challenges are prioritized, and measures to tackle them are called "vulnerability reduction and adaptation actions."
- **Set 4. Urban elements -** Assess the critical services provided to the population and their physical assets when appropriate. This data aims to collect data regarding the urban elements' performance and characteristics by considering the main aspects of the urban area – people, processes, and assets – and their interconnections. This assessment allows for identifying the urban systems' strengths and weaknesses.

It is essential to mention that the specific metrics and indicators for all the data sets are not publicly available, and there is no information regarding the computations or weights used for the resilience assessment using the CRPT.

After the data analysis, the fourth step of the campaign is the selection of Actions for Resilience. This step aims to provide strategic planning tools as a roadmap for local governments, supported by the data collected. These tools shall combine risk and vulnerability reduction measures with improvement capacity building. The Actions for Resilience are aligned with the three dimensions of the New Urban Agenda: urban planning and design, urban finances and economy, and urban legislation and regulations; and propose multi-thematic and multi-dimensions actions to be executed in short, medium, and long-term, through physical, spatial, social, economic, and institutional and governance dimensions (UN-Habitat, 2018).

The last step of the CRPT is called "Taking it further" and consists of defining responsibilities and finding funding mechanisms between government (at local, regional, national, and international levels) and stakeholders so that actions for resilience move from a plan to reality.

From the available information on the UN-Habitat's platform for the CRGP, the Urban Resilience Hub, the CRPT has been implemented in six cities: Asunción, Paraguay; Barcelona, Spain; Dakar, Senegal; Maputo, Mozambique; Port Vila, Vanuatu; and Yakutsk, Russia (UN-Habitat, 2022).

2.3.1.4. RESCCUE Project

RESCCUE (RESilience to cope with Climate Change in Urban arEas – a multisectoral approach focusing on water) was the first large-scale urban resilience-related project funded by the EU under the H2020 Programme (Grant Agreement no. 70017). The project started in May 2016 and finished in November 2020, with a total budget of around 8 million euros, and involved 18 partners, including the city councils of Barcelona, Lisbon, and Bristol, UN-Habitat, urban services companies (Endesa, EDP-D, Águas de Portugal, and Wessex Water), research centers (Cetaqua, FIC, LNEC, and IREC), universities (Exeter and EIVP) and SMEs (Hidra, Urban DNA and Opticits – the latter left the project before completion), coordinated by Aquatec – SUEZ Advanced Solutions (Aquatec, 2020).

RESCCUE aimed to develop innovative models and tools to allow city managers and urban services to better understand the city and improve its capacity to withstand and recover from multiple shocks and stresses, maintaining core functionalities and services. As the name implies, the project was focused on water, both on water-related risks and stresses (highly related to climate change and extreme weather events) and on critical urban water-related services (from water sourcing to urban drainage) (Brito et al., 2020). The complete RESCCUE workflow and consequent methodology were tested on three pilot cities/research sites: Lisbon, Barcelona, and Bristol. These cities were chosen due to their commitment to other resilient-related programs, such as the 100 Resilient Cities powered by the Rockefeller Foundation.

The project comprised a set of eight work packages (WP). WP1 to WP6 is where the technical work was focused, whereas WP7 dealt with communication and exploitation, and WP8 was related to project management. The progress of RESCCUE work does not follow a typical straightforward path, being developed with two simultaneous approaches (Figure 2-19) characterized by different levels of detail, allowing a better understanding of the functioning of the city as a whole while not losing the notion of its complexity (Barreiro et al., 2020):

- **Detailed approach**: From climate data collection and analysis, climate change projections and extreme events prediction for weather-related variables (such as rainfall intensity and sea level) were produced (WP1). These variables were used as inputs in sectorial models and tools to simulate and assess the consequent hazard of weather events (WP2). Then, the analysis of the impacts on services and infrastructures was achieved via the application of loosely coupled models and tools (integrated models), using the outputs of one as inputs of others (WP3). Later, adaptation strategies and measures were proposed and prioritized based on hazard and risk reduction and through multi-criteria analysis, providing an overview of other kinds of co-benefits (WP5).
- **Holistic approach**: Using the Hazur® methodology (Jaumà et al., 2014) to assess resilience by studying the relations between several urban services and infrastructures and infer cascading effects triggered by extreme weather events (WP4). In this case, adaptation measures and strategies were also considered, focusing on the recovery time needed to reestablish the regular operation of the urban services and infrastructures.

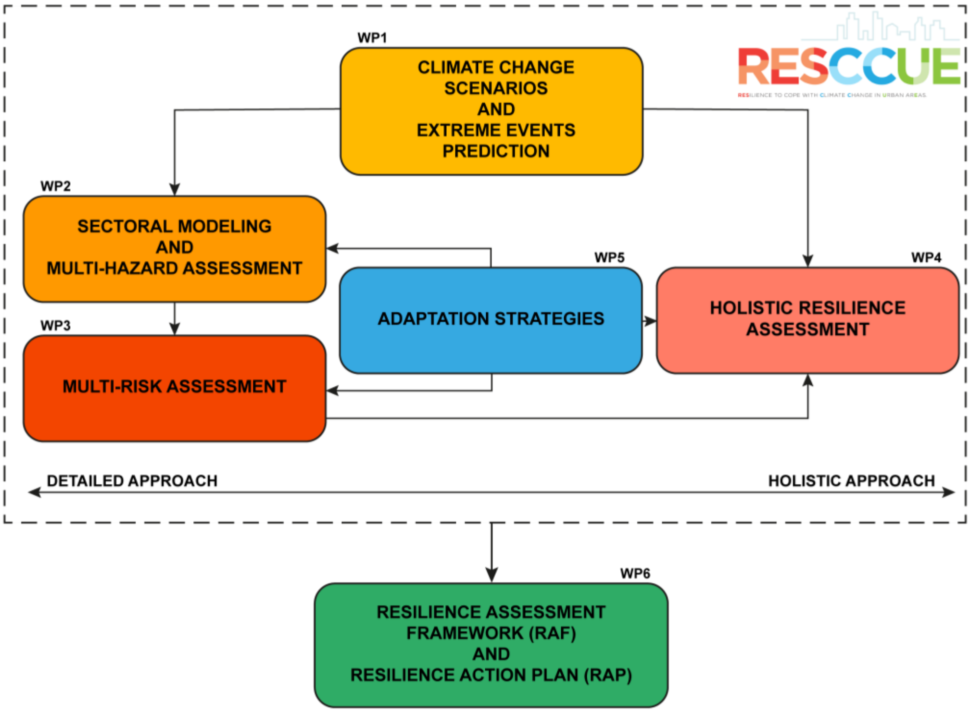


Figure 2-19. RESCCUE workflow: simultaneous detailed and holistic approaches (adapted from Velasco et al., 2018)

A Resilience Assessment Framework (RAF) was developed (Cardoso et al., 2020b) with the objective of:

1. Directing and facilitating a structured resilience diagnosis of the cities and the strategic urban sectors, following an objective-driven approach with defined assessment criteria and identifying data gaps, opportunities, threats, strengths, and weaknesses, highlighting the areas for improvement.
2. Outlining a path for developing cities' resilience action plans by supporting decision-making in selecting resilience measures and developing strategies to enhance resilience.
3. Monitoring the resilience progress of a city or service over time by applying it periodically and facilitating communication among stakeholders.

Developed under the RESCCUE scope, the RAF has some underlying assumptions:

- The scope of the RAF is urban resilience to climate change with a focus on the water cycle at the city, services, and infrastructure level. Thus, other threats like economic crisis or terrorism are not considered, nor are other urban resilience aspects, such as social or political attributes.
- The external context of the city and services is considered through a standardized characterization profile of the city and the services.

- The services considered in the RAF comprise the urban water cycle (water supply, wastewater, and stormwater) and those identified as directly interconnected or interdependent within the project development, namely, waste management, electrical energy supply, and mobility.
- The long-, medium- and short-terms are incorporated considering three different and aligned assessment levels for the city, services, and infrastructures (strategic - overlooking a long-term planning horizon and requiring the involvement of the entire organization, addressing the overall city and considering its vision; tactical - overlooking a medium-term planning horizon and addressing departmental or sectoral activities in the city, services and infrastructure; and operational - referring to short-term horizon, addresses the actions to be taken in the effective implementation of measures in the city, services and infrastructure).

The RAF is aligned with international frameworks for resilience assessment, particularly with the UNDRR Disaster Resilience Scorecard and the UN-Habitat Profiling Programme (described before). The RAF considers the UN-Habitat resilience dimensions (the time dimension is implicitly integrated as part of the analysis): Organizational - integrates top-down governance relations and urban population involvement at the city level, Spatial - refers to urban space and environment, Functional – refers to the resilience of strategic services, and Physical – refers to the resilience of services infrastructures.

The framework is organized in a hierarchical tree structure, and resilience objectives are defined for each dimension. The fulfillment of objectives is assessed through a set of criteria that assemble the answers of specific metrics (Table 2-5). The metrics of Functional and Physical dimensions, which are related to the urban services and infrastructures, are answered for each assessed service and vary between them (which justifies the metrics' number variation in Table 2-5). Each metric is classified with a relevance degree: essential, complementary, or comprehensive (Cardoso et al., 2020b).

The resilience assessment framework highlights where the cities and respective urban services stand regarding resilience to climate change and identifies the most critical aspects to be improved, considering both the reference situation and the expected impacts of future climate change scenarios. The diagnosis allows for understanding those aspects being tackled properly and determining gaps and areas of improvement thanks to the detail of the different dimensions that make up the assessment. It also provides a means to assess resilience progress, contributing to an integrated and forward-looking approach to resilient and sustainable urban development (Cardoso et al., 2020b). An example of the obtained results by applying the RAF in Lisbon is presented in Figure 2-20.

Table 2-5. Summary of RAF dimensions, objectives, criteria, and number of metrics (Cardoso et al., 2020b)

1. ORGANIZATIONAL	**Total metrics nr. 74**
Collective engagement and awareness	
Citizens' and communities' engagement	5
Citizens and communities' awareness and training	5
Leadership and management	
Government decision-making and finance	4
Coordination and communication with stakeholders	4
Resilience engaged city	19
City preparedness	
City preparedness for disaster response	13
City preparedness for CC	7
City preparedness for recovery and build-back	7
Availability and access to basic services	10

2. SPATIAL	**Total metrics nr. 29**
Spatial risk management	
General hazard and exposure mapping	5
Hazard and exposure for CC	3
Resilient urban development	7
Impacts of climate-related events	2
Provision of protective infrastructures and ecosystems	
Protective infrastructures and ecosystem services	9
Dependence and autonomy regarding other services considering CC	3

3. FUNCTIONAL	**Total metrics nr. 346**
Service planning and risk management	
Strategic planning	5
Resilience engagement	5-6
Risk management	7-12
Reliable service	6-11
Flexible service	4-6
Autonomous service	
Service importance to the city	2
Service interdependency with other services considering CC	2
Service preparedness	
Service preparedness for disaster response	0-4
Service preparedness for CC	6-8
Service preparedness for recovery and build-back	0-15

4. PHYSICAL	**Total metrics nr. 270**
Safe infrastructure	
Infrastructure assets criticality and protection	5
Infrastructure assets robustness	10-14
Autonomous and flexible infrastructure	
Infrastructure assets' importance to and dependency on other services	1-4
Infrastructure assets autonomy	1-6
Infrastructure assets redundancy	1-3
Infrastructure preparedness	
Contribution to city resilience	3-4
Infrastructure assets exposure to CC	3
Preparedness for CC	2
Preparedness for recovery and build back	7-9

The number of metrics for Functional and Physical dimensions varies with the service being assessed and is presented as a range. Total metrics are accounted for considering all the services available for the assessment.

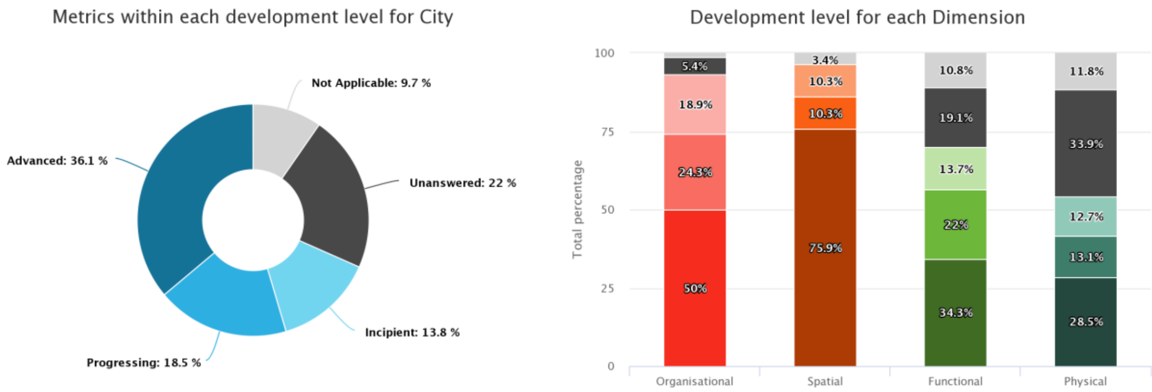


Figure 2-20. Results of RAF application in Lisbon regarding overall assessment (left) and overall assessment by dimension (right) (Cardoso et al., 2020b). Darker colors mean a higher development level, dark grey means unanswered, and light grey means not applicable.

At last, RESCCUE's works culminated in developing a Resilience Action Plan (RAP), a synthetic roadmap to enhance resilience to climate change, with the urban water cycle as the core (Cardoso et al., 2020a). The RAP is a guiding document that summarizes the global RESCCUE methodology. It is composed of the following steps (Cardoso et al., 2020c):

1. **Background and city characterization -** This includes work already in place and ongoing in the city and contextualization regarding existing information and knowledge, strategies, measures, or other plans already implemented. City characterization refers to the RAF city profile, including a description of the services and respective infrastructures.
2. **Climate change scenarios -** Summary of the available climate projections and extreme events prediction and definition of most the probable and most severe scenarios.
3. **Risk assessment -** Exposure, vulnerability, and impacts of each urban service are characterized (if possible) through sectoral models, as are the cascading impacts between different urban services and the effects of multiple hazards in the city.
4. **Resilience assessment -** carried out through the RAF based on the existing work in the cities and the previous risk assessment results for the identified hazards and hazardous events, considering the cascading effects analysis.
5. **SWOT analysis** – Summarizes all the previous information by identifying the city and services' internal Strengths and Weaknesses, as well as the external Opportunities and main Threats.
6. **Resilience Strategies** - Strategies comprise a set of measures identified by key sectorial stakeholders. Strategies are submitted to a TOWS analysis, identifying how they reduce Threats, take advantage of Opportunities, overcome Weaknesses, and exploit Strengths. Strategies must have a common set of descriptors such as type of strategy,

hazards and climate variables addressed, responsibilities, players and services involved, costs, economic, social, and environmental co-benefits, and implementation timeline. Strategies must be prioritized according to the city's needs and strategic plans.

7. **Implementation process -** The prioritization of strategies sets a schedule for implementation along the RAF timeline.
8. **Monitoring and review -** This step ensures the city's resilience as a continuous and dynamic process (Figure 2-21), allowing the resilience progress to be traced and the gaps and deviations that may require corrective actions to be identified. In this step, the RAP reviewing process is defined by a given periodicity, a responsible entity is assigned, and reviewing activities are included.

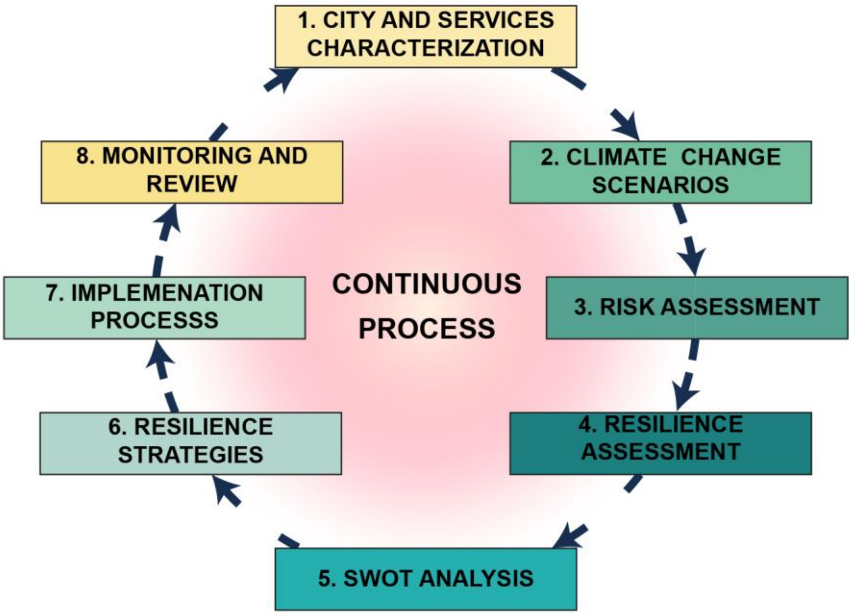


Figure 2-21. RAP as a continuous process (adapted from Cardoso et al., 2020a)

2.4. DISCUSSION AND CONCLUSIONS

The concept of resilience embraces a set of thinking systems that are not mutually exclusive. Engineering resilience focuses on the capacity of systems to return to a given steady state after the occurrence of a disruptive event. Ecological resilience accepts that the response to a disruptive event might not be the return to the initial state, and the change of the circumstances through adaptation can permit the system to operate in a different state. Socio-ecological resilience broadens the scope of the previous concepts by accepting that systems are constantly changing, forsaking the idea of a steady state, accepting a continuous change in the stability landscape of the system, and, if required, transforming the system and permanently changing its status quo.

A critical challenge from the socio-ecological perspective is to build knowledge, incentives, and learning capabilities into institutions and organizations for governance that allow adaptive management of local, regional, and global systems. Adaptive governance implies the interconnectivity between a large set of stakeholders at different scales without jeopardizing the importance of individual actors and social networks between different groups - with different knowledge and social memories (Folke, 2006).

When considering resilience from the perspective of the capacity to persist without shifting the steady state of the system, i.e., keeping within its original basin of attraction, five properties are suggested based on the concept of the basin of attraction: latitude (as the range that the state variable allows without losing its capacity to recover), resistance (as the capacity of the system to offer opposition to the change of its state variables), precariousness (as the initial distance of the system state to the recovery thresholds), robustness (as the system capacity to endure the disturbance), and panarchy (as the bidirectional influence of different time and space scales). Adaptation refers to the system's capacity to act on those properties, and, in extreme cases, transformation shifts the system to a different basin of attraction, i.e., changes the system's status quo.

In a broader sense, a critical aspect of resilience lies in assuming that the system will fail at some point and that the knowledge about the system and its threats is limited (When will the system fail, sooner or later? How will it fail, rapidly or at a slow pace? Why will it fail?), and that this failure must be used as a learning lesson to foster improvement at several scales. This thought can be very challenging in systems with a strong identity and often requires a shock or crisis to get beyond a mindset of failure denial. Resilience thinking proposes using failure moments to foster new opportunities to reevaluate the current situation, trigger social mobilization, recombine sources of experience and knowledge for learning, and spark novelty and innovation (Folke et al., 2010).

The existence of such different thinking systems around the concept of resilience can hinder its practical application, and understanding the entire spectrum is fundamental to allow for its proper application in any field. Only in that way, and considering the context of the system, can each thinking system's relevance and importance of its characteristics be taken into account to delineate a resilience assessment and management roadmap.

When considering the application of resilience in the urban field, the fuzziness regarding its concept is also imprinted on the literature. Nonetheless, there seems to be a trend for urban resilience approaches to develop from a specific engineering to a general and socio-ecological perspective while keeping the coexistence of characteristics of the different thinking systems (Nunes et al., 2019). The social-ecological system thinking - assuming that systems are constantly changing and aiming at dealing with uncertain future disturbances - provides a favorable theoretical background for cities to deal with future uncertainties, such as climate change (Meerow et al., 2016). This represents the reinforcement of the different conceptual focuses and the trend to multi-scalar resilience approaches, with contributions from both top-down (general to specific) and bottom-up (specific to general) approaches. Meerow et al. (2016) point out six tensions in the literature on urban resilience definitions: characterization of urban, notions of equilibrium (thinking systems), positivity of the concept, pathway to urban resilience, understanding of adaptation, and timescale of action. Those tensions reinforce the importance of the context and resilience objectives - resilience to who, to what, when, where, and why. Only in that way can resilience be used to promote rational and sustainable urban development.

The complexity of the urban systems can be seen as a difficulty in developing urban resilience approaches. This is partly reinforced by the large-scale resilience-related programs and projects developed in the last two decades with the involvement of governmental, inter-governmental, and non-governmental organizations and a diverse range of private actors, philanthropic foundations, and academic and research institutes. From such, stand out the Making Cities Resilient Campaign, launched by UNISDR in 2010 and, since 2020, running under the name Making Cities Resilient 2030; the City Resilience Profiling Programme, launched by UN-Habitat in 2012, and running, since 2016, under the name City Resilience Program; the Rockefeller Foundation with the 100 Resilient Cities, launched in 2013 and terminated in 2019, although having reemerged under the name Global Resilient Cities Network, in 2020; and the EU H2020 project RESCCUE – Resilience to Cope with Climate Change in Urban Areas, started in 2016 and finished in 2020.

These programs combined represent high investment costs in resilience-oriented programs, tools, and plans. However, as revealed in the work of Amaratunga et al. (2019b) regarding the Making Cities Resilient Campaign, there are great difficulties in translating such approaches into resilience action plans and even higher barriers to effective application of those. The critical barriers pointed out are the lack of financial resources, changes in government priorities, and lack of political interest. Moreover, as Laura Bliss (2019) states, the 100 Resilient Cities program shutdown is a potent reminder for local governments about depending on private investments and funds to create public policies and plan for critical threats.

This contrasts with the idea that generic resilience approaches suffice to answer urban challenges. Urban resilience should be understood as a key roadmap for bridging top-down and bottom-up approaches, facilitating a balance between a comprehensive assessment of critical aspects undermining urban development and technical, in-depth management. This involves bringing decision-makers and government agencies together with service providers, academia, and specialists. Additionally, resilience planning must be aligned and included in urban instruments and plans with dedicated budgets and allocation of those responsible for its effective operationalization.

Chapter 3. STORMWATER SYSTEMS AS URBAN SERVICES

"In the struggle between the stone and water, in time, the water wins."

Japanese proverb

3.1. INITIAL CONSIDERATIONS

The current chapter presents the stormwater systems from the scope of their role in the city, i.e., as urban service. Public stormwater drainage is the responsibility of local governments, namely municipalities/councils, having a specific department or team inside a department. While stormwater was initially conveyed through combined systems, along with wastewater, the current standards demand for new systems to be separated, i.e., storm and wastewater must be conveyed through distinct infrastructures. Thus, stormwater has become the "third leg" of urban water management, after water distribution and wastewater drainage (National Association of Flood and Stormwater Management Agencies, 2006).

Stormwater management has been evolving from an exclusive urban flood control function to a water and resource management function and an environmental protection and regulatory function. Nowadays, the tendency is for all three functions to co-exist as responsibilities of local government. This evolution has forced changes in how stormwater systems are planned, designed, constructed, operated, and financed. More specifically, the stormwater function has evolved from a basic capital construction and maintenance program, supported primarily by local taxes, to a program of integrated water resource management, environmental enhancement, and recreational services that requires a multi-faceted benefit-based finance system. These changes have also resulted in greater public expectations. In addition to effectively controlling drainage and flooding, the public expects co-benefits, such as riparian corridors, wetlands, recreation amenities, trails, visually pleasing facilities, etc. (National Association of Flood and Stormwater Management Agencies, 2006).

Stormwater systems are responsible for draining surface runoff generated by precipitation, typically rainfall (Butler et al., 2018). As urban service, stormwater systems have a clear main objective: properly dealing with water volumes originating from precipitation with no negative consequences to the population, goods, and services. For that reason, urban stormwater services can be considered an impact-driven service since they are purposefully designed to deal with weather-related events – namely rainfalls – and minimize their consequences (Evans, 2017).

In this sense, subchapter 3.2 presents the main tendencies of stormwater management and infrastructures, essential to the later assessment of its resilience. Subchapter 3.3 presents an analysis of the meanings of service performance and failure, again, from the perspective of its role as an urban service. This subchapter includes an analysis of critical aspects of the performance of the service, including predictable shocks and stresses, typical interdependencies with other urban services, and potential consecutive cascade effects. Subchapter 3.4 presents examples of stormwater resilience approaches found in literature, which include urban flood resilience approaches. At last, the discussion and conclusions are presented in subchapter 3.5.

3.2. STORMWATER MANAGEMENT AND INFRASTRUCTURES

3.2.1. CONVENTIONAL STORMWATER SYSTEMS AND INFRASTRUCTURES

Stormwater systems were firstly designed to get rid of runoff and convey it as fast as possible to a discharge point, i.e., an outfall (Matos, 2006). Outfalls are preferably located at the nearest water body capable of receiving the storm flows, usually streams/rivers or the sea. Outfalls must be designed to minimize the physical impacts (reduce erosive conditions and protect the stability of shorelines, channels, and ravine slopes) and quality impacts on the receiving water bodies and vice-versa, i.e., to avoid the influence of fluvial or sea tides on the stormwater system. Typically, stormwater systems are made up of a pipe-based network composed of storm sewers, manholes, and stormwater inlets:

- Storm sewers are responsible for the flow conveyance and can comprise an extensive range of materials and cross-sections. However, the most common materials nowadays are concrete or PVC, with circular cross-sections (Matos, 2006).
- Manholes have two primary purposes: firstly, they allow the change of the sewers' direction, gradient, and size, being used as junctions; secondly, they are access points for testing, inspection, and cleaning procedures. They typically consist of a precast concrete chamber with an iron cover and an invert elevation aligned with the invert of the outward sewer (Butler et al., 2018).
- Stormwater inlets (also called storm drain inlets or gutter inlets) are intended to capture surface runoff, delivered through sewer branches to a nearby manhole, and conveyed by the storm sewers. Thomason (2019) classifies stormwater inlets into four classes: curb opening inlets, grate inlets, linear drains, slotted drains or trench drains, and combination inlets (see examples in Figure 3-1). This type of equipment can be installed on grade, streets with longitudinal slopes, or sag locations – flat areas or depressions. The interception capacity of the inlets depends on the type of device and its geometry, and on the approaching flow conditions (depth and velocity, when located on grade) or on accumulated water above the opening (when located on sag locations) (Matos, 2006; Thomason, 2019).

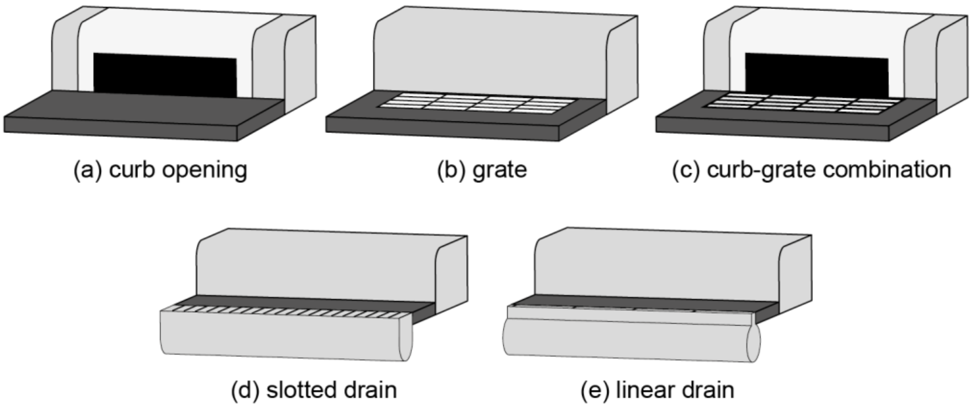


Figure 3-1. Conventional types of stormwater inlet devices

Other infrastructures and facilities can be used to allow proper performance of the system, namely, being the mainstream:

- Storage infrastructures are used to store water volumes and regulate the flows to be compatible with the conveying capacity of the downstream network. There are typically two types of storage infrastructures: retention/detention ponds (usually natural-based) and storm tanks (usually grey infrastructure) (Figure 3-2).

Figure 3-2. Examples of stormwater storage infrastructures

- Pumping stations lift flow from lower to higher elevations or force discharges under tidal influence. Although admissible, stormwater pumping stations are not encouraged due to high exploration costs and inflow variability, hindering the correct operation of the electromechanical equipment (Matos, 2006).
- Flow controls limit the inflow to/outflow from elements of the urban drainage system. This type of device is most used on combined systems to restrict CSOs. Still, it might also be used on combined/stormwater systems to control the water level at storage infrastructures and discharges when under tidal effect (Butler et al., 2018). Their operation can be fixed (the same relationship between flow rate and water level) or adjustable. Such devices include orifice plates, penstocks, vortex regulators, and front (or transversal)/side (or longitudinal) weirs (Figure 3-3).

Figure 3-3. Examples of flow control infrastructures

- Tidal valves control discharge conditions at outlets exposed to tides and prevent backwater from entering the network. The most used devices are flap and duckbill valves (Figure 3-4).

Figure 3-4. Examples of tidal valves

3.2.2. SUSTAINABLE URBAN DRAINAGE AND NATURE-BASED SOLUTIONS

As mentioned, conventional stormwater systems rely primarily on underground sewer networks. They intend to convey the stormwater as fast as possible to a discharge point, away from its origin. This approach, alone, has been criticized as being responsible for urban flooding and water quality degradation, entering into conflict with sustainable development objectives (Birgani et al., 2013). Conventional stormwater systems present a limited conveyance capacity (design capacity) and a lack of capability to deal with exceeding flows. In urban areas, the first rainfall events in the wet season usually promote the wash-off effect, transporting high pollutant loads from the streets into the sewers and discharging them into the receiving water bodies. Additionally, in urban areas, there is a substantial difficulty in proceeding with massive restructuration, reinforcement, or correction of drainage infrastructures due to its high costs at all levels, from social – due to the impact on the daily life of the population – to economic – due to the high investment needs of such works (Matos, 2006)

These constraints were a primary motivation for the emergence of alternative stormwater management techniques in the 1980s (Matos, 2006). At this time, the focus was mainly on source control, i.e., infrastructures that promote retention and infiltration at upstream locations of the catchment, reducing the peak flows and affluent volumes to the storm sewers.

Further, in the late 1990s, the sustainability approach for urban drainage added the vector of amenity, i.e., the need to handle drainage systems not only from the quantity and quality perspective but also to look at social aspects and embrace stormwater as a resource (Stahre, 2008).

Several approaches with different terminologies have been adopted since then, in other locations, and with some changes in the definitions: Low Impact Development (LID) has been mainly used in the USA to refer to natural small-scale and decentralized facilities focusing on stormwater treatment through infiltration on soil, close to the runoff origin; Water Sensitive Urban Design (WSUD) and Integrated Urban Water Management (IUWM) refer to the management of water balance and water cycle at the catchment level, respectively; Sustainable Urban Drainage Systems (SUDS), mainly used in UK, refers to a set of techniques used on urban drainage to restore drainage conditions existing before the urban development (Senes et al., 2021). Most recently, in the 2010s, the concept of "sponge city" emerged in China, a comprehensive approach incorporating the previous ideas within the Chinese concept of nature (Hamidi et al., 2021).

All these stormwater management approaches are firmly based on promoting green infrastructures as mimicry of natural catchments, i.e., nature-based solutions (NBS). The European Commission defines NBS as "cost-effective solutions inspired and supported by nature, which simultaneously provide environmental, social and economic benefits and help build resilience. Such solutions bring more, and more diverse, nature and natural features and processes into cities (…) through locally adapted, resource-efficient and systemic interventions." (Bulkeley, 2020). Thus, NBS are intended to present a broad spectrum of co-benefits to the cities and its population, allowing better integration with green infrastructure networks (Senes et al., 2021).

Nonetheless, it is essential to understand that sustainable urban drainage practices do not rely solely on NBS and that grey infrastructures can contribute to such an approach. Stahre (2008) categorizes sustainable urban drainage facilities/infrastructures into four groups, as described in Table 3-1 and illustrated in Figure 3-5. In developed cities, emphasis is usually put on source and onsite control since slow transport and downstream control facilities tend to need larger available areas and have more significant impacts on urban land planning.

Table 3-1. Categories of sustainable urban drainage facilities (adapted from Stahre, 2008)

Category	Description	Examples
Source control	Small-scale facilities that handle stormwater on private land.	Green roofs, lawns, permeable paving, rain gardens, and local ponds.
Onsite control	Small-scale facilities that handle stormwater in the upstream parts of the catchment on public land.	Permeable paving, green filters, strips, rain gardens, ponds, temporary flooding surfaces.
Slow transport	Facilities that transport the stormwater.	Swales, ditches/creeks, canals.
Downstream control	Facilities that promote temporary detention include large-scale facilities downstream of the catchment.	Large ponds, wetlands, lakes.

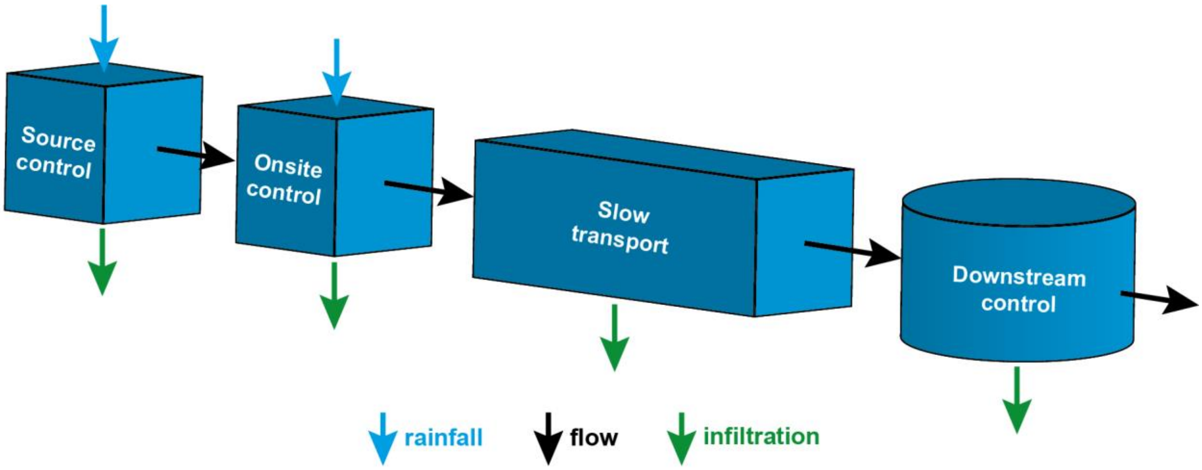


Figure 3-5. Categories and main fluxes of water in sustainable urban drainage facilities (adapted from Stahre, 2008)

Sustainable urban drainage approaches can add value to urban areas through co-benefits, such as aesthetic, biological, ecological, recreational, economic, and environmental values (Stahre, 2008). On the other hand, these added values bring a more complex and time-consuming planning process, with the need to bring several urban stakeholders and management departments to the discussion. In contrast, a traditional stormwater approach focuses more on the engineering and technical stakeholders.

The World Meteorological Organization (WMO) has introduced the concept of Integrated Flood Management as a process to promote an integrated, rather than fragmented, management of land and water resources in a river basin within the context of Integrated Water Resources Management (Associated Programme on Flood Management, 2009). Although very focused on the river and hydrologic management perspective, this approach is helpful by bringing the river basin as a territorial management unit, recognizing that gains and losses arise from changes in interactions between the water and land environments and that there is a need to balance development requirements and flood losses.

3.2.3. MINOR AND MAJOR STORMWATER SYSTEMS

With the evolution of stormwater management paradigms, there has been a tendency to expand stormwater management beyond the underground infrastructures and their interface devices with the surface. This tendency allows a more integrated approach to deal with the stormwater service's demands.

Thus, stormwater systems can be considered a composition of minor and major systems. The minor system consists of conventional infrastructures, such as inlets, manholes, sewers, open channels, pumps, etc., and SUDS infrastructures. The major system provides overland relief for stormwater flows exceeding the minor system's capacity and conveys the excessive runoff to natural or manmade receiving channels like streams, creeks, or rivers. This can be achieved by purposeful constructed or designated infrastructures at the planning stage, such as floodways, retention basins, flood-relief channels, and open and culverted watercourses – named design pathways; or unintended pathways that have not been specifically designed – named default pathways (Brown et al., 2009; Butler et al., 2018). These systems can also be called primary and secondary systems (Thomason, 2019).

Understanding the stormwater service as a composition of the minor and major systems leads to a broader and more complete approach regarding its design and integration in the urban space. However, the major system has traditionally been neglected in stormwater management and design, mainly focusing on the minor/conventional system.

3.2.4. DESIGN PRINCIPLES AND MAIN CRITERIA

Being an impact-driven service, the design criteria adopted for its infrastructures are critical for the system's performance. Typically, conventional stormwater infrastructures are designed for a reference rainfall event represented by a given probability of occurrence. This probability of occurrence is usually defined as the Annual Exceedance Probability (AEP) or, by its inverse value, the Annual Recurrence Interval (ARI) or Return Period (RP).

Thomason (2019) refers to three general principles for the design of stormwater systems, saying the system shall operate: 1) efficiently for floods smaller than the design flood; 2) adequately for the design flood; and 3) acceptably for greater floods.

The European standard CEN EN 752:2008 recommends designing rainfall frequencies that comply with corresponding allowable flooding frequencies as a function of land use categories. In Germany, these frequencies are translated into national standards (DWA-A118:2006) and, in addition, considered a corresponding admissible sewer overflow frequency for mathematical verification purposes. Moreover, some research has already advised considering more conservative design frequencies due to climate change impacts on rainfall frequency and intensity (Bayerisches Landesamt für Umwelt, 2019). Table 3-2 presents examples of such recommendations. The CEN EN 752:2017 establishes design rainfall return periods as a function of the expected flooding impact magnitude (Table 3-3).

Table 3-2. Examples of European design frequencies (1 in N years) recommended for stormwater minor system infrastructures

Source ►	EN 752:2008		DWA-A118:2006	Bayerisches Landesamt für Umwelt, 2019	
Design criteria ► Land use category ▼	Design rainfall frequency	Design flooding frequency	Design sewer overflow frequency	Design rainfall frequency	Design sewer overflow frequency
Rural areas	1	10	2	2	3
Residential areas	2	20	3	3	5
City centers/industrial/ commercial areas	5	30	< 5	10	< 10
Underground railways/underpasses	10	50	< 10	20	< 20

Table 3-3. European recommendations of rainfall design criteria for standing floodwater (EN 752, 2017)

Impact	**Example locations**	**Design rainfall return period (years)**
Very low	Roads or open spaces away from buildings	1
Low	Agricultural land (depending on land use)	2
Low to medium	Open spaces used for public amenity	3
Medium	Roads or open spaces adjacent to buildings	5
Medium to high	Flooding in occupied buildings, excluding basements	10
High	Deep flooding in occupied basements or road underpasses	30
Very high	Critical infrastructure	50

The United States design criteria for stormwater infrastructures tend to be more comprehensive than the European approach by typically considering not only the "conventional" or minor system but also the major system's infrastructures. The U.S. Department of Transportation recommends a minimum 10-year frequency of design rainfall for storm sewers in urban areas and a minimum 50-year frequency for stormwater inlets that drain sag locations (Brown et al., 2009). Table 3-4 summarizes the recommended design criteria for stormwater infrastructure in Weatherford, Texas. As observed, the minor and major systems have complementary design criteria. Urban storm sewers shall be designed for a minimum of 10-year rainfall with a combined capacity of the minor and major systems to convey the 100-year rainfall within the public right-of-way limits[1]. Low point inlets must be sized for a 25-year rainfall if a favorable overflow structure is constructed, i.e., an intentionally safe flood pathway. If such a structure is not possible, the low point inlets and underground infrastructures must be designed for the 100-year rainfall (Community Development Department, 2007).

Table 3-4. Recommended design criteria for stormwater infrastructure in the city of Weatherford, Texas (Community Development Department, 2007)

Infrastructure	**Minimum design rainfall return period**
On-grade inlets	10 years with 100 years in ROW
Low point inlets	25 years with 100 years positive overflow
Storm sewer upstream of low points	10 years with 100 years in ROW
Storm sewer downstream of low points	25 years with 100 years positive overflow
Street right-of-way	100 years
Channels and creeks	100 years
Permanent bar ditch and associated culverts	5 years with 100 years in ROW

In the United States, the designer should check storm conditions (typically the 100-year rainfall) and determine, at least in general, the major system's flow pathways and related depths and velocities (Brown et al., 2009). The purpose of the check flood standard is to ensure the safety of the drainage structure and downstream development by identifying significant risks to life or property in the event of capacity exceedance (Thomason, 2019). It is important to note that from a stormwater management perspective, the flooding or runoff return period can be more interesting than the rainfall return period. It is common to assume that the frequency of design rainfall is equivalent to the frequency of runoff or peak discharge, but that is not necessarily true (Butler et al., 2018). Studies have shown that constant watershed parameters are not the best assumption (Clar et al., 2004). For instance, different antecedent soil moisture conditions and spatial rainfall distribution over the catchment will influence the runoff generation even for rainfall events with the same return period. Thus, runoff frequency cannot be expressed by rainfall frequency. However, runoff data tends to be even scarcer than precipitation records, and the assumption of equivalent rainfall and flooding frequencies is

[1] Public right-of-way means the area on, below, or above a public roadway, highway, street, public sidewalk, alley, waterway, or utility easement in which the municipality has an interest. The term does not include (a) a private easement; or (b) the airwaves above a public right-of-way with regard to wireless telecommunications (City of Carrollton, Texas, 2020).

often considered the best option available (Butler et al., 2018). For instance, as grey infrastructures are typically designed for a specific peak flow rate associated with a probability of occurrence, uncertainties must be addressed. The most straightforward answer is over-dimensioning the infrastructure (Bruijn, 2004).

3.3. SERVICE PERFORMANCE AND FAILURE

3.3.1. FROM RAINFALL TO STORM SEWER FLOW

As mentioned, urban stormwater infrastructures are designed to deal with the runoff generated due to rainfall events. Runoff production results from a set of hydrological processes responsible for all the losses rainwater undergoes when reaching the catchment surface and before being conveyed by overland flow and through the sewer network to the catchment outfall (Figure 3-6).

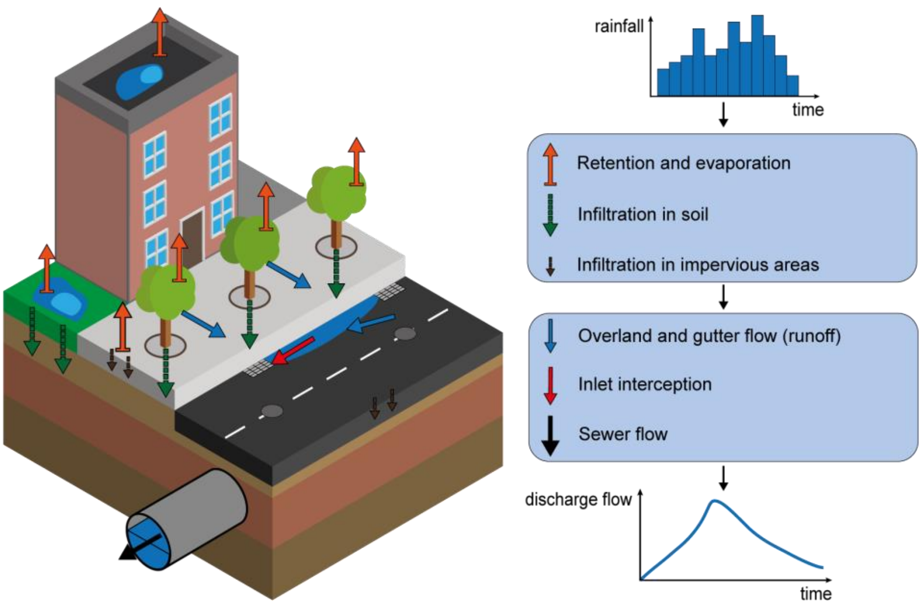


Figure 3-6. Processes from rainfall to runoff and discharge flow (adapted from Loucks and van Beek, 2017; Rammal and Berthier, 2020)

These hydrological processes represent "losses" of rainwater and are typically divided into three components: interception/retention, evaporation, and infiltration (Chow et al., 1988). These processes can be "instantaneous," such as retention due to interception by urban structures or vegetation, or continuous, as evapotranspiration from plants and accumulated water volumes at depressions and infiltration through the ground surface into soil pores. It is essential to mention that processes like evaporation and infiltration tend to act on time scales larger than typical rainfall events, being slower processes. From a theoretical perspective, the exceeding rainfall is called net, excess, or effective rainfall, and it is the rainfall share that is effectively transformed into runoff due to surface routing (Butler et al., 2018; Rammal and Berthier, 2020).

Thus, runoff is the volume of water that flows through the urban surface and, at some point, reaches the minor stormwater system. Conventionally, runoff is intercepted by stormwater inlet devices that convey it into the underground storm sewers. In other cases, runoff might not be intercepted by these devices but purposely conveyed superficially through gutters or small open channels or transported to natural/artificial areas to promote its retention and infiltration.

3.3.2. SERVICE FAILURE

Considering the stormwater system as a composition of the minor and major systems and considering the previously presented design principles, it's essential to understand what service failure means. Typically, a failure is intended as an affection of the system or its infrastructures such that performance levels reach undesired or inadmissible threshold values.

Typically, the major system is "activated" when the minor system loses its capacity to perform adequately. In turn, the major system failure occurs when the flow conditions at the surface have negative consequences for the population, goods, or other services. Undoubtedly, the direct outcome of minor system failure is urban flooding. The WMO (2017) classifies pluvial/rainfall floods as events when "heavy rainfall creates a flood event independent of an overflowing water body" that "may occur in urban environments when the local drainage system is not capable of collecting and conveying surface runoff." Pluvial floods in urban areas may cause inundation of streets, basements, ground-level floors of buildings, etc. These urban floods tend to be relatively short-lived but may occur more frequently (for instance, several times a year) and can result in loss of life, as well as significant disruption of economic and social activities (World Meteorological Organization and Global Water Partnership, 2017).

Butler et al. (2018) associate three flooding thresholds to the design criteria presented in Subchapter *3.2.4 Design principles and main criteria* (Figure 3-7). When designing the minor system to convey the runoff generated by rainfall with a given return period (design rainfall in Table 3-2), the first threshold to be considered corresponds to the sewers' full cross-section level, from which the system starts to surcharge. The second threshold refers to the maximum capacity of the minor system to convey the stormwater without generating exceedance flows, i.e., the level from which manholes overflow and surface flooding are observed (design sewer overflow in Table 3-2). Lastly, the third threshold relates to the level from which flooding reaches depths that cause direct impacts and property flooding (design flooding frequency in Table 3-2).

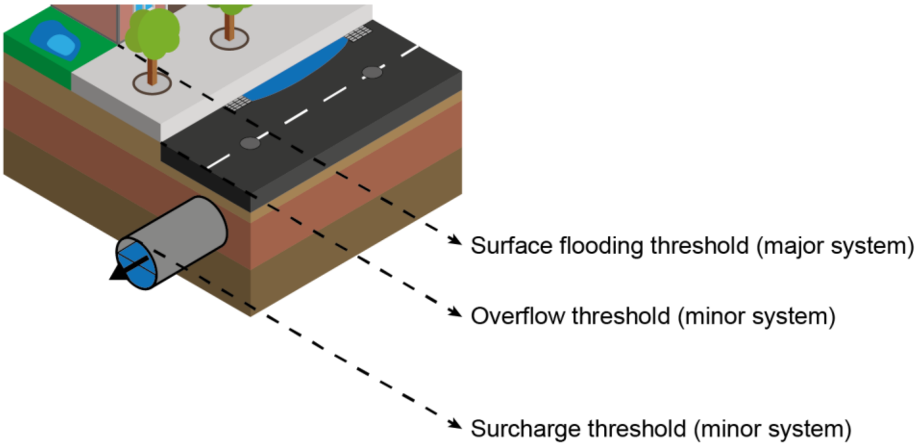


Figure 3-7. Stormwater flooding thresholds (adapted from Butler et al., 2018)

Mugume et al. (2015) define two different failure modes for the minor system of urban drainage systems:

- **Functional failure:** corresponding to hydraulic overloading due to excessive inflows. Examples of causes are extreme rainfall events and excessive infiltration into the system.
- **Structural failure:** corresponding to the malfunctioning of single or multiple components of the system, such as pumps, tanks, or sewers, leading to the inability of the failed part to perform its desired function fully or partially. Examples include sewer collapses, blockages, sediment deposition, or electromechanical equipment failure.

These types of failures are not necessarily exclusive. For instance, in coastal stormwater systems, the sand deposition in the final trenches of the sewers is frequent due to the influence of sea tides, which will decrease the conveyance and discharge capacity of the system, leading to upstream surcharging.

There seem to be few discussions regarding the meaning of failure of the stormwater service. It is generally agreed that the failure occurs when floods are observed at the surface. However, considering the design criteria, it does not seem completely legitimate to say that the stormwater service fails in the case of demands above the design criteria. It is hydraulically clear that if the flows are higher than the ones assumed for design purposes, the system will not be able to perform as desired, and floods will occur. This consideration evokes a typical issue of infrastructure design: the balance between the risk and protection degree that the designer is considering in contrast with the available investment capacity of the investor.

3.3.3. SHOCKS AND STRESSES

Although rainfall is the primary precursor of stormwater systems, other factors that endanger its performance should be considered. In the context of risk management, it is conventional to define such threats as shocks and stresses (Department for International Development, 2011; Sagara, 2018):

- **Shocks** are typically external short-term events that impact the system's vulnerability and components, adversely affecting people's well-being, asset levels, livelihoods, safety, or ability to withstand future shocks. Many disaster-related shocks strike at different levels, such as disease outbreaks, and weather-related and geophysical events, including intense rainfalls, floods, high winds, landslides, droughts, or earthquakes. There can also be conflict-related shocks, such as outbreaks of fighting or violence, or shocks related to economic volatility.
- **Stresses** are long-term trends or pressures that undermine the stability of a given system or process and increase the vulnerabilities within it. These can include natural resource degradation, loss of agricultural production, urbanization, demographic changes, climate change, political instability, and economic decline. Stresses can be cumulative, building slowly to become a shock, and both shocks and stresses may result in several different reactions.

In the context of stormwater systems, some clear shocks and stresses are important to analyze, briefly described below. Within the meteorologic-related causes, and apart from coastal overtopping, rainfall events are the leading cause of urban floods. There are typically two different rainfall typologies (Ramos, 2013):

- **Uninterrupted and prolonged events –** usually characterized by minor rainfall intensities over larger areas. Due to their long duration (typically days, weeks, or months), they lead to soil saturation and the refilling of groundwater reserves, which, in turn, increase the fluvial flows. These processes are mainly responsible for slow fluvial floods and can affect urban areas when unduly built in floodplains.
- **Intense (or extreme) events –** usually concentrated in time and space. With short duration (minutes or few hours) and high rainfall intensities, these events are the main trigger for "flash floods" due to the incapacity of the drainage systems to capture the generated surface runoff and to convey it properly.

As previously mentioned, stormwater infrastructures are typically designed for rainfall events up to a given return period, which is assumed to correspond to a given peak flow. In this sense, urban stormwater infrastructures usually properly handle prolonged low-intensity rainfall events. These events can constitute an issue for stormwater when discharges are made to streams or rivers that might significantly increase their water level and compromise the available energy to allow such discharges.

Extreme rainfall events are the major concern regarding urban stormwater management since they usually correspond to rainfalls with a return period higher than the one adopted for design purposes. In this type of event, the runoff generated in a short period is high, and two processes usually exceed the design criteria. Firstly, the inlet devices are confronted with higher flows, often surpassing their capture capacity, leading to higher flows bypassing downstream and/or accumulating in urban depressions. In such cases, floods are common, even with some spare capacity in the storm sewers (Matos, 2006). Secondly, when higher flows are captured, and the drainage system (or parts of it) is not designed to convey such flows, starting to surcharge. When the energy level reaches the surface level, manholes can overflow, aggravating the urban floods with surface discharges.

Apart from intense rainfalls, it is certain that discharge conditions strongly impact the performance of stormwater systems (Thomason, 2019). This issue takes particular importance on coastal systems, where outfalls are subjected to sea tides. The influence of tides on outfalls will decrease the discharge capacity, promoting flow deceleration and upstream surcharge, and might negatively impact electromechanical equipment, such as pumping stations, if they exist. The tide's influence on stormwater systems has been increasing due to climate change. It is certain that in the near term (2021-2041), the continued and accelerating rise of the sea level will encroach on coastal settlements and infrastructure. If trends in urbanization in exposed areas continue, this will exacerbate the impacts, creating more challenges where energy, water, and other services are constrained (IPCC, 2022).

Thus, in addition to the rise in the mean sea level, related events such as storm surges will pressure stormwater discharge in coastal areas. A storm surge is a rise above the normal water level along a shore resulting from strong onshore winds and/or reduced atmospheric pressure. The combination of storm surge and normal (astronomical) tide is known as a 'storm tide' (Figure 3-8). The worst impacts occur when the storm surge arrives on top of a high tide, especially when coincident with a new or full moon. When this happens, the storm tide can reach areas that might otherwise have been considered safe. Additionally, there are pounding waves generated by the powerful winds (Gray, 2019; National Oceanic and Atmospheric Administration of US Department of Commerce, 2016). Naturally, storm surges increase the flooding risk not only due to the decrease in the discharge capacity of the stormwater systems but also due to coastal overtopping and the impediment of the direct discharge of surface runoff, affecting both the minor and major systems.

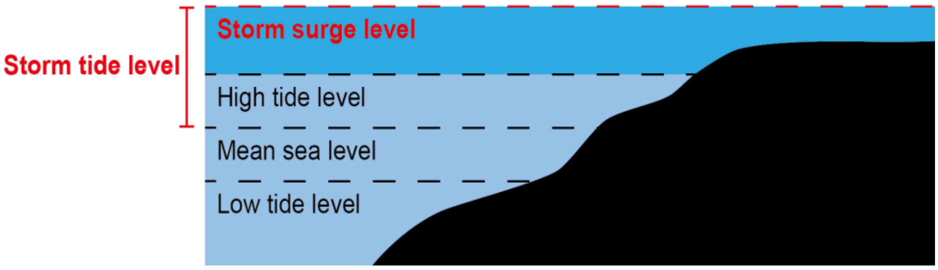


Figure 3-8. Storm surge and tide levels (adapted from Gray, 2019)

The IPPC has also reported that people are increasingly experiencing unfamiliar precipitation patterns, including extreme precipitation events. In the mid-to-long term, displacement will increase with the intensification of heavy precipitation and associated flooding and, increasingly, rising sea levels (IPCC, 2022). Climate change is not likely to change the nature of threads, such as intense rainfalls, but will change their severity, frequency, and geographical range (Howard and Bartram, 2010). In this way, multiple risks interact, generating higher vulnerabilities to climate hazards and compounding overall risk. Thus, future sea level rise, storm surges, and heavy rainfall will increase compound flood risks (IPCC, 2022).

As previously mentioned, the fast urban growth since the last decades of the XXI century has led to profound changes in the pre-existing hydrologic cycle and posed existing infrastructures under stress. A clear and direct change promoted by urbanization processes is the decrease in the perviousness of the catchment, leading to a reduction in the peak flow lag time, a decrease in flood peak duration but with the increase in peak discharges, and the reduction of groundwater recharge and consequent decrease of baseflow in urban streams (Paul and Meyer, 2001) (see Figure 3-9).

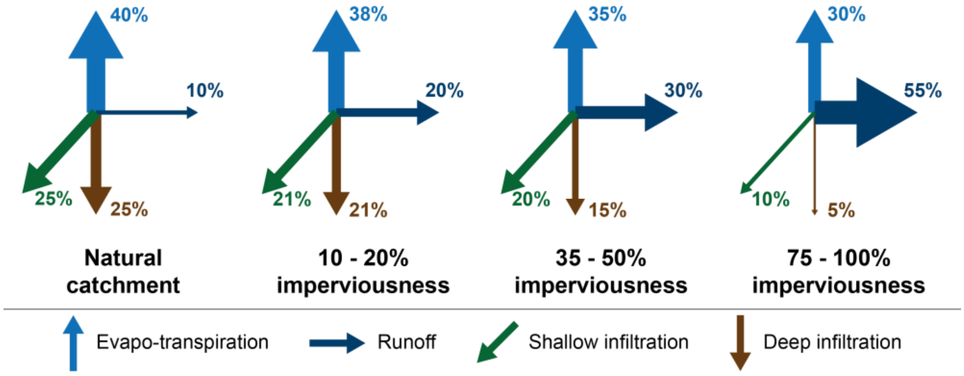


Figure 3-9. Impact of the imperviousness cover increase in urban catchments regarding hydrologic flows (adapted from Paul and Meyer, 2001)

Globally, the runoff increase has substantial consequences regarding the stormwater system performance (Matos, 2006), namely:

- Increase in frequency of overflow weir activation and discharge of combined sewer overflows in the receiving waters.
- Insufficient performance of stormwater sewers due to under-sizing or clogging, leading to upstream surcharges and potential manholes' overflow.
- Under-sizing of storm inlets, leading to the permanence of runoff at the surface and potential wasteful use of the total capacity of the storm sewers.
- Discharge of flows with urban contaminants into sensitive receiving waters.

As mentioned above, these issues were precursors to a more sustainable stormwater system management. On the one hand, the design of stormwater infrastructures started to better account for future urban developments and land uses; on the other hand, the quality of the discharged flows has taken on more importance, especially when receiving waters are sensitive.

Stormwater quality is mainly related to the land use of the respective catchment, and major pollutant sources include vehicle emissions, corrosion, and abrasion; building and road corrosion and erosion; bird and animal feces; street litter deposition, fallen leaves, and grass residues; and spills. These sources result in pollutants like solids, oxygen-consuming materials, nutrients, hydrocarbons, heavy metals, trace organics, and bacteria, mostly attached to particles of sediment that deposit on the catchment surface (Table 3-5).

Table 3-5. Typical pollutant concentrations (mg/l) in urban runoff (Loucks and van Beek, 2017)

Constituent (mg/l)	Highway runoff	Residential area	Commercial area	Industrial area
SS	28 – 1178	112 – 1104	230 – 1894	34 – 347
BOD5	12 – 32	7 – 56	5 – 17	8 – 12
COD	128 – 171	37 – 120	74 – 160	40 – 70
Ammonia (N)	0.02 – 2.1	0.3 – 3.3	0.03 – 3.3	0.2 – 1.2
Lead (Pb)	0.015 – 2.9	0.09 – 0.44	0.1 – 0.4	0.6 – 1.2

SS: Total suspended solids; BOD5: Biological oxygen demand; COD: Chemical oxygen demand.

A critical issue when addressing stormwater quality is the wash-off effect, which takes on special importance after long dry periods when the buildup of contaminants reaches high values. Wash-off occurs during rainfall/runoff due to raindrop impact, erosion, or solution of the pollutants from the impervious surface (Butler et al., 2018) and results in contaminant concentrations higher than the expected average values.

Figure 3-10 presents a summarized flowchart of stormwater systems' main stressors and shocks and their respective performance impact, as described in the present chapter.

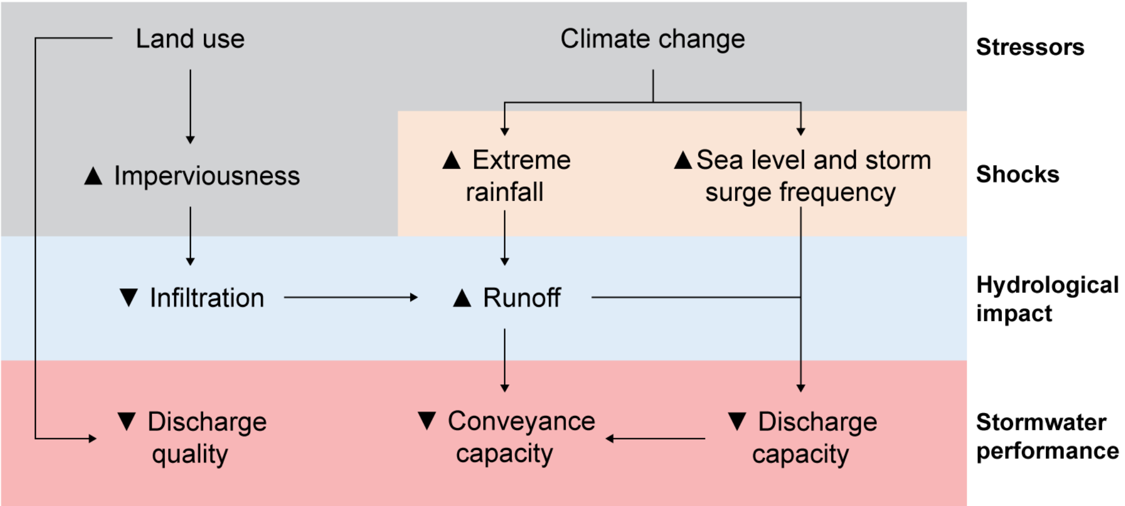


Figure 3-10. Flowchart of stormwater' stressors and shocks and their impact on stormwater performance

3.3.4. INTERDEPENDENCIES, REDUNDANCIES AND CASCADE EFFECTS

Urban services and infrastructures compose a network of flows, such as water, energy, waste, etc., that promote synergies and foster urban development (Figure 3-11). Interdependencies and redundancies define such a network of interconnections. Interdependencies exist when the performance of a service, the "receiver," depends on another service, the "donor." Redundancy is any human or material asset that allows the performance of a receiver service/infrastructure to be prolonged at satisfactory levels, even when the donor service/infrastructure is compromised. Typically, redundancies are achieved through internal assets or procedures, although in some cases, external assets can serve this purpose.

The detailed definition of interdependencies and redundancies amongst urban services and infrastructures is an iterative process that demands stakeholders' involvement and the collection of information at different levels within a service, from the service managers to the service operators (Barreiro et al., 2020). However, due to sensitivity or lack of access to critical infrastructure data, deriving direct known interdependencies may not always be possible, and the unknown relationships between donors and receivers might have to be derived using assumptions (Evans et al., 2018).

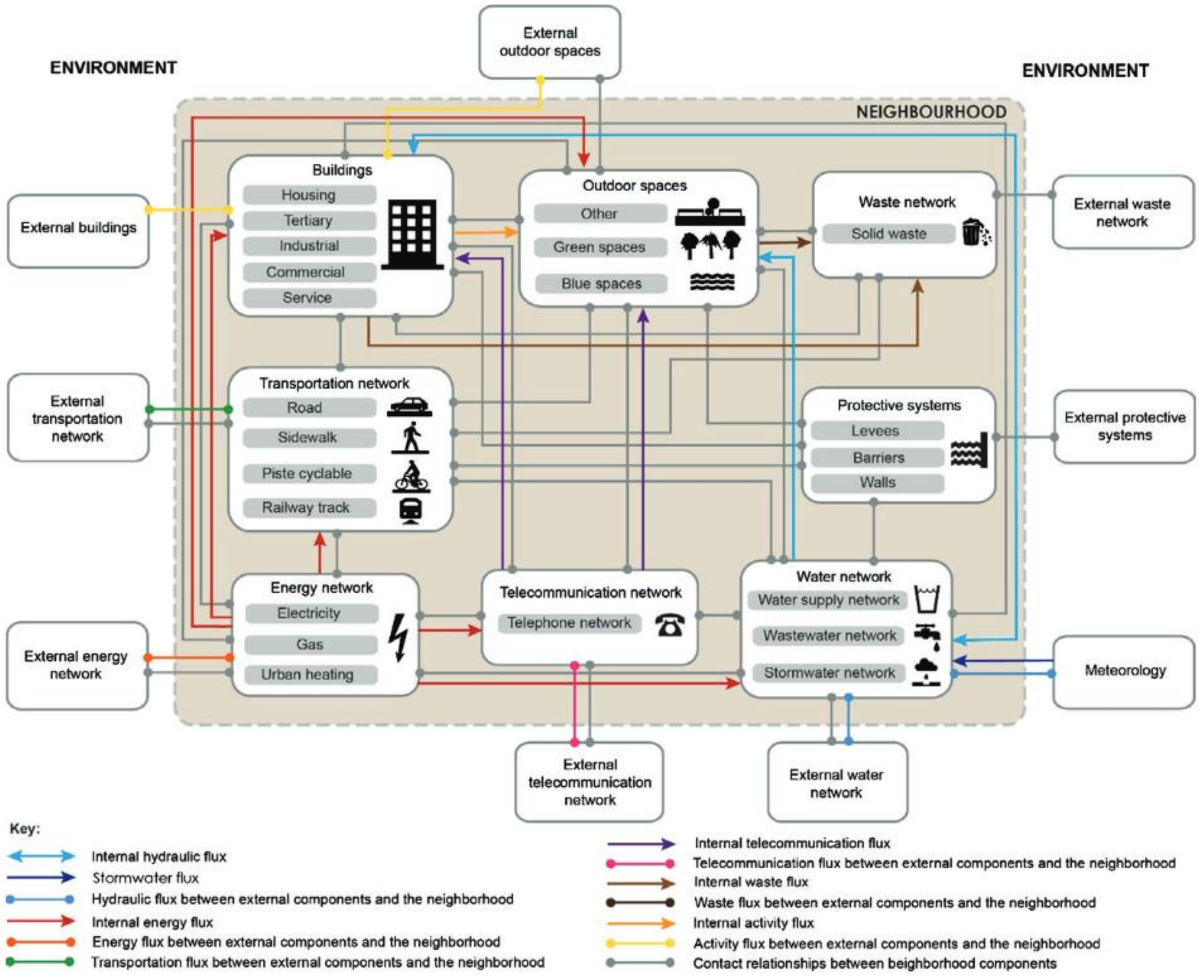


Figure 3-11. Example of functional diagram between urban services (Serre et al., 2018)

Naturally, studying interdependencies and redundancies in cities is a time-consuming process. Its efficiency depends on factors such as the spatial scope, the objectives, the capacity to involve stakeholders, and data availability, among others. Within the RESCCUE Project and focusing on the urban water cycle, interdependencies were studied for Barcelona, Bristol, and Lisbon research sites, following the Hazur methodology (Canalias et al., 2019). Figure 3-12 presents these interdependencies at the service level. Clearly, each city defined the interdependencies with different detail levels: Barcelona has considered 56 services and 786 infrastructures, Bristol has considered 23 services and 77 infrastructures, and Lisbon has considered 18 services and 146 infrastructures (Fontanals et al., 2020). A parsimonious approach to defining interdependencies is imperative since considering a more significant number of services and infrastructures does not necessarily result in better or more accurate outcomes and might confuse the analysis (Barreiro et al., 2020).

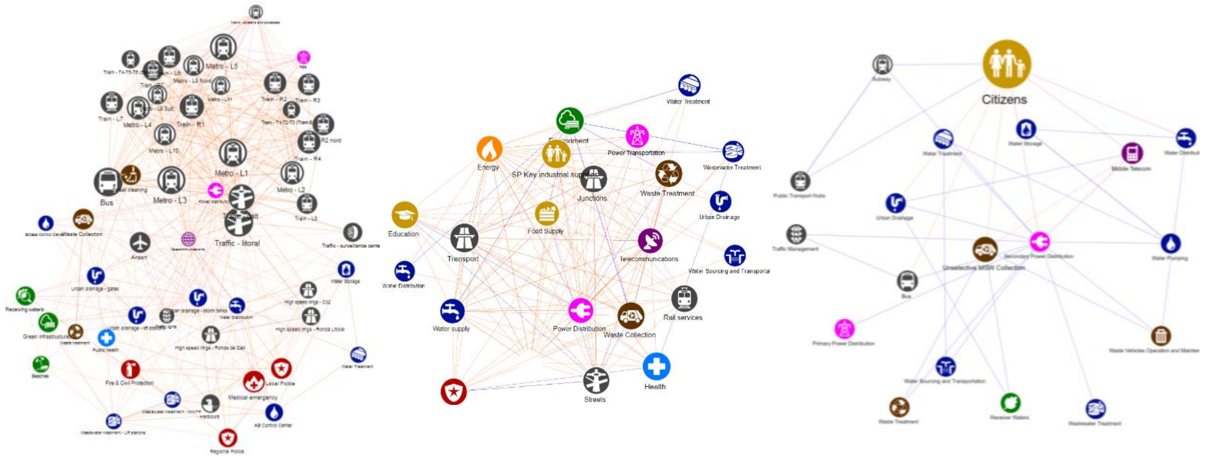


Figure 3-12. Example of interdependencies at service level studied in RESCCUE for Barcelona, Bristol, and Lisbon research sites (Fontanals et al., 2020)

In the presence of disruptive events, different protection levels among various urban services and infrastructures, along with existing interdependencies and redundancies, will define different chain reactions. It's important to understand that such consequences can result from direct interdependencies, i.e., when a given service/infrastructure depends on another for operation or from indirect outcomes of the failure. Both situations will likely trigger cascade effects, i.e., consecutive changes in urban services and infrastructure performance due to direct and indirect interconnections. Cascading effects pose significant issues to cities' infrastructures and services, and due to the complexities of models and the way service providers work, they are not always fully understood (Evans et al., 2018).

Such interdependencies will also play a critical role in re-establishing operational conditions of the services in flooding events. For instance, as energy networks are a vital donor infrastructure since many services rely on them to operate, it seems logical to ensure the proper functionality reinstatement of these networks as a priority. However, this rehabilitation might require the adequate functioning of transport and communication networks. So, dependency and interdependency between infrastructures will always significantly affect the amount of damage and the recovery period of infrastructural failures and, thus, the resilience of the infrastructural systems (Lhomme et al., 2010).

Generally, although service providers are aware of existing interdependencies among urban services, they typically do not allocate resources and time to studying and deepening these relations, and collaborative emergency and response protocols are not always encouraged (Barreiro et al., 2020).

Stormwater service dependencies are determined by the type of infrastructure and assets that compose the system. In short, if there is electromechanical equipment (e.g., pumping stations, storm tanks, and flow regulators/gates), there is dependence on the power supply service; if such equipment operates with telemetry systems, there is a dependence on mobile telecommunication service; if there is no such equipment, conventional stormwater infrastructures have no explicit dependence on other urban services, except for storm inlets whose performance is strongly dependent on street cleaning procedures. As an ecological service that typically includes sensitive water streams and bathing waters (marine or riverine), receiving water is the critical dependent service on stormwater performance mainly due to pollution loads.

Urban flooding is the most critical outcome of stormwater service failure. Such events affect the performance of several urban services that rely primarily on public space for operation (Barreiro et al., 2020)—typically, affected services include mobility (buses, trams, etc.) and dependent services (e.g., municipal waste collection and the population itself due to mobility constraints) (Birgani et al., 2013), tertiary activities (shops, offices, restaurants, etc.), and power distribution (although with a low probability of service failure (Almeida et al., 2020)). Naturally, each city's urban flooding impacts are unique, and other impacts can be verified. In mature cities, which have already experienced several flooding episodes, it is expected that no critical infrastructures are located within areas prone to flooding, namely emergency (e.g., police and fire departments), health (e.g., hospitals, healthcare, nursing homes), and even power supply infrastructures. It is relevant to emphasize that these services do not rely directly on the performance of the stormwater service to operate. Still, they can be affected by the consequences of its inadequate performance.

In addition, the surcharge of storm sewers can have direct impacts on other services as a result of the displacement of manhole covers, which can be a danger to traffic (including emergency services) and pedestrians, especially if the water depth at surface makes de manhole not visible; and structural failures on manholes or sewers due to flow pressure, which can result in washout of pipe bedding and formation of voids in surrounding soils and potential surface collapse or sinkhole formation. This situation poses an even greater danger to traffic and pedestrians. It can also compromise other underground infrastructures, such as wastewater sewers, water distribution conduits, gas pipes, or electric and telecommunication cables (Evans et al., 2018).

Considering the presented direct interdependencies and flooding impacts on urban services, it is important to mention that most of the services affected by stormwater failure/flooding do not produce strong cascade effects ("end-of-chain" services), and the citizens are mainly affected due to mobility restrictions (Barreiro et al., 2020). Figure 3-13 depicts a generic cascade chain in the case of urban flooding derived from an assessment of potential services and infrastructures' vulnerabilities to flooding carried out on RESCCUE research sites (Vela, 2018) and presented in detail in Table A1 of Annex 1.

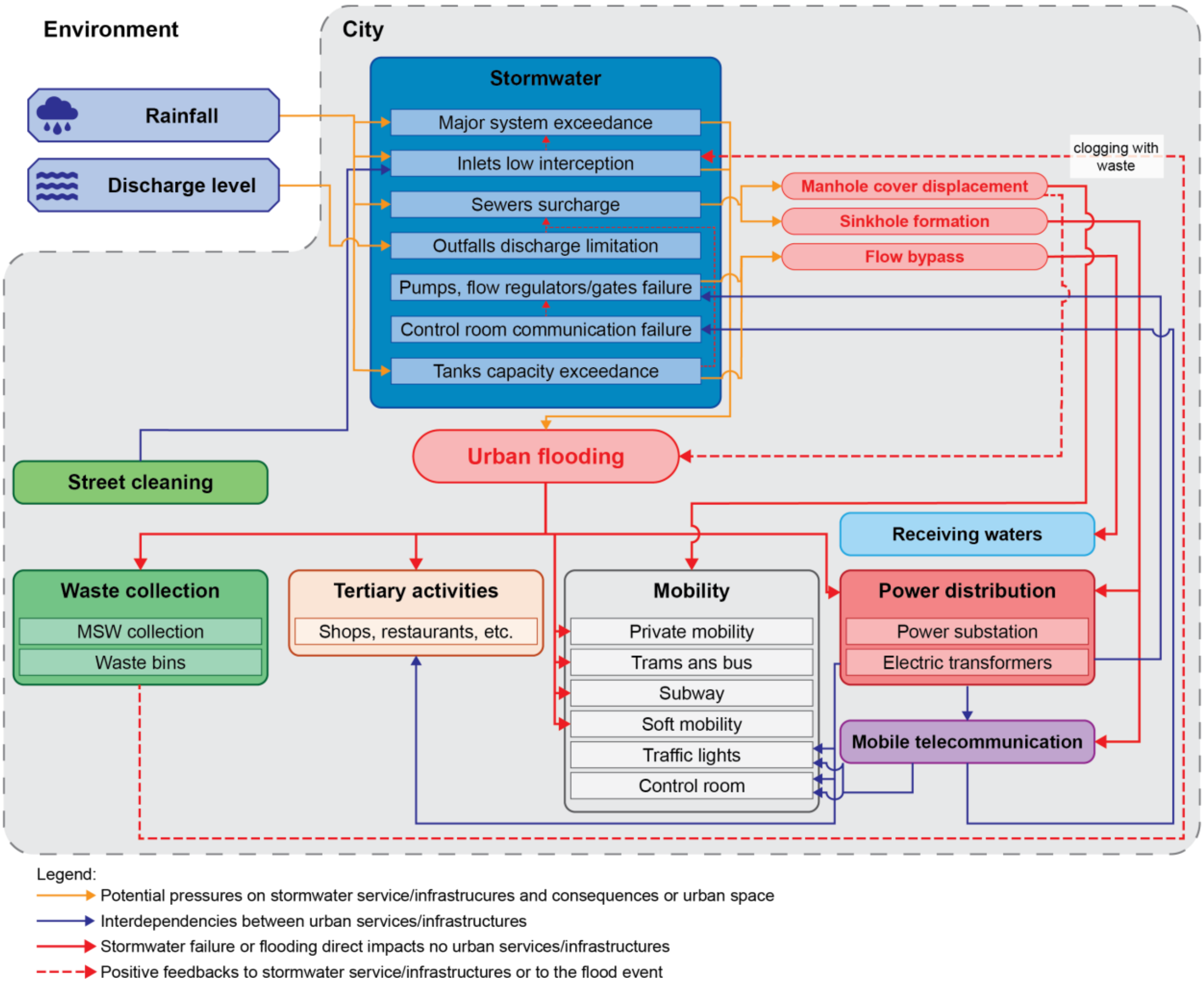


Figure 3-13. Potential cascade effects due to stormwater failure and flooding direct impacts

3.4. STORMWATER AND FLOOD RESILIENCE APPROACHES

Flood risk analysis is particularly significant since the hazard, although related to the probability of storm occurrence (the natural event that triggers the process), is materialized by the subsequent flooding. Flooding results from rainfall, transforming into runoff by the watershed and where socioeconomic activities occur. The hazard results from the interactions between the storm and the watershed, depending on the drainage system's performance, any defenses already implemented, and floodplain interactions (Bertilsson et al., 2019a). Therefore, urban floods must be understood as human problems with both natural and social, economic, and political causes (Bruijn, 2004).

The growing concerns regarding the sustainability of urban stormwater systems have induced a trend to adopt more green and blue infrastructures to mimic natural hydrological processes, the NBS as mentioned earlier. Although these solutions improve the capacity to manage peak flows naturally, they do not provide a miraculous solution against flooding, and it is accepted today that floods are virtually impossible to prevent (Valizadeh et al., 2016). Even if preventive measures allow for better coping with floods, it is challenging to prevent their dangerousness (Balsells et al., 2015), and efforts should be put into reducing the cities' vulnerability to flooding dangers and adverse impacts (Valizadeh et al., 2016).

Recovering the concept of panarchy, presented in Chapter 2, from a complex adaptive system perspective, urban resilience explicitly considers fast/slow dynamics and cross-scale interactions and interdependencies (Folke, 2006). In this sense, in an initial phase, urban resilience is a property that allows it to respond to a disturbance at a local scale. On a larger scale, resilience is understood as a process that considers the long-term impact of small-scale disturbances and leads to the condition of being resilient. This cycle allows the system to respond to challenges in a bidirectional way by feeding the long-term and larger scales with the short-term and local experiments and adjustments (allowing experimentation and testing) and by returning the accumulated memory of the past and successful experiments to local scales (Folke, 2006; Balsells et al., 2015). This circle represents the resilience "continuum" that allows cities and services to prepare better for new floods (Bruijn, 2004) (Figure 3-14).

In this context, resilience is recognized as a new paradigm for flood risk management, allowing us to cope with a complex environment. Urban resilience can potentially reduce the effects of disturbances, embracing them as opportunities for more sustainable urban development and as an important part of the operation of an urban system. From this perspective, flood risk management would not be limited to resistance, based on the idea that there is only one equilibrium situation for the system, but would create other viable situations that allow urban systems to continue operating (Balsells et al., 2015). In other words, the resilience approach represents a paradigm shift from conventional "fail-safe" approaches to a holistic "safe-to-fail" view that accepts, anticipates, and plans for failure under exceptional conditions (Bruijn, 2004; Mugume et al., 2014), enhancing the ability to cope with and recover from flooding, especially when considering future risks and related uncertainties (Martínez-Cano et al., 2014; Almeida et al., 2020).

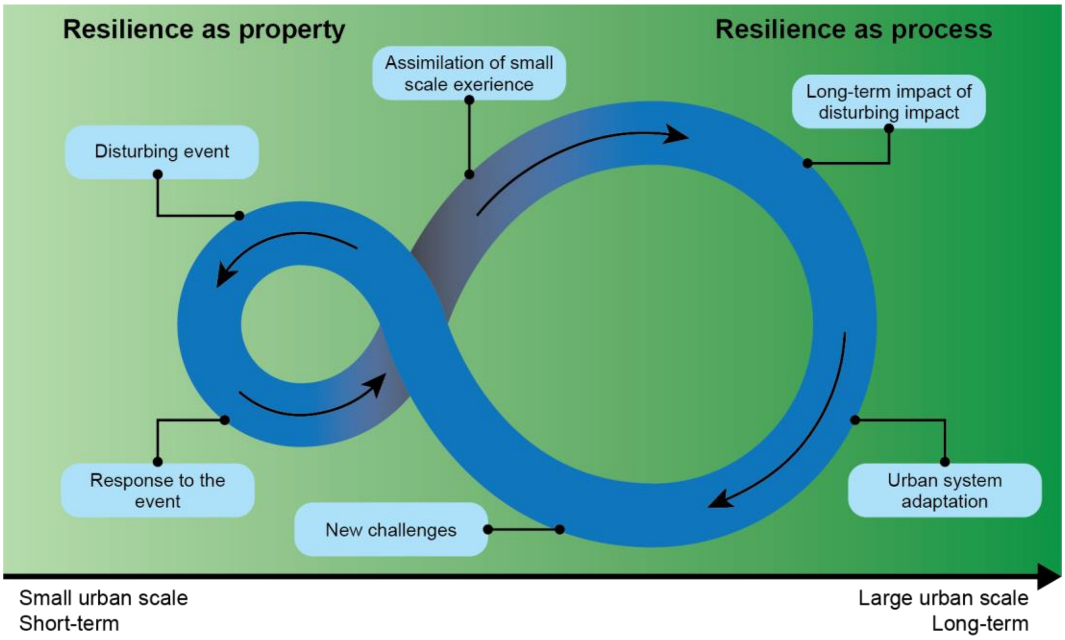


Figure 3-14. Panarchy adapted to the urban resilience to floods (adapted from Balsells et al., 2015)

However, many organizations and stakeholders do not yet fully understand the concept of resilience (Lhomme et al., 2010; Restemeyer et al., 2015; Balsells et al., 2015). This lack of understanding makes it challenging to transpose and implement resilience at the level of urban services, such as the stormwater service. As mentioned before, the concept of resilience is evolving, and although there is a tendency towards stabilization, the absence of a definitive definition creates confusion among stakeholders (Balsells et al., 2015). Additionally, since cities are complex systems of interdependent systems, adopting resilience-oriented planning and coordinating multiple stakeholders with different responsibilities, objectives, and concerns can be challenging management tasks (Balsells et al., 2015).

The lack of comprehensive guidelines, standards, and suitable quantitative evaluation methods is still a constraint for operationalizing resilience in urban drainage and flood management (Martínez-Cano et al., 2014; Mugume et al., 2015). Decision-makers need tools that help them decide on the best recovery actions after floods and how to manage critical services/infrastructures under different disruptive scenarios (Lhomme et al., 2010). For instance, a related missing key is the system failure scenario space that includes other causes of surface flooding, such as equipment failure, sewer collapse, and blockage (Mugume et al., 2015).

Different types of approaches have been used to quantify the concept of resilience, which can complement each other (Blanco-Londoño et al., 2017; Hosseini et al., 2016):

- **Qualitative methodologies** include conceptual frameworks, providing a notion of resilience without quantifying it, and semi-quantitative indices, which involve the opinion of experts in their qualitative estimation.
- **Quantitative methodologies** include general resilience metrics, which evaluate resilience in the performance of a system, and structural-based models, which evaluate resilience by components.

Flood risk is usually presented as a function of two variables: the hazard probability, typically related to peak flows and surface water depth and velocity, and the consequences of that hazard, i.e., the outcoming damages at physical and socio-economic levels (Bruijn, 2004; Restemeyer et al., 2015). Measures or strategies that aim at reducing the first term are usually referred to as resistance or robustness strategies since they prevent the occurrence of floods or reduce their hazard, typically by increasing the capacity to deal with greater flows or decreasing the peak flows (Bruijn, 2004). Adaptability refers to the second term, as lowering the consequences of a flood event means that the urban space is prepared for flooding (Restemeyer et al., 2015).

Bruijn (2004) presents three main characteristics of reactions that apply to flood risk management systems:

- The amplitude or severity of the reaction, which corresponds to the economic, social, psychological, and ecological impacts of floods and depends on hydraulic parameters related to the hazard (maximum water depth, velocity, flooded area, duration of the flood, etc.), socio-economic parameters that define the respective damage (land use and preparedness to floods), and ecological parameters (which are more suitable to fluvial floods).
- The graduality of the reaction, which is related to the system's capacity to handle continuous or consecutive events or waves. It depends on the same parameters as the reaction amplitude but is additionally influenced by the capacity to manage system infrastructures, such as weirs, bypasses, detention areas, etc.
- The recovery rate of the reaction corresponds to how quickly the system can return to its previous state or a state equivalent to a non-disturbed system. Since the severity of the reaction is already described by the reaction's amplitude, it is important to describe the recovery rate independently from the flood damage itself. Factors that might

determine this rate include the duration of the floods, the fundraising capacity for recovery, health, and equity, among others. The assessment of the recovery rate might require multidisciplinary cooperation.

Restemeyer et al. (2015) established a qualitative framework to assess flood resilience in light of three resilience qualities related to the three resilience systems thinking presented in Chapter 2: robustness (engineering resilience), adaptability (ecological resilience), and transformability (socio-ecological resilience). Robustness is understood as the city's capacity to withstand a flood event, mainly through preventive infrastructures, where most stormwater infrastructures are included; Adaptability is related to the capacity to deal with floods so that no substantial damages occur, mainly through physical measures (protective/defensive infrastructures, such as elevating houses, for example); Lastly, transformability is defined as the capacity of the city and citizens to "live with water," instead of "fight the water." This framework is conceptualized in three dimensions, summarized in (Table 3-6).

Valizadeh et al. (2016) present a qualitative framework to assess the technical/physical resilience of stormwater management systems considering three dimensions of the stormwater systems (hydrology, hydraulic, and network structure) as well as two resilience properties (robustness and recovery). Some indicators to assess both phases are presented, although no specific metrics are stated (Table 3-7).

Table 3-6. Framework for qualitative assessment of flood resilience (Restemeyer et al., 2015)

Resilience qualities► Resilience dimensions▼	Robustness Reduce flood probability	Adaptability Reduce flood damage	Transformability Foster societal change
Content **Measures and policy instruments**	Technical measures	Land use adaptation in flood-prone areas Flood-proofing buildings and infrastructures in flood-prone areas	Risk communication and awareness raising among: Private stakeholders (e.g., brochures, public campaigns, early education)
	Spatial measures	Early warning and evacuation routines Flood insurance and recovery funds	Public stakeholders (e.g., consensus-building, partnership practices, decision support tools)
Context **Strategic issues, institutional structures, and legislation**	Water and climate: water as a threat	Land-use and socio-economic changes: need to create synergies	Societal changes: need to establish water as an asset
	Strong public responsibility for water management	Shared legal responsibility between the public and private sector	Informal networks fostering a new "water culture"
	Collaboration between water management and spatial planning on specific projects	Strong collaboration between water management, spatial planning, and disaster management on all projects	New interdisciplinary networks (e.g., learning tanks) and learning organizations
Process			
Intellectual capital	Expert knowledge in engineering and planning	Expert knowledge and local knowledge (vulnerability reduction and adaptation options)	Creativity, openness toward new knowledge and learning
Social capital	Good relations among water managers and spatial planners	Good relations among water managers, spatial planners, and disaster management; Civil awareness and willingness to invest in flood risk	Mutual trust between public and private stakeholders and social acceptance of new interdisciplinary networks
Political capital	Strong political and financial support for bigger infrastructures (public funds)	Strong political and financial support for adaptation and risk-based approach	Change agents, leadership, and financial support for informal and interdisciplinary networks.

Table 3-7. Stormwater resilience dimensions and indicators' contribution for robustness and recovery (adapted from Valizadeh et al., 2016)

Resilience dimensions	Indicators	Robustness	Recovery
Hydrology Hydrological characteristics of the catchment	Catchment characteristics	●	○
	Land use	●	○
	Infiltration capacity	●	○
	Depression storage capacity	●	○
	Interception capacity	●	○
	Temporary storage discharge	○	●
	Hydrological abstraction restoration	○	●
Hydraulic Hydraulic criteria of the system	System capacity	●	○
	Flooded area	●	○
	Flow Rate	●	○
Network Structure Connectivity of the network components and degree of redundancy	Redundancy	●	●
	Connectivity	●	○
	Drain density	●	○
	Network discharge rate	○	●

Serre (2011) proposes the Spatial Decision Support System (DS3) model, which considers three essential capacities to qualitatively analyze the resilience of urban networks through alternative stormwater management options, focusing on the physical dimension of the urban assets:

- **Resistance capacity:** system's ability to sustain minimal damage. It's necessary to know the potential damage (or hazard) of the flood to understand how much the system can resist and how measures through stormwater design can improve its resistance capacity. Resistance capacity is achieved by reducing surface runoff and appropriately reducing its affluence to the sewers. Typical measures aim to retain and store stormwater, such as green roofs and gardens, vegetated roadside swales, and permeable paving.
- **Absorption capacity:** system's capability to keep functioning after the disruption or failure of one or more components by activating alternative configurations to mitigate that failure. Thus, redundancy properties are critically important to enhance the absorption capacity. Absorption capacity is improved by measures that promote rainwater storage and alternative flood pathways, which provide redundancy when the sewer's capacity is surpassed, allowing for failure mitigation, such as water plazas, multifunctioning car parks, and water detention basins next to sidewalks.
- **Recovery capacity:** This is associated with a rapid return to the system's "normal" functionality, not necessarily the previous state. The shorter the time required to

recover the affected assets, the greater the recovery capacity. Recovery capacity is increased by measures that act on storage and retention by reducing surface runoff and allowing faster accessibility in the public space, such as increasing curb height and plazas' depth and alternative flow pathways.

The American Society of Civil Engineers considers similar qualities to measure infrastructure resilience at a physical level: robustness, redundancy, resourcefulness, and rapidity (Rader and Habluetzel, 2014). As in Balsells et al. (2013), robustness refers to the capacity of the infrastructures to endure a given stress with minimal damage. This does not mean the system cannot experience performance loss for a given period but can continue operating at some minimum acceptable performance level. The minimum acceptable performance level should be considered in designing and assessing infrastructure systems (Rader and Habluetzel, 2014). Redundancy is the capacity of the system to provide a given level of service through alternative means, previously mentioned as absorption capacity. The closer the alternative service level is to the normal one, the higher the redundancy capacity. In urban systems, redundancy is achieved through backup infrastructures designed to operate while the main infrastructures are being restored (Rader and Habluetzel, 2014) or through network reconfiguration.

While robustness and redundancy are related to the system's capacity to maintain the service level as close to normal conditions, resourcefulness and rapidity are associated with restoring the infrastructures and system to acceptable or normal service levels. They can relate to the recovery capacity mentioned by Balsells et al. (2013). Resourcefulness is associated with the capacity to effectively organize and channel resources to repair or replace the affected assets; rapidity is the system and its infrastructure's ability to recover faster and reflects the effectiveness and practical outcome of resourcefulness. Problem-solving flexibility, adaptive decision-making capacity, updated planning, and inter-jurisdictional and organizational cooperation are key to fostering resourcefulness (Rader and Habluetzel, 2014).

Based on a bibliographic review of urban drainage resilience and associated keywords, Blanco-Londoño et al. (2017) propose a set of four resilience factors for urban drainage systems: flexibility, resourcefulness, redundancy, and robustness (Table 3-8).

Tahmasebi Birgani et al. (2013) propose two technical resilience indicators to evaluate stormwater systems' sustainability from a technical perspective: total flood volume and recovery time. Both indicators are quantified using 1D dynamic modeling. The total flood volume corresponds to the total volume above all the nodes of the urban drainage network and the recovery time is the time between the beginning of the flood at least in one node of the urban drainage system and the finishing of the flood at all nodes (Birgani et al., 2013).

Table 3-8. Resilience factors, variables and indicators proposed by Blanco-Londoño et al. (2017)

Factors	Variables	Indicators	Measurement/quantification
Flexibility Capacity to recover from disturbances	Recover capacity	Index of failure	Probability of system failure
		Gradualness	Change in the response of the system with respect to the change of magnitude in a flood
		Recovery duration	Time needed for the system to recover from an unsatisfactory condition
		Recovery rate	Recovery rate of the system after a flood
		Recovery loss	Loss of quality in the system
		Environmental load capacity	Amount of pollutant emissions that the system can endure
		Recovery indicator	Recovery time from a flood at each node of the system
Resourcefulness Availability and capacity to allocate economic and social resources when in adverse conditions	Response capacity	Response capacity	Evaluates how the components of a drainage system respond to disturbances through the response magnitude in the area surrounding a flooded node
	Amplitude	Damage expected per year	Average annual damage costs
		Expected number of affected individuals per year	Average annual affected individuals
Redundancy Capacity to provide alternative flow pathways	Capacity of absorption	Severity	Magnitude and duration of the maximum failure
Robustness Capacity to keep functioning in the occurrence of a disturbance	Resistance capacity	Overload of the system	The greatest precipitation intensity that a system can endure
	Response curve	Resistance threshold	The point at which the response becomes greater than zero
		Severity of the response	The point at which a system is no longer in a normal situation
		Proportionality of the response	Relates the response change to the magnitude of the disturbance
		Point of no recovery	The point at which a system changes its identity into a new configuration

Mugume and Butler (2017) use a similar approach, combining flooded volumes and flood duration in a single stormwater functional resilience indicator (Equation 3-1). This functional resilience index ranges from 0 (lowest) to 1 (highest resilience), and its variables are calculated using 1D drainage models.

$$Functional\ resilience = 1 - Severity = 1 - \frac{V_{TF}}{V_{TI}} \times \frac{t_{fn}}{t_{mf}} \qquad \textbf{Equation 3-1}$$

Where V_{TF} is the total flood volume of the system, V_{TI} is the total inflow into the system, $t_{fn}$is the mean duration of nodal flooding (computed for all flooded nodes in the system), and $t_{mf}$is the maximum nodal flood duration (maximum duration of flooding that occurs at any node in the system)

Figure 3-15 presents theoretical system performance curves (TSPC) applied to stormwater systems, representing different resilient and system performance-related properties and processes. The upper curve is related to the performance of the minor system, and the bottom curve is associated with the major system. These curves are only demonstrative, making multiple combinations possible in real cases.

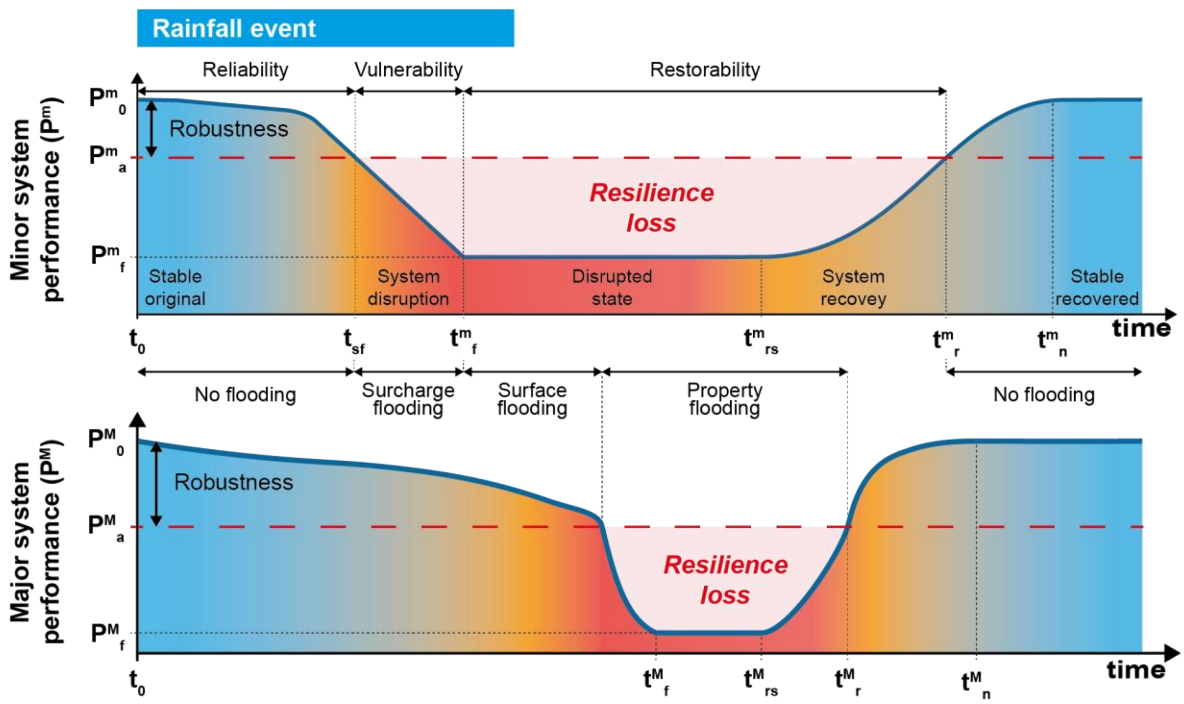


Figure 3-15. Theoretical system performance curve applied to stormwater systems (Mugume et al., 2014; Hosseini et al., 2016; Matzinger et al., 2019)

As mentioned before, robustness depends on built infrastructures that allow the system to maintain its functionality ("fail-safe") or to minimize the magnitude of failure when faced with exceptional discharges. This can be expressed as in Equation 3-2.

$$Robustness = f(P_0 - P_a) \quad \textbf{Equation 3-2}$$

Where P_0 is the original stable state performance level under normal conditions (before surcharging and P_a is the minimum acceptable system performance level.

Robustness is maximized if water height until surcharge in the minor system or the minimum acceptable level is increased. When considering the minor system, acceptable performance levels should comply with the design criteria: up to sewer surcharge. In the case of the major system, Mugume et al. (2014) propose flooding depths up to property flooding as acceptable performance levels, i.e., before large hazard/damage levels, usually around 10-20 cm. Up to acceptable performance levels, the minor system properly conveys the inflows, and the runoff from the major system should not threaten citizens or services and infrastructures.

The response is determined by the system's capacity to alleviate shocks and maintain functionality, even if at performance under acceptable levels, until its complete failure/disruption. It is performance- and time-dependent (Equation 3-3), an indicator of the system's sensitivity to disruptive events. It also measures how "safe to fail" the system is.

$$Response = f\left(\frac{P_f - P_0}{t_f - t_0}\right) \quad \textbf{Equation 3-3}$$

Where P_f is the system failure performance level (suggested by authors: flood depths higher than 0.60 m) and t_f is the corresponding time.

Regarding the minor system, the response is considered up to the moment when the system begins to be unable to handle the inflows, resulting in manholes and surface flooding. At this point, the minor system is in a state of disruption. As for the major system, the failure threshold is typically related to flooding depths that pose a significant hazard to people or cause damage to buildings. This depends on the demands of urban managers and the most vulnerable people and assets. For instance, flooding depths above 1 m already pose a significant hazard to non-vulnerable people.

Finally, restorability is defined as the function of the return time to an acceptable system state after failure (Equation 3-4).

$$Restorability = f(t_r - t_f) \quad \textbf{Equation 3-4}$$

Where t_r is the time corresponding to a return to an acceptable state after a failure.

Minor system restorability is achieved when the system meets its design performance. This aspect is critical to the start of major system recovery (${t^M}_{rs}$) since, typically, the flooding depth at the major system start decreasing when the minor system begins to recover its conveyance capacity (${t^m}_{rs}$). The recovering time of the major system is also influenced by human and capital resources, as well as the efficiency of emergency and contingency plans.

Matzinger et al. (2019) suggested an indicator regarding recovery time. It's the proportion of recovery time over the total time while the performance level is below the acceptable level.

$$t_{rec} = \frac{t_r - t_{rs}}{t_r - t_f}$$ **Equation 3-5**

It is proposed by Matzinger et al. (2019) that when the performance level, $P(t)$, is lower than the acceptable performance threshold, P_a (reddish area in Figure 3-15), resilience loss should be taken into account. This resilience loss is normalized by the difference between that threshold and the failure threshold (P_f), as well as by the duration of the event (Equation 3-6). This approach considers robustness as a system property that fosters resilience.

$$Resilience = 1 - \frac{1}{P_a - P_f} \times \frac{1}{t_n - t_0} \times \int_{t_0}^{t_r} P_a - P(t)\, dt$$

$$being\, P(t) = \begin{cases} P_a & \frac{P_a - P(t)}{P_a - P_f} < 0 \\ P(t) & \frac{P_a - P(t)}{P_a - P_f} \geq 0 \end{cases}$$ **Equation 3-6**

In practice, system performance curves can be obtained by monitoring the systems or using simulation models. The properties of interest of the systems can vary depending on critical system issues. For instance, from an urban flood management perspective, the water depth in sewers or manholes can be chosen for the minor system and the water depth at the surface for the major system. When considering stormwater discharges' quality, the choice could be pollutants such as the total suspended solids load at the outlet. Typically, the curves are normalized concerning a maximum threshold, corresponding to the failure threshold, as shown in Equation 3-7 (Mugume et al., 2014).

$$P(t) = 1 - \frac{V(t)}{V_{max}}$$ **Equation 3-7**

Where $P(t)$ is the performance value at time t, $V(t)$ is the system variable at time t, and V_{max} is the failure threshold for the system variable V. Figure 3-16 presents an example of depth-performance curves derived from depth-damage curves, in this case, dependent on the rainfall return period(Mugume et al., 2014).

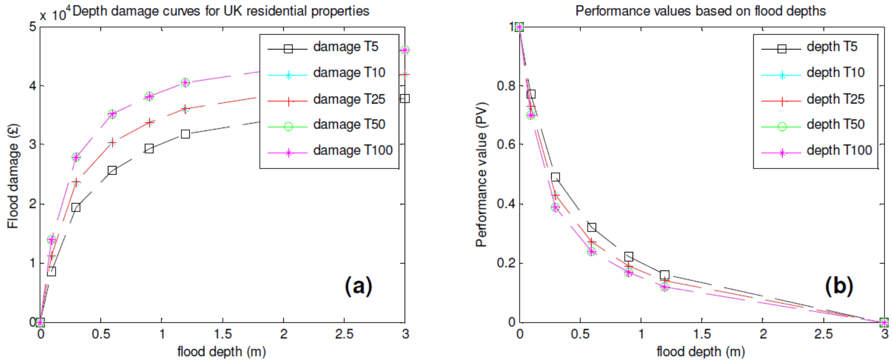


Figure 3-16. Example of depth-damage curves (a) and derived depth-performance curves (b) (Mugume et al., 2014)

Valizadeh and Wotherspoon (2018) propose a methodology to quantify hydraulic resilience by considering the flow depth in sewers over time as the performance curve of the system. This is done using the basic principle of dividing the urban system into several sub-catchments, each with a weight proportional to its area. These authors propose that the performance curve for each sub-catchment can be inferred by 1D modeling and the system performance over time and that the total resilience is calculated as a weighted average based on the area of each sub-catchment.

Barreiro et al. (2018) propose the Integrated Urban Resilience Index (IURI) by considering a set of five indicators related to urban drainage performance and potential consequences on buildings and critical urban services. These indicators are assessed through 1D/2D hydrodynamic modeling, namely, the percentage of manhole flooding volume over the total runoff volume, the percentage of the area flooded, the flood duration over the rainfall event duration, the percentage of potential buildings affected, and the percentage of critical services/infrastructures affected.

The work of Rezende et al. (2019b) presents the Urban Flood Resilience Index (UFRI), an evolution of the FRI (Flood Risk Index) (Zonensein, 2007), the FResI (Flood Resilience Index) (Veról, 2013; Miguez and Veról, 2017) and the S-FResI (Spatialized Flood Resilience Index) (Bertilsson et al., 2019a).

The FRI is a multicriteria methodology that assesses different climate scenarios and strategic adaptation options through a weighted product of two risk components: probability of occurrence (FP) and consequences (C). Each of the components is calculated from a weighted sum of normalized indicators between 0 (lowest risk contribution) and 1 (highest risk contribution): flood depth, velocity factor, and permanence factor as indicators for the FP calculation, and the household density, income, traffic, and sanitation quality as indicators for the component (Zonensein, 2007).

The introduction of S-FResI (Bertilsson et al., 2019a) changes the paradigm adopted in FRI by shifting from risk-based thinking to resilience-based thinking, even though the structure of the respective indexes is very similar. The S-FResI considers three dimensions (Table 3-9). The S-FResI value ranges between 0 and 1, but with an inverse logic since 0 represents the lowest flood resilience value and 1 represents the highest flood resilience value.

Table 3-9. Flood resilience dimensions and indicators to calculate the S-FRESI indicator, as proposed by Bertilsson et al. (2019a)

Dimension - Indicator		Related with
Resistance	Hazard – I_H	Flood depth
	Exposure – I_E	Households in the flooded area
	Susceptibility – I_S	Households directly affected and damaged
Material recovery – I_{MR}		Annual savings
Duration effect – $\boldsymbol{I_{DE}}$		Duration of the flooding affecting pedestrians, mobility, and buildings

The resistance dimension reflects how the population and households are protected from damage, combining flood hazard with households' exposure and susceptibility to floods. The homonymous indicator translates the material recovery dimension and aims to assess the economic recovery capacity from flood damages to residential buildings and their contents. The third dimension, the duration effect, pretends to assess the drainage system's capacity to recover from excessive flows by draining the flooded areas, related to the permanence time of certain water depths above critical thresholds (Bertilsson et al., 2019a).

Rezende et al. (2019a) present the UFRI as an expansion of S-FResI. This index maintains a similar structure and three main dimensions, although with a different terminology (more resilience-oriented), and includes more indicators. The resilience dimensions are now classified as (1) absorptive capacity, as the ability of the system to absorb the disruptive event, and translated by the sub-index of risk to resistance capacity; (2) adaptive capacity, as the ability to adapt to the event, represented by the sub-index of risk to system functional capacity; and (3) restorative capacity, as the ability to recover, translated by the sub-index of risk to material recovery capacity (Rezende et al., 2019b). The whole structure of the UFRI is presented in Table 3-10. Following the rationale of the previous indexes, all the indicators (and sub-indicators) are normalized. Usually, this normalization corresponds to the admission of a reference value (from which the indicator takes the value 1, i.e., the worst situation). Up to that threshold, the indicator is obtained through a mathematical function, such as linear, logarithmic, or exponential.

Table 3-10. Structure of UFRI (adapted from Rezende et al., 2019a)

Dimension	Sub-index	Indicator	Sub-indicator
Absorptive capacity	Risk to Resistance Capacity – Si_R	Building exposure – I_{eb}	-
		Urban infrastructure exposure – I_{ei}	-
		Flood depth – I_H*	-
Adaptive capacity	Risk to System Functional Capacity – Si_F	Aid access difficulty – I_{da}	-
		Mobility Risk – I_{MR}	Road hierarchy – I_{rh}
			Non-rail transport service – I_{nrt}
			Permanence factor – I_{PF} *
Restorative capacity	Risk to Material Recovery Capacity – Si_C	Relative value – I_{rv}	Building susceptibility – I_S
		Social vulnerability – I_{sv}	Vulnerability of people – I_{vp}
			Velocity factor – I_{VF}*

*Hazard-related indicators (H – related with flood depth; VF related with flood velocity; PF – related with flood duration)

There are different data needed to quantify the indicators, namely, dependent on hydrodynamic models (I_H, I_{VF} and I_{PF}), dependent on flooding data (I_{rv}, I_{sv}, I_{MR} and I_{da}), and socio-economic independent indicators (I_{eb}, I_{ei}, I_S, I_{sv}, I_{vp}, I_{rh} and I_{nrt}), which have no dependence on flooding characteristics. A brief explanation of the indicators' meanings and assumptions is presented next. The risk to resistance capacity (Si_R) represents resistance to damage. It aims to assess the degree of exposure of the population and the existing assets in the urban basin, relating the exposure of buildings and urban infrastructure to the potential damages of a given flood (Rezende et al., 2019a). This indicator comprises components related to the flooded property (water depth in the case) and its consequences (exposure of buildings and urban infrastructure). The risk to material recovery capacity (Si_C) represents the socioeconomic part of the flood risk. The relative value indicator (I_{rv}) makes a ratio between the damages to buildings and their contents (obtained from depth-damage curves) and the income and average replacement capacity of the population, representing the capacity to recover from material damages. The sub-indicator I_S is related to the height of the buildings and assumes that buildings with one floor are more susceptible to flooding damages. The social vulnerability (I_{sv}) considers the potential affection of vulnerable and nonvulnerable people as a function of a velocity factor that results from the product of flood depth and velocity modulus (flow momentum). At last, the risk to system's functional capacity (Si_F) represents the city's ability to continue providing part of its services during a flood event, namely regarding mobility. The aid access difficulty indicator (I_{da}) represents the impact on the mobility of fire brigades by assessing the water level in the surroundings of the fire brigade's headquarters. The mobility risk indicator (I_{MR}) takes into account the hierarchy of the affected roads (I_{rh}), the availability of subway or train stations in a radius of 500 and 1000 m from the flooded areas as measure of mobility redundancies (I_{nrt}), and the permanence factor (I_{PF}) of flood depth ranges as an indirect assessment of the stormwater network's capacity to deal with the flood.

Veról (2013) presents the FResI as a resilience scale to assess the resilience of a given project or strategy, comparing flood risk values in the future in relation to their values in the present, as resilience is understood as the capacity of the city to maintain flood risk under control over time (Miguez and Veról, 2017). It is calculated as a function of two components, P1 and P2 (left side of Equation 3-8, Equation 3-9, and Equation 3-10), and varies between 0 (worst situation) and 1 (best case). The ratio P1 measures the project's loss of efficiency (resilience decrease) in a future scenario compared to the present. The ratio P2 measures the efficiency of the project in the future, compared with the future situation if the project is not implemented. (business as usual). Rezende et al. (2019b) present the aFResI, with the same structure but adding a powered weight (a, b) to both components, dependent on stakeholders priorities (right side of Equation 3-8, Equation 3-9 and Equation 3-10). Figure 3-17 provides a theoretical example of FResI variables.

$$FResI = P1 \times P2 \quad \rightarrow \quad aFResI = P1^a \times P2^b$$ **Equation 3-8**

$$P1 = 1 - \frac{FRI_{Project}^{Future} - FRI_{Project}^{Present}}{FRI_{Project}^{Future}} \quad \rightarrow \quad P1 = 1 - \frac{UFRI_{Project}^{Present} - UFRI_{Project}^{Future}}{UFRI_{Project}^{Present}}$$ **Equation 3-9**

$$P2 = \frac{FRI_{Doing\ nothing}^{Future} - FRI_{Project}^{Future}}{FRI_{Doing\ nothing}^{Future}} \quad \rightarrow \quad P2 = \frac{UFRI_{Project}^{Future} - UFRI_{Doing\ nothing}^{Future}}{UFRI_{Project}^{Future}}$$ **Equation 3-10**

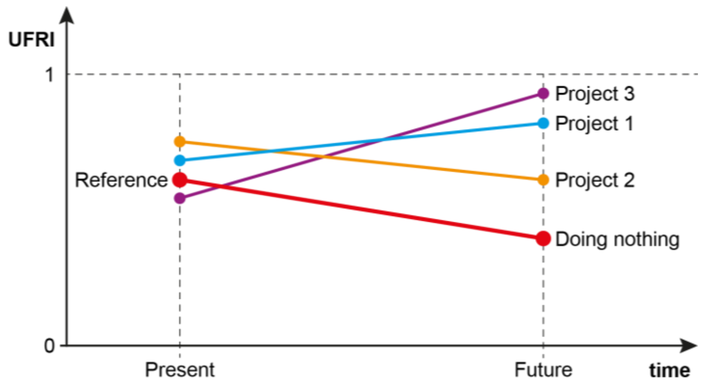


Figure 3-17. Theoretical example of aFResI variables (Rezende et al., 2019b)

Additionally, suppose a given resilience index, such as UFRI, is calculated for several events with distinct probabilities of occurrence (or return periods). In that case, their values can be plotted against their probability of occurrence in a planning horizon of "n" years (Rezende et al., 2019a). The integral of such a curve allows calculating a single urban flood resilience level for a given planning horizon of "n" years (Figure 3-18). This methodology can also help assess different resilience strategies or climate scenarios.

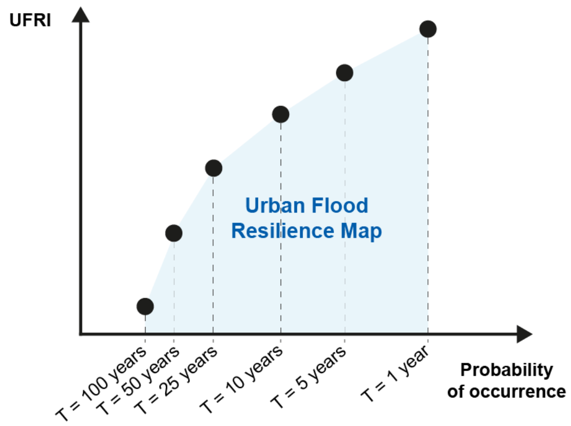


Figure 3-18. Multi-event methodology for Urban Flood Resilience Map (adapted from Rezende et al., 2019a)

As mentioned in 2.3.1.4 RESCCUE Project, a Resilience Assessment Framework (RAF) was developed within this project, focused on the urban water cycle and threats related to climate change. From the four dimensions of RAF - Organizational, Spatial, Functional, and Physical - urban services and infrastructures are directly addressed in the last two, respectively, where stormwater service and infrastructures are included. Regarding the stormwater service, the Functional dimension includes 54 performance indicators (PI) with metrics, and the Physical dimension includes 48 PI (objectives and criteria are presented in Table 2-5, page 38). The application of RAF in the three RESCCUE research sites (Barcelona, Bristol, and Lisbon) resulted in a range of non-applicable metrics up to 10% and 20% in the Functional and Physical dimensions, respectively. Additionally, in the Functional dimensions, the unanswered metrics varied between 10 and 23%, while in the physical dimension, this range is between 17% and 27% (Cardoso et al., 2020a). The high percentage of unanswered metrics might reveal that cities are in an incipient stage regarding stormwater service data collection (either by the collection itself or the access to collected data by other entities) or that the needed data is deviated from the current service needs and priorities. When considering and implementing new approaches or frameworks for service management or performance assessment, it is understandable that most adequate equipment or technologies or needed human or financial resources might not be available, and higher initial efforts are needed (Santos, 2021).

3.5. CONCLUSIONS

The municipalities are typically responsible for managing stormwater systems. Commonly, this management is made from the engineering and infrastructural perspective, focusing on the physical assets and their performance and maintenance. Thus, storm drainage design efforts have focused on components of the minor system and the inclusion of the major system as a part of the stormwater management has been neglected. In the words of Browen et al. (2009), « (…) lack of attention to the supplementary functioning of the major storm drainage system is no longer acceptable. » Moreover, highlighted in the field of water resource management (Associated Programme on Flood Management, 2009), the administrative boundaries must not limit water management; thus, neither municipality boundaries can limit urban stormwater management.

Stormwater management seems relatively independent as urban service, i.e., typically does not depend on other urban services to operate. However, this independence tends to change if innovative strategies are taken. For instance, implementing monitoring systems or real-time-controlled equipment creates new dependencies on the power supply and telecommunication. Dependencies must not be seen as a limitation for resilience. On the contrary, they must be understood as a property that confers the capacity to improve due to synergies with external services. Dependencies are only a weakness when they are not correctly identified or managed. Strictly focusing on the stormwater system and its infrastructures, one could also state that there are no strong dependencies on other services on the stormwater service. However, due to its intrinsic goal of correctly dealing with runoff from rainfall, its performance will undoubtedly affect other urban services. Theoretics can state these services are not dependent on the stormwater service per si but on the consequences of rainfall and its improper management by the service. Both interpretations coincide in the fact that, as urban service, stormwater systems are the key service to allow the proper functioning of the city and, thus, a critical service for the city and services ' resilience.

Stormwater management must consider internal and external risks by maintaining its infrastructure by planning and acting for climate-related shocks and stresses. The latter will signify higher demands upstream due to increased rainfall intensities and downstream by limiting the discharge capacity at outfalls. In this way, multiple risks interact, generating higher vulnerabilities to climate hazards and compounding overall risk.

Ultimately, the design criteria adopted (even related to the rainfall or the flood return period) determines the degree of protection from stormwater flooding provided by the service. This protection should relate to the cost of any damage or disruption caused by flooding. However, cost-benefit studies are rarely conducted for ordinary urban drainage projects (Butler et al., 2018). Moreover, the growing concerns regarding the sustainability of urban stormwater systems have induced a trend to adopt more green and blue infrastructures to mimic natural hydrological processes. Although these solutions improve the capacity to manage peak flows naturally, they do not provide a miraculous solution against flooding, and it is accepted today that floods are virtually impossible to prevent (Valizadeh et al., 2016).

In this context, resilience is recognized as a new paradigm for flood risk management by potentially reducing the effects of disturbances, embracing them as opportunities for more sustainable urban development, and as an important part of the operation of an urban system. Resilience represents a paradigm shift from conventional "fail-safe" approaches to a holistic "safe-to-fail" view that accepts, anticipates, and plans for failure under exceptional conditions, enhancing the ability to cope with and recover from flooding, especially considering future risks and related uncertainties. However, many organizations and stakeholders still poorly understand the concept of resilience, hindering its implementation at the level of urban services, such as stormwater services.

Different methodologies and approaches can be found in the literature to assess flood and stormwater resilience. Blanco-Londoño et al. (Blanco-Londoño et al., 2017) categorize these into qualitative methodologies—which include conceptual frameworks, providing a notion of resilience without quantifying it, and semi-quantitative indices, which involve the opinion of experts in their qualitative estimation; and quantitative methodologies—include general resilience metrics, which evaluate resilience in the performance of a system, and structural-based models, which assess resilience by components.

A typical segmentation is found between these categories, although they can and should complement each other. The diversity in existent approaches is closely linked to the conceptual fuzziness around the resilience concept, and there is still room for the development and improvement of standardized but flexible frameworks for operationalizing resilience in urban drainage and flood management. Moreover, Lhomme et al. (2010) highlight that decision-makers need tools that help them operationalize such methodologies and decide how to tackle critical infrastructures under different disruptive scenarios.

Chapter 4. DEVELOPMENT OF A 1D/2D URBAN FLOOD MODEL

"All models are wrong, but some are useful; the practical question is how wrong do they have to be to not be useful."

George E. P. Box, 1987

The current chapter of the thesis corresponds to the published paper: Barreiro, J., Santos, F., Ferreira, F., Neves, R., & Matos, J. S. (2022). **Development of a 1D/2D Urban Flood Model Using the Open-Source Models SWMM and MOHID Land**. Sustainability, 15(1), 707. https://doi.org/10.3390/su15010707

4.1. INTRODUCTION

Urban pluvial floods usually result from intense or extreme rainfall events, concentrated in time (typically a few hours) and space, which may result in generated runoffs that are higher than the design capacity of the drainage systems (Ramos, 2013; World Meteorological Organization and Global Water Partnership, 2017). IPCC reported that people are increasingly experiencing unfamiliar precipitation patterns, including extreme precipitation events (IPCC, 2022). Climate change will not likely change the nature of intense rainfalls, but it will change their severity, frequency, and geographical range (Howard and Bartram, 2010). Moreover, the fast urban growth that has been ongoing since the last decades of the XXI century has led to profound changes in the pre-existing urban hydrologic cycle and has put existing infrastructures under stress. In 1950, 30% of the world's population lived in cities; in 2018, this fraction was 55%, and in 2050, it is expected to rise to 68% (United Nations, 2018). A clear and direct change promoted by urbanization processes is the decrease in the perviousness of the catchments, which leads to a reduction in the peak flow lag time and a decrease in flood peak duration, but with an increase in peak discharges, a reduction in groundwater recharge, and a consequent reduction in base-flow in urban streams (Paul and Meyer, 2001).

Aging drainage infrastructures face not only demanding challenges (due to climate change, land use, and demographic changes), requiring investments in new infrastructures, but also require proper rehabilitation to preserve their functionality from a long-term perspective. Decision-support tools regarding the prioritization of rehabilitation interventions benefit from condition assessment techniques and protocols and from service-oriented approaches, supported by sewer system 1D/2D modeling, that minimize uncertainties and urban flood hazards (Sousa et al., 2014; Tscheikner-Gratl et al., 2019).

Conventional drainage systems are designed to get rid of urban runoff and convey it as fast as possible to an outfall, typically located at the nearest water body, usually at streams/rivers, lakes, or the sea (Matos, 2006). The discharge condition is a critical factor in the performance of drainage systems, especially in coastal systems subjected to sea tides. The influence of tides on outfalls decreases the discharge capacity, promoting flow deceleration and upstream network surcharge. According to IPCC, the tides' influence on stormwater systems has been increasing due to climate change, and it is certain that, in the near term (2021–2041), continued and accelerating sea level rise will encroach on coastal settlements and infrastructure and, if trends in urbanization in exposed areas continue, this will exacerbate the impacts on urban services (IPCC, 2022). Additionally, meteorological-related events such as storm surges will pose higher pressures on stormwater discharges in coastal areas. This way, multiple factors interact, generating higher vulnerabilities to climate hazards and intensifying overall risk. Thus, future sea level rise, storm surges, and heavy rainfall will increase combined flood risks (IPCC, 2022).

Decision-makers need tools that can help them decide on the best recovery actions after floods and how to tackle critical services/infrastructures under different disruptive scenarios (Lhomme et al., 2010). In the case of urban flooding, modeling tools are essential to assessing drainage system performance and its influence on the city's overall response to rainfall events.

Typically, stormwater drainage models are composed of two steps: the first concerns the hydrologic processes, where rainfall is transformed into runoff as the outcome of a set of hydrological processes responsible for all the losses that rainwater undergoes when reaching the catchment surface (Chow et al., 1988); the second concerns the runoff transport along the drainage network. In the second step, the drainage network is typically conceptualized as a set of nodes, corresponding to manholes, and connections/links between them, representing sewers or open channels reaches. The runoff generated in a given catchment is routed to an entry node and is then conveyed along the drainage network by solving the one-dimensional (1D) Saint-Venant equations (SVE) (Rossman, 2017).

However, using such models alone presents limitations concerning the interaction processes between runoff and drainage systems, undermining their full potential for studying urban floods. Firstly, simplifying the urban topography and assuming a set of sub-catchments leads to neglecting several urban infrastructures that influence the runoff behavior, such as walls or terrain depressions. Secondly, considering that the generated runoff in each sub-catchment is fully routed to the drainage system implies a 100% interception efficiency of the storm inlet devices, which tends not to be the reality. Thirdly, when the drainage system surcharges, outflows can result from manholes, and the 1D models cannot deal with these flows' propagation at the surface, assuming that they are either lost from the system (Figure 4-1a) or ponded in a virtual volume above the flooding manhole, returning to the same node when possible (Figure 4-1b).

In response to these issues, 1D/1D models were introduced, where both the runoff and drainage systems' flow are modeled by solving the 1D SVE (e.g., (Djordjević et al., 1999; Leandro, 2008; Nanía et al., 2015). This way, streets are represented by open channels placed over the drainage network, and it is possible to consider flow exchanges between both manholes and inlet devices. Although there are automatic GIS procedures for the delineation of the preferential courses of surface runoff, allowing faster assembly of 1D/1D models (Leitão et al., 2013), the topography of cities is varied, and when runoff occurs in wide areas, it tends to assume a bidirectional behavior. Therefore, the 1D flow simplification should not be used to represent the runoff propagation (Henonin et al., 2013; Leitão et al., 2013).

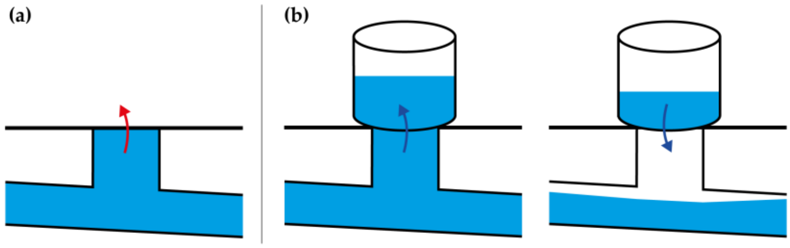


Figure 4-1. Graphical representation of 1D models dealing with manhole overflow: (a) lost from the system or (b) ponded in virtual storage volume

Consequently, 1D/2D dual drainage models arose, solving the 2D SVE for surface runoff and keeping a 1D approach to flow in the drainage network. Recently, commercial software programs considering 1D/2D urban flood modeling have become available, such as Mike Urban (DHI, 2012), Infoworks ICM (Innovyze, 2012), and OpenFlows FLOOD (Bentley, 2019). These rely on licensed software, and the availability of open-source or freeware programs is still scarce in this domain (Leandro and Martins, 2016).

Various 1D/2D modeling approaches with different degrees of complexity regarding the physical processes involved can be found in the literature. Some authors present simplifications of the 2D SVE, ignoring the inertial term (Hsu et al., 2002; Leandro and Martins, 2016; Chen et al., 2017). Different approaches are also found regarding the inlets' interception capacity (e.g., capture flows up to a given maximum threshold (Hsu et al., 2002) or inlet interception curves obtained from experimental studies (Gómez and Russo, 2011; Russo et al., 2021)). Free weir and orifice equations are mostly found in the literature to compute the inlets' interception capacity and surcharged weir and orifice equations to define the manhole overflow (Russo et al., 2015; Leandro and Martins, 2016; Martins, 2015; Courty, 2018; Jang et al., 2018; Wu et al., 2018; Fernández-Pato and García-Navarro, 2018; Sañudo et al., 2020) and inlet overflow (Gómez et al., 2019), although the respective weir and orifice coefficients typically require calibration (Rubinato et al., 2017; Russo et al., 2015). In other cases, inlet location is not considered, and flow is assumed to be intercepted at the manhole locations (Leandro and Martins, 2016; Martins, 2015; Courty, 2018; Wu et al., 2018; Fernández-Pato and García-Navarro, 2018; Jahanbazi and Egger, 2014).

4.2. MATERIALS AND METHODS

4.2.1. HYDROLOGIC AND HYDRAULIC MODELS

4.2.1.1. EPA-SWMM

The Storm Water Management Model (SWMM) is a hydrologic and hydraulic model that started to be developed by the United States Environment Protection Agency (EPA) in 1971 (EPA, 1971). Since then, the model has undergone several upgrades, including the EXTRAN block in 1977, which allowed the 1D dynamic simulation of flow transport through channels and closed pipes; it was one of the most used blocks in various applications of SWMM. In 1988, version 4.0 was released in Fortran-77 (Huber and Dickinson, 1988). The most recent substantial update occurred in 2004, in version 5.0, with the rewriting of all the code in C language, allowing its compilation in dynamic-link library files (.dll) and enabling it to run on the command line via an executable file (.exe). Version 5.1, released in 2014, has undergone several updates for the computational methods and the Graphical User Interface (Rossman, 2015). At last, in February 2022, version 5.2 was launched, and its major new feature consists of a 1D/1D explicit approach, allowing users to define inlet devices that capture street runoff using the U.S. Federal Highway Administration's HEC-22 methodology (Rossman and Simon, 2022). Apart from sewers and manholes, SWMM allows us to consider various drainage infrastructures, such as storage/treatment facilities, pumps, and flow regulators.

The basic unit of the SWMM rainfall-runoff model is a catchment. SWMM uses a nonlinear reservoir model to estimate runoff by conceptualizing a catchment as a rectangular surface with uniform slope and width. From the conservation of mass, the net change of the water depth per unit of time is the difference between inflows (rainfall rate) and outflows (infiltration, evaporation, and runoff rates) over the catchment (Rossman and Huber, 2016).

4.2.1.2. MOHID LAND

MOHID Land, developed by the MARETEC (Marine and Environmental Technology Research Center) at the Instituto Superior Técnico of the University of Lisbon, is a hydrologic–hydraulic integrated model with four compartments: the atmosphere, porous media, surface land, and river drainage network (Figure 4-2). It is part of a broader model, MOHID, an open-source model written in Fortran, which also includes MOHID Water, a three-dimensional numerical program to simulate surface water bodies.

In MOHID Land, water moves through the media based on solving the complete SVE (2D in surface runoff and 1D in river networks), allowing for kinematic wave and diffusion wave approximations. The atmosphere is not explicitly simulated but provides data necessary to impose boundary conditions (precipitation, solar radiation, wind, etc.) on the remaining compartments. The model is based on finite volumes arranged in a structured grid. Surface land is described by a 2D horizontal grid and the porous media by a 3D domain that includes the same horizontal grid as the surface, complemented by a vertical grid with layers of varying thickness. Infiltration can be calculated using different models, such as the Curve Number model developed by the Soil Conservation Service, the Green-Ampt model, and the Richards Equation, which is also used to model water movement along the soil's porous media. The river drainage network is a 1D domain defined from the digital elevation model (DEM), with reaches connecting the centers of the surface cells. Fluxes are calculated over the faces of the finite volumes, and state variables are calculated at the center to ensure the conservation of transported properties. The model uses an explicit algorithm with a variable time step (Brito et al., 2015; MARETEC, 2020).

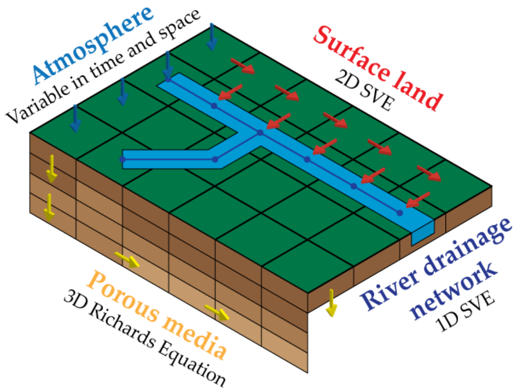


Figure 4-2. MOHID Land compartments (adapted from MARETEC, 2020)

The basic unit of the MOHID Land rainfall-runoff model is a cell of the 2D horizontal grid representing the water elevation, i.e., the sum of the surface elevation and the water column at each cell. Thus, likewise SWMM, from the mass balance, the net change in the water depth per unit of time is the difference between the inflows (rainfall rate) and outflows (infiltration and evaporation rates) over the cell, with the difference of adding/subtracting the water fluxes from/to the neighboring cells.

4.2.2. SWMM/LAND COUPLING METHODOLOGY

4.2.2.1. Coupling Rationale

The interest in coupling MOHID Land with SWMM is due to the possibility of better reflecting real flooding behavior due to interactions between the runoff and the flow in the drainage network, namely the runoff capture by inlet devices and the flow propagation at the surface when overflow through manholes occurs. Considering this, the fundamentals of the coupling rationale are as follows (Figure 4-3):

1. Stormwater inlets capture surface runoff (on MOHID Land) and route it to the urban drainage network. The captured water will decrease the water level at the surface, i.e., the water column in the corresponding cell of the 2D surface grid. In abnormal conditions, flooding occurs if the stormwater inlets are insufficient in number and/or have insufficient capacity, leading to water accumulation at the surface.
2. Water captured by the stormwater inlets is conveyed by the urban drainage network and discharged at the outfall (on SWMM), often a river or sea.
3. When the captured flow surpasses the carrying capacity of the urban drainage infrastructures, such that the water depth inside the network reaches the surface level, part of the captured water can return to the surface through manhole overflow. If a given manhole is overflowing, the intake capacity of the connected inlet devices is set to zero.

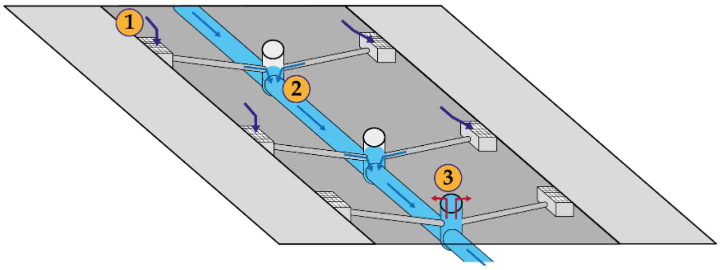


Figure 4-3. Fundamentals of the SWMM/Land coupling rationale

4.2.2.2. Data Requirements

The main information required to assemble a MOHID Land domain in a typical application in an urban environment consists of geo-referenced data that enable the building of different 2D horizontal grids to be used in the computation of the involved hydrologic/hydraulic processes (Table 4-1).

Table 4-1. Main data required, typical formats, and respective uses in MOHID Land

Data required	Typical formats	Relevant grid	Main process
Contour lines/DEM	Vectorial/raster	Surface grid	Runoff
Buildings and urban obstacles	Vectorial	Surface grid	Runoff
Land use	Vectorial/raster	Manning's coefficient grid	Runoff
Imperviousness factor	Raster	Imperviousness grid	Infiltration
Soil properties	Vectorial/raster	Soil properties1	Infiltration

[1] One grid by soil propriety. Required soil properties depend on the infiltration method chosen.

Regarding the SWMM component, the key data needed are the infrastructures' registers with their basic properties and characteristics, which are also geo-referenced (Table 4-2).

Table 4-2. Main data required for SWMM implementation

Infrastructure	Main Data Required
Manholes	Invert elevation; depth from invert to ground
Sewer/channel	Cross-section shape; length; roughness
Storm tank	Invert elevation; depth of the storage unit; storage curve (surface area as a function of water depth)
Pump	Pump type and curve; startup and shutoff depths
Outfall	Invert elevation; discharge boundary condition

The rationale for coupling MOHID Land and SWMM requires one additional layer of data to capture runoff from the surface, that is, to model inlet devices (Figure 4-4).

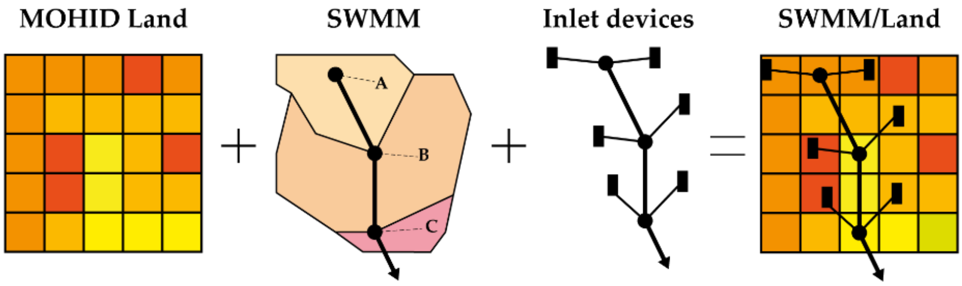


Figure 4-4. Data layers considered in the rationale of the coupling methodology between MOHID Land and SWMM

As mentioned, SWMM assumes that all the runoff generated by a given sub-catchment is conveyed to its respective outlet node, assuming that inlet devices can fully capture runoff, which is not true for most real situations. In this sense, stormwater inlets are not directly considered in typical SWMM 1D applications (although if calibration data exists, the efficiency of the inlet devices is blended in data with other processes). Within the current coupling, the need for additional data regarding the inlet devices, namely their location and geometry, will result in a better representation of the real processes, which is the model's primary goal.

4.2.2.3. Coupling Procedure

In practice, the current coupling follows an offline procedure, i.e., models interact by changing data through several time series by the end of the run of each model. MOHID Land is responsible for generating runoff due to rainfall, and when runoff reaches an inlet device, it is partially removed from the cell, and the captured flow is written on a time series. SWMM is responsible for conveying the captured flows along the drainage network and writing time series regarding outfall discharges and manhole overflow (if existent). At the end of the

MOHID Land run, there will be two main outputs in the form of time series that will be used on SWMM: the captured flow by the manhole, i.e., the sum of the flows captured by all the inlet devices linked to that manhole, and the surface water level at each manhole location. The first will be used as flow input at each SWMM node (manhole), and the second will be used as a boundary condition for manhole overflow. The water head at the surface conditions the manhole overflow, as the overflow value is computed as a function of the gradient between the SWMM node's water head and the surface's water head. The run of SWMM produces a time series containing the flows leaving the model through outfall discharges and manhole overflow.

Thus, the urban flood model run is composed of cycles: a first run of MOHID Land followed by a run of SWMM (Figure 4-5). Since the coupling is offline, the interchange of flows always depends on the conditions of the previous run. A procedure to analyze the need for successive runs is also proposed, the S/L-OCA (SWMM/Land Operational Convergence Analyst). This procedure allows us to verify if there is a need to proceed with another simulation cycle by analyzing two criteria:

1. Manhole overflow occurrence: if there is any manhole overflow during the simulation time, another simulation cycle is required to model such inflows at the surface.
2. Water depth convergence between cycles: from the second cycle onwards, the water depth results in a set of user-defined 2D probe cells that are compared, and a new simulation cycle is required if the convergence is smaller than a given user-defined threshold.

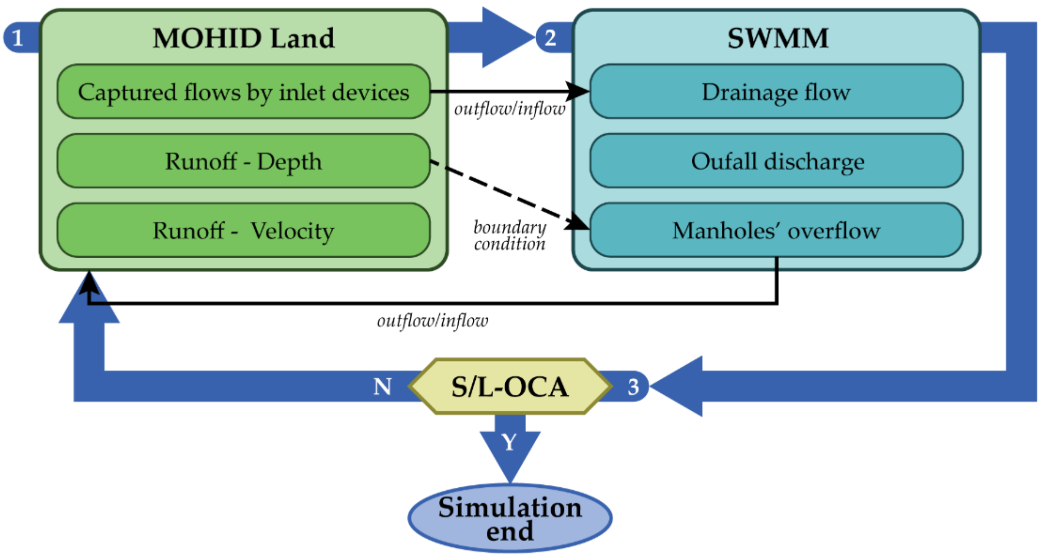


Figure 4-5. SWMM/Land coupling steps and simulation cycles

The presented coupling procedure also allows for the rainfall-runoff process to be simulated by SWMM, starting with step 2 of Figure 4-5. This way, SWMM built-in functionalities that operate on SWMM catchments, such as Low-Impact Developments, can still be considered. If such an option is chosen, an interaction between the flow in the drainage network and the surface only exists if manholes overflow.

The current implementation required the creation of a new module for MOHID Land and specific adaptations/settings for the use of SWMM, the latter with no change in the code. The new module for MOHID Land allows the model to read urban drainage infrastructures, namely, manholes and inlet devices, fed to the model through ASCII files.

Thus, MOHID Land can capture runoff from each cell containing at least one inlet device. For the current implementation, inlet captured flow is mediated by a weir equation (Equation 4-1) (Leandro and Martins, 2016; Russo et al., 2015).

$$Q_{2D/1D} = c_w \times L \times {h_{2D}}^{3/2} \times \sqrt{g} \qquad \textbf{Equation 4-1}$$

Where $Q_{2D/1D}$ *is* the inlet captured flow (m³/s), c_w is the weir coefficient (assumed as 0.2), L is the length of the inlet (m), h_{2D} is the water depth at the MOHID Land cell, and g is the acceleration of gravity (m²/s).

Concerning SWMM, an outfall link was added to each node corresponding to a manhole through an outlet link type. This way, the runoff head is considered as the outfall boundary condition and the link mediates the manhole outflow rate through an orifice equation (Equation 4-2) (Courty, 2018; Jang et al., 2018; Leandro and Martins, 2016; Martins, 2015).

$$Q_{1D/2D} = c_o \times A_{mh} \times \sqrt{2g(z_{1D} - z_{2D})} \qquad \textbf{Equation 4-2}$$

Where $Q_{1D/2D}$ is the manhole overflow rate (m³/s), c_o is the orifice coefficient (assumed as 0.5), A_{mh} is the area of the manhole (m²), $(z_{1D} - z_{2D})$ is the difference between the water head at the SWMM manhole (z_{1D}) and the respective MOHID Land cell water surface elevation (z_{2D}) and g is the acceleration of gravity (m²/s).

4.3. APPLICATION TO CASE STUDY AND RESULTS

4.3.1. SYNTHETIC CASE STUDY: SIMPLIFIED STREET

This case study is suggested by Sañudo et al. (Sañudo et al., 2020) to allow the verification of the coupling procedures. It consists of a synthetic domain with street elements, as described in Table 4-3. The drainage system consists of four manholes (M1, M2, M3, and M4) and one outfall (O1), linked with sewers with a 1% slope and eight inlets connected to the nearest manhole. The sewer along the road has an inner diameter of 500 mm, while the sewer connecting M4 to M2 has an inner diameter of 300 mm. The domain elements and the 2D elevation grid, composed of a 0.5 × 0.5 m structured mesh of 2780 cells, are shown in Figure 4-6.

Table 4-3. Street elements of the synthetic domain (Sañudo et al., 2020)

Element	Dimension (m)	Slopes (%)	Manning Coefficient (s/m$^{1/3}$)
Road	L = 40, W = 7	S_T = 2, S_L = 1	0.016
Sidewalk	L = 40, W = 2	S_T = 1, S_L = 1	0.016
Green area	L = 14.5, W = 10	S_T = 1, S_L = 1	0.032
Buildings [1]	L = 40, W = 10 L = 14.5, W = 10	-	-

Legend: L: length, W: width, S_T: transversal slope, S_L: longitudinal slope.
[1] Buildings are not considered for the 2D mesh, being directly linked to the drainage system.

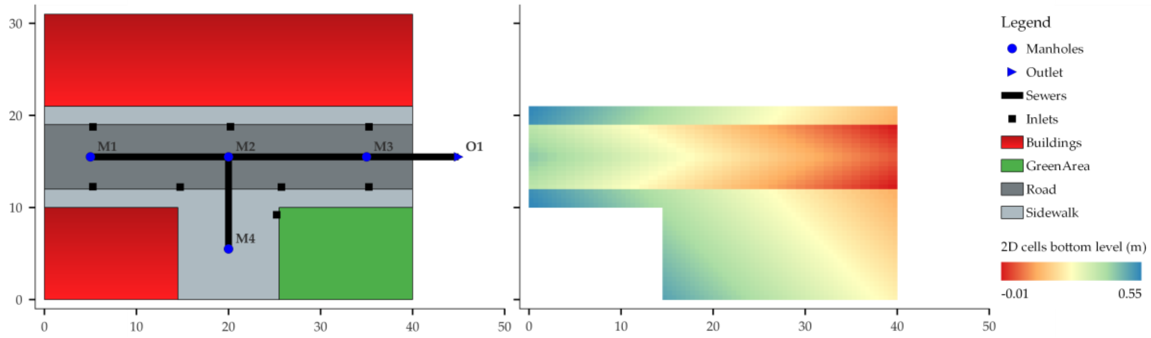


Figure 4-6. Synthetic case study: SWMM/Land domain

The suggested boundary conditions are set to force the system surcharge and simulate manhole overflow conditions: the manholes M1 and M4 are forced with input hydrographs, the outfall is forced with a conditioning boundary level, and a constant rainfall intensity of 80 mm/hour is imposed (Figure 4-7a). Figure 4-7b presents the results regarding inflows and outflows at each manhole, i.e., runoff captured by the inlet devices and manhole overflow. Figure 4-7 presents the water head at the SWMM nodes and at the respective 2D cell.

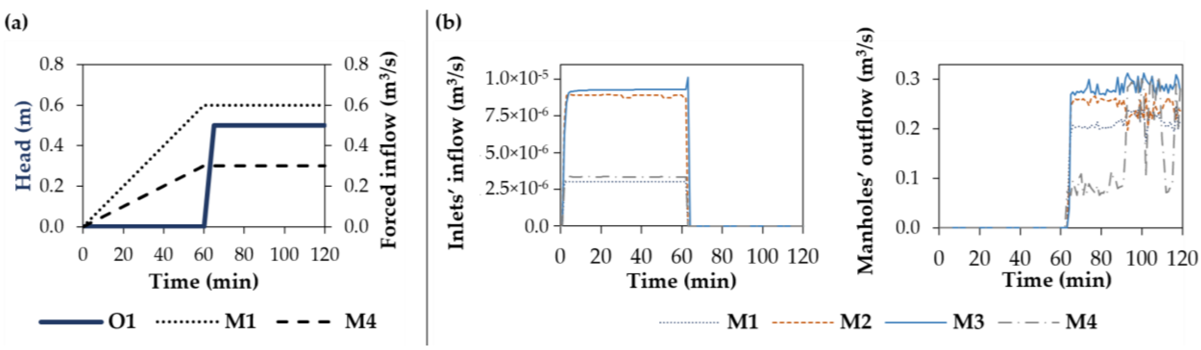


Figure 4-7. Synthetic case study: (a) imposed boundary conditions; (b) captured runoff by inlet devices and manhole overflow

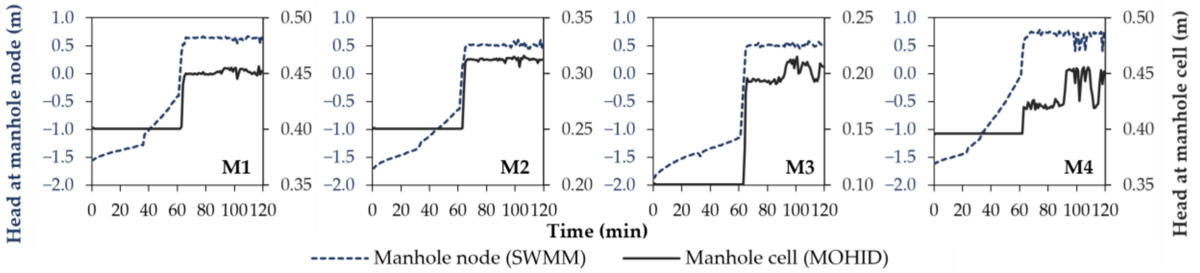


Figure 4-8. Synthetic case study: resulting water head at manholes (SWMM nodes) and at respective 2D cell (MOHID)

The resulting behavior is consistent with the coupling rationale and procedure presented. As expected, the head in manholes increases gradually up to 60 min due to the imposed hydrographs and the inflow from inlets and buildings. When reaching 60 min, due to the boundary condition at the outfall, the system rapidly surcharges, manholes start to overflow, and, consequently, inflow from the inlets stops. As stated, the outflows are mediated by the gradient between the head at the nodes and the respective surface cell. The higher variability of manhole M4's outflow and respective water head is due to a local deceleration of the flow on its surroundings, namely on the nearest inlet, caused by the green area and its associated Manning coefficient.

Figure 4-9 represents the maximum water depth and velocity modulus at maximum water depth in the cells of the 2D domain. The manholes' locations stand out clearly in both results due to the manhole overflow effect. It is observed that the flow spreads accordingly with the road slope, downstream and towards the curb direction, with an increasing velocity along the road.

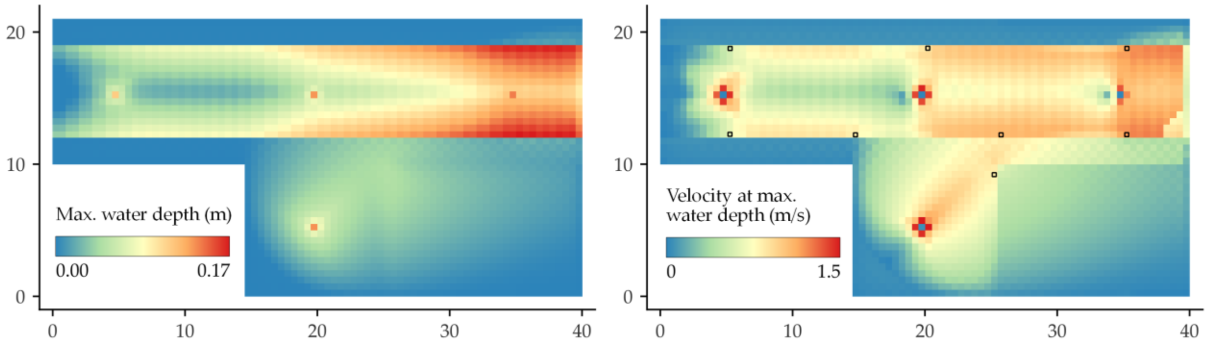


Figure 4-9. Synthetic case study: resulting maximum water depth (left) and velocity modulus at maximum water depth (right)

There are three interesting observations regarding the velocities at maximum water depth: first, there is a local effect of flow acceleration around manhole locations due to the overflows; secondly, there is a deceleration effect upstream of the manholes due to the higher water depths in the cells representing manholes; thirdly, the higher Manning coefficient in the green area results in lower velocities, as expected, and due to such lower velocities, the water is captured by the nearest inlet.

The presented results relate to the third run of MOHID Land, meaning that stability was reached at this point. Across the three runs, the MOHID Land simulation times showed minimal variation (18 min 43 sec, 19 min 04 sec, and 19 min 23 sec), with an average simulation time to the real-time ratio of 16%. All three SWMM runs were completed in under one second.

4.3.2. REAL CASE STUDY: DOWNTOWN ALBUFEIRA

4.3.2.1. REAL CASE STUDY DESCRIPTION

Albufeira is a coastal town in Algarve, south of Portugal, bathed by the Atlantic Ocean. Downtown Albufeira is located at the final section of the Albufeira watershed. The watershed has an area of 26.6 km² and a 4% average slope. Albufeira Creek develops naturally until it reaches the urban area, where it is piped along a stormwater drainage tunnel. This tunnel has an initial rectangular section of 3.0×2.5 m and discharges into Pescadores' beach; it is recurrently silted with sand, limiting its discharge capacity. A sea outfall with a diameter of about 1 m is located at the outfall of this tunnel to convey polluted overflows from the wastewater system into the sea, avoiding potential contamination of coastal waters by non-rainwater that may flow into the tunnel. However, it is silted up frequently, thus having deficient performance. A smaller part of the downtown area watershed of about 40 ha is drained into a minor tunnel with an initial sectional of three barrels of 0.8 × 1.2 m, which suffers some changes along its length, namely cross-section reductions. This tunnel discharges into the sea through a moving bed pontoon, approximately 4 m wide, which also presents discharge limitations due to sand accumulation because of non-self-cleansing velocities and tidal effects (Matos et al., 2016). Figure 4-10 presents the Albufeira watershed, the main urban drainage infrastructures described above, and the urban altimetry. The concave altimetry of the urban area is a major hazard for the occurrence of urban floods.

Figure 4-11 presents photographs of flooding events that occurred in September 2008 and November 2015. The top left and top right images were taken at the same location during different events. Although the study area has no drainage monitoring data, comparison of the rainfall data registered by rain gauges located in its surroundings with respective rainfall probability curves induces an estimated return period of about 10 and 100 years for these events, respectively (Matos et al., 2016).

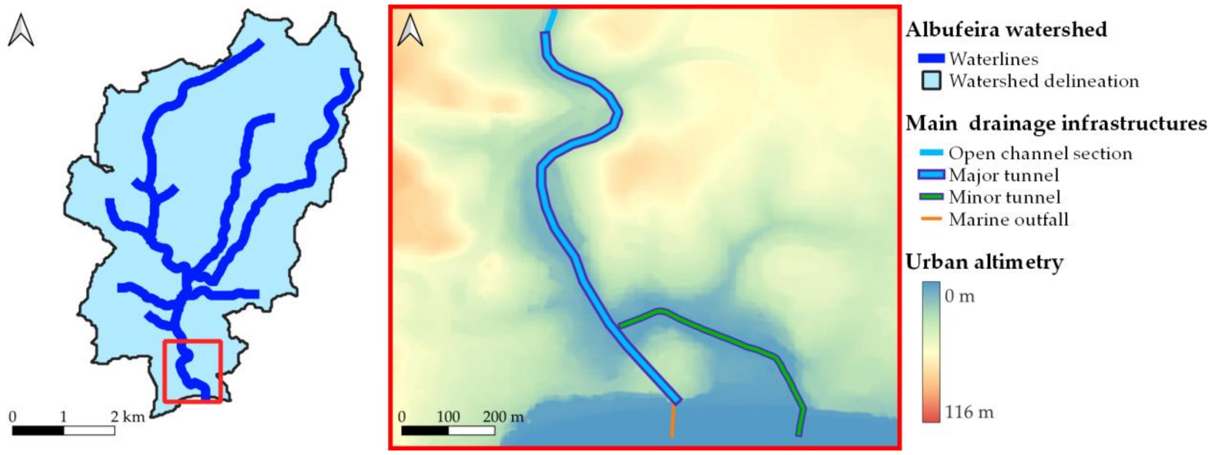


Figure 4-10. Albufeira watershed and main urban drainage infrastructures and altimetry.

The 2D regular mesh used to assemble the urban MOHID Land model is composed of 52,030 cells with a spatial resolution of 5 m. Altimetry data was obtained from a LiDAR DTM of a 1 m spatial resolution, and the surface imperviousness factor was derived from Copernicus Land monitoring services (© European Union, Copernicus Land Monitoring Service, 2018). The municipality delivered vectorial data regarding green and constructed areas and building delineation. The first data set was used to define different Manning coefficients (0.015 for streets, 0.030 for urban green areas, 0.065 for upstream flood plain, and 0.023 for others (Chow, 1959)), while the latter was used to raise by 15 m the elevation of cells that have at least 80% of their area covered by buildings. Infiltration was calculated using the Green-Ampt model, and the soil parameters were selected according to the topsoil USDA classification database for Europe (Ballabio et al., 2016) and reference values (Rawls et al., 1983).

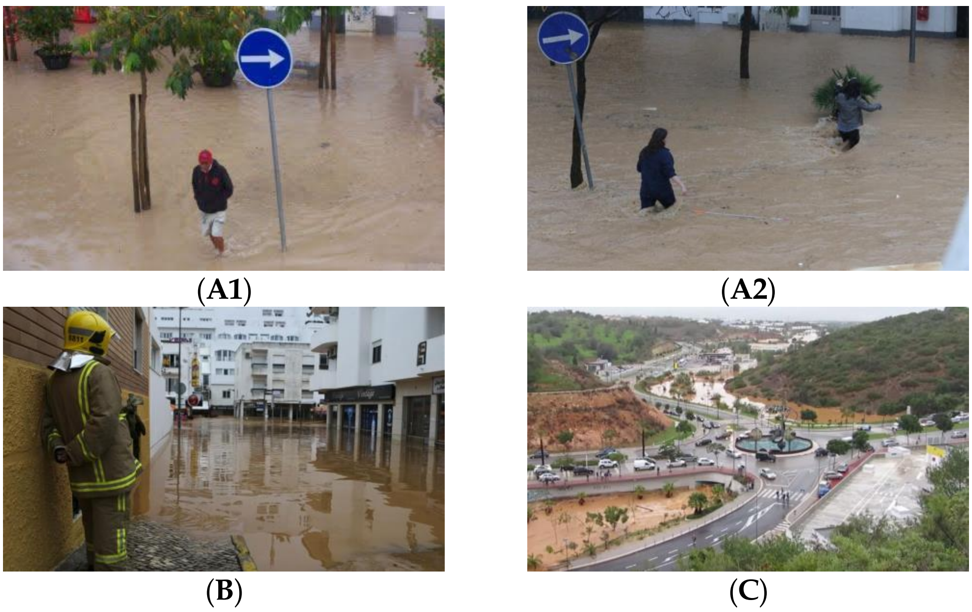


Figure 4-11. Consequences of the rainfall event occurred in September 2008 (A1) and November 2015 (A2, B, C)

The SWMM model comprises 1168 inlets, 403 manholes, 11.9 km of sewers, and three outfalls. Such data were obtained from the municipal drainage infrastructures register and complemented by satellite imagery. Figure 4-12 depicts the SWMM/Land domain and considered drainage infrastructures.

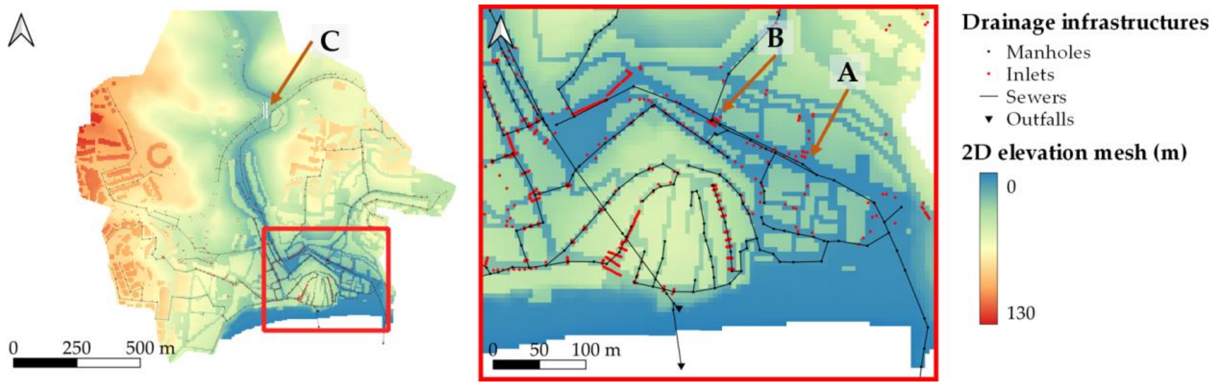


Figure 4-12. Albufeira case study: full SWMM/Land domain (left) and detailed view (right) with the location of the photos (A, B, and C) presented in Figure 11

The described model was submitted to a project rainfall hyetograph fitted to the precipitation regimes in Portugal, with a total duration of 4 hours and a centered rainfall peak of 1 hour (Matos, 1987). The rainfall intensities were estimated using intensity–duration–frequency (IDF) curves estimated to Faro (Brandão et al., 2001), the nearest location with such statistical rainfall treatment. Two return periods were considered: 2 and 10 years. Additionally, outfalls were exposed to tide levels, with the maximum high tide reaching two meters and coinciding with the critical period of rainfall (Figure 13, left). MOHID Land was also used on the upstream watershed area to obtain the Albufeira's Creek hydrograph as inflow into the major drainage tunnel (Figure 4-13, right). The simulations were run for a complete day.

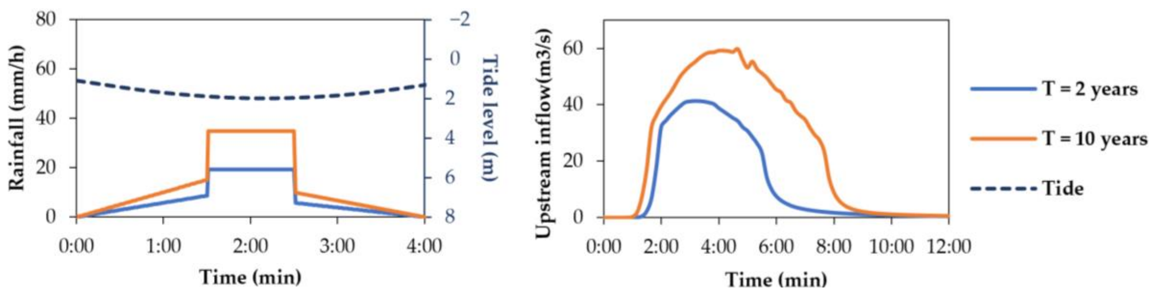


Figure 4-13. Albufeira case study: rainfall intensities by return period and tide level (left) and upstream inflow generated by the rainfalls with different return periods (right)

4.3.2.2. Real case study results

Figure 4-14 presents the results regarding the maximum water depth at each cell. As expected, higher maximum water depths are observed for the 10-year return period rainfall. The 2-year return period rainfall already results in maximum water depths of around 10–20 cm in some areas of the downtown area, owing to its concave orography. In the case of the 10-year return period rainfall, in addition to the aggravation in the area and the depth of the maximum water height reached in the lower part of the city, a retention effect is also visible in the upper part of the domain. This retention occurs in a green park located in the northern area of the city, where the entrance of the major drainage tunnel is located. The retention effect occurs since the tunnel's entrance cannot convey the total flow generated by Albufeira's Creek, leading to the accumulation of water volumes in this area.

The total inlet inflow and the percentage of the domain area affected by maximum water depth ranges are presented in Figure 4-15. The behavior of the inlet inflow evidences higher inflows in the case of the 10-year return period rainfall, as expected due to the higher generated runoff. Additionally, there is a slowly decreasing plateau reached after the rainfall event caused by the water volumes accumulating at sag cells with inlet devices. Since these cells have lower elevations than their neighbor cells, the neighbor water volumes are attracted to these cells due to the inlet water abstraction.

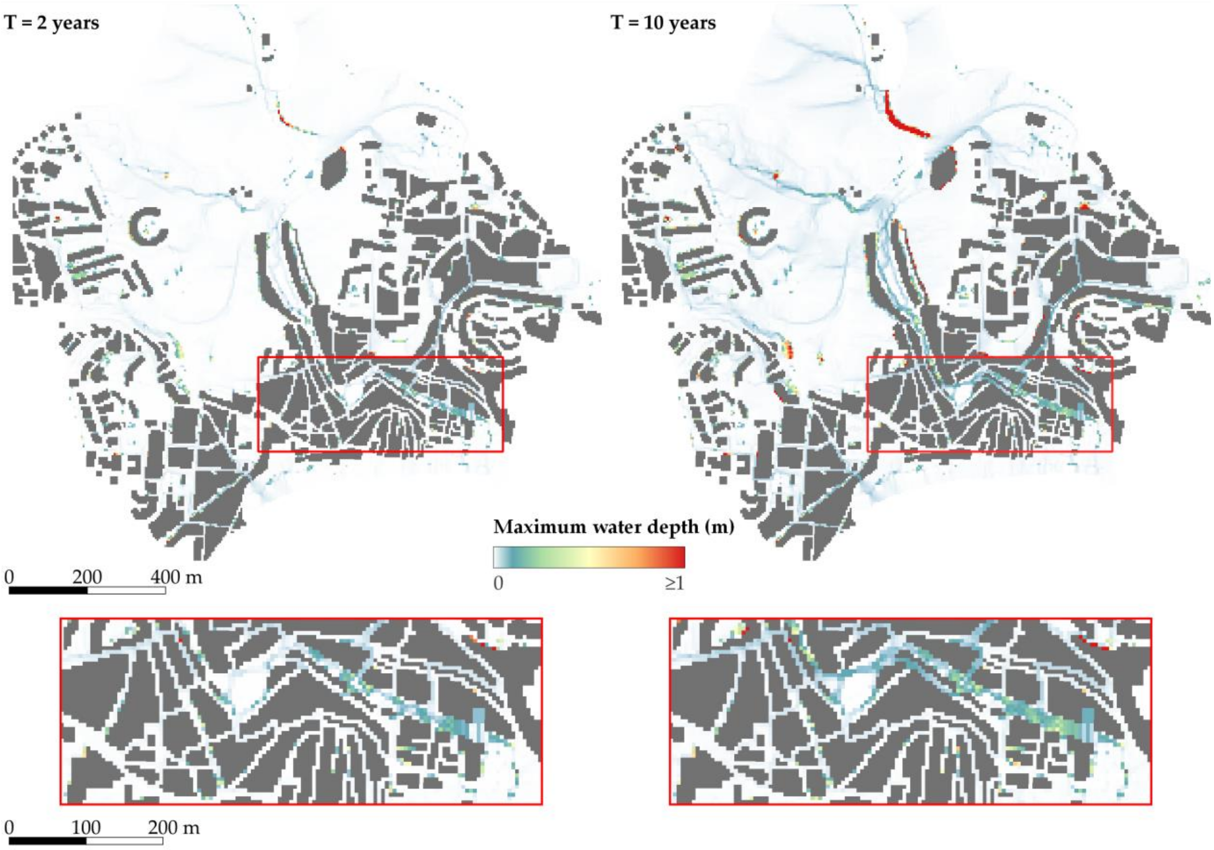


Figure 4-14. Albufeira case study: maximum water depth distributions for the 2- and 10-year return period rainfall

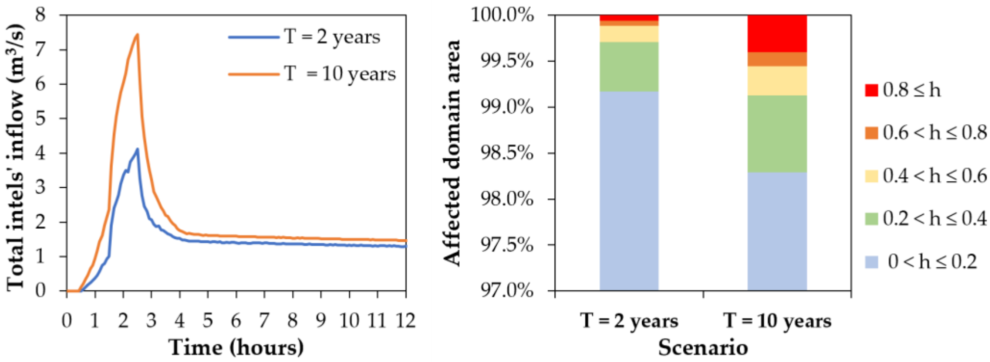


Figure 4-15. Albufeira case study: total inlet inflow (left) and percentage of the domain area affected by maximum water depth ranges for the 2- and 10-year return period rainfalls (right)

Figure 4-16 presents the inflow at three manholes; for example, manhole 1 is located on a narrow street in a location with higher elevation and has one inlet device assigned; manhole 2 is located near the downtown area and has three inlet devices assigned; and manhole 3 is in a critical downtown area, with four inlets assigned. The inflow behavior is coherent with the rainfall pattern, as most of it is captured up to the fourth hour of the simulation. As manhole 3 is in downtown, where water volumes accumulate, runoff is captured over a longer period, gradually decreasing.

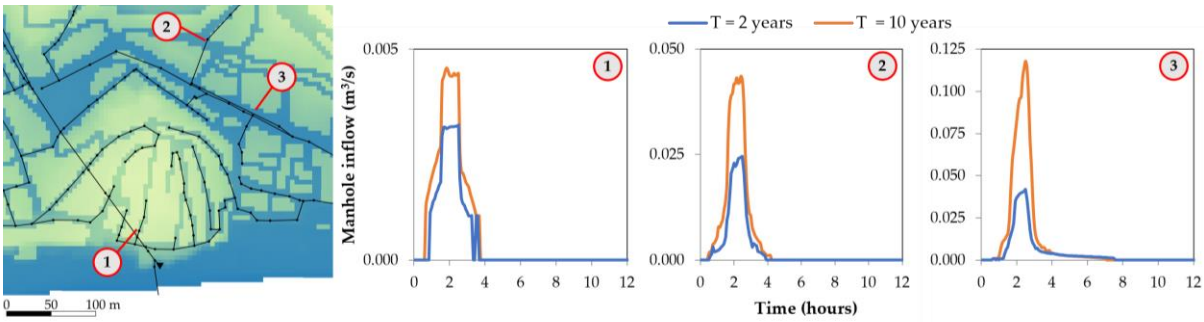


Figure 4-16. Albufeira case study: example of inflows in three manholes at locations 1, 2, and 3

The hydraulic profiles at the maximum water depth of the major and minor drainage tunnels for the 10-year return period rainfall are presented in Figure 4-17. These profiles evidence that, although sewers surcharge, the water level does not reach the surface level for the 10-year return period. Nonetheless, the available spare capacity up to the surface level is reduced in both infrastructures.

Such results reveal that water accumulation at the surface is strongly related to the inlet devices' inefficiency along the urban catchments and highlight the relevance of the 1D/2D simulation to model such processes. The inlet devices for events with higher return periods have dual behavior: on the one hand, with higher generated runoff, higher inflows are expected to be captured, contributing to the surcharge of the sewers and potentializing manhole overflow in downstream locations. On the other hand, as the global efficiency of the inlet devices decreases with higher runoffs, the runoff at the surface keeps increasing along the urban catchments, inevitably accumulating at low points and sag areas.

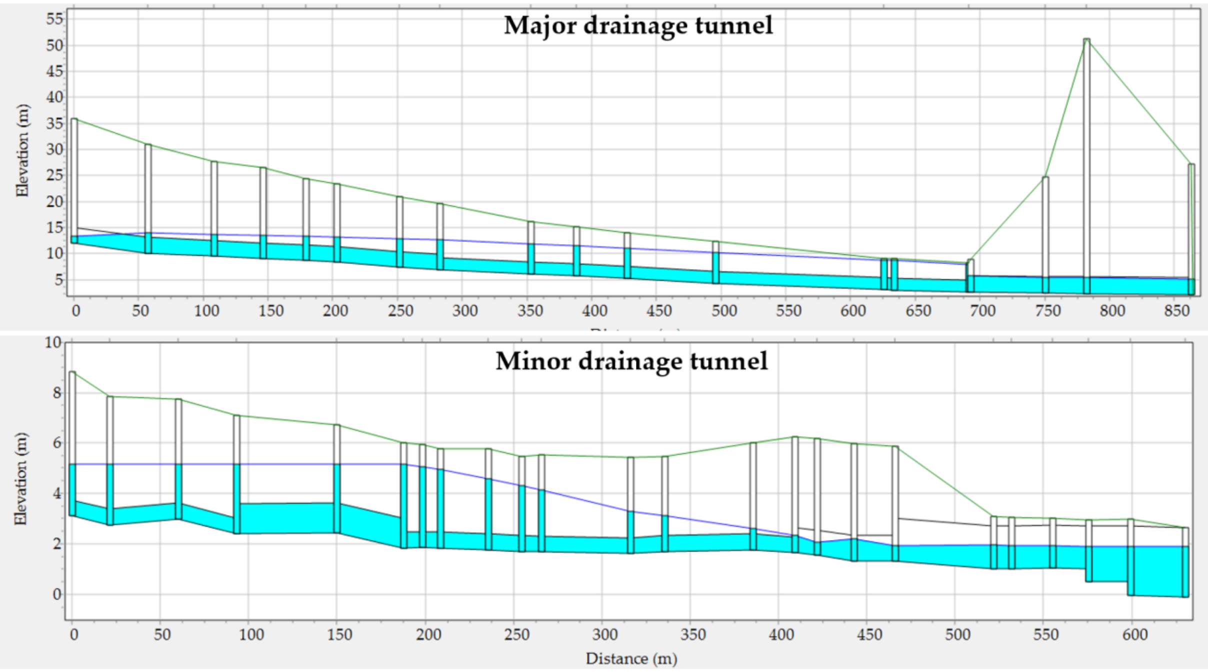


Figure 4-17. Albufeira case study: hydraulic profile at maximum water depth of the major and minor drainage tunnels for the 10-year return period rainfall (top and bottom, respectively)

As no manholes overflowed, no second iteration was needed, and the presented results are related to the first iteration of SWMM/Land. The MOHID Land simulation times were 1 hour and 08 minutes and 1 hour and 58 minutes for the 2- and 10-year return period rainfalls, respectively. These running times mean a ratio of simulation time over real simulated time of 4% and 8%, respectively. For the SWMM runs, the simulation times were 22 and 21 seconds, respectively.

4.4. CONCLUSIONS

The coupling between the SWMM and MOHID Land models assumes that regular 1D simulation models fall short of simulating runoff inflow limitations due to inlet performance constraints and manhole overflow processes. The proposed coupling procedure between two open-source models allows us to consider such processes along the simulation time. Storm inlet devices and manholes are considered contact elements between the two models: the first allows the interception of surface runoff, and the second is responsible for the return of excessive inflows to the surface through manhole overflow.

The SWMM/Land coupling procedure lies in an offline methodology where each model is run sequentially, exchanging information through the resulting time series. The theoretical principle is that the more simulation cycles run, the more accurate the results are. For such purposes, a results analysis (the S/L-OCA) that investigates the need to repeat the simulation cycle is also suggested, based on the existence of manhole overflow and the convergence of the water depth results between the simulation cycles. Although online coupling could be preferable, the methodology herein developed allows us to easily couple other 1D models with MOHID Land, as the only change required is the conversion of the resulting time series to formats readable by each model. Moreover, an online procedure would require more profound changes in computational coding for both models.

Two case studies were considered: a synthetic case study representing a simplified street with a 2D grid made of 2780 cells of 0.5 × 0.5 m, and a real case study in Albufeira, Portugal, with a 2D grid composed of 52,030 with a spatial resolution of 5 m. The results obtained for both case studies are coherent with the theoretical rationale of the coupling. When balancing the achieved simulation times and the results obtained, for the case studies presented, these are considered satisfactory and a step forward compared to conventional 1D urban drainage modeling. Naturally, if applied to larger simulation domains, i.e., with more 2D cells, the MOHID Land running times are expected to be larger. If overflows occur, the overall iterative simulation times can be aggravated.

As for any model, calibration, and validation are only possible in the presence of monitoring data, which we did not have. Nonetheless, considering that both models, SWMM and MOHID Land, present several parameters that allow their calibration, the calibration of the coupled model is also an assured possibility. The results obtained for the case of Albufeira also evidence the need for an accurate elevation grid, especially in low-slope and -sag areas. It is important to emphasize that the simulated events are not real, as rainfall intensities are depicted by a project rainfall hyetograph. Nonetheless, despite the lack of urban drainage monitoring data, the obtained results regarding flooded areas and depths are aligned with past flooding events and critical areas identified by the municipality.

Additionally, considering the complexity of the involved processes, improvements are always possible. Future works on this specific coupling procedure should address the possibility of defining other inlet interception and manhole overflow coefficients, expressions, or relationships based on tabular data, for example. In addition to manholes, overflow is a process that also occurs through inlets. As this process is not directly considered herein, and overflow is only considered in manholes, future developments might also consider such processes. Moreover, the current coupling procedure has the potential to be developed towards a direct coupling procedure, i.e., simultaneous running and data interchange between the models.

Finally, using the SWMM/Land model has a strong potential to better inform decision-makers by simulating different climate projections or flood-related strategies and evaluating the outcomes of such scenarios.

Chapter 5. PROPOSAL OF A RESILIENCE FRAMEWORK FOR URBAN STORMWATER SERVICES

"A map is not the territory it represents, but, if correct, it has a similar structure to the territory, which accounts for its usefulness."

Alfred Korzybski, 1933

The current chapter of the thesis corresponds to the published paper: Barreiro, J., Ferreira, F., Brito, R., & Matos, J. S. (2024). **Development of Resilience Framework and Respective Tool for Urban Stormwater Services**. Sustainability, 16(3):1316. https://doi.org/10.3390/su16031316

5.1. INTRODUCTION

Under the urban scope, resilience theory has become very popular in the last two decades, being applied in diverse fields such as natural disasters, risk management, and climate change adaptation, as well as at different organizational levels, including academics, practitioners, and policymakers (Meerow et al., 2016; Nunes et al., 2019; Cinner and Barnes, 2019; Fourniere et al., 2017).

Three mainstream resilience conceptual focuses are found in the literature: engineering resilience, ecological resilience, and socio-ecological resilience (Fourniere et al., 2017; Nunes et al., 2019).

The engineering resilience concept is mainly connected to the literal definition of resilience, that is, the capacity of the system to return to a previous single steady state after a disturbance. In this sense, the sooner the steady state is reinstated, the more resilient the system is (Angeler et al., 2018).

The work of the ecologist Holling in 1973 (Holling, 1973) is frequently cited in the literature (e.g., (Fourniere et al., 2017; Nunes et al., 2019; Ribeiro and Pena Jardim Gonçalves, 2019)) as a major contributor to the modern resilience theory and a starting point for the adaptation and application of the resilience concept in diverse fields. Holling presented a new paradigm to analyze ecologic systems where, instead of the conventional approach on their stability around an equilibrium state and on the maintenance of a predictable world, the focus is made on the capacity of the system to endure and keep its relationships on the face of unexpected future events (Holling, 1973). The ecological resilience concept reconsiders the notion of a unique steady state, and the focus of the system behavior analysis is shifted to its capacity to absorb disturbances and persist, i.e., to keep its core functionalities but not necessarily to remain the same (Walker et al., 2004). Thus, according to ecological resilience, the higher the magnitude of the disturbance that the system can absorb before being forced to change to a different steady state (not necessarily the initial state), the more resilient the system is (McClymont et al., 2020).

In dynamic and complex systems, continuous disturbances, i.e., stresses, occur over time and have a slow and long-term impact. Considering that a system can be constantly changing even if not threatened by disturbing events (denying the existence of steady states), the socio-ecological conceptual focus considers resilience as an evolutive process that transforms challenges into opportunities (McClymont et al., 2020). Thus, resilience is also about influencing continuous development as a dynamic interplay between sustaining and keeping the status quo and developing towards more sustainable trajectories (Folke, 2006). This approach includes people (as individuals or as a community) as a significant factor for resilience, with a high capacity to influence the trajectory of a system through self-organization (versus lack of organization or organization forced by external factors) and learning and adaptation capacity (Folke et al., 2010).

Angeler et al. (2018) point out that these are not mutually exclusive despite such different conceptual approaches. Meyer (2015) highlights context as a critical factor in determining which resilience characteristics might be more suitable. Consequently, strategies for resilience are also context-dependent and will tend to change over time due to the intrinsic dynamic of the systems (Walker et al., 2004).

Understanding that cities function as complex, interdependent, and integrated socio-ecological systems is crucial to recognizing how resilience-based planning, development, and management can protect life and assets and maintain the continuity of functions (Fourniere et al., 2017). This complexity, in turn, is also imprinted in the existing methodologies for assessing and managing urban resilience. The major developments in this area have been carried out through large-scale R&D projects, typically in partnership and funded by large government agencies and philanthropic associations (Fourniere et al., 2017). Examples of such projects include the Making Cities Resilient Campaign, launched in 2010 by UNISDR (United Nations International Strategy for Disaster Reduction) (UNISDR, 2010); the 100 Resilient Cities campaign, launched in 2013 and pioneered by The Rockefeller Foundation (The Rockefeller Foundation, 2013); the City Resilience Profiling Program, announced in 2012 by UN-Habitat (UN-Habitat, 2012); or the RESCCUE Project (2016–2020), the first large-scale urban resilience-related project funded by the European Union under the Horizon 2020 framework (Aquatec, 2020). Such comprehensive approaches tend to blend conceptual focuses and embrace multi-scalar resilience strategies with top-down (general to specific) and bottom-up (specific to general) contributions. Although granting some malleability and adaptability, they can also create theoretical confusion (Nunes et al., 2019; Wilkinson, 2012), making planning, operationalizing, and measuring resilience challenging (Meerow et al., 2016). Additionally, it is essential to keep in mind that resilience and sustainability are not mutually exclusive developmental rationales (Marchese et al., 2018). Instead, complementary approaches that enhance cities' capacity to endure future uncertainties and promote rational urban development should be considered (Anderies et al., 2013; Zhang and Li, 2018). Such an approach is also imprinted in the UN's 11th Sustainable Development Goal, which aims to make cities and human settlements inclusive, safe, resilient, and sustainable and reinforces the need to deepen the relationship between urban resilience and urban sustainability (Zeng et al., 2022).

Many organizations and stakeholders still poorly understand the concept of resilience [22–24], making it difficult to transpose and implement at the level of urban services, such as stormwater services. The fact that there is no closed resilience definition, although there is a tendency for stabilization (Nunes et al., 2019) and that the complexity of urban systems and different players' responsibilities, objectives, and concerns creates confusion among stakeholders, making resilience-oriented management a challenging task (Balsells et al., 2015).

Blanco-Londoño et al. (2017) refer to two types of methodologies found in the literature to assess flood and stormwater resilience: qualitative methodologies—which include conceptual frameworks, providing a notion of resilience without quantifying it, and semi-quantitative indices, which involve the opinion of experts in their qualitative estimation; and quantitative methodologies—include general resilience metrics, which evaluate resilience in the performance of a system, and structural-based models, which assess resilience by components. Examples of such methodologies are synthesized next.

Restemeyer et al. (2015) propose a qualitative framework based on the contribution of content, context, and process to three resilience characteristics: robustness, adaptability, and transformability, while Balsells et al. (2013) use resistance, absorption, and recovery as characteristics to compare the resilience of different urban design features. Valizadeh et al. (2016) propose the assessment of stormwater infrastructure resilience through an indicator-based model to quantify robustness and recovery capacity by considering urban hydrological characteristics, hydraulic parameters, and network structure properties but without mentioning the respective indicators or calculations. Cardoso et al. (2020) propose a citywide resilience assessment framework (RAF) for climate change focused on the urban water cycle through four dimensions—organizational, functional, spatial, and physical. This framework includes a detailed assessment of citywide and service-related metrics, including the stormwater service. Each metric answer option is assigned a resilience development level, ranging from 1 (incipient) to 3 (advanced), and averaged to get each dimension's development level.

Birgani et al. (2013) suggest a quantitative resilience assessment of urban stormwater systems through four criteria: technical—reflecting the system performance regarding flood volume and recovery time; environmental—reflecting stormwater quality regarding total suspended solids; social—reflecting the aesthetic benefit of measures to beautify the city; and economic—reflecting the construction and maintenance costs. The works of Zonensein et al. (2008), Miguez and Veról (2017), Bertilsson et al. (2019a), and Rezende et al. (2019b) develop a consolidated multi-criteria index to integrate flood resilience into urban planning. Although not directly linked to the minor stormwater systems (dealing only with surface runoff), this index assesses resilience through quantitative indicators at the city block/neighborhood scale. The index evaluates the capacity of resistance—through exposure of buildings and other infrastructures; the capacity of recovery—through economic recovery capacity and social vulnerability; and the capacity to maintain the system—through impact on mobility.

Mugume et al. (2015) use the performance curve concept in stormwater systems and propose a simplified functional resilience index based on the total nodal flood volume and duration, while the work of Matzinger et al. (2019) follows the same concept but uses the complete range of values in the curve—both concepts recurring in 1D models. Barreiro et al. (2021) use an index-based approach to assess urban resilience in flooding scenarios, analyzing the impact of the performance of the drainage systems on the urban space. They propose five indicators to be calculated from 1D/2D model results—the flooding volume at anodes, flooded area, flood duration, the ratio of affected buildings, and affected services—which are averaged to calculate an integrated urban resilience index to floods.

A typical segmentation between qualitative and quantitative methodologies is found in the literature, although they can and should complement each other. The diversity in existent approaches is closely linked to the conceptual fuzziness around the resilience concept, and there is still room for the development and improvement of standardized but flexible frameworks for operationalizing resilience in urban drainage and flood management. For example, the recent work of Cardoso et al. (2020) analyzed 14 urban resilience assessment frameworks for climate change; only two considered stormwater as an urban service/sector. The previously mentioned RAF would benefit from a deeper assessment of the infrastructure performance during a disruptive event. In addition to theoretical discussions, Lhomme et al. (2010) highlight that decision-makers need tools that help them operationalize such methodologies and decide how to tackle critical infrastructures under different disruptive scenarios.

5.2. RESILIENCE FRAMEWORK FOR URBAN STORMWATER SYSTEMS (RESILISTORM)

5.2.1. STORMWATER MANAGEMENT AS AN URBAN SERVICE

As an urban service, stormwater systems are impact-driven structures since they are purposefully designed to deal with weather-related events—namely rainfalls—and can minimize the consequences of rain on the population, goods, and services (Evans, 2017).

Conventionally, such is done by relying on underground sewer networks to convey the runoff as fast as possible to a discharge point, away from its origin. In some cases, this approach alone has been criticized as being accountable for urban flooding and water quality degradation (Birgani et al., 2013), conflicting with sustainable development objectives. In fact, conventional stormwater systems present a limited conveyance capacity (design capacity) that poses great difficulty in dealing with exceeding flows. Additionally, in consolidated urban areas, it is difficult to proceed with massive restructuration, reinforcement, or correction of drainage infrastructures due to the high social and economic costs.

Such limitations were a major motivation for the emergence of sustainable stormwater management techniques in the late 1980s and 1990s (Stahre, 2008). Several approaches, with similar conceptual ideas but different terminologies, have been adopted worldwide since then (Senes et al., 2021): Low Impact Development (LID), used in the USA; Water Sensitive Urban Design (WSUD), used in Australia; or Sustainable Urban Drainage Systems (SUDS), used in the United Kingdom. In the 2010s, the "sponge city" concept emerged in China (Nguyen et al., 2019). These management approaches rely firmly on mimicking the natural catchment properties by adopting nature-based solutions (NBS).

The stormwater management paradigm has shifted from an exclusive urban flood control function to a water and resource management function and an environmental protection and regulatory function (National Association of Flood and Stormwater Management Agencies, 2006). Consequently, the urban stormwater spatial/infrastructural domain spreads beyond the underground infrastructures. It tends to be considered a composition of the minor and the major systems, also called dual-drainage systems (van Duin et al., 2021). The minor system consists of conventional infrastructures, such as inlets, manholes, sewers, open channels, pumps, etc., and most NBS infrastructures. The major system is responsible for conveying runoff to receiving waters and providing overland relief for flows exceeding the capacity of the minor system. This can be achieved by purposefully designed pathways, such as floodways, retention basins, flood relief channels, or unintended pathways that have not been specifically designed—called default pathways (Brown et al., 2009; Butler et al., 2018).

Being an engineering-based service, the design of stormwater systems is based on physical design criteria. These criteria aim to guarantee a proper performance up to given thresholds. Above those thresholds, consequences with a potential negative impact are presumed. From the dual-drainage concept, three flooding thresholds can be considered, associated with different design criteria (2018) (see Figure 5-1):

1. **Drainage surcharge threshold**—corresponds to the sewers' full cross-section level. It is considered when designing the minor system to convey the runoff generated by rainfall with a given return period (design rainfall criteria). From this threshold on, the system starts to surcharge.
2. **Drainage flooding threshold**—corresponds to the level from which manholes overflow and contribute to more significant surface flooding (design sewer overflow criteria). It refers to the maximum capacity of the minor system to convey the stormwater without generating exceeding flows.
3. **Surface flooding threshold**—corresponds to the flow depth from which the flooding's direct impacts on people, goods, or services are expected (design flooding criteria)—also referred to as property flooding threshold.

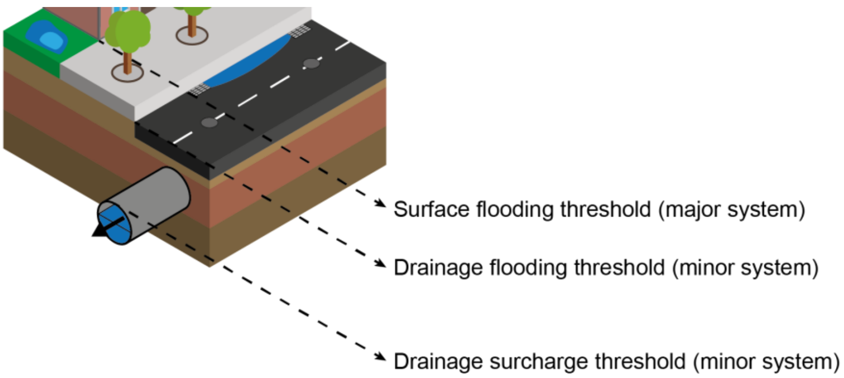


Figure 5-1. Stormwater flooding design thresholds

Apart from the designing perspective, there seems to be little discussion regarding the meaning of such thresholds. It does not seem entirely legitimate to state that the stormwater service fails when demands exceed the design criteria. It is hydraulically clear that if the demands are higher than the ones assumed for design purposes, the system will not be able to perform as desired. Pluvial urban floods, as a hazard, result from the interactions between the rainfall and the watershed, strongly depending on the performance of the drainage system, eventual defenses already implemented, and floodplain interactions (Bertilsson et al., 2019b).

Urban floods must be understood as human problems with natural but also social, economic, and political causes (Bruijn, 2004). Additionally, the increasing pressures induced by climate change on stormwater systems' performance poses a true management challenge. The coastal system's performance is strongly conditioned by sea tides due to a decrease in the discharge capacity, promoting flow deceleration and upstream network surcharge. According to the IPCC, the influence of tides on stormwater systems has been increasing due to climate change. It is certain that, in the near term (2021–2041), the continued and accelerating rise of the sea level will encroach on coastal settlements and infrastructure. If trends in urbanization in exposed areas continue, this will exacerbate the impacts on urban services. Thus, multiple factors interact, generating higher vulnerabilities to climate hazards: rising sea levels combined with storm surges and heavy rainfall will increase combined flood risks [3]. Even if preventive measures and sustainable-oriented management allow cities to better cope with more unpredictable events, it is challenging to prevent their dangerousness entirely (Balsells et al., 2015). Today, it is commonly accepted that floods are virtually impossible to avoid, and efforts must be put into reducing the cities' vulnerability to flooding dangers and adverse impacts (Valizadeh et al., 2016).

In this context, resilience has been recognized as a new paradigm for flood risk management, helping to reduce the effects of disturbances by embracing them as opportunities for more sustainable urban development and as a reality of operating an urban system. From this perspective, stormwater and flood risk management would not just be limited to resistance, based on the idea that there is only one equilibrium situation for the system offered by design criteria, but would also create other viable situations that allow urban systems to continue operating (Balsells et al., 2015). In other words, the resilience approach represents a paradigm shift from conventional "fail-safe" approaches to a holistic "safe-to-fail" view that accepts, anticipates, and plans for failure under exceptional conditions (Bruijn, 2004; Mugume et al., 2015), enhancing the ability to cope with and recover from flooding, especially when considering future risks and related uncertainties (Martínez-Cano et al., 2014; Almeida et al., 2020).

In the presence of such disruptive events, different protection levels amongst urban services and infrastructures and the existing interdependencies and redundancies will define different chain reactions. Such consequences can result from direct interdependencies, i.e., when a given service/infrastructure depends on another for operation or from outcomes of the failure. Both situations trigger cascade effects, i.e., consecutive changes in the performance of urban services and infrastructures due to direct and indirect interconnections (Barreiro et al., 2021). Cascading effects pose significant issues to urban infrastructures and services, although due to the complexity of models and the way service providers work, they are not always completely understood (Evans et al., 2018). Generally, although service providers are aware of existing interdependencies amongst urban services, they typically need to allocate more resources and time to studying and deepening these relations, and collaborative emergency and response protocols are not always encouraged (Barreiro et al., 2020).

Such events affect the performance of several urban services that rely mostly on public space for operation (Barreiro et al., 2020; Evans et al., 2018)—typically, affected services include mobility (buses, trams, etc.) and dependent services (e.g., municipal waste collection and the population itself due to mobility constraints) (Birgani et al., 2013), tertiary activities (shops, offices, restaurants, etc.), and power distribution (although with a low probability of service failure (Almeida et al., 2020)). Naturally, urban flooding impacts are singular in each city, and other effects can be verified. In mature cities, which have already experienced several flooding episodes, it is expected that no critical infrastructures are located within areas prone to flooding, namely emergency (e.g., police and fire departments), health (e.g., hospitals and nursing homes), and power supply infrastructures (Almeida et al., 2020). As an ecological service that frequently includes sensitive water streams and bathing waters (marine or riverine), receiving water is a critical dependent service on stormwater performance mainly due to pollution loads. It is relevant to emphasize that these services do not rely directly on the performance of the stormwater service to operate. However, they can be affected by the consequences of inadequate performance. Thus, profound cascade effects are not expected, and the citizens are mainly affected due to mobility restrictions and "end-of-chain" services (Barreiro et al., 2020). Figure 2 depicts a generic cascade chain in case of failures of stormwater systems and consequent urban flooding impacts.

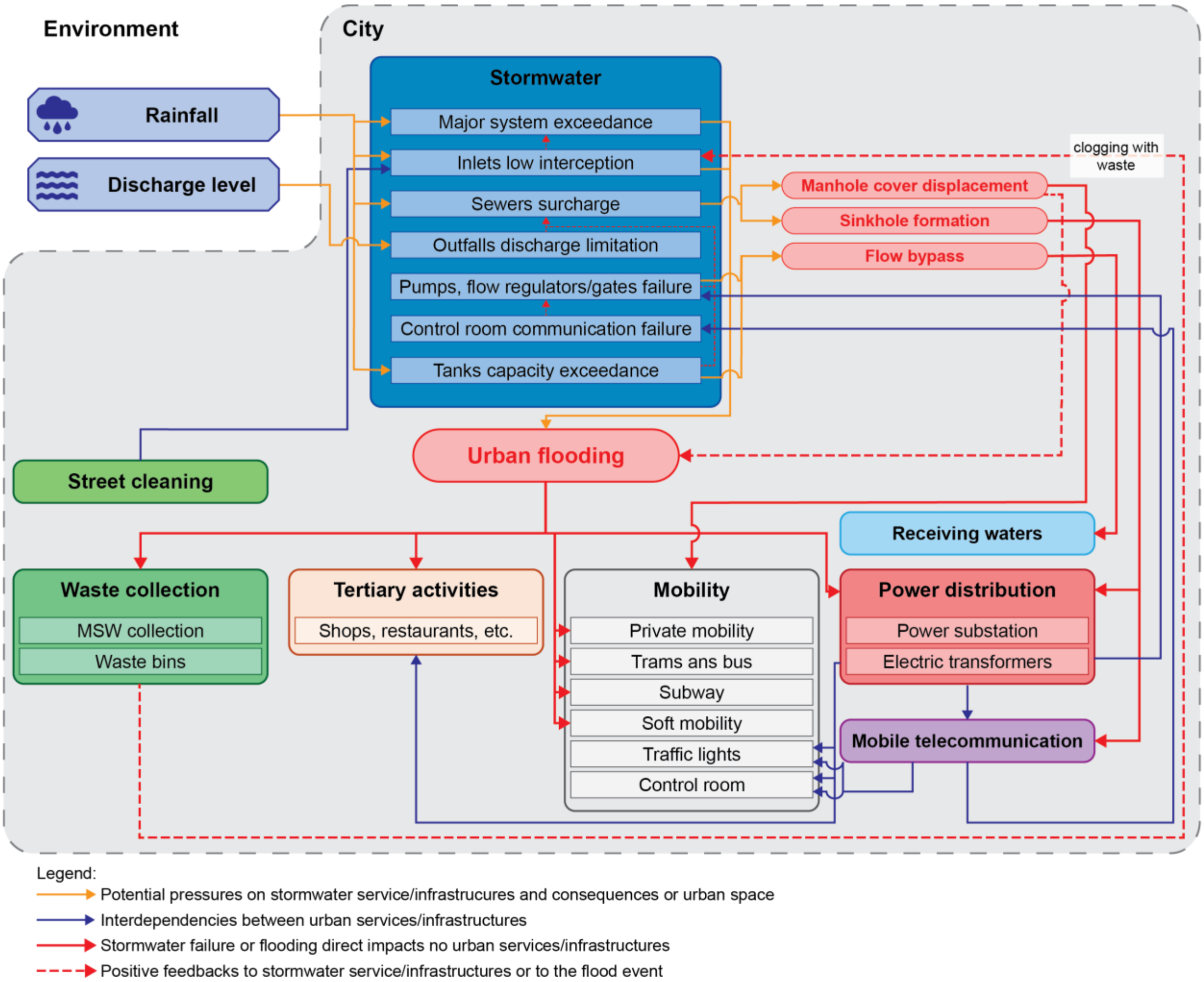


Figure 5-2. Generic cascade chain and feedback for urban stormwater system failure

5.2.2. FRAMEWORK SCOPE

The Resilience Framework for Urban Stormwater Systems (RESILISTORM) fits into a specific resilience approach, i.e., the resilience of a part of a system and to a particular issue or set of problems (Folke et al., 2010). Thus, the framework intends to contribute to the general domain of urban resilience by deepening the understanding of stormwater service resilience and its contributions to overall city resilience (bottom-up approach).

Although there is no closed definition of urban resilience, the adopted definition herein is as follows: «Urban resilience refers to the ability of an urban system—and all its constituent socio-ecological and socio-technical networks across temporal and spatial scales—to maintain or rapidly return to desired functions in the face of a disturbance, to adapt to change, and to quickly transform systems that limit current or future adaptive capacity.» (Meerow et al., 2016). Therefore, RESILISTORM stands within the following boundaries:

- Focuses on the stormwater service as an urban socio-ecological and technical system.

- Considers the temporal scale by integrating past experiences, assessing preparedness for future conditions, including climate change, and allowing a continuous resilience assessment over time.
- Considers the spatial scale by assessing interactions between the stormwater service and other urban services and infrastructures.
- Integrates a comprehensive approach between the three mainstream conceptual focuses of resilience and its main properties and characteristics: engineering resilience through robustness and recovery, ecological resilience through adaptation and flexibility, and socio-ecological resilience through the human potential to transformation.
- Combines qualitative and quantitative resilience approaches into a single framework.

5.2.3. FRAMEWORK STRUCTURE AND RESILIENCE DIMENSIONS

A critical property for resilience and, consequently, for stormwater service resilience is Panarchy. This concept reflects fast and slow dynamics across temporal and spatial cross-scale interactions and interdependencies (Folke, 2006). This property represents the resilience "continuum" that allows cities and services to better prepare for new floods (Bruijn, 2004). It confers to resilience a double behavior as a system's property and a process over time. In this sense, in an initial phase, urban resilience is a property that allows the system to respond to a disturbance at a local and short time scale. On a larger scale, resilience is understood as a process that considers the long-term impact of small-scale disturbances and leads to the condition of being resilient. This cycle allows for a response to challenges in a bidirectional way by feeding the larger and long-term scales with the local and short-term experiments and adjustments (allowing experimentation and testing) and by returning the accumulated memory of the past and successful experiments at large scales to local scales (Balsells et al., 2015; Folke, 2006) (Figure 5-3). Taking advantage of this notion, RESILISTORM considers two dimensions of stormwater service resilience:

- **Strategic Dimension (S)**—Relates to the medium- and long-term planning and organizational capacity to reach the desired objectives by analyzing the internal and external conditions to identify opportunities, threats, strengths, and weaknesses. It aims to assess resilience as a process from the perspective of service management and knowledge.
- **Performance Dimension (P)**—Related to the effective capacity of the service to reach its goals and perform adequately as an urban service. It aims to assess resilience as a

property that allows the service infrastructures to function adequately and minimize adverse outcomes for the city.

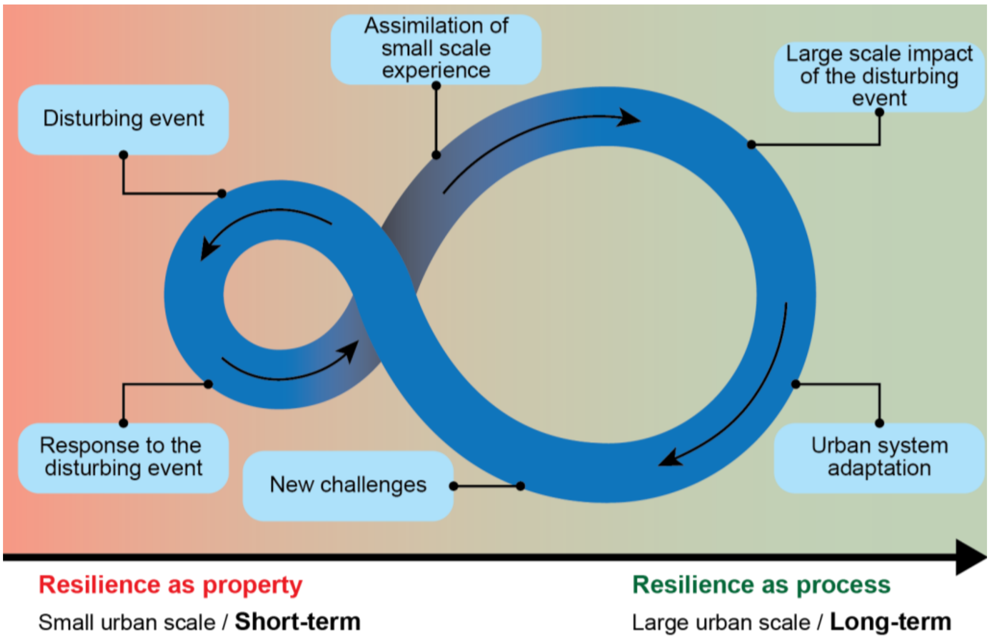


Figure 5-3. Panarchy adapted to stormwater service resilience (adapted from Balsells et al., 2015)

As depicted in Figure 4, the framework follows a hierarchical tree structure: a set of resilience objectives are defined for each dimension, representing the main resilience goals to be achieved and described by criteria that incorporate different aspects to be considered in the objective assessment. In the case of the Strategic Dimension, each criterion is evaluated through a set of indicators resulting from answering question-oriented indicators. For the Performance Dimension, the objectives are assessed through context-dependent indicators that rely on quantitative and model-based indicators.

The development of RESILISTORM is aligned with the Resilience Assessment Framework (RAF) developed on the H2020 project RESCCUE (Aquatec, 2020). The RAF considers four urban resilience dimensions: organizational (integrates top-down governance relations and urban population involvement at the city level), spatial (referring to the urban space and environment), functional (resilience of strategic services), and physical (resilience of services infrastructure) (Cardoso et al., 2020b). While the RAF is firmly focused on urban resilience to climate change, RESILISTORM also focuses on the shocks, stresses, and risks that the service and the infrastructure can endure, allowing a more flexible and context-dependent approach.

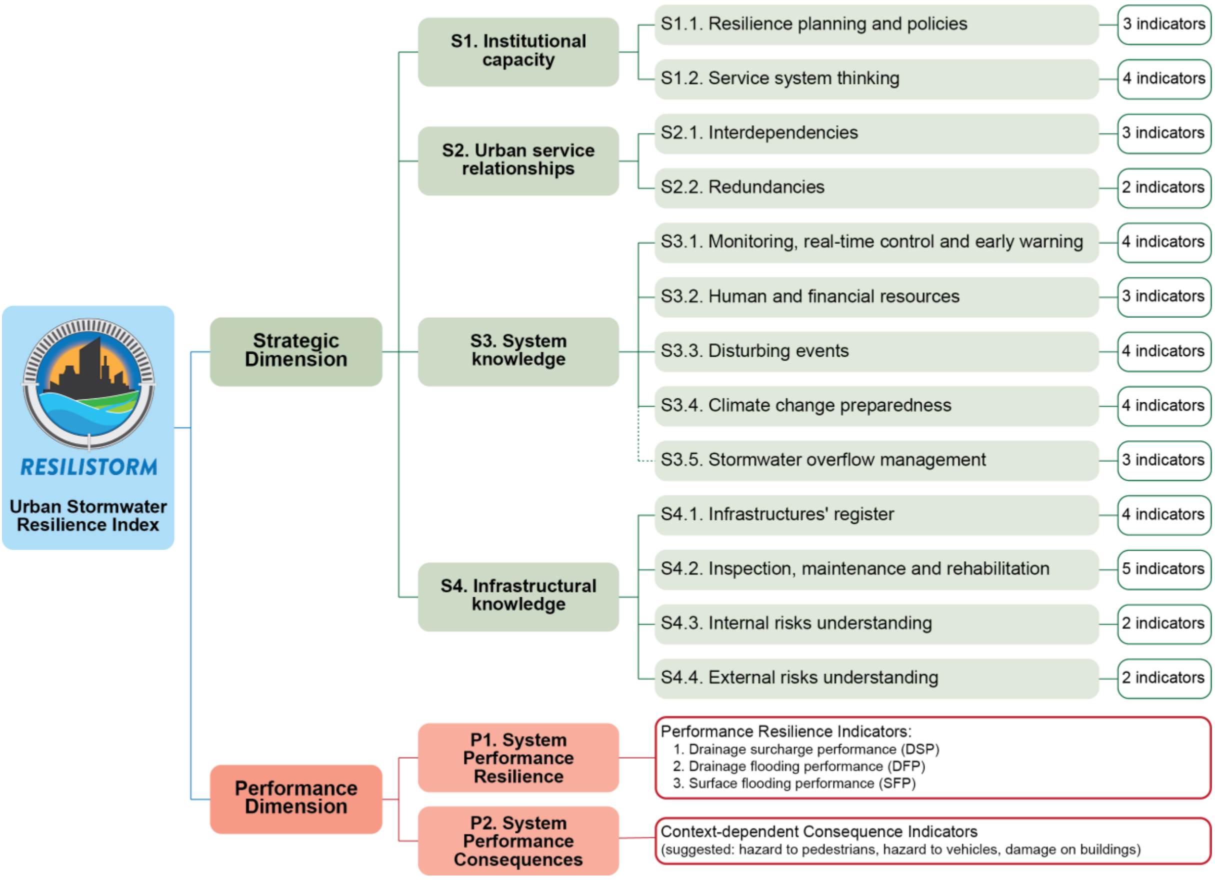


Figure 5-4. Resilience Framework for Urban Stormwater Systems: dimensions, objectives, and criteria

5.2.4. OBJECTIVES, CRITERIA, AND INDICATORS

The selected objectives reflect several factors contributing to urban resilience within each dimension, addressing internal and external aspects of stormwater systems as urban services.

5.2.4.1. STRATEGIC DIMENSION DESCRIPTION

Within the Strategic Dimension, four objectives are defined, aiming at assessing the stormwater service's institutional role and value on the city, relationships with other urban services, and knowledge regarding critical service operational aspects, as follows:

- **Objective S1. Institutional capacity**—This objective aims to understand the stormwater system's institutional positioning as an urban service. Criterion *S1.1. Resilience planning and policies* addresses the existence of a strategic plan and its alignment with other municipal plans and with resilience-oriented thinking, while criterion *S1.2. Service system thinking* assesses the stormwater service's capacity to be included in the city's strategic planning, exchange knowledge with other urban services, be involved in R&D and innovation activities, and provide public engagement and participation opportunities.

- **Objective S2. Urban service relationships**—This objective evaluates three crucial aspects of the stormwater service's positioning from the perspective of the city as a system of interconnected systems. In the first criterion, *S2.1. Interdependencies*, the knowledge regarding dependencies of the stormwater service on other urban services, and vice versa is assessed. The existence of a degree of autonomy of dependent infrastructures is also considered in this criterion. Criterion *S2.2. Redundancies* evaluates the existing redundancies in place as alternative passive or active ways to ensure system performance (e.g., oversized sewers, storm tanks, and multi-purpose flooding areas) and if and how they are communicated to the population, when suitable.
- **Objective S3. System knowledge**—This objective incorporates criteria that reflect practical operational aspects of the stormwater systems. This knowledge is crucial since a key contribution to resilience is the expertise that provides the know-how to address existing problems and future predictable and unpredictable issues. The first criterion, *S3.1. Monitoring, real-time control, and early warning*, evaluates the existence of monitoring equipment and the uses of such collected data, along with the existence of real-time controlled equipment and early warning procedures. Criterion *S3.2. Human and financial resources* reflects the service's adequacy regarding human, financial, and material resources for normal and exceptional conditions. Criterion S*3.3. Disturbing events* verifies the existence of response protocols and recording procedures when a disturbing event occurs while also addressing past/current adaptation and transformation measures/strategies taken as a consequence of such events. Another criterion of this objective, *S3.4. Climate change preparedness*, addresses the knowledge regarding relevant local-scale climate variables/events projections/predictions, the performance evaluation under such conditions, and the implemented/planned measures to address climate change, including mitigation actions. The last criterion, *S3.5. Stormwater overflow management*, applies to combined drainage systems, i.e., systems that convey wastewater and stormwater on the same infrastructures. This criterion is aligned with the recent concerns regarding the discharge of polluted stormwater overflows (European Commission, 2022) and assesses the system's capacity to control and monitor those overflows with adequate equipment.
- **Objective S4. Infrastructural knowledge**—This objective aims to assess three criteria related to the potential fragilities of the system's infrastructure and the existence of procedures to address the consequent risks. The first criterion, *S4.1. Infrastructures'*

register, assesses the existence, completeness, and format of the register of infrastructures and what criteria exist for its update and data sharing. Criterion *S4.2. Inspection, maintenance, and rehabilitation* assesses the existence of and criteria for inspection and maintenance procedures, the rehabilitation trend for sewers/open channels, and the financial effort for such procedures. Criterion *S4.3. Internal risks understanding* pretends to identify intrinsic infrastructural issues such as structural conditions of sewers and manholes and discharge conditions at outfalls, for example, and to what extent they are identified and mapped (if suitable). The last criterion, *S4.4. External risks understanding* follows the same rationale regarding the exposure of the infrastructures to external conditions, such as the exposure of sewers to tide influence (from the hydraulic perspective) or the exposure of inlet devices to clogging.

Each criterion of the Strategic Dimension is assessed through a set of indicators consisting of questions that integrate, mostly, qualitative, multi-, or single-choice answers. All answers are rated between 0 (worst case) and 1 (best case). The complete list and descriptions of the Strategic Dimension's indicators are included in Table A2 of Annex 2, including source references (Cardoso et al., 2020b; LNEC and NOVA, 2023). In this sense, each criterion is rated as the average of the respective indicators' rate, according to Equation 5-1:

$$CR_j = \frac{1}{n}\sum_{i}^{n} RI_i \qquad \textbf{Equation 5-1}$$

where CR_j is the rating of the criterion j, RI_i is the rate of the indicator i, and n is the number of indicators of the criterion j.

5.2.4.2. PERFORMANCE DIMENSION DESCRIPTION

Regarding the Performance Dimension, two resilience objectives were established to address the performance of the service under several disruptive scenarios and its consequences in the urban space. This dimension presents a different structure from the previous one. While the Strategic Dimension is assessed mainly through qualitative or procedure-based data, the Performance Dimension assessment is a model-based approach, requiring data from one-dimensional (1D) and two-dimensional (2D) hydrodynamic models. 1D models are typically used to assess the performance of the minor system, while 1D/2D models are required to determine the flow behavior at the surface and its interactions with the minor system (Leandro and Martins, 2016). The objectives of this dimension are defined as follows:

- **Objective P1. System performance resilience** — This objective assesses the performance of the stormwater system under disruptive scenarios by analyzing its performance curves in light of the three design criteria previously mentioned, i.e., surcharge and overflow thresholds for the minor system and the surface flooding threshold for the major system.
- **Objective P2. Failure performance consequences** — This objective assesses the consequences of the system's performance on the urban space and services. Although context-dependent, a set of hazards is recommended: the hazard to pedestrians, vehicles, and building damage.

The concept of performance curves allows for analyzing the system's reaction during a disruptive event. There are some interpretations and naming variations on these curves' main characteristics and variables when applied to stormwater systems (Hosseini et al., 2016; Matzinger et al., 2019; Mugume et al., 2015), and an effort was made to harmonize them (Figure 5). The time variables in Figure 5 are as follows: t_i is the initial time of the rainfall event; t_{ds} is the time where disruption of the system starts, i.e., performance values reach the admissible performance value (AP); t_{fs} is the time from which the system is in a failure state, i.e., the maximum admissible water depth is reached; t_{rs} is the recovering starting time; t_{ar} is the time where the system retrieves the admissible performance; and t_f is the final time of analysis.

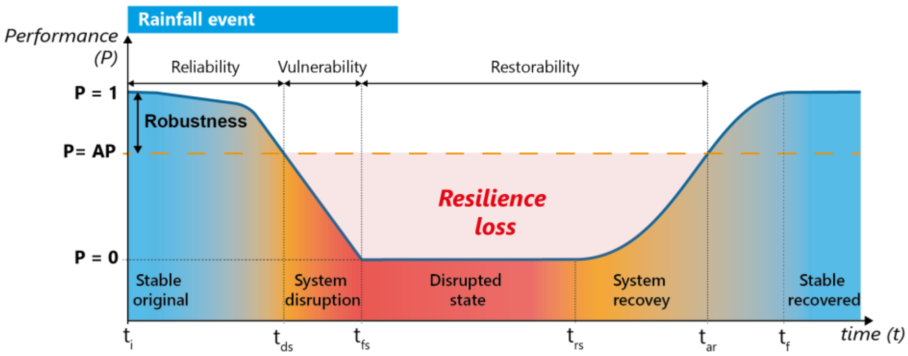


Figure 5-5. Theoretical generalized performance curve for stormwater systems

This performance curve concept is used for the assessment of objective *P1. System performance resilience*, varying the admissible performance thresholds and the failure threshold. The performance curves are obtained by normalizing a state variable of the system, between 0 and 1, through its maximum admissible value and the analysis time (Figure 5-6 and Table 5-1). The state variable curve is controlled by the admissible depth (AD) and failure depth (FD) thresholds, and the normalized performance curve is governed by the admissible performance (AP) and performance failure (PF) thresholds. Resilience loss (R_L) occurs when the performance values surpass the admissible threshold; when the failure threshold is reached, the system enters failure mode. If the admissible threshold is not reached, no resilience is loss and resilience keeps its initial value (R_0 or ${R_0}^P$). Robustness plays a vital role in mediating the possible performance loss. Resilience (R) is then normalized (R_N), considering the duration of the analysis and the available range between the admissible and the failure thresholds.

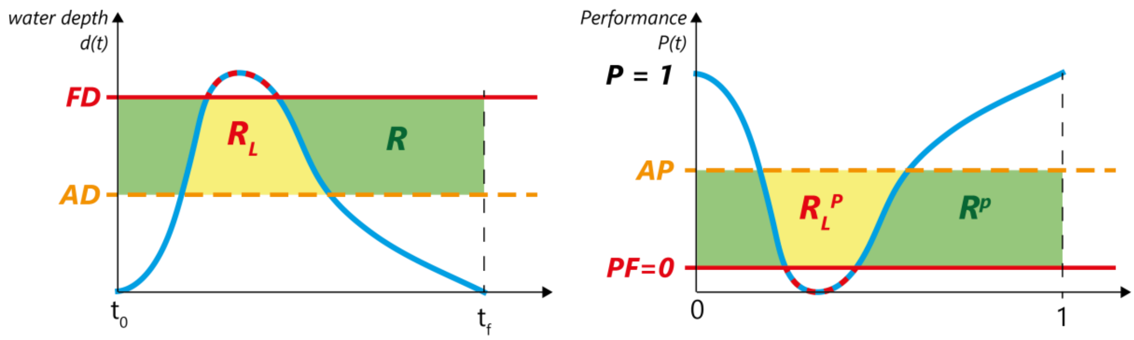


Figure 5-6. State variable performance (left) and normalized performance curve (right)

Table 5-1. Equations for state variable (left) and performance (right) curves

State Variable Curve	Performance Curve
$R_0 = (FD - AD)(t_f - t_0)$	${R_0}^P = AP$
$R_L = \int_{t_0}^{t_f} d(t) - AD$ $being\ d(t) = \begin{cases} AD & if \quad d(t) \le AD \\ d(t) & if \quad AD < d(t) \le FD \\ FD & if \quad d(t) \le FD \end{cases}$	${R_L}^p = \int_0^1 AP - P(t)$ $being\ P(t) = \begin{cases} AP & if \quad P(t) \ge AP \\ P(t) = 1 - \frac{d(t)}{FD} & if \quad PF < P(t) \le AP \\ PF = 0 & if \quad P(t) \le FD \end{cases}$
$R = R_0 - R_L$	$R^P = {R_0}^P - {R_L}^p$
$R_N = 1 - \frac{R_L}{R_0}$	${R_N}^P = 1 - \frac{{R_L}^p}{{R_0}^P}$

In the current implementation, two performance curves are considered for the minor system: the node surcharge performance and the node overflow performance. For both curves, the water depth at the nodes (manholes) is used as a state variable. Regarding the major system, one performance curve is considered: the surface flooding performance, where the water depth at the surface is used as a state variable. The reference and threshold values for these curves are presented in Figure 5-7. In this figure, blue sections represent performance values up to the admissible performance threshold (identified in orange); yellow sections represent performance values between admissible and failure performance thresholds (the latter identified in red); and red sections represent performance values below the failure threshold.

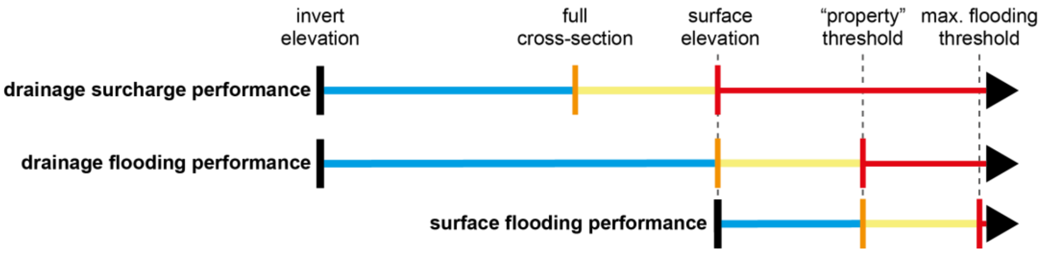


Figure 5-7. Reference and threshold values of stormwater performance curves

Regarding the minor system, each node is weighted as a function of the maximum flow capacity of the linked sewers as in Equation 5-2:

$$NW_j = \frac{max(Q_i, \ldots, Q_n)_j}{\sum_j^m max(Q_i, \ldots, Q_n)_j}$$

being

$$\sum_j^m NW_j = 1$$

Equation 5-2

where NW_j is the weight of the node j and $(Q_i, \ldots, Q_n)$ is the transport capacity of the i to n linked sewers to node j, on a total of m nodes. This weighting method gives higher relevance to infrastructures that convey higher flows, typically increasing to downstream direction. The performance curves are obtained from the results of 1D hydrodynamic models, such as the widely used EPA-SWMM (Rossman, 2015), and the RESILISTORM-tool includes a script for its calculations.

Concerning the major system and the surface flooding performance, its calculation requires the treatment of results from 1D/2D models to get the necessary data. Several types of 1D/2D models have become available in the last decade, including open-source/freeware models (e.g., (Martins, 2015; Courty et al., 2017; Wu et al., 2018; Barreiro et al., 2022)) and licensed software (e.g., (Bentley, 2019; DHI, 2012; Innovyze, 2012)). Due to the heterogeneity of the results' format of such models and the complexity and mesh refinement used, a straightforward methodology to process such results is not herein presented. It needs to be dealt with within each application. For the sake of simplicity, the authors suggest analyzing the surface flooding performance curves at sample points in representative locations of the 2D simulation domain, which can be weighted according to user-defined criteria.

To assess the impact of system performance on the urban space and services, objective *P2. Failure consequences resilience* is strongly context-dependent on identified dependencies or infrastructure/services vulnerable to flooding. A suggestion of indicators for such is presented in Subchapter 6.2.3.2 of the thesis.

5.2.5. URBAN STORMWATER RESILIENCE INDEX

Each objective is rated as the weighted sum of the respective criterion rate, as expressed in Equation 5-3:

$$OR_j = \sum_{i}^{n} CW_i \times CR_i \qquad \textbf{Equation 5-3}$$

where OR_j is the rating of the objective j, CW_i and CR_i are, respectively, the weight and the rate of the criteria i, and n is the number of criteria of the objective j.

The rating of each dimension follows the same rationale as the objectives, being calculated as the weighted sum of the respective objective rate (Equation 5-4).

$$DR_j = \sum_{i}^{n} OW_i \times OR_i \qquad \textbf{Equation 5-4}$$

where DR_j is the rating of the dimension j, OW_i and OR_i are, respectively, the weight and the rate of the objective i, and n is the number of objectives of the dimension j.

A global index, the Urban Stormwater Resilience Index (USRI), is proposed from the dimension rate. The USRI follows the same calculation rationale presented up to now (Equation 5-5) and is also categorized in resilience ranges (Barreiro et al., 2021), as depicted in Figure 5-8.

$$USRI = SDW \times SDR + PDW \times PDR \qquad \textbf{Equation 5-5}$$

where SDW and SDR are the Strategic Dimension weight and rate, respectively, and PDW and PDR are the Performance Dimension weight and rate, respectively.

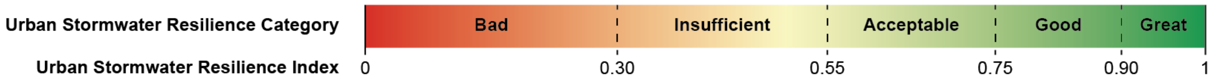


Figure 5-8. Resilience-normalized rating and categorization ranges

5.2.6. RESILISTORM-TOOL

To ease the application of the RESILISTORM framework, an open-source digital tool with a graphical user interface (GUI) was developed based on Python (complete code and testing case available at *GitHub: RESILISTORM-tool*). The tool aims to understand better the RESILISTORM framework roadmap through its application. It allows for the expedited answering of the indicators, aggregate results, and automatic calculation of the metrics/indicators, criteria, objectives, and dimensions ratings of the Urban Stormwater Resilience Index.

The tool introduces the concept of Situation within the framework. A Situation is a given state in the space and time of the system and is defined by:

1. The stormwater system configuration—the combination of infrastructures that compose the system and operational/management rules. For instance, the user may be interested in comparing the current system configuration's resilience with the system's resilience after implementing a given adaptation strategy.
2. The scenario/time frame—a temporal reference for the Situation. It allows for comparing past, present, and future conditions, including climate change.
3. The rainfall return period—a single or a set of rainfall return periods included in the Performance Dimension analysis. These can be real rainfall events or be defined by synthetic hyetographs.

A set of the Strategic and Performance Dimensions answers corresponds to each Situation and, consequently, an USRI. The tool allows users to compare the Stormwater Resilience Index obtained for each Situation.

The GUI of the RESILISTORM-tool is divided into six sections, available from the menu:

- Home Page: where RESILISTORM and the main concepts are presented.
- Study Profile: where the user defines context indicators relative to the study's urban area (such as territorial and catchment domain, population, climate, and built environment) and the stormwater service (such as service utility information and system properties).
- Analysis Manager: where the user finds the Situations Manager, Weights Setup, and Performance Setup. In the Situations Manager, the user defines the Situations intended to be studied. In the Weights Setup, the user sets the weights of each criterion, objective, and dimension. In the Performance Setup, the user selects the performance indicators to be considered in the situation analysis.
- Strategic Dimension: where the user is guided along the several objectives and criteria to answer the respective indicators (Figure 9, left).
- Performance Dimension: where the user gives input regarding the System performance resilience and system performance consequences indicators (Figure 9, right).
- Resilience Dashboard: where the user visualizes the results for a given selected Situation through a series of graphs. This section is divided into three sections: the Situation rating—presents a graph for each dimension rating and for the Stormwater

Resilience Index; the Strategic Dimension rating—presents three graphs: a plot for the answer's completeness, indicating the percentage of indicators answered in each objective, and the objectives and criteria rating, showing the aggregated rating results by objectives and criteria, respectively; and the Performance Dimension rating—presents a graph for each objective, *P1. System performance resilience* and *P2. System performance consequences*, which shows the ratings obtained for the respective indicators for the rainfall return periods considered (Figure 10).

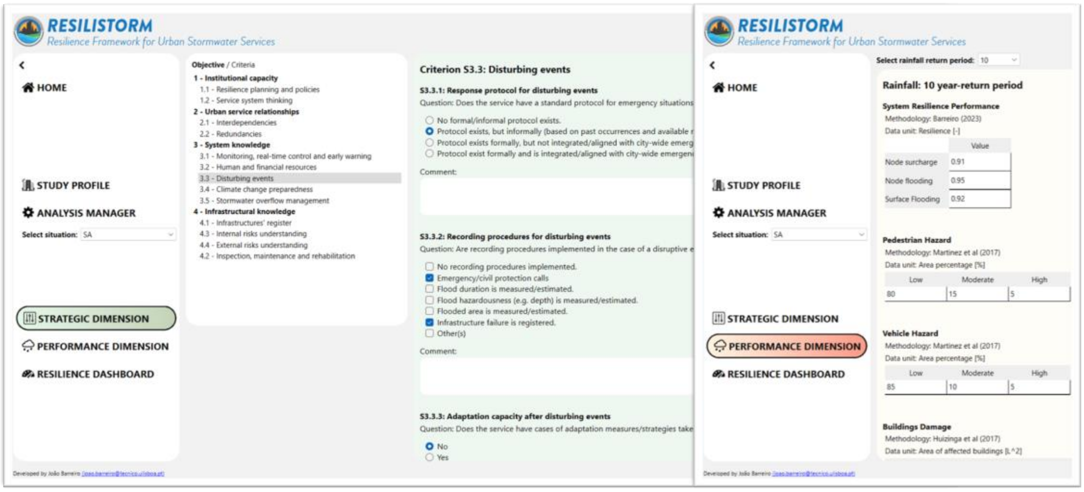


Figure 5-9. RESILISTORM-tool: examples of the Strategic Dimension (left) and Performance Dimension (right) answering

Figure 5-10. RESILISTORM-tool: example of the Resilience Dashboard for testing a stormwater service

5.3. DISCUSSION

RESILISTORM can be applied by government entities or local authorities, urban planners, consultants and professionals in the field, and researchers. Naturally, it requires close contact with the stormwater utility for data collection, including georeferenced data. The first statement regarding application by users is of utmost importance for answering the Strategic Dimension, while the latter statement regarding contact plays a critical role in modeling the system performance and answering the Performance Dimension. Additionally, other urban/municipal georeferenced data, such as terrain elevation and cartography (buildings, roads, etc.), are necessary to set 2D models to assess the consequences of flooding in urban services and infrastructures. Using 1D/2D models is still a developing practice within the urban stormwater field, although examples can be found in the literature (e.g., (Barreiro et al., 2022; Courty et al., 2017; Martins, 2015; Park et al., 2014; Russo et al., 2015; Sañudo et al., 2020)). In this sense, implementing the RESILISTORM framework advances the digital modeling competencies of practitioners engaging with the methodology.

The heterogeneity of the stormwater services' management and the maturity state of utilities pose a challenge in proposing the current resilience objectives and criteria, as well as response options and answer rates for each indicator. Additionally, assigning weights to dimensions, objectives, and criteria introduces an inherent level of subjectivity, as there are no ideal criteria no assign such weights. This subjectivity is also intricately linked to the stormwater services' maturity state, the presence and capacity of data collection mechanisms, and internal/external priorities defined by/for the service. For example, the Strategic Dimension considers organizational, managerial, and maintenance aspects, while the Performance Dimension assesses the actual system performance and its urban repercussions. The query arises: can a stormwater service be considered resilient with a weak level of performance but a robust organizational component? Although subjectivity is acknowledged, there is a hypothesis that the Performance Dimension may generally assume greater weight values, reflecting the practical outcomes of effective strategic service management. These issues underscore the importance of context in evaluating and managing the resilience of urban stormwater services. Recognizing the impact of contextual nuances is critical for enhancing the effectiveness of stormwater management practices and fostering resilience.

The structure of the presented framework accommodates, with relative ease, considerations for improvements or alternative objectives/criteria for the resilience of stormwater services without fundamentally challenging the content presented herein. This adaptability is essential for addressing evolving challenges and incorporating refinements in resilience assessments over time. Similarly, diverse context-induced performance and urban consequences indicators can be pertinent and incorporated into specific applications of the framework and tool. The framework can be used for traditional gray stormwater systems based on buried infrastructure, blue and green NBS systems, or hybrid systems combining gray and blue-green solutions. One notable advantage of an open-source tool is its potential for refinement and improvement by the community. Issues and new developments can be addressed in the online repository structure, facilitating continuous enhancement and fostering a collaborative approach to problem-solving processes and tool enrichment.

5.4. CONCLUSIONS

The lack of a widely accepted definition of resilience poses significant challenges to implementing resilience in urban services like stormwater management. Traditionally, stormwater management aimed to minimize the impact of rainfall through fail-safe approaches. In contrast, the resilience approach embraces a holistic “safe-to-fail” perspective that acknowledges the inevitability of disturbances in complex systems.

To address this, the current work presents a resilience framework and tool for urban stormwater services—RESILISTORM. This framework offers a comprehensive and structured approach to measuring resilience in urban stormwater services. It incorporates a Strategic Dimension and a Performance Dimension, providing segmented and overall resilience ratings that enable management entities to identify critical aspects that may undermine the service’s resilience. The Strategic Dimension emphasizes the system’s organizational and planning capacity to reach the desired resilience objectives. In contrast, the Performance Dimension focuses on the service’s ability to maintain core functions and minimize the impact of disturbances, namely, urban flooding. The RESILISTORM framework is complemented by an open-source digital tool, the RESILISTORM-tool, which expedites data integration, analysis, and visualization. This tool provides a user-friendly interface to input data and generate visual reports, enabling management entities to quickly identify areas of improvement and prioritize investments.

Upon achieving a state of readiness, the framework and tool are primed for practical application to case studies, with several potential applications in urban stormwater management and planning. For instance, decision-making processes can be supported by a systematic approach to measuring and managing resilience by comparing the Urban

Stormwater Resilience Index across different situations. The framework's flexible and context-dependent performance indicators can also facilitate the development of resilience-based management practices, allowing customization and adaptation to specific urban and stormwater contexts. The outcomes of these applications will validate the framework's robustness and play a pivotal role in informing strategies for enhancing the resilience of urban stormwater systems. Future directions may involve continuous refinement of the framework based on feedback from case studies, deepening its applicability to a broader spectrum of performance-related indicators, and expanding to consequences in other urban services with specific sectorial indicators, fostering continual improvement and adaptability.

Ultimately, this work contributes to the practical implementation of resilience theory in urban stormwater systems. It empowers stormwater utilities and stakeholders to proactively address current and future challenges, potentially enhancing the management of urban stormwater services. This will help ensure the uninterrupted functioning of urban services while protecting the population and assets. Additionally, it can bolster urban sustainable development through better planning towards becoming a water-wise city.

Chapter 6. RESILIENCE ASSESSMENT OF URBAN STORMWATER SERVICES: CASE STUDIES IN LISBON, PORTUGAL

"Our struggle for global sustainability will be won or lost in cities."

Ban Ki-Moon, 2012

6.1. INITIAL CONSIDERATIONS

This chapter aims to apply the proposed resilience framework for urban stormwater systems (RESILISTORM) to two real cases in Lisbon City. The case studies were selected due to data availability and past study experiences that allow to know their reality better.

Several objectives are intended regarding this implementation, namely the internal validation of question-oriented indicators of the Strategic Dimension; the endorsement of adequacy and use of context-dependent indicators in the Performance Dimension; the testing of the RESILISTORM-tool whenever possible and fitted to its present capabilities; and naturally, the effective resilience assessment of the study cases under the scope of RESILISTORM framework.

The current chapter corresponds to an initial version of a paper in preparation: Barreiro, J., Ferreira, F., & Matos, J. S. **Resilience Assessment of Urban Stormwater Services: Case Studies in Lisbon, Portugal**.

6.2. METHODOLOGY

6.2.1. RESILIENCE FRAMEWORK FOR URBAN STORMWATER SERVICES

The RESILISTORM framework was used to assess the resilience of the stormwater services (Barreiro et al., 2024). This framework considers Strategic and Performance dimensions for stormwater services' resilience assessment. The Strategic Dimension relates to planning and organizational capacity to reach the desired resilience objectives by analyzing the internal and external conditions to identify opportunities, threats, strengths, and weaknesses. This dimension aims at assessing resilience as a process from the perspective of service management and knowledge. The Performance Dimension relates to the capacity of the service to reach its goals through adequate performance as an urban service. It assesses resilience as property that allows the service infrastructures to function adequately and minimize negative consequences to the city, namely flooding due to rainfall events.

The framework follows a hierarchical tree structure: a set of resilience objectives are defined for each dimension, representing the main resilience goals to be achieved, described by criteria that incorporate distinct aspects to be considered in the objective assessment. In the case of the Strategic Dimension, the framework defines four objectives – *S1. Institutional capacity, S2. Urban service relationships, S3. System knowledge,* and *S4. Infrastructural knowledge* – with a total of 13 criteria. Each criterion is evaluated through a set of indicators resulting from answering question-oriented indicators, totaling 43. For the Performance Dimension, two objectives are defined: *P1. System performance resilience* and *P2. System performance consequences*. The first is assessed through three performance indicators related to the design criteria of the stormwater systems, and the second is evaluated through context-dependent indicators related to the consequences of the performance in the city, such as hazards to pedestrians and vehicles and damage to buildings. This dimension relies on quantitative and model-based indicators that result from 1D and 1D/2D drainage models.

With such a structure, RESILISTORM provides segmented ratings that enable management utilities to identify critical aspects that may undermine the service's resilience. A global resilience rating, the Urban Stormwater Resilience Index, is suggested using a weighted average of each dimension.

6.2.2. 1D/2D STORMWATER MODELLING

As mentioned, the performance indicators are calculated from the outputs of 1D and 1D/2D drainage models. Such models allow the simulation of the underground drainage infrastructure (1D) and the surface runoff (2D).

In the current study, the 1D/2D modeling was carried out using the Storm Water Management Model (EPA-SWMM), developed by the United States Environmental Protection Agency (Rossman, 2015), and the Basic Simulation Environment (BASEMENT), created by the Laboratory of Hydraulics, Hydrology and Glaciology of the ETH Zürich (Vetsch et al., 2006). A loosely-coupling procedure was used (Barreiro et al., 2021), as presented in Figure 6-1.

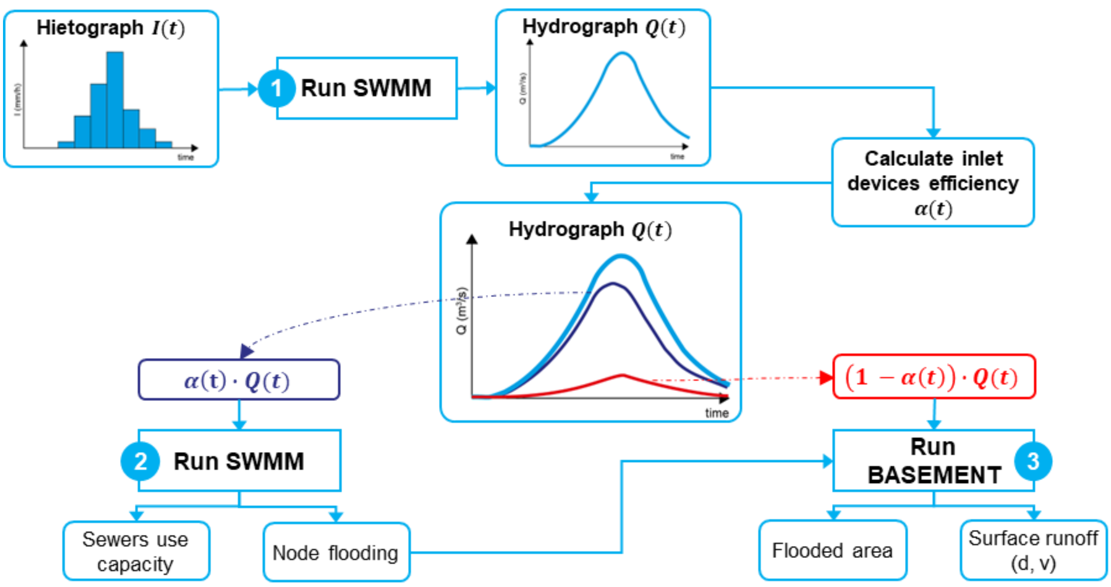


Figure 6-1. Loosely-coupling procedure for SWMM/BASEMENT modeling

This procedure is summarized in the following steps:

1. Run SWMM with the desired hyetograph to obtain each sub-catchment-generated runoff (hydrograph).
2. Calculate the inlet devices' efficiency (α) and the intercepted and non-intercepted runoff parcels in each sub-catchment.
3. Run SWMM with the intercepted runoff, obtaining the hydraulic variables of the flow in the drainage system, including the overflow rates in manholes (nodes flooding), if it occurs.
4. Run BASEMENT with the non-intercepted runoff, obtaining the hydraulic variables of the flow at the surface (such as depth and velocity) and consequently flooded areas. If overflow rates in manholes occur, they are considered an input discharge in the 2D mesh cell where the manhole is located.

The setup of the SWMM project requires specific data for various infrastructural components. Manholes require information regarding invert elevation and the depth from the invert to the ground. Sewers or channels need details on cross-section shape, length, and roughness. Storm tanks require data on invert elevation, storage unit depth, and a storage curve, which indicates the surface area as a function of water depth. Pumps require information on the type and characteristic curve of the pump, as well as startup and shutoff depths. Finally, outfalls necessitate data on invert elevation and the discharge boundary condition. This data is typically available in the drainage infrastructure register.

To assemble the BASEMENT project, it is necessary to construct a topographic 2D triangular mesh of the study area, combined with a particular type of covering, each with distinct roughness coefficients. Moreover, flow sources must be considered, namely non-intercepted runoff and manhole overflows. Finally, reference sections can be designated to obtain results such as flow rates and water heights at specific cross-sections, apart from the results obtained for each node or face of the mesh.

6.2.3. INDICATORS OF THE PERFORMANCE DIMENSION

As mentioned, the RESILISTORM framework sets the Performance Dimension indicators as context-dependent, meaning that depending on each application, different indicators can be considered to reflect better the needs of the resilience assessment and the context of the city and the stormwater service. This dimension is divided into two objectives: *P1. System performance resilience* and *P2. System performance consequences*. The current application uses the suggested indicators by Barreiro et al. (2024), although with minor differences, explained next.

Each indicator of the Performance Dimension is calculated by performing a weighted average of the resilience of each element (nodes for the minor system and surface cells for the major system). The nodes of the minor system (1D) are weighted as a function of the maximum flow capacity of the linked sewers (Barreiro et al., 2024), and cells of the major system (2D) are weighted as a function of their area.

These indicators are assessed based on performance curves, where an admissible performance level (AP) is set. When the system's performance is below this threshold, resilience is lost (R_L) as the system is not operating at the desired levels. When the performance reaches the performance failure level (PF), the system fails. The integral of the performance curve between these thresholds defines the resulting resilience (R).

6.2.3.1. Objective *P1. System performance resilience*

The performance curves considered for objective *P1. System performance resilience* are obtained by normalizing the selected state variables with the performance failure depth (corresponding to the performance failure threshold), as in Equation 6-1 and Figure 6-2:

$$P_i(t) = 1 - \frac{d_i(t)}{FD_i} \qquad \textbf{Equation 6-1}$$

Where $P_i(t)$ is the performance level at the instant t, $d_i(t)$ is the state variable value at the instant t, and FD_i is the failure threshold/depth considered for the state variable i. The respective admissible depth (AD) and failure depth (FD) thresholds are presented in Table 6-1.

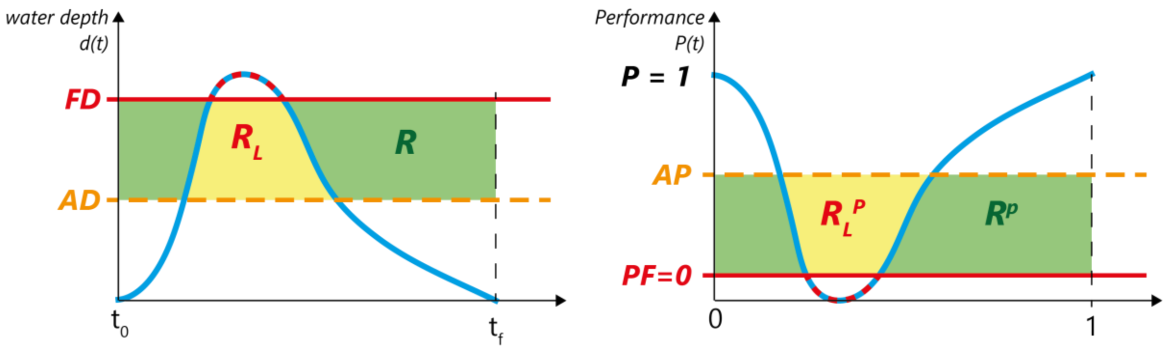


Figure 6-2. State variable performance (left) and normalized performance curve (right)

In practice, for the minor system, the water depth time series resulting from the SWMM simulations are analyzed and converted to performance curves, allowing the calculation of the minor system surcharge and minor system flooding indicators for each node and for the system. This procedure is made through a developed auxiliary tool that reads data from the resulting binary files from SWMM (.out). This tool is open-source and available at the

RESILISTORM repository, with a graphical user interface (GUI) as presented in Figure A1 of Annex 3.

Table 6-1. Considered state variables and performance thresholds for the indicators of the System performance resilience objective

Indicator	State variable	Admissible depth (AD)	Failure depth (FD)
Minor system surcharge	Water depth above the node invert	Maximum full cross-section depth of the connected sewers	Node maximum depth
Minor system flooding	Water depth above the node invert	Node maximum depth (up to terrain elevation)	Node maximum depth + Minor system threshold
Major system flooding	Water depth at surface*	Minor system threshold (0.15 m)	Major system threshold (0.30 m)

*If the 1D model is set adequately regarding the ponding at nodes, this state variable can also assume the water depth above the node invert.

Regarding the major system flooding indicator, as the SWMM projects of the case studies were not defined to allow ponding at nodes, its calculation is made from the water depth results obtained from BASEMENT. The resulting output files from the BASEMENT simulations (*.dat or *.sol), namely water depth and velocity, are also analyzed with a developed open-source tool to calculate the indicator of major system flooding (MSF), the indicator of hazard to pedestrians (IHP), and the indicator of hazard to vehicles (IHV). The GUI of this tool is presented in Figure A2 of Annex 3.

6.2.3.2. OBJECTIVE *P2. SYSTEM PERFORMANCE CONSEQUENCES*

Regarding the second objective, *P2. System performance consequences*, three indicators were considered, as suggested by Barreiro et al. (2024): Indicator of Hazard to Pedestrians (IHP), Indicator of Hazard to Vehicles (IHV), and Indicator of Damage to Buildings (IDB).

INDICATOR OF HAZARD TO PEDESTRIANS (IHP)

The Indicator of Hazard to Pedestrians is calculated using the pedestrian's hazard classification proposed by the Department of Environment, Food, and Rural Affairs of the UK Environmental Agency (Udale-Clarke et al., 2005) as a flow velocity and depth function. The degree of flood hazard for pedestrians is calculated according to Equation 6-2.

$$HR = d \times (v + 0.5) + DF \qquad \textbf{Equation 6-2}$$

Where HR is the degree of flood hazard for pedestrians, d is the flow height (m), v is the flow velocity (m/s), and DF is the debris factor, calculated based on the flow height (0.5 if $d \leq 0.25$ or 1 if $d > 0.25$). According to this methodology, four hazard classifications are considered, and in the present assessment, each hazard class was assigned a rate (HP^{rate}), as presented in Table 6-2.

Table 6-2. Degree of flood hazard for pedestrians (Udale-Clarke et al., 2005) and respective assigned weights

Flood Hazard Degree	Hazard Classification	Description	HP^{rate}
$HR \leq 0.75$	Low	Caution for all	1.00
$0.75 < HR \leq 1.25$	Moderate	Danger for some—includes children, the elderly, and the infirm	0.53
$1.25 < HR \leq 2.00$	High	Danger for most—includes the public	0.21
$HR > 2.00$	Very high	Danger for all—includes emergency services	0.00

Thus, the degree of flood hazard for pedestrians (as a function of the flow velocity and depth) is the state variable, which is normalized by the assigned rate, resulting in the related normalized performance curve for each cell of the simulation domain (as exemplified in Figure 6-3). Following the rationale of the previous indicators, the resilience associated with the IHP at each cell corresponds to the integral of the respective performance curve (green area in Figure 6-3).

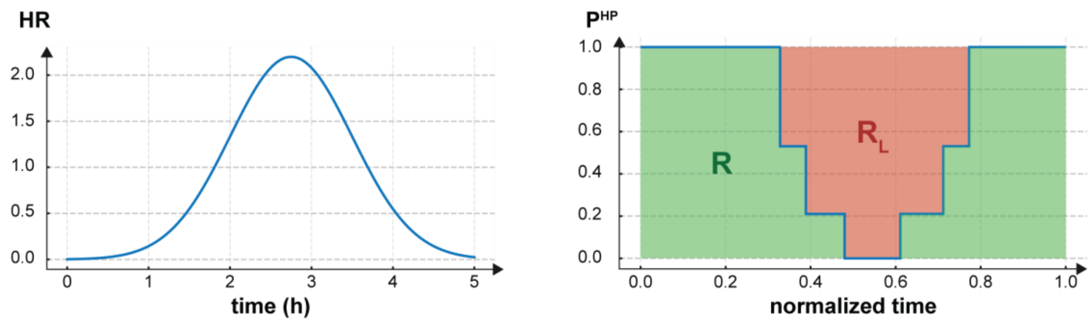


Figure 6-3. Example of a flood hazard for pedestrians' curve (left) and normalization into the respective performance curve (right)

Consequently, the calculation of the IHP for the entire domain is performed by weighting the IHP at each cell regarding the respective area, as shown in Equation 6-3 and Equation 6-4.

$$IHP = \sum w_i \times \int_0^1 P_i^{HP} \quad \textbf{Equation 6-3}$$

$$w_i = {}^{A_i}/_{A_t} \ \ and \sum w_i = 1 \quad \textbf{Equation 6-4}$$

Where w_i is the weighted area and A_i is the area of the cell i, P_i^{HP} is the performance curve of the flood hazard to pedestrians, and A_t is the full domain area.

INDICATOR OF HAZARD TO VEHICLES (IHV)

The assessment of the hazard to vehicles was conducted according to the vehicles' hazard classification proposed by Martínez-Gomariz et al. (2017), assuming the *Seat Ibiza* as the reference model for light passenger vehicles. Like the previous indicator, hazard classifications are defined based on flow characteristics, as presented in Table 6-3, and rates are assigned accordingly (HV^{rate}).

Table 6-3. Degree of flood hazard for vehicles (Martínez-Gomariz et al., 2017) and respective assigned weights

Flow Properties	Hazard Classification	Description	HV^{rate}
$d \leq 0.28$ and $M \leq 0.40$	Low	No damage to vehicles, regular traffic expected	1.00
$d \leq 0.28$ and $0.40 < M \leq 0.55$	Moderate	Low probability of damage to vehicle, traffic might be conditioned	0.35
$d > 0.28$ or $M > 0.55$	High	Considerable probability of damage to vehicle, traffic must be conditioned	0.00

Definitions: d is flow depth (m); $M = d \times |v|$ is the flow momentum (m²/s); and $|v|$ is the flow velocity modulus (m/s).

Thus, the conjugation of the flow velocity and depth constitutes the state variable, normalized by the assigned rate, resulting in a related performance curve for each cell of the simulation domain (as exemplified for the previous indicator in Figure 6-3). Following the same rationale as the IHP, the calculation of the IHV for the whole domain is performed by weighting the IHV at each cell regarding the respective area, as shown in Equation 6-5.

$$IHV = \sum w_i \times \int_0^1 P_i^{HV} \qquad \textbf{Equation 6-5}$$

Where w_i is the weighted area and A_i is the area of the cell i (Equation 6-4), P_i^{HV} is the performance curve of the of hazard to vehicles, and A_t is the full domain area.

INDICATOR OF DAMAGE TO BUILDINGS (IDB)

The potential damage to buildings considers the typology of building uses and the maximum water level reached at the façade of the building. European curves of Damage Factor vs. Water Height for different building uses were considered (European Commission. Joint Research Centre. et al., 2016). These curves were normalized according to their maximum building damage factor and, for the sake of easiness of data processing, transformed into a step-like function (Figure 6-4).

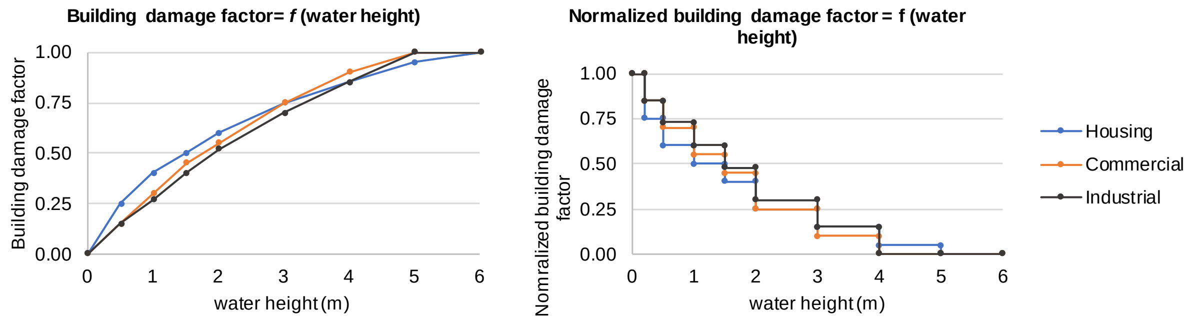


Figure 6-4. Curves of damage factor and normalized damage factor to buildings

The IDB is calculated by weighting the fraction of the number of affected buildings by using typology and water height class with the weight estimated from the damage curves, as represented in Equation 6-6.

$$IDB = \frac{1}{K}\sum_{u}\sum_{i} K_{u,i} \times FD_{u,i}^{N}$$ **Equation 6-6**

Where K is the total number of buildings, u is the building use typology, i is the class of maximum water height reached at the facade of the building, $K_{u,i}$ is the number of buildings with use typology u affected with maximum water height reached at the facade of the building of class i, and $FD_{u,i}^{N}$ is the normalized building damage factor to buildings of use typology u affected with maximum water height reached at the facade of class i.

6.2.4. URBAN STORMWATER RESILIENCE INDEX

Each dimension of the framework is rated as the weighted average of the respective objectives, as the objectives' rating is calculated likewise concerning the respective criteria. Ultimately, the application of RESILISTORM provides the Urban Stormwater Resilience Index (USRI), the weighted average between the Strategic and Performance Dimensions. A qualitative categorization of this index is also suggested (Barreiro et al., 2024), as shown in Figure 6-5.

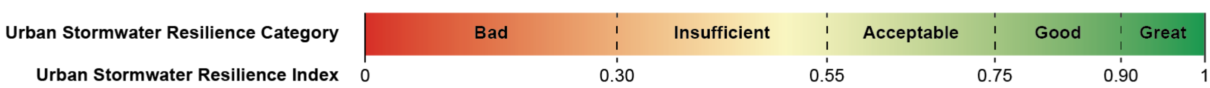


Figure 6-5. Resilience normalized rating and categorization ranges

The chosen scale imposes a higher degree of demand on the values obtained for this index by applying a decreasing exponential progression. The same relationship was considered for the proposed rates for the IHP and IHV indicator categories, following the function of Equation 6-7 and presented in Figure 6-6.

$$f(x) = (1 - x)e^{0.7x}$$ **Equation 6-7**

Where $f(x)$ is the rate for hazard indicator classes or USRI category and x is the i-nth threshold ([0.0, 0.5, 1.0] for IHV and [0, 0.33, 0.67, 1.0] for IHP).

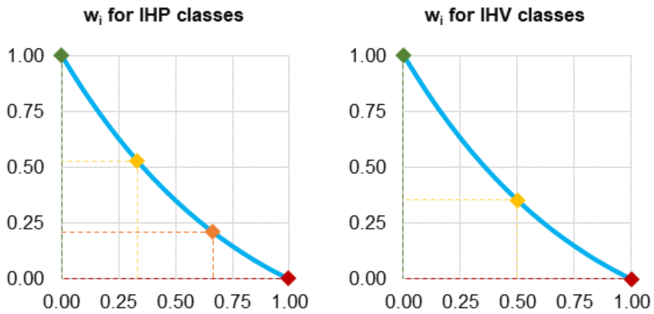


Figure 6-6. Weight function for IHV and IHP classes

6.3. RESILIENCE ASSESSMENT OF THE STUDY CASES

6.3.1. OVERVIEW OF THE CASE STUDIES

6.3.1.1. LISBON CITY AND DRAINAGE SYSTEMS

Lisbon is Portugal's capital city, with a total of nearly 546 thousand inhabitants in 2021, and it is estimated that the daily population increases by 60% due to commuting movements (Lisboa E-Nova, 2021), to which tourist movements must be added. This phenomenon increases the demands on the city's essential and critical services.

Lisbon's vision is to be one of the best cities in the world to live in, a globally more sustainable city at environmental, economic, social, financial, and political levels, to have the resources managed to safeguard its identity and increase its resilience and to improve the present situation without jeopardizing future generations. Lisbon Municipality has been developing intensive work towards resilience. It is proactively committed to increasing the city's resilience, from social exclusion to economic stresses and seismic shocks to flooding. This vision is mirrored not only by international partnerships, such as the Making Cities Resilient campaign's framework from UNISDR, the 100 Resilient Cities, hosted by the Rockefeller Foundation, and the C40 Cities Network but also through several strategic and action plans at the local level, such as the Municipal Master Plan and the Municipal Strategy for Climate Change Adaptation. Moreover, Lisbon has been an active partner in several EU projects, crucial media of experiences and know-how interchange (Telhado et al., 2020).

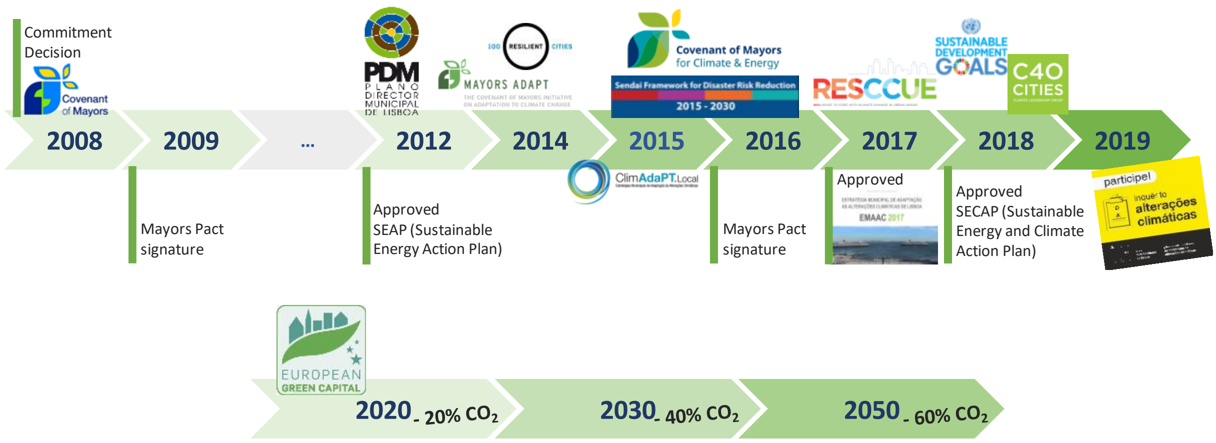


Figure 6-7. Timeline of Lisbon's main resilience-related commitments and partnerships (Telhado et al., 2020)

Regarding urban drainage, the municipality is served by three systems: Alcântara, Beirolas, and Chelas (Figure 6-8). The most extensive system, Alcântara, serves about 755.000 population-equivalents. Despite the efforts to enforce separate drainage systems since the last decade of the XX century, the Alcântara system has a practical combined behavior, transporting wastewater and stormwater through the same infrastructure. Due to the terrain's orography, the "retail" drainage system is entirely gravity-fed, flowing towards the banks of the Tagus River. When reaching the lower areas of the city, the flow is pumped by 11 pumping stations (PS) through approximately 10 km of interceptors and lift conduits to the Alcântara wastewater treatment plant (WWTP). The exception lies in the "upper zone" of the Alcântara catchment (E), which flows are directed by gravity to the WWTP from the Caneiro de Alcântara. The control of stormflows reaching the "bulk" system and the WWTP is made through the PS and storm overflows (typically side or frontal weirs) equipped, or not, with flow control and tidal valves, although with limited capacity for acting on polluted discharges.

In Lisbon, the "retail" drainage system is managed by the Sewage Department of the Municipal Maintenance and Conservation Office. Águas do Tejo Atlântico (AdTA), a limited company with public capital, operates the "bulk" system with a concession contract. Given the shared objectives between these entities regarding the proper functioning of the drainage system, there has been an environment of close collaboration concerning interventions and procedures.

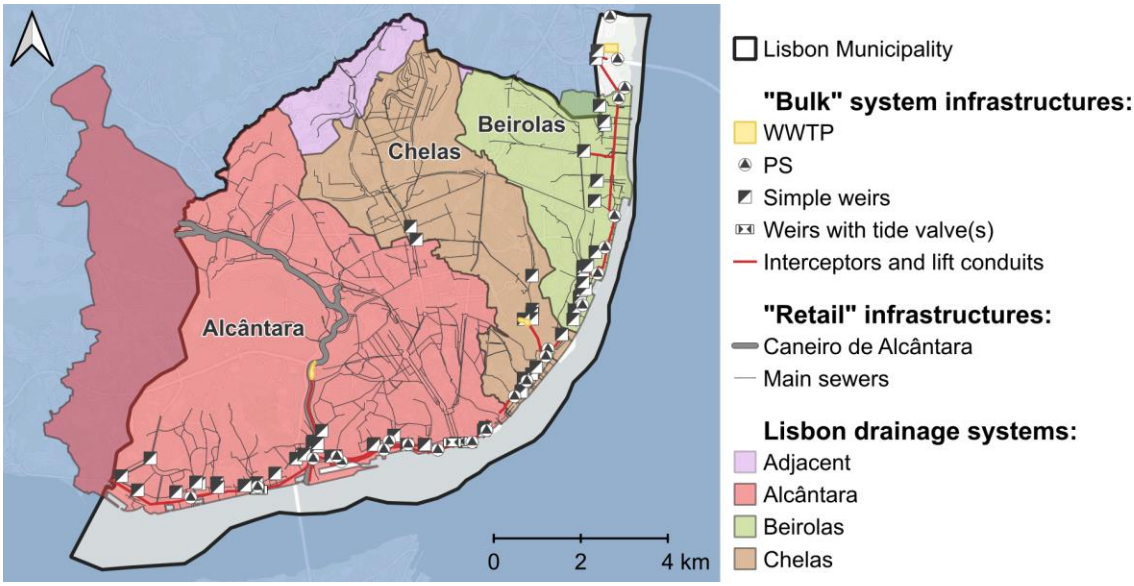


Figure 6-8. Lisbon drainage systems and main infrastructure

The present resilience assessment is physically circumscribed by two sets of sub-catchments in the Alcântara system: the Alcântara catchment and the Historic downtown catchment. These catchments are defined in the Lisbon Drainage Masterplan 2016-2030 (HIDRA, ENGIDRO and BLUEFOCUS, 2016). The first is composed of the Alcântara catchment itself (catchment E) and its confluence with the riverine catchment (catchment KE), and the latter is composed of catchments J and L, which drainage infrastructures converge in the lower part of the riverine basin (KJL). The city's altimetry and the catchment's location are shown in Figure 6-9.

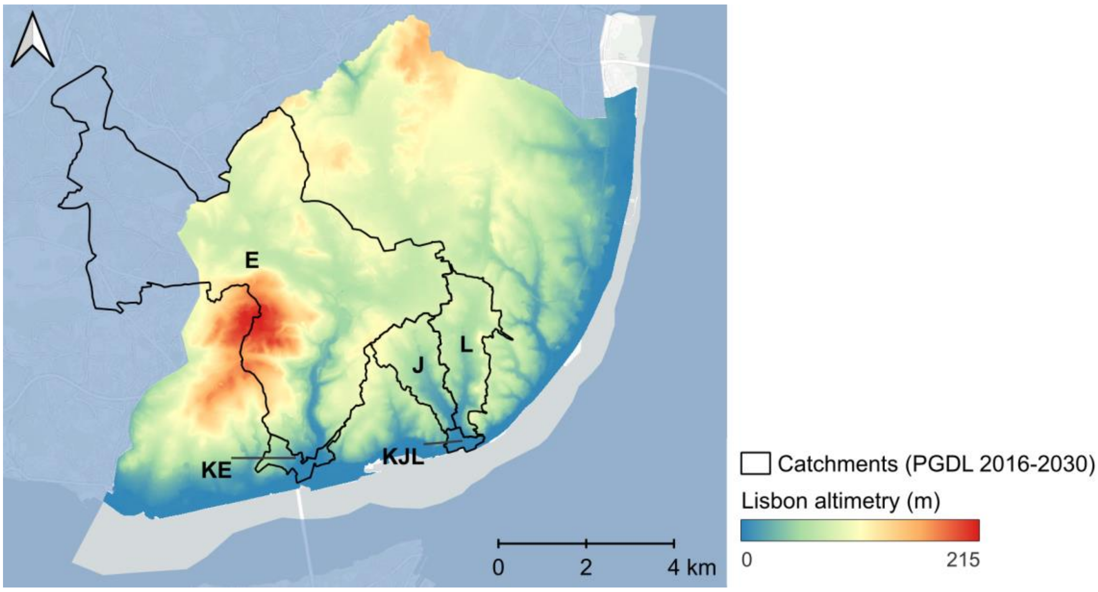


Figure 6-9. Lisbon Council and small-scale case study

6.3.1.2. The Historic downtown catchment

This catchment has about 627 ha and is of utmost importance for Lisbon. It includes the most expensive avenue in the city (Avenida da Liberdade), which joins its upstream area with the old and historic center. It is the center of the city's economic and touristic activities and the core of its urbanistic and demographic development. At the same time, it is vulnerable to several risks, such as flooding, tidal effects, slope movements, earthquakes, and tsunamis, most of which are expected to be aggravated by climate change.

Both catchments J and L are served with a combined drainage network. The drainage network of catchment J has a total length of about 54 km, and it is estimated that approximately 85% was built before 1919. The drainage network of catchment L has a total length of about 80 km, and nearly 45% of the network was built before 1919 (HIDRA, ENGIDRO and BLUEFOCUS, 2016). It is essential to highlight the construction works regarding the wastewater interception system and the tide valve chambers of Terreiro do Paço, completed in 2009. This project included two control chambers of large dimensions: one composed of eight "duckbill" valves (DN1800), eight tide control valves (1000x1800), two flow control valves (DN1000 and DN500), an outlet and a wastewater interceptor (DN1200); and the other included six "duckbill" valves (DN1800), six tide control valves (1000x1800), and a float control valve (DN100). This system was completed with the respective interception system to convey the wastewater flows into the Alcântara WWTP (DRENA and HIDRA, 2004). This work was of monumental importance in the city, allowing for the proper routing of domestic flows for treatment, which until then were being discharged into the Tagus River. This represented a critical change in the system, a new status quo.

In both catchments, infrastructural problems are reported in the Lisbon Drainage Plan, including sewers with low conservation and insufficient hydraulic capacity, a deficit in inlet devices caption efficiency, deficient connections in downstream sewers with localized head losses, and strong influence of estuarine tides and silting at discharges. The confluence catchment KJL has reported deterioration problems on joints, defects in inverts, and insufficient hydraulic capacity (HIDRA, ENGIDRO and BLUEFOCUS, 2016).

6.3.1.3. The Alcântara catchment

The Alcântara catchment is the largest in the city, covering an area of about 3200 hectares, including areas outside the Lisbon Municipality that belong to the Amadora and Oeiras Municipalities. As observed in Figure 6-9, the altimetry ranges from practically the water level to about 215 m high in the Monsanto forest and head sub-catchments. The downtown area of

Alcântara is situated in the terminal section of the catchment, near the Tagus River, and is developed at very low elevations.

This catchment is named after a stream that runs along its valley, about 13 km long, now totally channeled. The channeling started in the 1940s and was completed in the 1960s with the channeling of Benfica and Carnide upstream branches. The total height of its cross-section is slightly above 5 meters, and the maximum width is 8 meters. The Caneiro de Alcântara was designed assuming, in the final section, a peak flow of 217 m^3/s, corresponding to rainfall with a return period of 50 years at that date, also accounting for a larger tributary area (about 25% of the area was latter diverted by a tunnel to Chelas municipality). However, when intense rainfall events or prolonged precipitations coincide with high tides, the flows generated in the catchment and transported by the Caneiro do not have the gravitational capacity to discharge into the river. Under these circumstances, and with the Caneiro operating under pressure, a significant portion of the flows overflow from the manhole covers or through the inlet devices' openings, accumulating in sag areas.

Regarding the "retail" system, it is noteworthy to mention the existence of branched networks, meshed networks, and pseudo-meshed networks, that is, networks that close into a mesh from the plan view perspective but where sewers at the manholes have different elevations. This means the system behaves as branched up to specific flows, beyond which it acts as a meshed network. Additionally, the influence of the tide in the riverside areas and the diversity of infrastructure it contains, such as overflow weirs and interceptors (designed to divert domestic effluents from combined sewer systems and convey them to the "bulk" system), pumping stations, force mains, inverted siphons, and tide valves, contribute to the high complexity of this system.

The Lisbon Drainage Plan identifies as main problems the poor conditions and hydraulic incapacity of sewers, silted sewers, inadequate surface drainage due to the lack of suitable inlet devices, inadequate interception of domestic flows in some combined sub-catchments, and overflow weirs under the influence of the tide. Additionally, its location downstream of a large catchment, development at elevations slightly above the highest sea level, high imperviousness, and significant tidal influence are cumulative risk factors for urban floods (HIDRA, ENGIDRO and BLUEFOCUS, 2016).

6.3.2. STRATEGIC DIMENSION ASSESSMENT

The assessment of the Strategic Dimension for the case studies was conducted considering the previously mentioned resilience-related works, along with municipal plans and publicly available documents, and was focused on the "retail" system. Specific information regarding the drainage system was mainly collected from the Lisbon Drainage Plan 2016-2030 (HIDRA, ENGIDRO and BLUEFOCUS, 2016).

The first resilience objective - *S1. Institutional capacity* - aims to understand the stormwater system's institutional positioning as an urban service in the city. In this aspect, it is relevant to mention the Lisbon Drainage Plan 2016-2030 (HIDRA, ENGIDRO and BLUEFOCUS, 2016), developed in 2015, which has significantly improved medium/long-term planning for the service. This plan also contributed to including specific measures regarding the drainage system and the reduction of urban flooding occurrences in the principal axes of the city's investment and strategic plans (CML, 2023, 2019).

Regarding the second objective – *S2. Urban service relationships* – it pretends to translate the relations of the service with other relevant urban services, focusing on the knowledge regarding three essential resilience-related concepts: interdependencies – as the dependencies from other urban services to operate, and vice-versa; autonomy – as the capacity of infrastructures dependent on other services to keep functioning autonomously; and redundancies – purposely design choices that confer to the system the ability to continue operating at satisfactory performance levels when under pressure. In assessing this objective, the participation of the Municipality in the EU H2020 Project RESCCUE provided a pivotal opportunity to investigate and study the relationship between the city's urban drainage (as a service) and other urban services. This analysis focused on the Historic downtown catchment to explore typical relations between urban services, assuming that drainage service infrastructures and management over the city do not vary significantly. The study of such interdependencies included 146 infrastructures from the urban water cycle, power, mobility, waste, telecommunication, environment, and social sectors (Barreiro et al., 2020). The resulting mapping is presented in Figure 2-9, where interdependent services are connected (blue lines represent interdependencies defined at a detailed level, yellow lines represent a partial failure, and red lines represent a complete failure of the dependent service).

In the scope of Project RESCCUE, the "bulk" and "retail" system were treated as a single service (urban drainage). If analyzed separately, the interdependencies map might change its configuration. For instance, the "retail" system in the catchments under study is conventional and grey-based, meaning that, as a service, it is very independent since it does not rely on other services to operate; neither do other services depend on it to function. Additionally, as the "retail" system does not present significant green/blue infrastructures, other special equipment (such as storm tanks, stormwater pumping stations, and real-time controlled equipment), technological, or innovative infrastructures, its autonomy, and redundant capacities are highly limited. When the system is under pressure and has difficulties conveying the flows, its margin to failure and provoking negative consequences in the city is restricted.

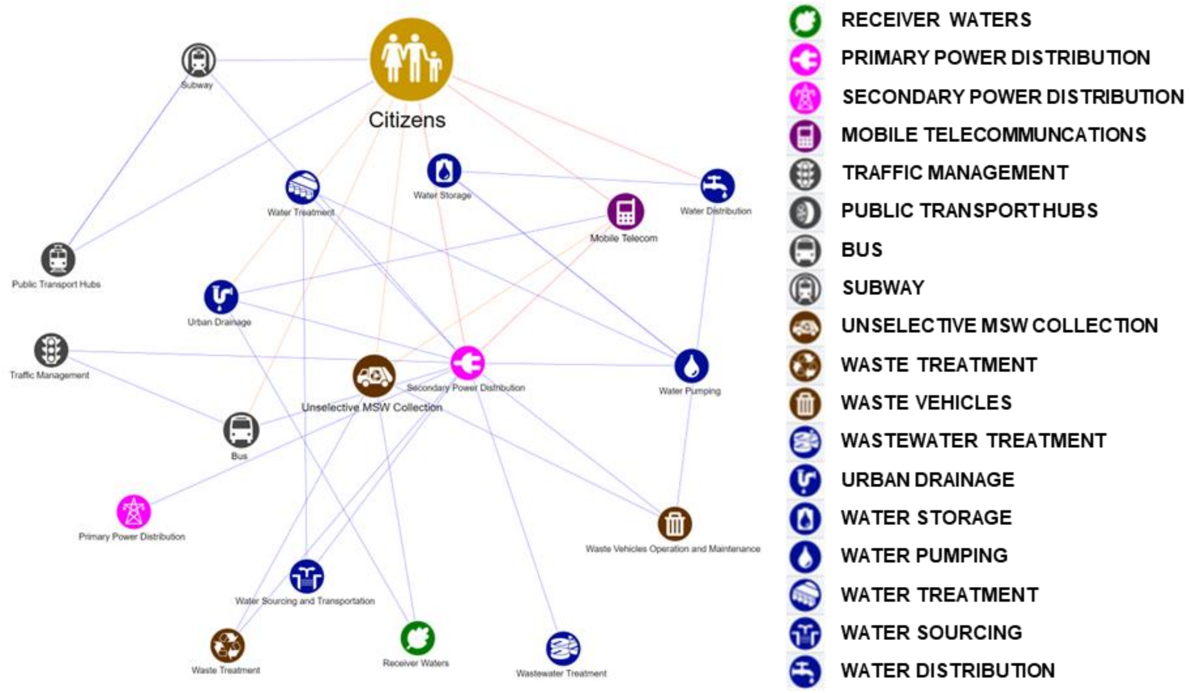


Figure 6-10. Interdependencies map obtained for Lisbon from the analysis focused on the Historic downtown catchment (Barreiro et al., 2020)

The third objective – *S3. System knowledge* – includes criteria that reflect practical managerial aspects of the stormwater systems, such as monitoring and real-time control (*S3.1*), human and financial resources (*S3.2*), disturbing events protocols (*S3.3*), climate change preparedness (*S3.4*), and proper management of stormwater overflows (*S3.5*). The Lisbon Municipality lacks proactive data collection through monitoring equipment, which undermines the drainage service's capacity for learning and understanding, putting the service in a passive position and incapable of acting in real-time. Although some rain gauges are installed along the city and its surroundings, those are managed by external entities and do not serve the objectives of the Municipal Sewage Department. Likewise, flow monitoring equipment is installed in some points of the "bulk" drainage system, mainly for control of WWTP inflows and inter-municipal flows, which, again, do not fit the purposes of a monitoring system for "retail" drainage systems and flood control.

The Municipality aims to tackle this limitation. As a consequence of the Lisbon Drainage Plan, which identified this gap, the “Monitoring and Warning System for Lisbon's Drainage Network” plan was developed, proposing the installation of monitoring equipment all along the city, including 84 depth meters, 8 flow meters, and 5 rain gauges, that represents a total investment of more than 1.5 million euros (HIDRA and ENGIDRO, 2018). Some of these are already being installed under the scope of other construction works resulting from the Lisbon Drainage Plan.

In parallel, the Municipal Civil Protection Department initiated a pilot project with the start-up *greenmetrics.ai* in 2023 and started to install a surface flood sensor system. In the initial phase, equipment was installed in the city's main road tunnels (João XXI, Entrecampos, Campo Pequeno, Campo Grande, and Batista Russo), in the critical streets Rua da Palma (in catchment J) and Rua da Fábrica da Pólvora (in catchment KE), and in one sewer at Av. Almirante Reis (in catchment L) (greenmetrics.ai, 2023). Although in a testing phase, when Rua da Prata flooded on May 23rd, 2023, between 5 and 6 pm, the rainfall recorded was equivalent to over 30% of the historical monthly precipitation average, the dashboard detected a ten times increase in underground water level (Figure 6-11), and a flood in Lisbon's downtown began 15 minutes later (helium, 2023).

Figure 6-11. Greenmetrics.ai monitoring dashboard (helium, 2023)

Regarding human and financial resources, the Municipal Sewage Department is considered to have proper assets for normal operation conditions. When a disturbing event occurs, the Municipal Emergency Plan and the Civil Protection Department activate the necessary response resources (CML, 2017). However, in part due to the lack of monitoring equipment, apart from the occurrences register of the Civil Protection Department, there are no recording procedures for disturbing events within the Sewerage Department. This undermines the capacity to analyze and understand the system's performance and consequences, typically only evaluated by assessing financial losses resulting from urban floods.

There are, however, response mechanisms after the occurrence of urban floods to improve the drainage system's performance, either with adaptation or transformation measures/strategies. Adaptation measures refer to those that will enhance the current infrastructure's performance by improving or updating them. Transformation measures include actions that commit marks to the system's behavior, introducing a new paradigm, and changing its status quo. Typically, such approaches are studied and planned after a flood, partly by activating the memory of other past flooding events.

In the catchments under study, there are examples of both types of approach. In the Historic downtown catchment, as previously mentioned, the works in Terreiro do Paço (Figure 6-12), finished in 2009, resulted in a new paradigm of the drainage system. Flows started to be separated downstream and properly conveyed for treatment in Alcântara WWTP and the stormwater overflows discharged to the receiving waters (DRENA and HIDRA, 2004). This work was part of a significant effort in the first decade of the XXI century to properly convey wastewater to adequate treatment in Alcântara WWTP through a riverine interceptor system, composed of pumping systems and pressurized and gravity sewers all along the riverbank of the Alcântara system. These works are a landmark in the city's urban drainage management.

Figure 6-12. Schematics (HIDRA, 2008) and photos of the construction works of the combined flow control chambers and wastewater interception strategy in Terreiro do Paço (photographs kindly provided by HIDRA)

An example of an adaptive measure occurred recently in the upstream zone of catchment J, where there is an essential green area, Eduardo VII Park (Figure 6-13). This park's potential to reduce the generated runoffs, alleviate the downstream network, and mitigate downstream floods was being misused. Its sewerage network was in a poor conservation state, with limited capacity to convey flows generated by the 10-year return period rainfall. In 2022, with an investment of more than 2 million euros, the Municipality finished works regarding the rehabilitation of the sewerage network of this area, moving from a combined to a separate network and implementing source control methods to promote retention and infiltration with a pair of modular retention/infiltration underground basins and two drainage trenches. This work aims to enhance Eduardo VII Park, maintaining its unique characteristics and respecting the heritage, socio-cultural, landscape, and environmental interest of this green space to improve the conditions of enjoyment for leisure and recreation for the population (VFLOW.GES, 2018).

Figure 6-13. Photos of the construction work carried out in Eduardo VII Park (from May 2021, photographs kindly provided by VFLOW.GES)

The Municipality of Lisbon has been striving to cultivate an eco-friendlier and citizen-oriented urban landscape in recent years. This effort was formalized in 2012 when climate change was added as one of the seven key urban policies. Drawing upon a territorial development model anchored by two critical pillars - the ecological system and the mobility and transportation system - the Municipality devised a comprehensive framework of measures and guidelines for effective municipal management. In 2016, the city joined the Covenant of Mayors for Climate and Energy and developed and approved the Local Action Plan for Biodiversity. In 2017, the Municipal Strategy for Adaptation to Climate Change and the Sustainable Energy and Climate Action Plan entered into force. In 2019, the municipality joined the C40 Cities Network, reaffirming its responsibility to meet the Paris Agreement objectives by implementing its Climate Action Plan (PAC). The Lisbon PAC 2030 intensifies the GHG reduction target for 2030, hastening the path to neutrality by 2050. Lisbon thus sets a more ambitious goal of reducing its emissions by 70% by 2030 compared to the base year 2002 (2.3 tCO_2e per capita). By 2050, Lisbon aims to reduce city emissions by between 85% and 90%. As an organization, the CML universe commits to achieving climate neutrality by 2040 (CML and Lisboa E-Nova, 2021).

Regarding relevant climate variables for the drainage system, the Municipality has agreed on climate change scenarios that establish a decrease in the total annual precipitation (up to 51%

at the end of the century) and an increase in the frequency of extreme precipitation events (Tomás Calheiros et al., 2016). There are also several scenarios regarding the mean sea level in 2100, where values range between 0.45 m (+170%) for the least dangerous scenario and 2.61 m (+904%) for the most hazardous scenario (Antunes et al., 2017). As presented in the section regarding the evaluation of the Performance Dimension, the municipality has also been making efforts to understand the potential deterioration in system performance due to the trend of worsening conditions it is subjected to due to climate change, both at the level of the underground drainage network and at the level of surface runoff and potential consequences.

A critical issue regarding separated wastewater and combined drainage systems is the occurrence of stormwater overflows, which represent the system's incapability to deal with rainwater inflows that ultimately will end up as polluted discharges into the receiving waters. In the case of the catchments under analysis, stormwater overflows are partially controlled by some flow control chambers that limit the overflow discharge rate. As previously identified, there is a lack of monitoring equipment to monitor such overflows, although most outfalls are identified.

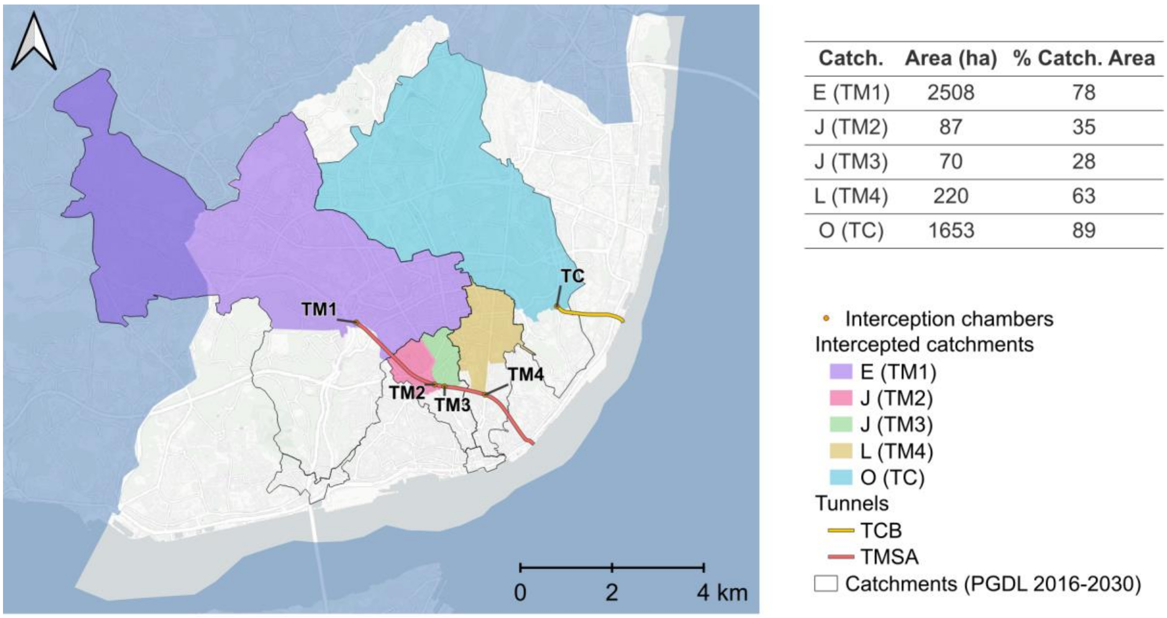
The last objective – *S4. Infrastructural knowledge* – assesses the system's knowledge regarding its infrastructure through adequate register, internal and external risk assessment, and inspection and maintenance procedures. The Municipal Sewerage Department has an extensive and detailed infrastructure register shared with other municipal departments and interested institutions or enterprises upon a justified request. This system has no known updating criteria, although it is updated frequently and when studies and interventions on the network are required. Physical internal risks of the infrastructures, such as structural conditions of sewers and manholes, are known for critical areas. However, knowledge regarding other critical internal risks has room for improvement, like inlet devices' capacity and storm overflow frequency. The best-known external physical risks are equipment and sewers' exposure to tides. In contrast, consistent knowledge regarding clogging of inlet devices or sewers' exposure to silting and sediments' deposition is still incipient. Some of these risks could be better understood if an effective monitoring system existed. Additionally, there is a need to reinforce inspection and maintenance routines to establish priorities and preventive action on threatened infrastructures.

6.3.3. PERFORMANCE DIMENSION ASSESSMENT

6.3.3.1. PERFORMANCE SITUATIONS

The Performance Dimension was assessed by considering several situations for both case studies. Within the RESILISTORM framework, a situation is a given state of the system in the space and time defined by the drainage system configuration, i.e., the system infrastructures; a given time frame/climate scenario; and the rainfalls' event/return periods considered (Barreiro et al., 2024).

In both case studies, present and future system configurations were considered. The future system configuration considers structural interventions approved by the Lisbon Drainage Plan, namely constructing two diversion tunnels: the Tunnel Monsanto - St^{a} Apolónia (TMSA) and the Tunnel Chelas - Beato (TCB). These tunnels will intersect major drainage catchments in the city, diverting the flows from the upper zones and alleviating the downstream network (Figure 6-14). This will allow the use of the existing sewerage transport capacity and decrease the flooding potential in the downstream areas of the city. Both multi-purpose tunnels provide room for flow transport and support a pipe network to transport treated wastewater to reuse in compatible uses.



Catch.	Area (ha)	% Catch. Area
E (TM1)	2508	78
J (TM2)	87	35
J (TM3)	70	28
L (TM4)	220	63
O (TC)	1653	89

Figure 6-14. Tunnels: associated drainage catchments and intersection locations (HIDRA, 2018)

In the scope of the current work, the TMSA is extremely important since it intersects the catchments under study. At the entrance, the TMSA will have an anti-pollution retention basin designed to pre-treat the inflow of combined flows, promoting a better quality of the discharged flows into the Tagus River. After a rainfall event, the stored volumes and the retained solids are pumped to the Caneiro de Alcântara to be treated in the Alcântara WWTP. This anti-pollution and retention basin has a storage capacity of 16 000 m^3 and a treatment capacity of 7.5 m^3/s. The flows exceeding the treatment capacity and up to 43.5 m^3/s are pre-treated by sieving. The TMSA was designed to transport 170 m^3/s (100-year return period rainfall) along its total length of about 4.6 km, with a circular cross-section of 5.5 m diameter and slopes between 0.45% and 0.83% at the initial and final lengths, respectively. The interception chambers are equipped with vortex drop shafts to prevent deterioration by the flows dropping from heights between 13 m and 24 m. Near the outfall, the tunnel can work under pressure for the 100-year return period flow, with velocities between 7 and 8 m/s. The discharge cross-section is rectangular, progressively widening to reduce the discharge velocities to about 2 m/s (HIDRA, 2018). The TMSA construction works started in December 2023 and are expected to be completed in July 2025, and a total investment of 250 million euros is predicted.

This way, a set of situations with different objectives was defined for each case study. For the Historic downtown catchment, the assessment focused on climate change's impacts at the end of the century and the resilience improvement granted by the TMSA to rainfall events with distinct return periods (RT), as shown in Table 6-4.

Table 6-4. Situations considered for the assessment of the P-dimension of the Historic downtown catchment

Situation name	System configuration	Climate scenario	Rainfall RT
Current situation (CS)	Existing	Present (2020)	10, 20 and 100 years
Business as usual (BAU)	Existing	Future (2100)	
Future situation (FS)	Existing + TMSA	Future (2100)	

Regarding the Alcântara catchment, besides the impacts of climate change and the construction of TMSA, the framework was used to compare the impacts on the performance resilience and consequences of two additional adaptation strategies (AS), which aim to benefit the downtown area of the catchment (Table 6-5). The adaptation strategies intend to reduce the flood risk in the downtown area of Alcântara, ensure the proper interception of dry weather and wet weather contributions for treatment purposes, and guarantee the adequate hydraulic and sanitary functioning of the urban drainage system as urban service.

Table 6-5. Situations considered for the assessment of the P-dimension of the Alcântara catchment

Situation name	System configuration	Climate scenario	Rainfall RT
Current situation (CS)	Existing	Present (2020) and Future (2100)	10 years
Future situation (FS)	Existing + TMSA		
Adaptation Strategy 1 (AS1)	Existing + TMSA + S1		
Adaptation Strategy 2 (AS2)	Existing + TMSA + S2		

ADAPTATION STRATEGIES FOR THE ALCÂNTARA DOWNTOWN AREA

The first adaptation strategy (AS1), represented in Figure 6-15 (left), consists of the redesign of six weirs located at the right side of the Caneiro de Alcântara (D16, D17, D19A, D19B, D19C, and D20), a set of weirs located at the left side (D8), and the redesign of a wastewater sewer associated to another weir (D20). Such interventions were already studied and projected (HIDRA, 2007; COBA, 2014; HIDRA, 2014). In summary, the AS1 aims to rehabilitate most existing weirs in the study area to intercept wastewater carried by the upstream combined sewers in a controlled way through flow regulation chambers, directing them to the existing separate sewers. The flow regulation valves are designed to limit the flow to the "bulk" system up to twice the dry weather peak flow.

The second adaptation strategy (AS2), represented in Figure 6-15 (right), involves disconnecting the existing connections at the right side of Caneiro de Alcântara and constructing a new parallel combined sewer with a downstream wastewater pumping station. This way, the wastewater flows are lifted to the PS3 (the main PS of the Alcântara system that conveys all the flows to the Alcântara WWTP), and the stormwater is discharged into the Tagus River. Two tide valves, a side discharge outfall, and inlet screening or sieving equipment should be installed at the proposed new PS. This strategy also includes redesigning weir D19B and interventions associated with weir D8. Likewise, this strategy is supported by existing studies and projects (CHIRON et al., 2007; COBA, 2011; HIDRA, 2007).

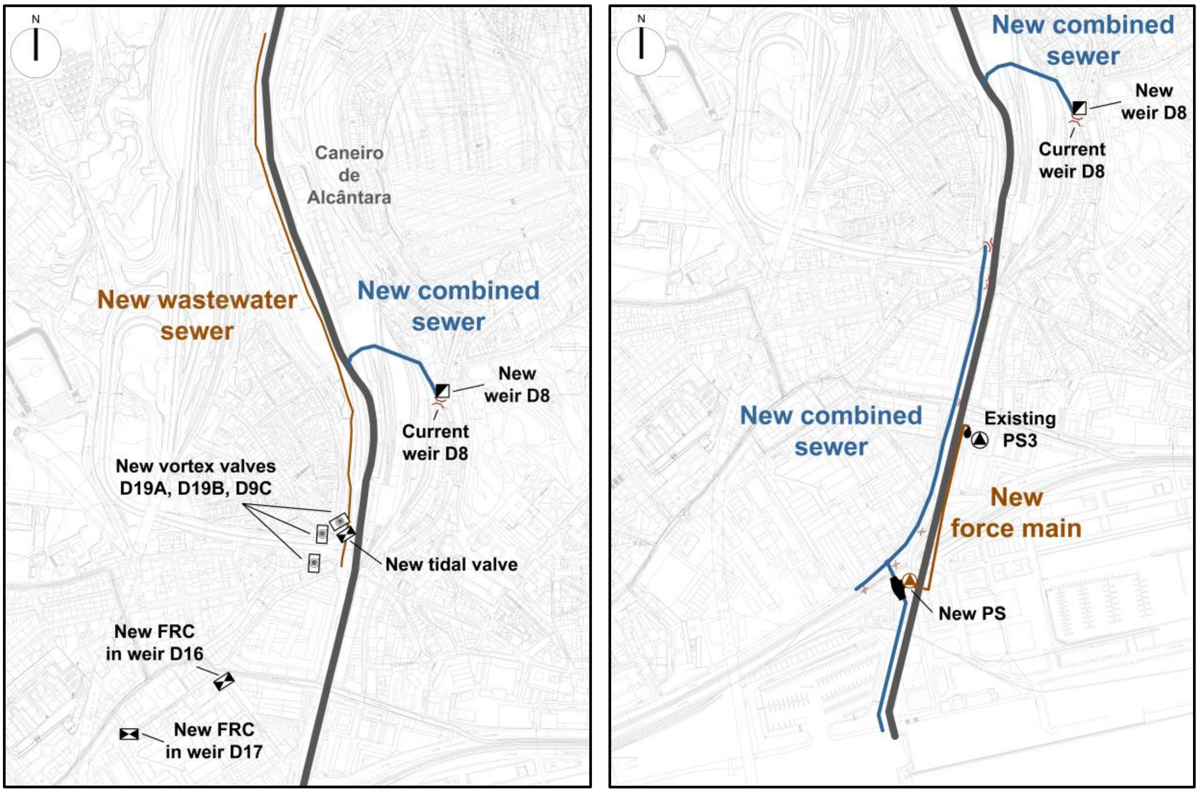


Figure 6-15. Schematic representation of main interventions regarding AS1 (left) and AS2 (right) (adapted from HIDRA, 2019). FRC stands for Flow Regulation Chamber

CLIMATE SCENARIOS AND DEMANDS ON THE SYSTEM

In both case studies, two timeframes were considered: present (2020) and future (2100). Each defines the demands on the system (rainfall intensities) and the boundary conditions (tide levels). For both case studies and timeframes, the Portuguese design/project hyetograph with a total duration of 4 hours and a centered intense period of 1 hour proposed by Matos (1987) was adopted. For the present time frame, the rainfall intensities of each considered return period were estimated from the intensity-duration-frequency (IDF) curves proposed for Lisbon by Brandão et al. (2001). Regarding the boundary conditions, a moving tide with a high tide level coincident with the centered rainfall period was considered. The high tide value adopted was 1.95 m, about 6/7 of the maximum level of spring high tide (MLSHT). It is relevant to highlight that the coincidence of the centered intense rainfall period with the high tide level is a very demanding condition of combined events, increasing the corresponding return period for an equivalent real event.

In what respects the future time frame (2100), different climate scenarios were considered for the case studies. Regarding the rainfall intensities for the Historic downtown catchment, the local rainfall projections resulting from Project RESCCUE were considered, representing an average increase of about 15% (Monjo et al., 2019). In the case of the Alcântara catchment, a less severe scenario was considered, with a 5% increase in rainfall intensities. Concerning the rise of the sea level, scenarios with different severities were also considered, following the projections of the work of Antunes et al. (2017). Figure 6-15 summarizes the rainfall and tide conditions considered. It is important to mention that the performance-related indicators were calculated considering a 5-hour range since the beginning of the rainfall event.

Table 6-6. Reference values and scenarios considered for future high tide levels in meters.

	MLSHT	6/7 MLSHT	Relative change
Scenario severity ▼ | Present ref. values ▶	2.28	1.95	-
Medium (Alcântara catchment)	2.98	2.55	+ 0.70 (31%)
Medium-high (Historic downtown catchment)	3.28	2.81	+ 1.00 (44%)

MLSHT: maximum level of spring high tide (m)

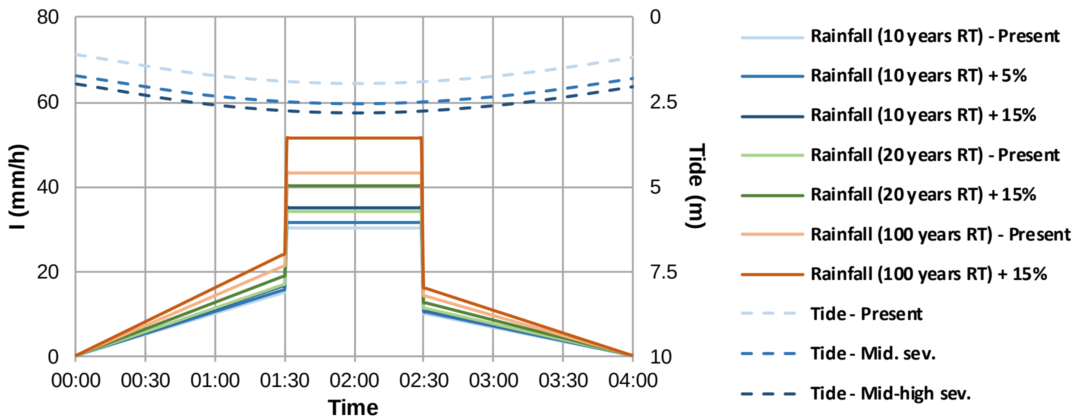


Figure 6-16. Summary of rainfall intensities and tide levels considered in the Performance Dimension assessment

6.3.3.2. Simulation models assembly

Historic downtown catchment

The assembly of the SWMM project of the Historic downtown catchment took advantage of previous studies developed, namely the previous work of Barreiro et al. (2017; 2021) and Project RESCCUE (Russo, 2018). For the construction of the network to be modeled, the main sewers of the drainage network, namely those which cross-section is higher than 800 mm (or equivalent), and the system of chambers in Terreiro do Paço were considered. The model comprises 32 sub-catchments, 331 links (sewers), 312 nodes (manholes), and 6 outfalls. It comprises about 15 km of modeled sewers (about 10% of the total sewerage network extension). Concerning the BASEMENT domain, the triangulation process resulted in a mesh with 30 539 vertices and 43 661 faces, applying a 150 m² maximum face area limitation.

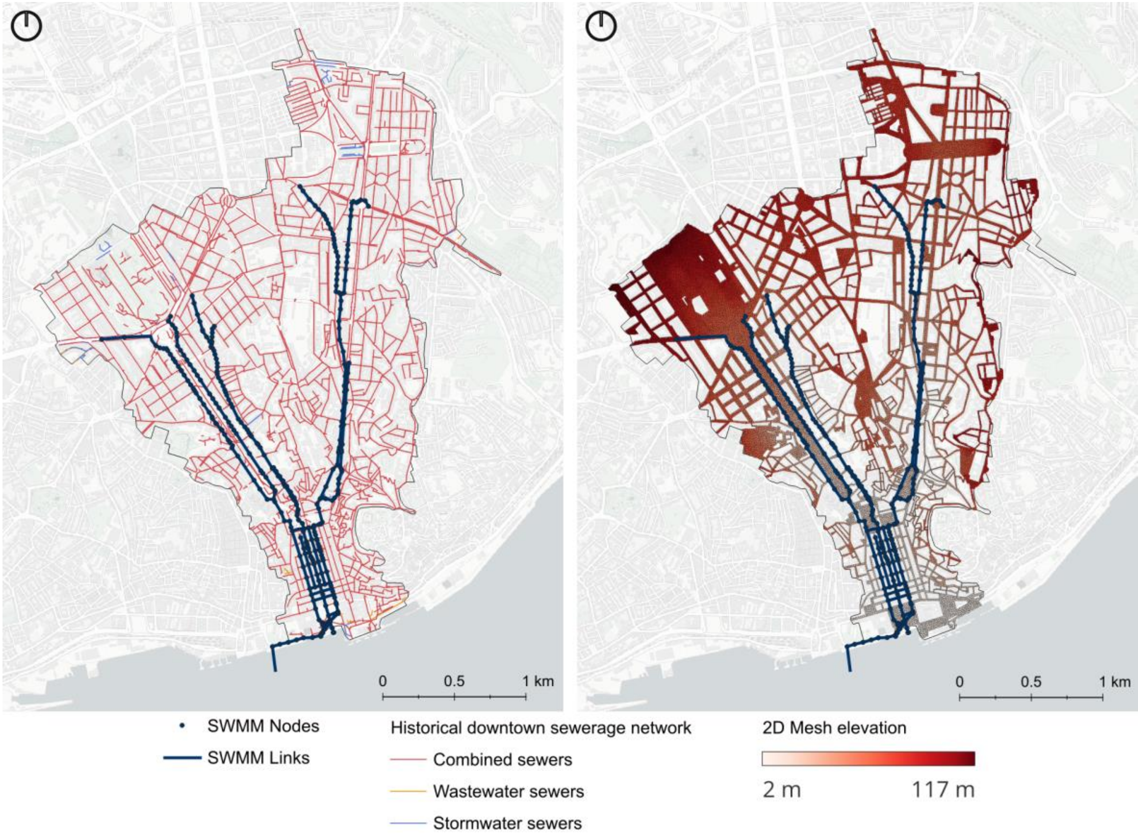


Figure 6-17. Assembled projects for SWMM and BASEMENT applications in the Historic downtown catchment

ALCÂNTARA CATCHMENT

The construction of the SWMM model for the current situation was based on a wide range of elements, including previous studies and projects developed for the lower area of the Alcântara catchment, partial hydraulic models, and cadastral elements. This model takes particular complexity due to this catchment's important and complex drainage infrastructure. An existing SWMM model was developed and calibrated in 2013/2014 within the framework of the Si-GEA project – Intelligent System for Advanced Management Support of Urban Wastewater Systems (Siemens, S.A. et al., 2013). This model was updated and expanded, considering recent cadastral information, studies, and projects, mainly in the downtown area of the catchment. The resulting model for the current situation comprises 121 sub-catchments, 1370 nodes, and 1400 links. It includes pumping stations, tide valves, outfalls from the wastewater drainage fronts, and the Alcântara WWTP. Concerning the BASEMENT domain, the triangulation process resulted in a mesh with 30 960 faces and 19 179 vertices.

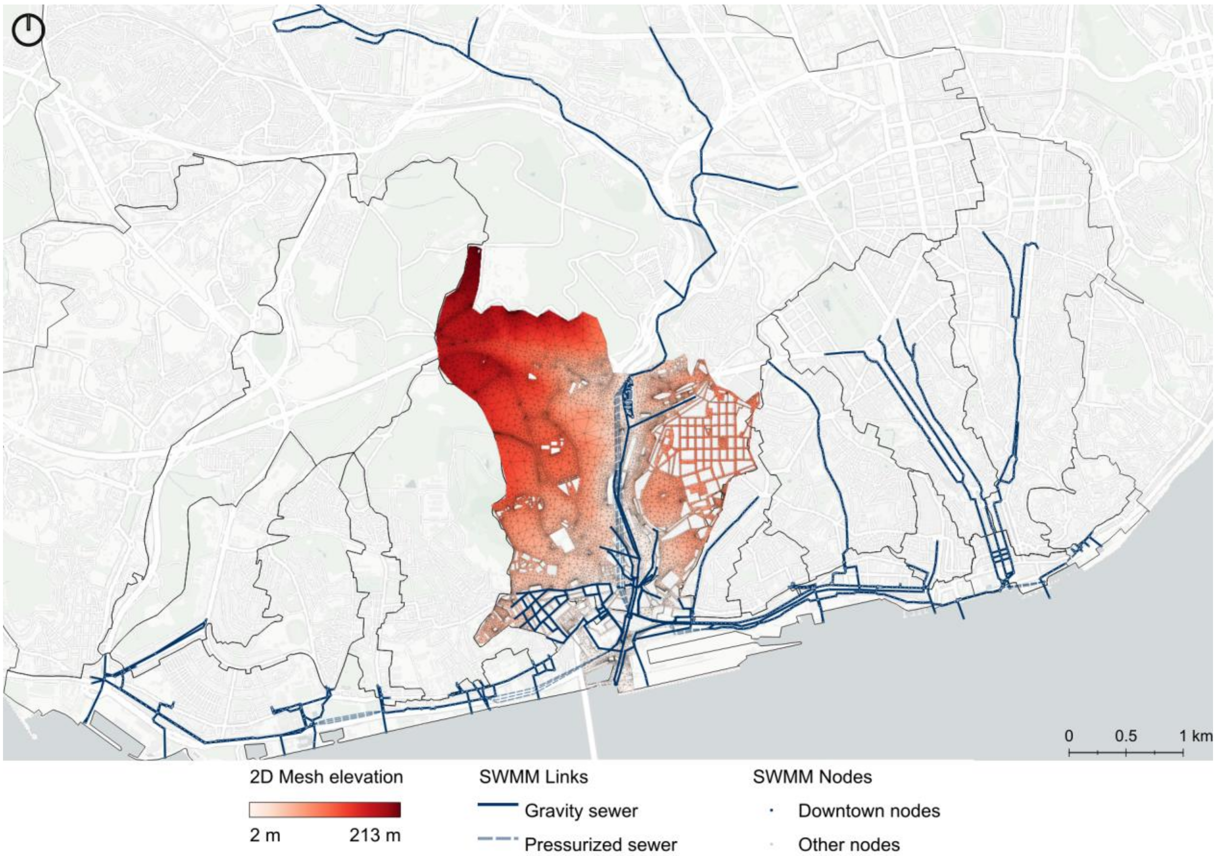


Figure 6-18. Assembled projects for SWMM and BASEMENT applications in the Alcântara catchment

Regarding the Future Situation, which considers the TMSA (for both case studies) and the Adaptation Strategies (for the Alcântara catchment), the current model was updated according to the respective design studies and projects.

6.4. RESULTS AND DISCUSSIONS

6.4.1. STRATEGIC DIMENSION RESULTS

The ratings obtained for the Strategic Dimension result from selecting the most appropriate answer according to the assessment developed in subchapter 0. Figure 6-19 presents the ratings obtained for each objective and the consequent strategic dimension rating and classification. The detailed results are presented in Figure 6-20**,** with the rating for each criterion.

As observed, the service has a satisfactory rating regarding its institutional capacity (Objective S1), demonstrating a good capacity to plan and be included as a strong service within the city priorities. However, moving to the relationship with other urban services (Objective S2), although the system presents few direct dependencies with other services, there is still a need to search deeper into what kind of synergies that lead to interdependencies can be developed. As for redundancies, since the drainage systems are grey-based and conventional, the Alcântara and the Historic downtown catchments present low infrastructural capacity to deal with unexpected pressures.

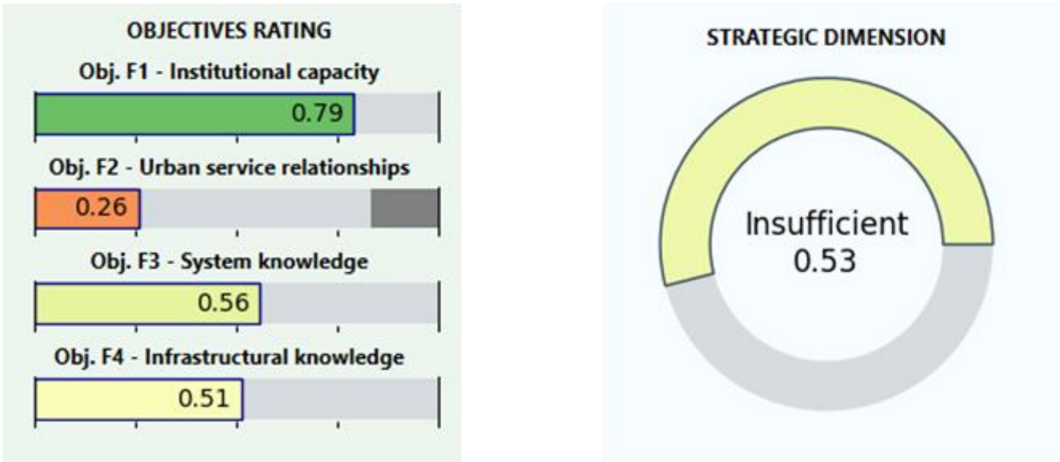


Figure 6-19. Objectives and Overall Strategic Dimension Resilience ratings

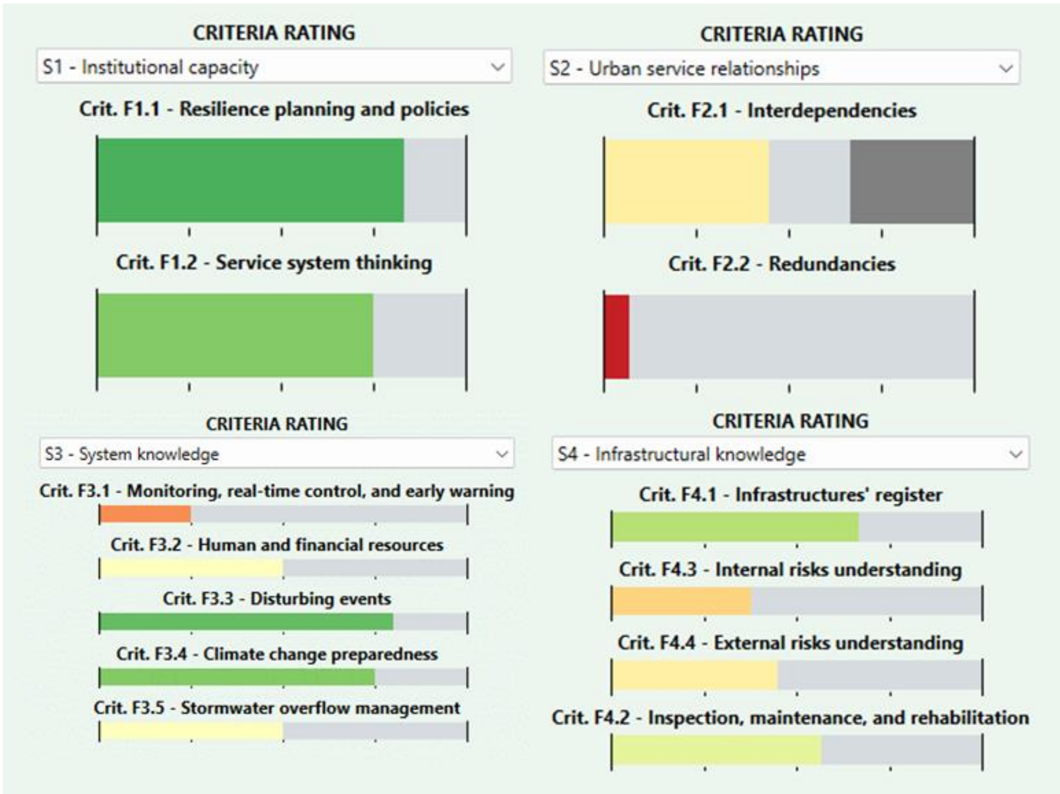


Figure 6-20. Strategic Dimension Resilience ratings for each criterion

As mentioned in the previous section, the monitoring capacity of the service is still incipient, which limits its capacity for real-time control and operation and to provide adequate early warning, even internally (Criterion S3.1). The service reports adequate human and financial resources to the national regulator authority, although for abnormal circumstances, these could be reinforced (Criterion S3.2). Participation and involvement in resilience and climate-related networks and partnerships provide the system with a good background related to the understating and knowledge regarding the potential impacts of climate change. Thus, the service is aligned with the city's efforts to mitigate and adapt to climate change (Criterion S3.3). As for the last criterion of the system knowledge objective, regarding stormwater overflows, although joint efforts have been being developed between the Sewerage Department and Águas do Tejo Atlântico (the "bulk" system utility), at present, there are difficulties in controlling and managing their occurrence, even for rainfalls with low return periods.

The service presents a global and detailed infrastructure register for infrastructural knowledge due to the diverse plans and studies developed, namely the Lisbon Drainage Plan (Criterion S4.1). However, efforts must be put into updating this register and proceeding to planned and routinized inspection and maintenance procedures, including reinforcement of cleaning inlet devices (Criterion S4.2). The insufficient knowledge regarding internal and external infrastructural risks (Criterion S4.3 and S4.4, respectively) is intimately linked to the monitoring, inspection, and maintenance procedures, and there is the need, once again, to have the capacity to assess such risks systematically.

6.4.2. PERFORMANCE DIMENSION RESULTS

HISTORIC DOWNTOWN CATCHMENT

The main objective of the Performance Dimension in the Historic downtown catchment was to assess the TMSA's contribution to the system's overall performance and its impact on the drainage system's resilience and capacity to reduce urban floods. Thus, an analysis area located downstream of the TMSA interception chambers was considered for calculating the 2D-related indicators (major system), and the entire drainage network was considered for calculating the 1D-related indicators (minor system), as presented in Figure 6-21.

The results obtained for the indicators of objective *P1. System performance resilience*, for the Historic downtown catchment, are summarized in Figure 6-22 for each situation considered. As each situation is defined by three return periods, each indicator is calculated by the normalized integral $(\int)$ of the respective values. The objective rating for each situation results from the average of the respective indicators.

The indicators present coherent values, and the observed changes between situations align with expectations. In this sense, all indicators decrease from the Current Situation to the BAU Situation, highlighting the impacts of more demanding requests (rainfall intensities) and boundary conditions (tide levels) on the system's performance in the future. The indicators show a significant improvement concerning the Future Situation, resulting in a decrease in the sewers' surcharge and consequent overflows at the manholes. It is also noted that on the surface (major system flooding), although with smaller relative variations, there is an analogous behavior. Thus, the results demonstrate that the resilience regarding the system's performance in the Future Situation, with the construction of the TMSA, will be superior to the current one.

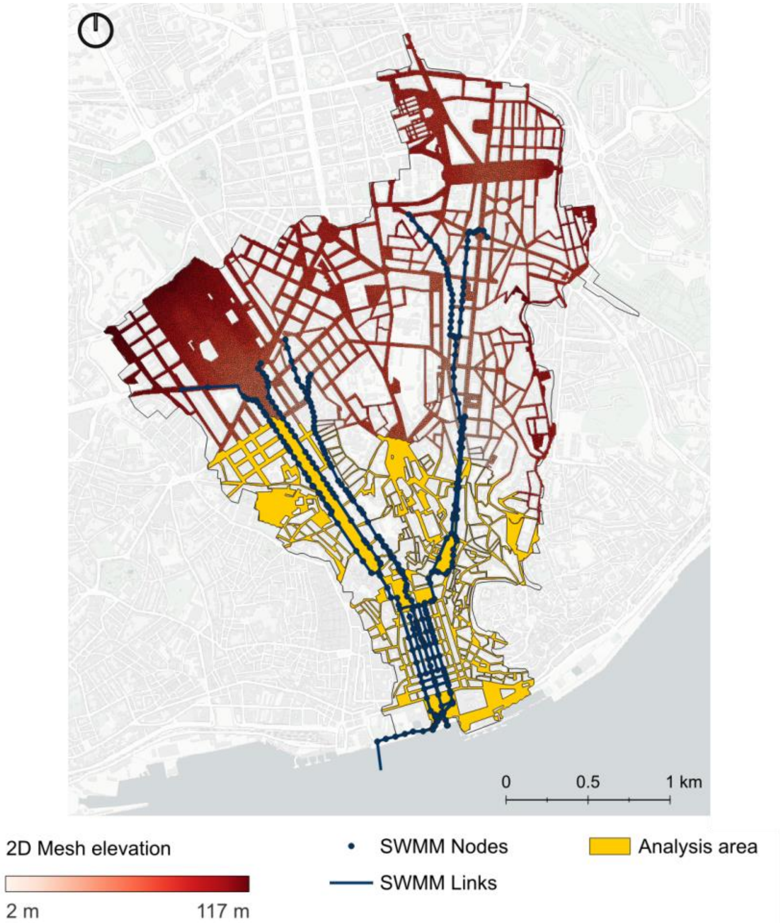


Figure 6-21. Critical area and drainage elements considered for the Historic downtown catchment Performance Dimension assessment

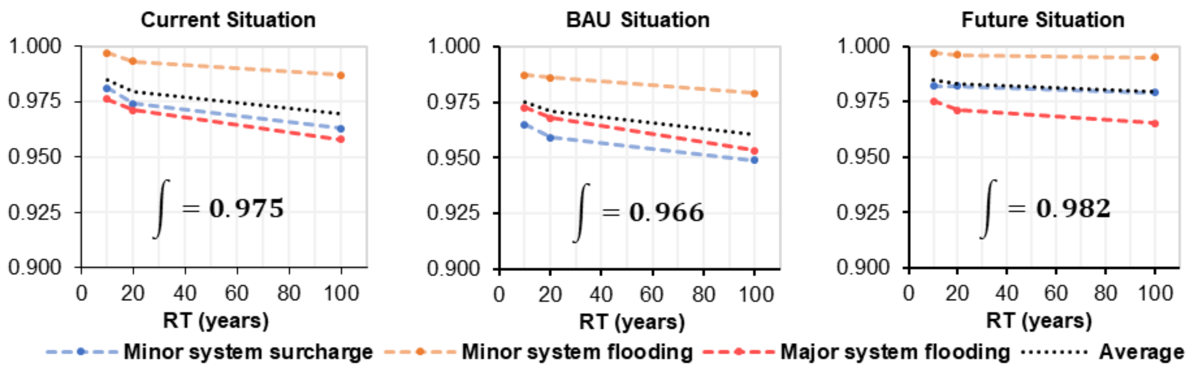


Figure 6-22. Results obtained for the indicators of objective *P1. System performance resilience* for each situation as a function of the rainfall return period, in years, for the Historic downtown catchment

Figure 6-23 presents the minor system performance indicators obtained for the three return periods at each situation by plotting the performance rating at each node vs. the respective node weight. The horizontal dashed lines in the figure represent the system performance obtained by calculating the weighted average of the node's rating, i.e., the indicator for each return period. The KDE curves (Kernel Density Estimation), presented at the axis margins, allow to visually infer the distribution of the performance values along the weights of the nodes. The effects of the climate change scenario considered are clearly expressed in the decrease of the node's surcharge and flooding resilience, especially on those with lower weights, i.e., that link sewers with less transport capacity. When considering the construction of the TMSA (Future Situation), there is a significant improvement regarding the nodes' surcharge and flooding resilience. It is essential to observe that the nodes that still flood after the construction of the TMSA are located immediately upstream of the Tagus River discharge, with the rim elevation lower than the maximum tide level considered. The surcharged nodes are also located downtown, with lower gravity availability to discharge due to the high tides.

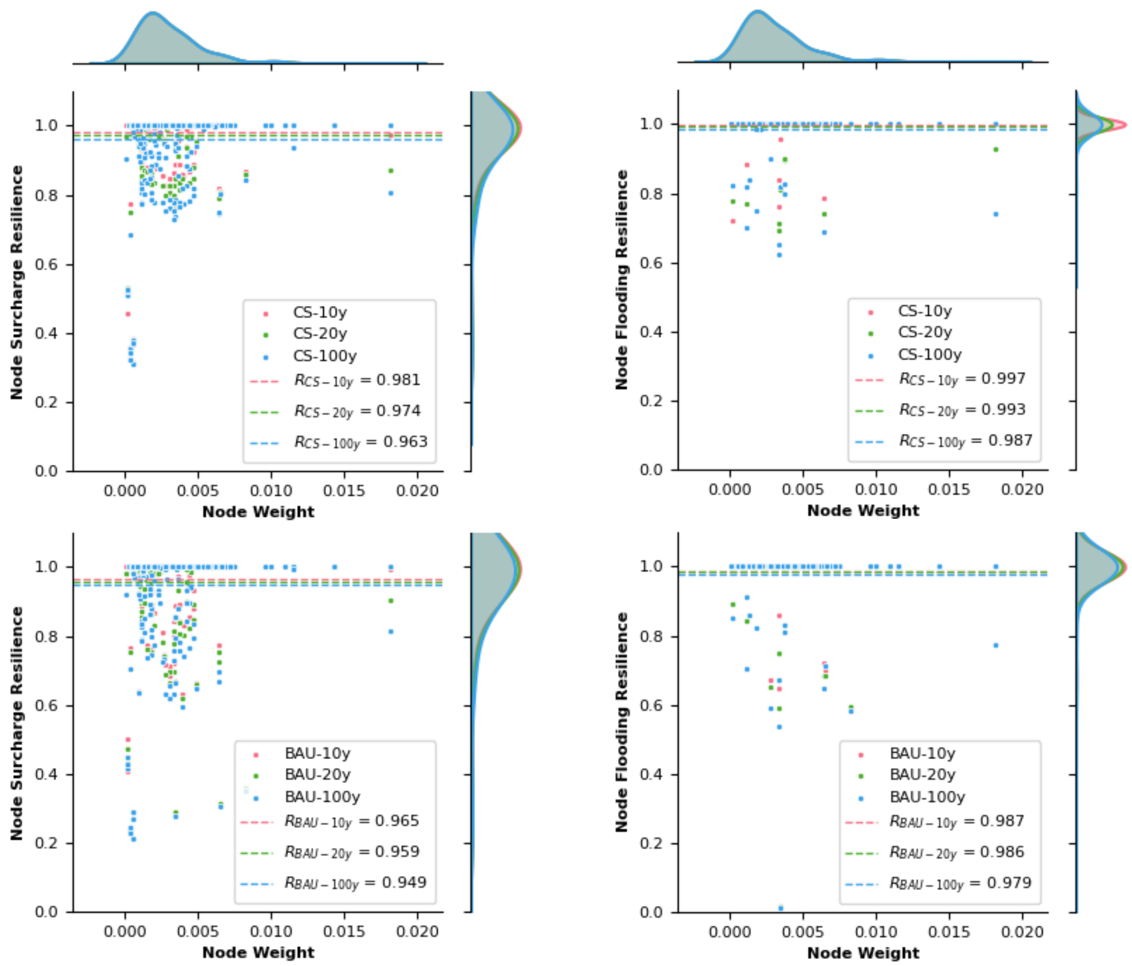


Figure 6-23. Plots of node weights vs. node surcharge resilience (left) and node weights vs. node flooding resilience (right) for the CS (top), BAU (middle), and FS (bottom) in the Historic Downtown catchment

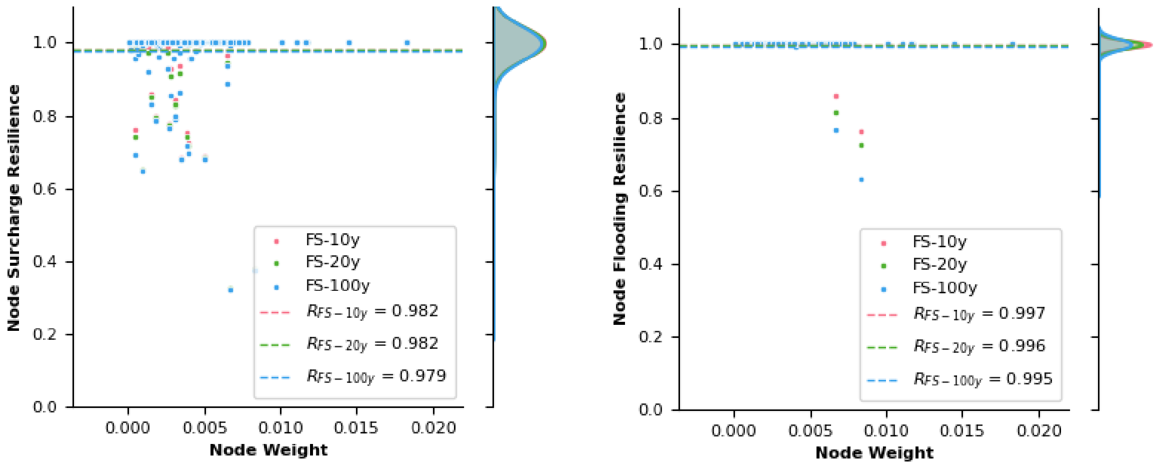


Figure 6-23. Plots of node weights vs. node surcharge resilience (left) and node weights vs. node flooding resilience (right) for the CS (top), BAU (middle), and FS (bottom) in the Historic Downtown catchment (cont.)

Figure 6-24 presents examples of node surcharge and flooding performance curves obtained for the 100-year return period rainfall for the Current Situation of the Historic Downtown catchment. Due to the high number of nodes and scenarios under analysis, these nodes are presented as examples.

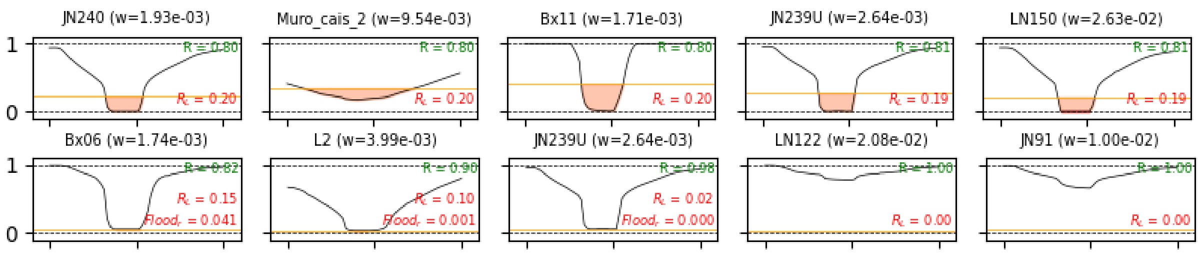


Figure 6-24. Examples of node surcharge (top) and flooding (bottom) performance curves obtained for the 100-year return period rainfall in the Current Situation of the Historic Downtown catchment. The x-axis represents the duration of the event under analysis (5 hours), and the y-axis represents the performance relative to the corresponding state variable. The *w* value stands for the node weight.

Figure 6-25 shows the locations of nodes that present overflows (node flooding), complementing the previous analysis. The colors of the nodes represent the node flooding ratio, i.e., the ratio between the total overflow volume and the total inflow volume to the node. It is observed that, in the Current Situation (CS), the minor system capacity to accommodate the inflows is insufficient, a condition that naturally worsens considering the implications assumed for the future climate scenario (BAU). Additionally, it is noted that with the implementation of the TMSA (Future Situation), there is a clear improvement in the system's performance regarding node flooding.

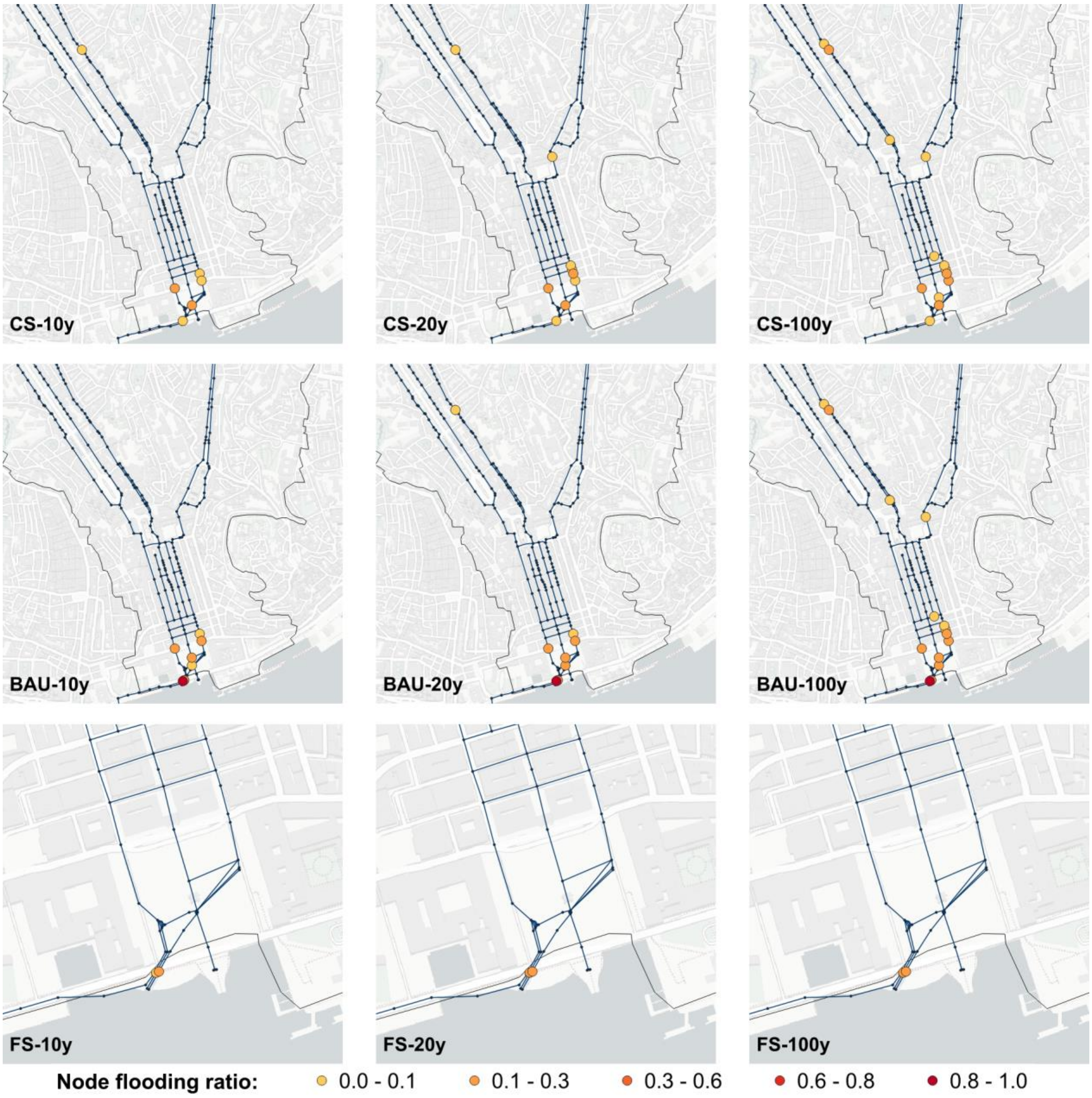


Figure 6-25. Minor system node flooding ratio in the Historic Downtown catchment

The resilience ratings present high values as the performance indicators were calculated considering a total event analysis of 5 hours after the rainfall started. Considering the rainfall pattern and the coincident high tide, the critical moment of the system performance corresponds to the end of the central intense rainfall period. However, before and after that moment, the system does not present significant constraints to proper performance. Figure 6-26 presents the minor system sewer capacity results for the 100-year return period rainfall at the critical event time, approximately 2h30 after the rainfall starts, evidencing the criticality of overlapping the highest tide level with the intense rainfall period.

Figure 6-26. Minor system sewer capacity at the critical event time for the 100-year return period rainfall at CS (left), BAU (center), and FS (right) in the Historic Downtown catchment

Figure 6-27 presents the results obtained for objective *P2. System performance consequences* for the situations considered in the Historic downtown catchment. The Indicator of Damage to Buildings was not considered due to data unavailability regarding building uses. Naturally, these indicators follow the trends of the indicators of the previous objective since they are dependent on the properties of surface runoff, namely the Major System Flooding indicator.

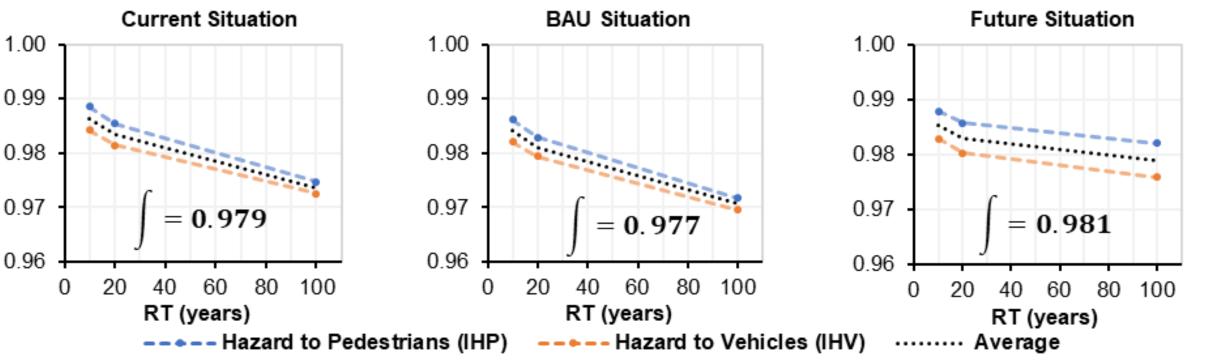


Figure 6-27. Results obtained for the indicators of objective *P2. System performance consequences* for each situation as a function of the rainfall return period, in years, for the Historic downtown catchment

Figure 6-28 and Figure 6-29 present the Indicator of Hazard to Pedestrians and the Indicator of Hazard to Vehicles, respectively. Similarly, as these values were calculated considering a total duration of the event analysis of 5 hours, they are diminished most of the time when rainfall intensities are not intense, and runoff water depths and velocities do not pose significant threats. However, the system performance consequences ratings decrease significantly when considering the lowest performance value at each domain cell, as presented in Figure 6-30.

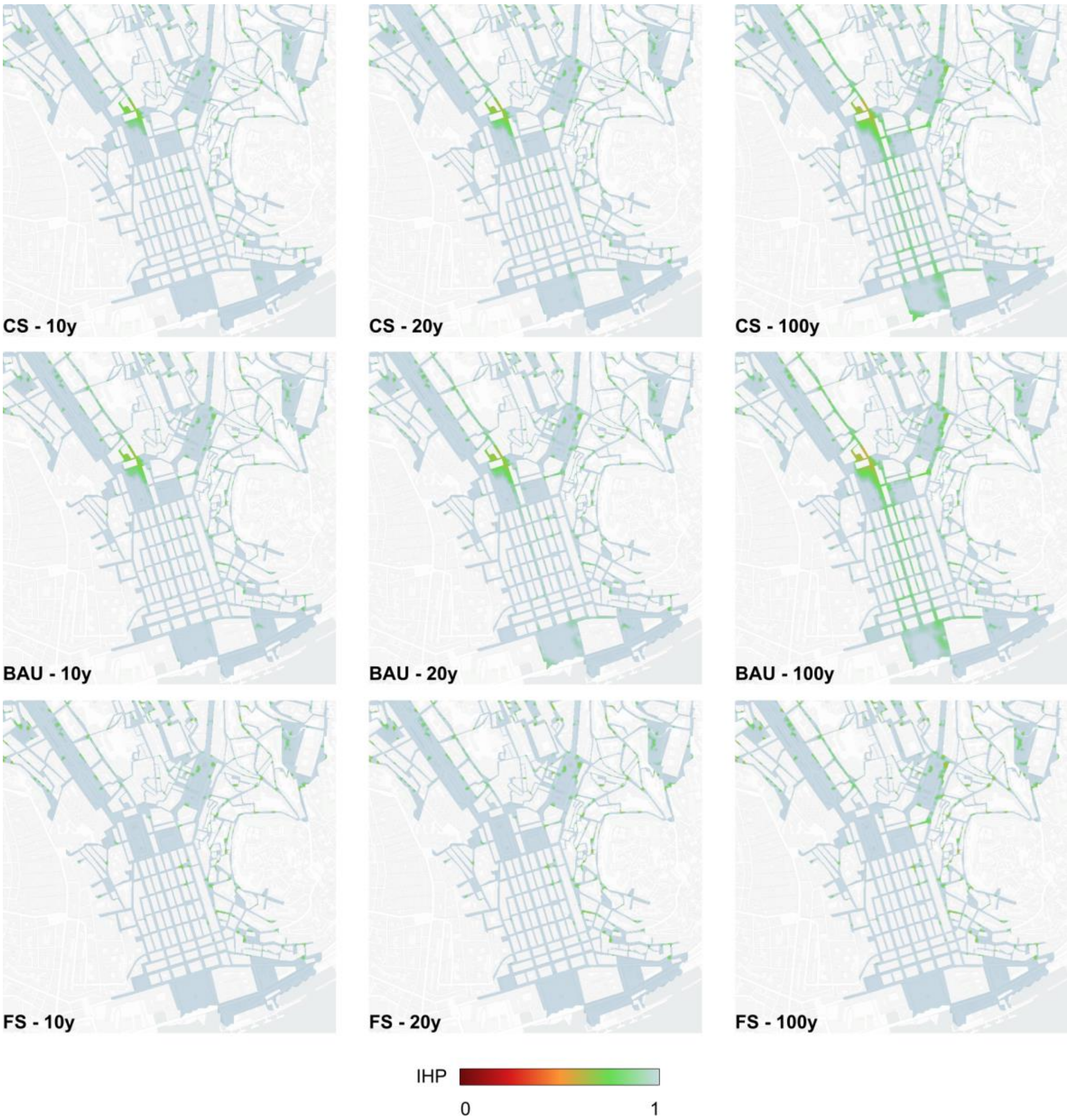


Figure 6-28. Results obtained for the Indicator of Hazard to Pedestrians in the Historic downtown catchment

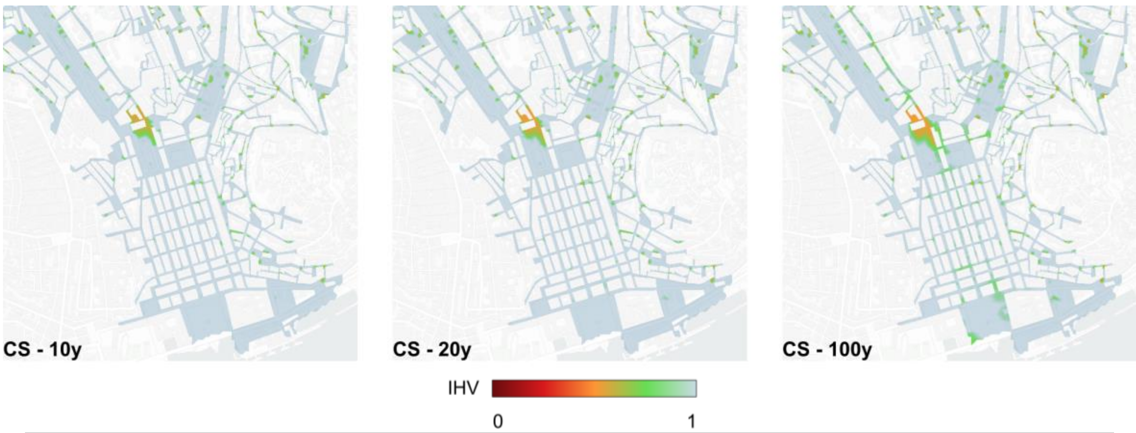


Figure 6-29. Results obtained for the Indicator of Hazard to Vehicles in the Historic downtown catchment

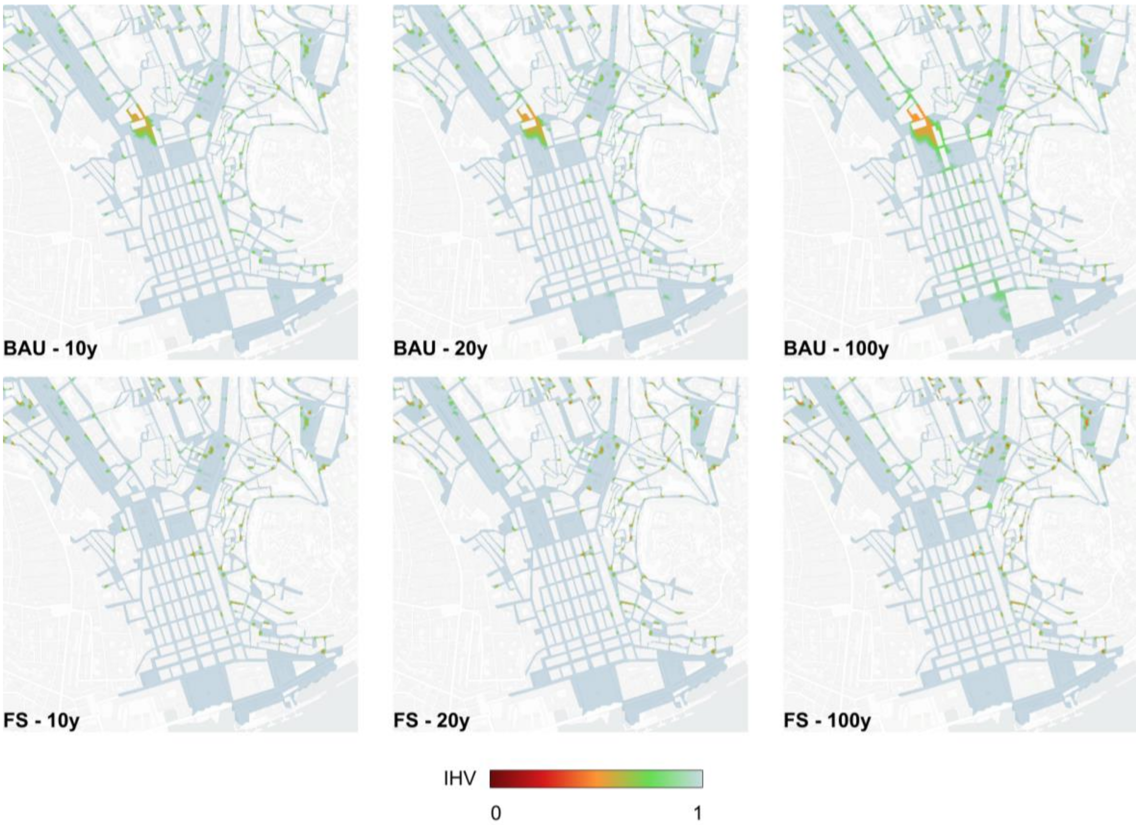


Figure 6-29. Results obtained for the Indicator of Hazard to Vehicles in the Historic downtown catchment (cont.)

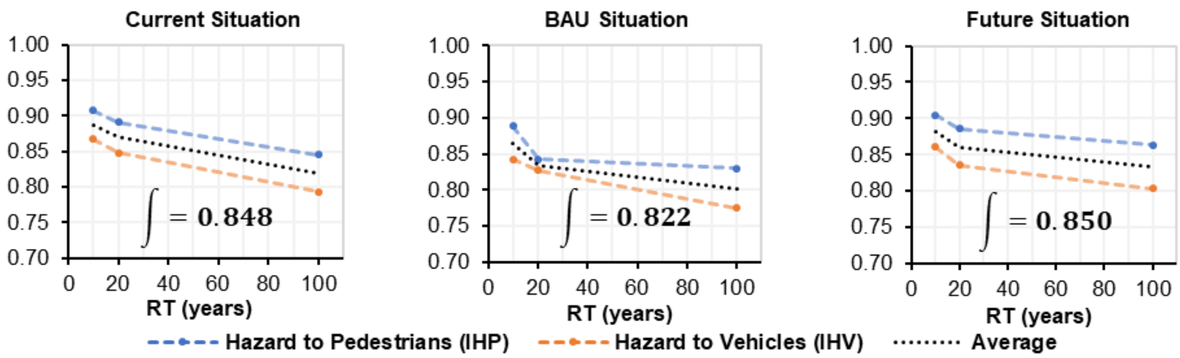


Figure 6-30. Results obtained for the indicators of objective *P2. System performance consequences* for each situation as a function of the rainfall return period, in years, for the Historic downtown catchment, considering the lowest performance level

To exemplify this condition, Figure 6-31 compares the Indicator of Hazard to Pedestrians considering the lowest and the weighted indicator values along the total analysis time. It is observed that with respect to the lowest values of the indicator, there is a clear improvement in the lower zone of the catchment, especially due to the reduction of overflow flows in the manholes. Additionally, some areas continue to present reduced values in the indicator, indicating that the flow capture capacity of inlet devices should be enhanced.

Table 6-7 summarizes the ratings obtained for the Performance Dimension and respective objectives in the Historic downtown catchment. Overall, the Performance Dimension assessment for the three situations highlights important considerations. Firstly, the existing drainage system shows deficiencies in its performance even for current climatic conditions and a rainfall event with a return period of 10 years, especially in the lower and downstream areas of the catchment. Given the expected worsening of boundary conditions and demands on the system, the performance of the drainage system will be further constrained, exacerbating the contribution to the occurrence of floods due to overflow in the manholes, as observed in the BAU Situation. Lastly, the assessment allows us to ascertain that the construction of the TMSA will enable the use of the existing network sewers' capacity without overflows occurring in the current critical zone. However, it is observed that there are still areas downstream of the TMSA interception chambers where surface runoff may pose a danger to people and vehicles, making it of high importance to reinforce the interception of surface runoff in critical areas.

Figure 6-31. Comparison between the lowest and the weighted values of the Indicator of Hazard to Pedestrians in the Historic downtown catchment

Table 6-7. Summary of ratings obtained for the Performance Dimension and respective objectives for the Historic downtown catchment

	Objective P1 System performance resilience	Objective P2 System performance consequences	Performance Dimension	ΔCS
Current Situation	0.975	0.979	**0.977**	-
BAU Situation	0.966	0.977	**0.972**	-0.6 %
Future Situation	0.982	0.981	**0.982**	+0.4 %

ALCÂNTARA CATCHMENT

The approach to assessing the Performance Dimension in the Alcântara catchment was focused on the critical downtown area, which lies at low and flat elevations and is highly prone to the influence of tide levels and the system's surcharge due to backwaters. The objective was to assess the TMSA's contribution to the system's overall performance and its impact on reducing urban floods. Additionally, considering the high vulnerability of the downtown area of the Alcântara catchment, the framework was also used to evaluate the respective impact of two adaptation strategies (AS1 and AS2). Thus, the downstream area was considered for the calculation of the 2D-related indicators (major system), and the "retail" drainage network at downstream of the Alcântara WWTP was considered for the calculation of the 1D-related indicators (minor system), as presented in Figure 6-32.

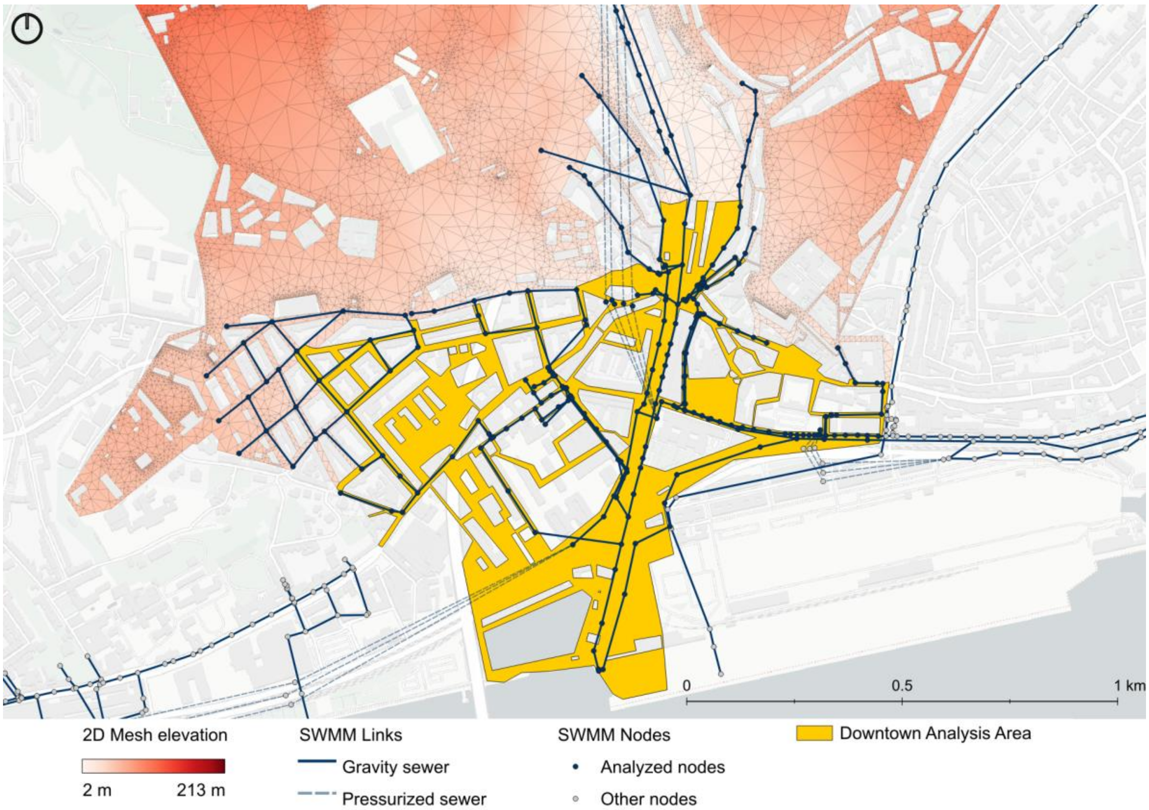


Figure 6-32. Critical area and drainage nodes considered for the Alcântara catchment Performance Dimension assessment

Figure 6-33 depicts the node weights vs. nodes surcharge resilience (left) and node weights vs. nodes flooding resilience (right) for the Current Situation and Future Situations of the Alcântara catchment. A clear positive impact on the minor system performance due to TMSA construction is evidenced regarding the surcharge and the flooding resilience indicators. As predicted, the TMSA capacity to divert flows originating in the "upper zone" of the catchment enhances the system in the low-lying area with greater capacity to accommodate the inflow volumes. Highlights must be put on the gained transport capacity of the Caneiro de Alcântara, although it will continue to struggle with downstream conditions due to rising sea levels (Future Situation). Additionally, the known circumstances of the low-lying areas in the catchment, the limited conveyance capacity conferred by the sewers' low slopes, and the influence of the tide level still represent factors prone to surcharge and flood. This is reflected in the significant number of surcharged and flooded nodes in the Future Situation.

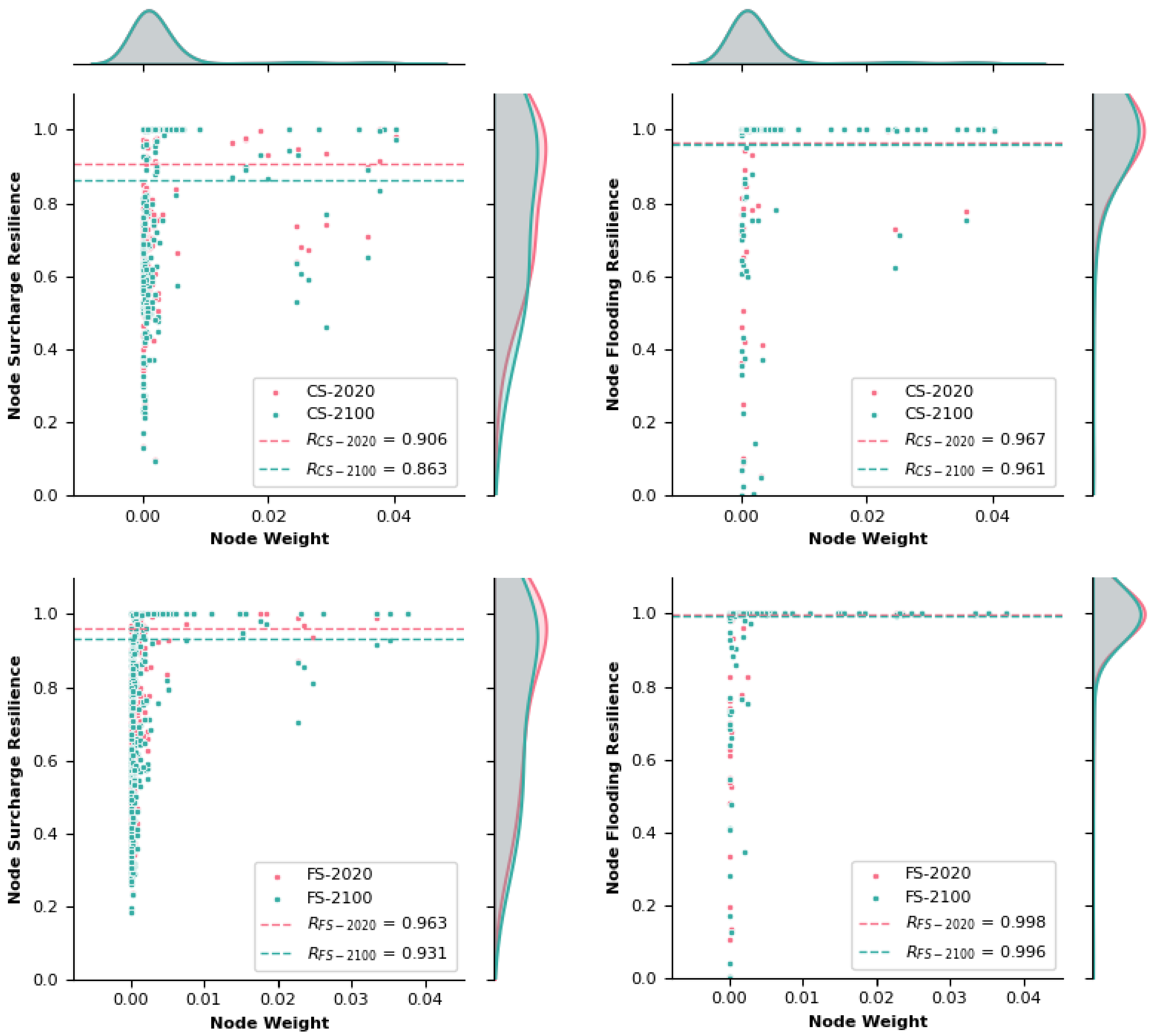


Figure 6-33. Plots of node weights vs. node surcharge resilience (left) and node weights vs. node flooding resilience (right) for the Current Situation (CS) and Future Situation (FS) in the Alcântara catchment

Figure 6-34 presents examples of node surcharge and flooding performance curves obtained for the 100-year return period rainfall in the Current Situation of the Historic Downtown catchment. Due to the high number of nodes and scenarios under analysis, these nodes are presented as examples.

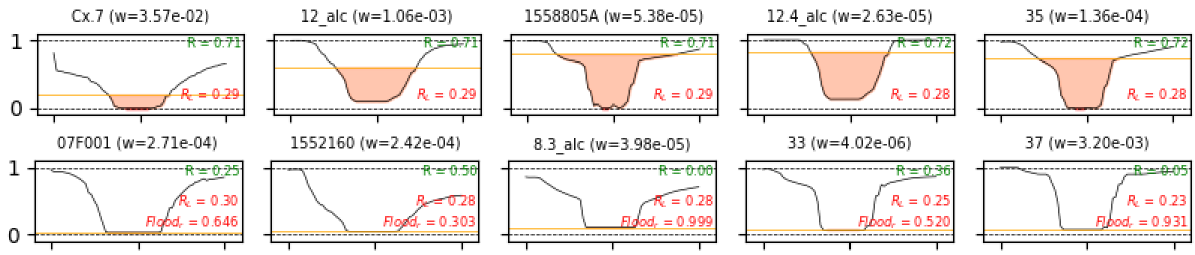


Figure 6-34. Examples of node surcharge (top) and flooding (bottom) performance curves obtained for the CS-2020 Situation in the Alcântara catchment. The x-axis represents the duration of the event under analysis (5 hours), and the y-axis represents the performance relative to the corresponding state variable. The *w* value stands for the node weight.

The results obtained for the indicators of objective *P1. System performance resilience* for the Current and Future Situations are presented in Figure 6-35. The upper and lower deviation bars refer to the current (2020) and future (2100) climate scenarios, respectively, with the indicator value corresponding to the average of these values, as only one RT was considered.

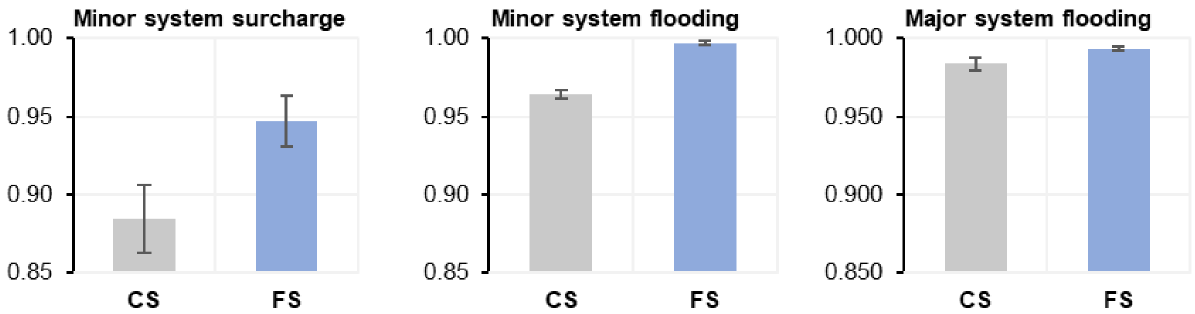


Figure 6-35. Results obtained for the indicators of objective *P1. System performance resilience* for the Current and Future Situations in the Alcântara Catchment

Likewise, Figure 6-36 presents the results obtained for the objective *P2. System performance consequences* for the current and future situations considered in the Alcântara catchment. From the observation of the obtained values, and as expected, the improvement in the drainage system's performance is reflected in the reduction of consequences at the surface.

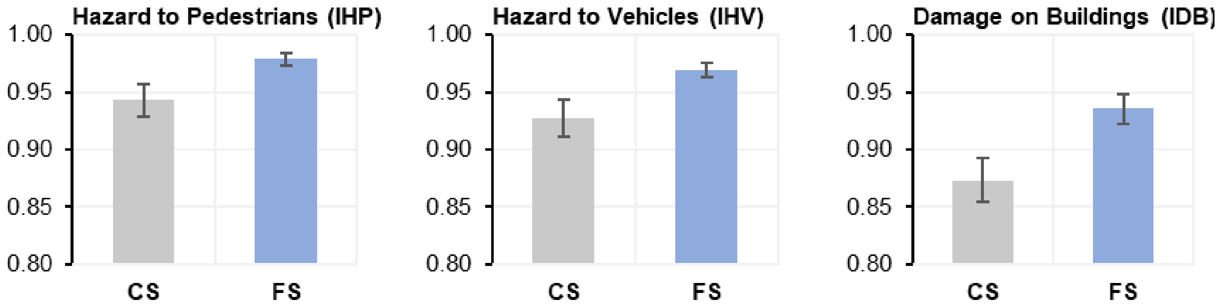


Figure 6-36. Results obtained for the indicators of objective *P2. System performance consequences* for the Current and Future Situations in the Alcântara Catchment

Figure 6-37, Figure 6-38, and Figure 6-39 present the Indicator of Hazard to Pedestrians, the Indicator of Hazard to Vehicles, and the Indicator of Damage on Buildings, respectively, and for the current and future situations.

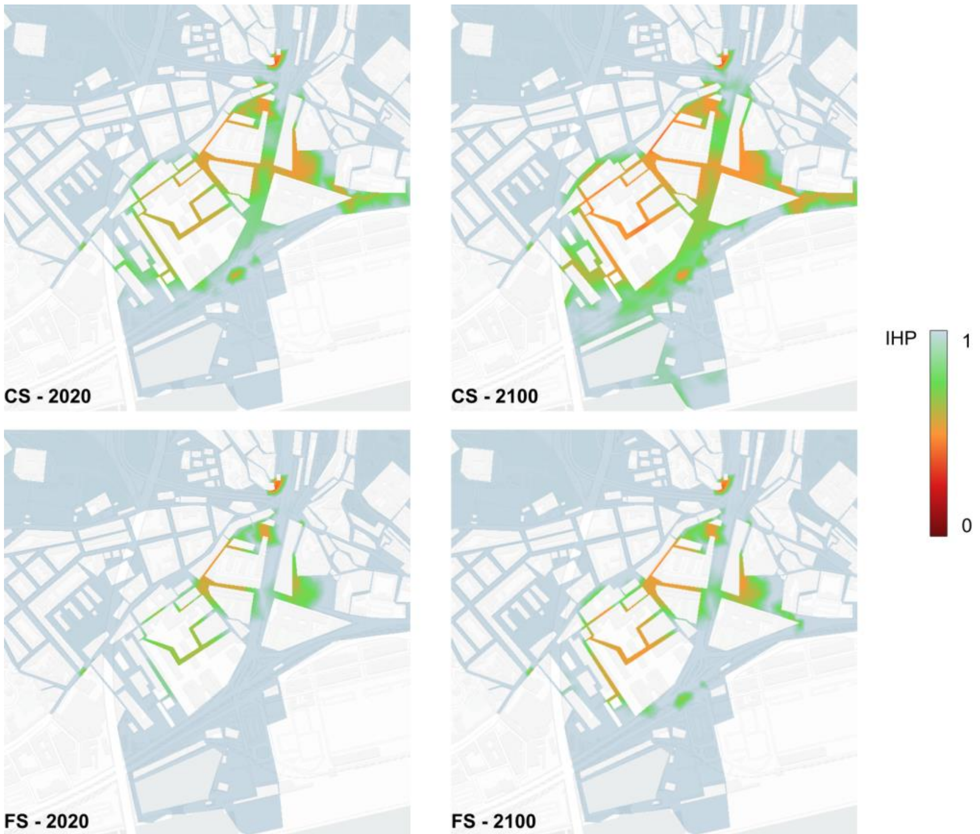


Figure 6-37. Results obtained for the Indicator of Hazard to Pedestrians for the Current and Future Situations in the Alcântara catchment

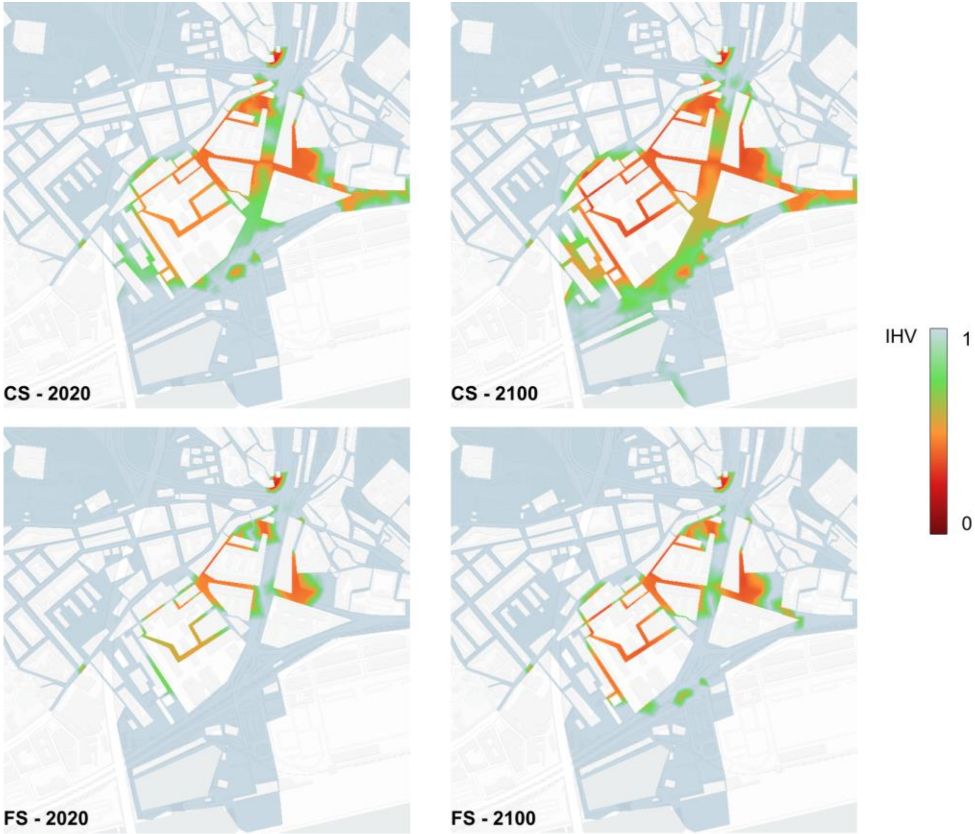


Figure 6-38. Results obtained for the Indicator of Hazard to Vehicles for the Current and Future Situations in the Alcântara catchment

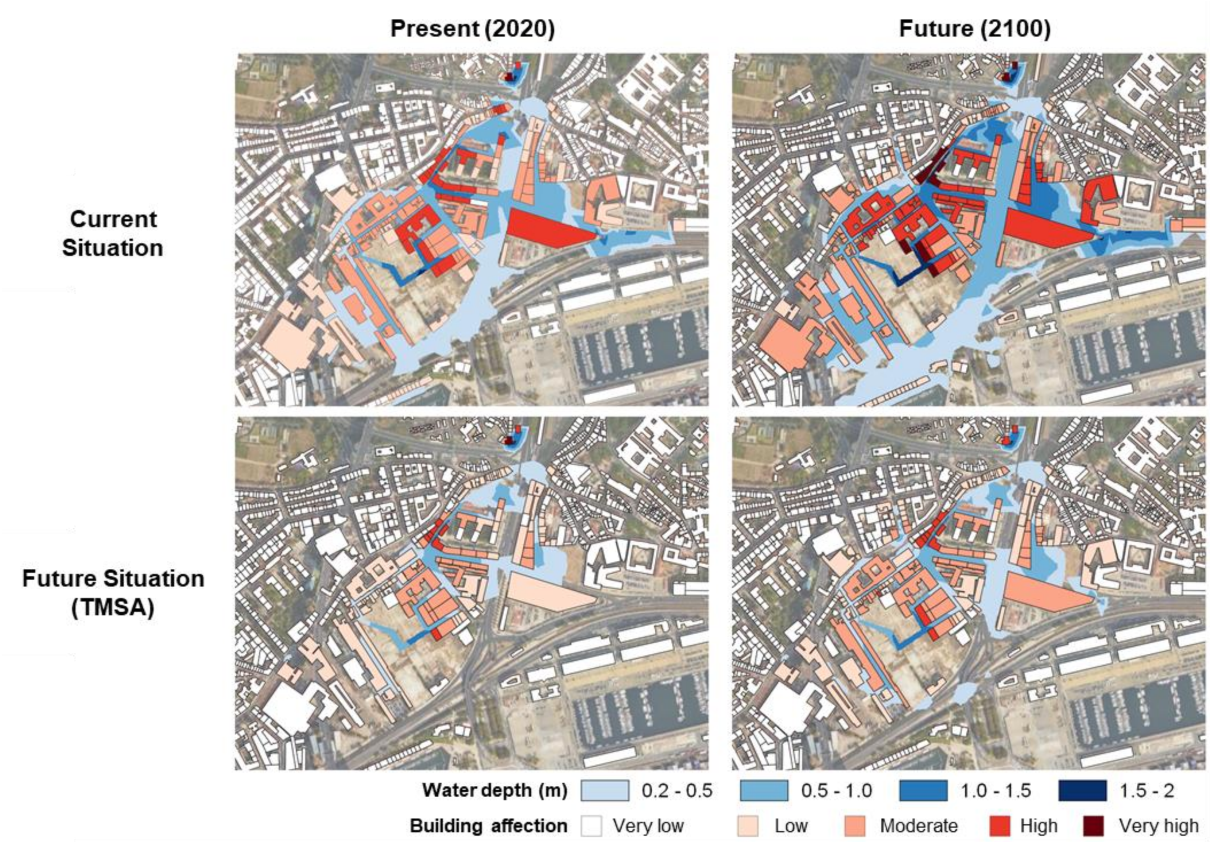


Figure 6-39. Results obtained for the Indicator of Damage on Buildings for the Current and Future Situations in the Alcântara catchment

When considering the Adaptation Strategies, the results of the indicators of objective *P1. System performance resilience* show a negligible variation in relation to the results obtained for the Future Situation (Figure 6-40).

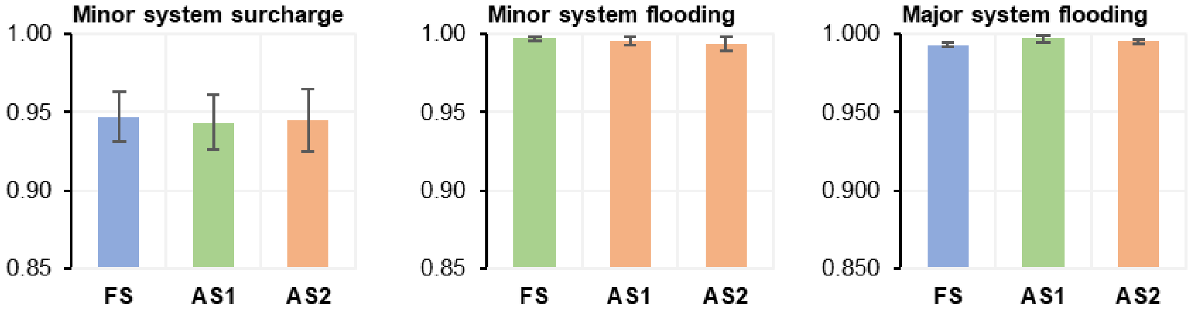


Figure 6-40. Results obtained for the indicators of objective *P1. System performance resilience* for the Future Situation and with the implementation of the adaptation strategies in the Alcântara Catchment

However, there is a slight improvement regarding objective *P2. System performance consequences*, with a highlight on Adaptation Strategy 1, as presented in Figure 6-41.

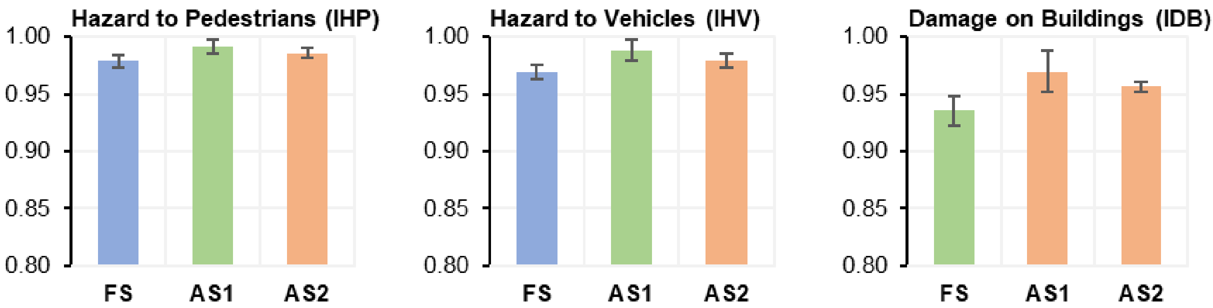


Figure 6-41. Results obtained for the indicators of objective *P2. System performance consequences* for the Future Situation and with the implementation of the adaptation strategies in the Alcântara Catchment

The Indicators of Hazard to Pedestrians, Hazard to Vehicles, and Damage to Buildings for the Adaptation Strategies are represented in Figure 6-41, Figure 6-42, and Figure 6-43.

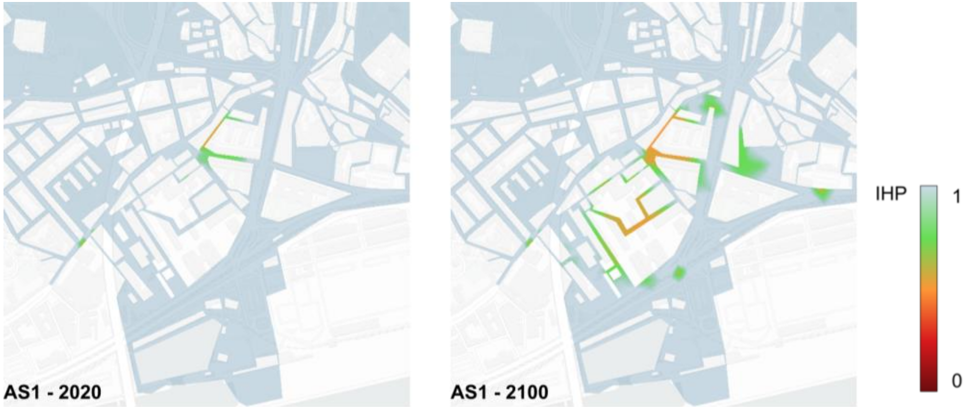


Figure 6-42. Results obtained for the Indicator of Hazard to Pedestrians with the implementation of the Adaptation Strategies in the Alcântara catchment

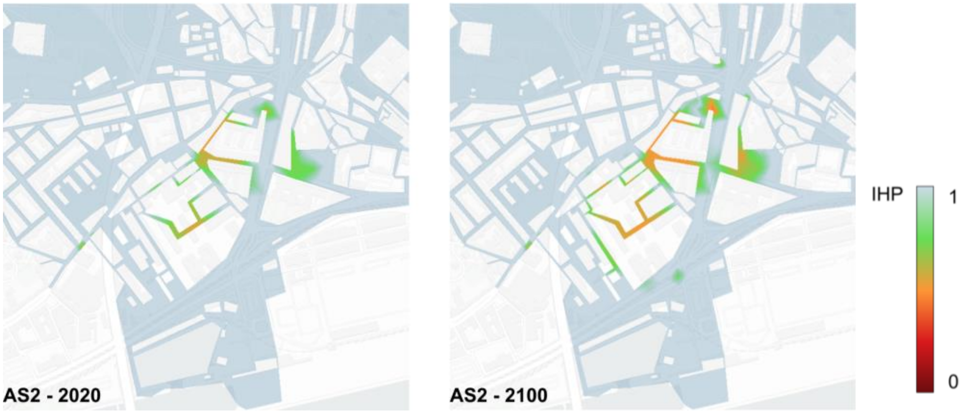


Figure 6-42. Results obtained for the Indicator of Hazard to Pedestrians with the implementation of the Adaptation Strategies in the Alcântara catchment (cont.)

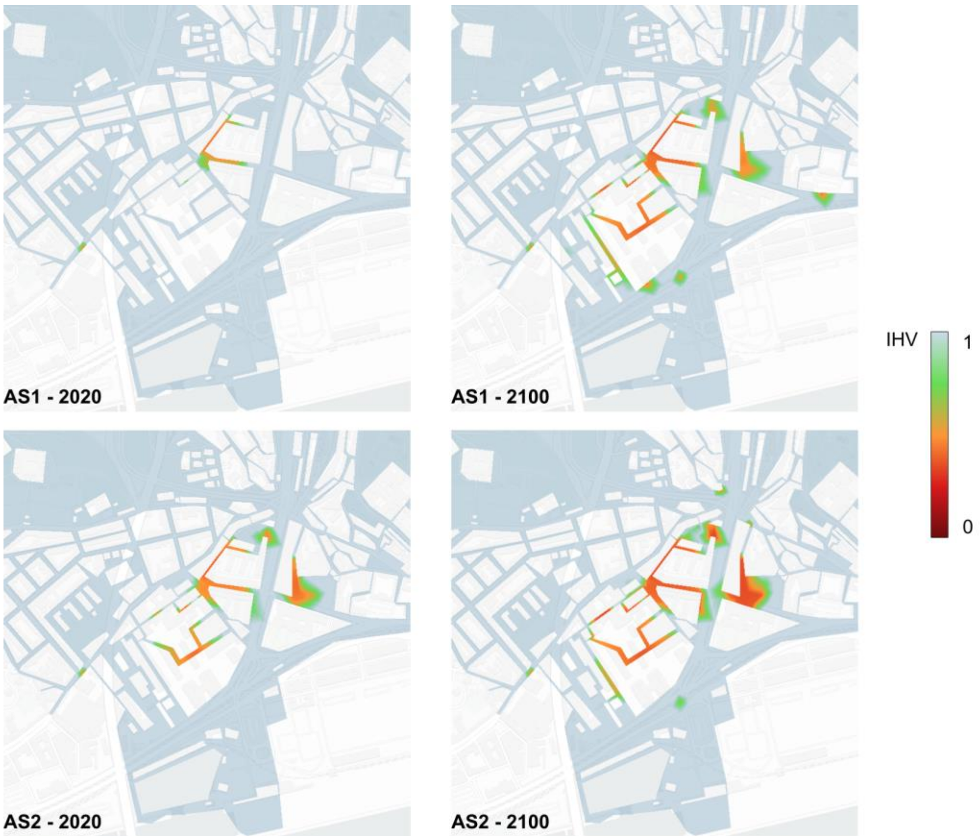


Figure 6-43. Results obtained for the Indicator of Hazard to Vehicles with the implementation of the Adaptation Strategies in the Alcântara catchment

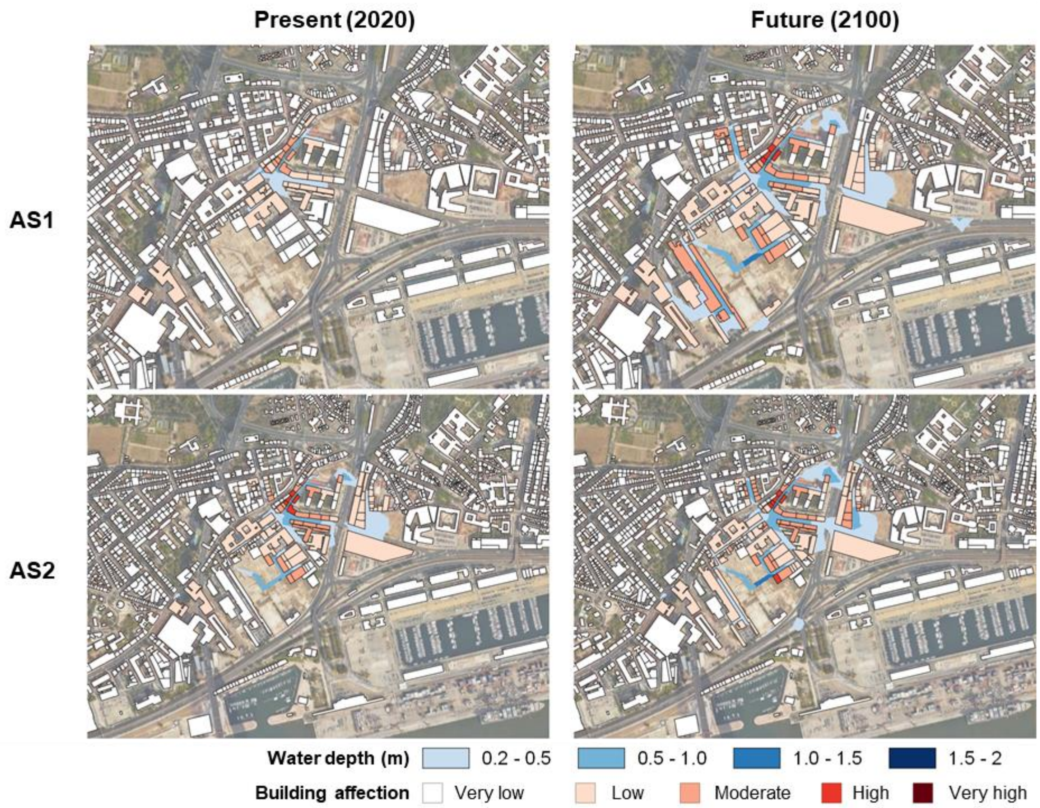


Figure 6-44. Results obtained for the Indicator of Damage on Buildings with the implementation of the Adaptation Strategies in the Alcântara catchment

Table 6-8 summarizes the ratings obtained for the Performance Dimension and respective objectives in the Alcântara catchment. Overall, the Performance Dimension assessment demonstrates that the TMSA introduces the highest contribution to the benefit of the drainage system performance by increasing the minor system surcharge and the minor system flooding indicators by about 7% and 4 %, respectively. Regarding the Adaptation Strategies, the System performance resilience ratings are alike, which does not add any clear advantage to one over the other. However, when considering the system performance consequences, there is a higher rating for the Adaptation Strategy 1 over the Adaptation Strategy 2.

Table 6-8. Summary of ratings obtained for the Performance Dimension and respective objectives for the Alcântara Catchment

	Objective P1 System performance resilience	Objective P2 System performance consequences	Performance Dimension	ΔCS
Current Situation	**0.944**	**0.914**	**0.929**	**-**
Future Situation	**0.979**	**0.961**	**0.970**	+4 %
Adaptation Strategy 1	**0.979**	**0.983**	**0.981**	+6 %
Adaptation Strategy 2	**0.978**	**0.974**	**0.976**	+5 %

6.4.3. URBAN STORMWATER RESILIENCE INDEX RESULTS

The Urban Stormwater Resilience Index was calculated for each of the analyzed situations in both case studies. The Strategic Dimension was considered constant even for situations considering a future timeframe. This is because it is not deemed pertinent to assess hypotheses of different future management of the service, as this dimension should be evaluated considering the current state of the service. In other words, evaluating the Strategic Dimension of the future in light of plans, studies, and projects that may not be implemented can be perilous.

In the current application, a weight of 1/3 and 2/3 was applied to the Strategic and Performance Dimensions, respectively. The assignment of these weights aims to reflect greater consideration for the system's actual performance and its respective consequences for the city, prioritizing resilience as a property that allows for an adequate response to precipitation events.

The Urban Stormwater Resilience Indexes calculated for each Situation of the Historic downtown catchment and the Alcântara catchment are shown in Table 6-9 and Table 6-10, respectively.

Table 6-9. Urban Stormwater Resilience Index for the situations considered in the Historic downtown catchment

	Strategic Dimension	Performance Dimension	USRI
Current situation	0.53	0.977	0.828
Business as usual		0.972	0.825
Future situation		0.982	0.831

Table 6-10. Urban Stormwater Resilience Index for the situations considered in the Alcântara catchment

	Strategic Dimension	Performance Dimension	USRI
Current situation	0.53	0.929	0.796
Future situation		0.970	0.823
Adaptation Strategy 1		0.981	0.831
Adaptation Strategy 2		0.976	0.827

6.5. CONCLUSIONS

In the current chapter, the RESILISTORM framework, developed and proposed in this thesis, was applied to two case studies in Lisbon: the Historic downtown catchment and the Alcântara catchment. Both these catchments often face challenges in responding to intense precipitation events, especially when coinciding with high tide levels, and floods occur. Although there have been projects and improvements in the past aiming at enhancing the performance of these catchments, the increasing pressures posed by the impacts of climate change, particularly due to the rising sea levels, create an almost constant need to assess when the subsequent intervention will be necessary. In Lisbon, the General Drainage Plan 2016-2030 included the construction of two major drainage tunnels, one of which, the TMSA, intercepts a large part of the city of Lisbon, including the catchments under study. The framework's implementation sought to assess the system's present condition and potential gains from such interventions from a resilience system thinking perspective.

The evaluation of the Strategic Dimension of the framework enabled the identification of critical aspects that limit the capacity of Lisbon's Sewerage Department to become more resilient. Specific examples include the necessity to seek redundancies within the urban space that allow for the safe management of increased surface runoff and the need to improve the monitoring of the system to have accurate and continuous information regarding its performance in critical locations. Furthermore, from an environmental perspective, the service must enhance its ability to control and minimize the occurrence of stormwater overflows. From answering the question-oriented indicators of this dimension, its overall assessment is rated as insufficient, scoring 0.53 out of 1.

Regarding the Performance Dimension, the Urban Stormwater Resilience Index and the ratings obtained for objective *P1. System performance resilience* and objective *P2. System performance consequences* evidence an improvement in both case study catchments due to the construction of the TMSA. Additionally, the indicators proved helpful by reflecting the impacts on resilience due to the different configurations of the system and the increasing demands due to intense rainfalls and boundary conditions settled by rising sea levels. In the case of the Alcântara catchment, the indicators proved also useful in aiding the selection of a suitable Adaptation Strategy in the light of a resilience perspective. Adaptation Strategy 1, consisting of the rehabilitation of most of the existing weirs in the study area to intercept wastewater carried by the upstream combined sewers through flow regulation chambers, has proven to enhance the service's resilience more effectively than Adaptation Strategy 2, consisting in the disconnection of the existing connections at the right side of Caneiro de Alcântara and construction of a new parallel combined sewer with a downstream wastewater pumping station. Moreover, it is also relevant to highlight the different investment costs estimated for these strategies, around 2.36 million euros for AS1 and 5.36 million euros for AS2

(HIDRA, 2020). Thus, when combining the investment costs and the improvement in the performance resilience of the system, Adaptation Strategy 1 presents a clear benefit over Adaptation Strategy 2.

The Performance Dimension indicators, except for the damage to buildings, were calculated considering the performance curve's evolution over the analysis period. In the current application, given the 4-hour duration of the rainfall event, an analysis period of 5 hours was considered, meaning the duration of the rainfall event plus one hour after its end. This type of calculation, on the one hand, makes the results sensitive to the selected analysis period's duration and, on the other, tends to dilute lower performance levels as they occur in smaller time proportions. This latter effect can overlook the occurrence of low-performance levels unless a thorough analysis is conducted that goes beyond merely looking at the overall indicator values. As these indicators are calculated from the results of 1D/2D hydrodynamic models, it is essential to bear in mind that they will reflect not only the simplifications and assumptions but also the numerical instabilities and accuracy of the simulations. Additionally, in the case of the minor system indicators, the consideration of different system configurations will most probably result in the attribution of different weights to the nodes, which must also be considered when analyzing results.

Overall, the RESILISTORM framework has proven to be consistent and suitable in relation to the established resilience dimensions and objectives, as well as applicable to the study of real cases. As indicated in the definition of this framework, its utility is not limited to the numerical results obtained; equally or more important is the defined roadmap, which enables the establishment of critical thinking for managing the resilience of urban stormwater services.

Chapter 7. FINAL REMARKS AND RECOMMENDATIONS FOR FUTURE WORKS

"Chop your own wood and it will warm you twice."

Henry Ford, 1923

7.1. OVERVIEW AND GENERAL CONCLUSIONS

The work developed and presented in this thesis aimed primarily at developing a resilience framework for urban stormwater services, on the one hand, covering some identified gaps and, on the other, leveraging the rationale of existing works, allowing progress in this domain coherently and continuously. This objective is underpinned by the need to improve and make a "step-up" concerning conventional stormwater management based on infrastructural maintenance, given the high importance of this service in cities as it is responsible for managing the flows generated by precipitation.

A literature review on the concept of resilience and how it has been applied in cities, carried out in Chapter 2, emphasizes that this concept has started to gain greater relevance in the second decade of this century, meaning there is still some confusion regarding its definition. This fuzziness is increased because various thinking systems have emerged around the concept, resulting in different approaches, properties, and paths to achieve resilience. Nonetheless, these thinking systems are relatively consolidated, and each presents characteristics useful for cities, highlighting the capacity for recovery (originating from engineering resilience), the capacity for adaptation (originating from ecological resilience), and the capacity for transformation (originating from socio-ecological resilience). It is extremely important to understand that these concepts are not exclusive but mutually reinforcing, and their combination is the best way to ensure resilience both as a property (acting on short temporal and spatial scales) and as a process (acting on larger temporal and spatial scales). Through this duality, called Panarchy, resilience takes on a multi-spatial and multi-temporal dimension, promoting approaches that consider the past (as acquired knowledge), the present (as a moment of alert and action), and the future (as a goal to be achieved sustainably).

The trend of approaches for holistically assessing urban resilience has been developed mainly through international projects and partnerships involving major global stakeholders such as the United Nations, the European Commission, and the Rockefeller Foundation, corresponding to investments of millions in the last decade. However, these partnerships and projects have not always resulted in an effective paradigm shift in cities, with the lack of financial resources and the change of political cycles and interests pointed out as the main factors. Moreover, the need for concrete and urgent results, which do not always align with the planned and even executed strategies, can promote a false sense of futility.

In the context of application and assessment trends concerning the resilience of urban stormwater services and flooding, which are inherently inseparable concepts, resilience is recognized as a novel paradigm for urban stormwater management, as studied in Chapter 3. This paradigm potentially mitigates the impacts of disturbances by viewing them as opportunities for more sustainable urban development, and it plays a crucial role in the functioning of an urban system. Resilience signifies a shift from traditional "fail-safe" strategies to a comprehensive "safe-to-fail" perspective. This approach accepts, anticipates, and prepares for failure under extraordinary conditions, thereby enhancing the capacity to manage and recover from flooding events, particularly in light of future risks and associated uncertainties to climate change. Nonetheless, many organizations and stakeholders poorly understand the concept of resilience, which obstructs its implementation at the urban services level, such as in stormwater services. This issue is closely linked to the diverse approaches to understanding and operationalizing resilience. The literature presents various qualitative and quantitative approaches, which are typically segmented and do not leverage different perspectives and methodologies. Qualitative approaches often focus on the theoretical properties of resilience and employ expert-based assessments. In contrast, quantitative approaches primarily concentrate on engineering resilience, considering the system's performance in response to rainfall events.

Given this background, the current thesis introduced, in Chapter 5, a resilience framework for urban stormwater systems named RESILISTORM. This framework is enclosed within the following standpoints:

- It emphasizes the stormwater service as a socio-ecological and technical urban system.
- It incorporates the temporal dimension by integrating past experiences, evaluating preparedness for future conditions—including climate change—and facilitating an ongoing resilience assessment over time.
- It accounts for the spatial dimension by examining the interactions between the stormwater service and other urban services and infrastructures.
- It integrates a comprehensive approach encompassing the three main conceptual focuses of resilience—engineering, ecological, and socio-ecological—along with their primary properties and characteristics. This includes engineering resilience through robustness and recovery, ecological resilience through adaptation and flexibility, and socio-ecological resilience through human capacity for transformation.
- It merges qualitative and quantitative resilience approaches into a unified framework.

Leveraging this concept, RESILISTORM considers two dimensions of stormwater service resilience. The Strategic Dimension relates to medium and long-term planning and organizational capacity to achieve desired goals by analyzing internal and external conditions to identify opportunities, threats, strengths, and weaknesses. It aims to evaluate resilience as a process from the perspective of service management and knowledge. This dimension includes 13 criteria to assess 4 objectives: *S1. Institutional capacity*, *S2. Urban service relationships*, *S3. System knowledge*, and *S4. Infrastructural knowledge*, through a set of indicators derived from 43 question-oriented indicators. The Performance Dimension is related to the actual capacity of the service to achieve its objectives and perform effectively as an urban service. It seeks to evaluate resilience as a property that enables the service infrastructures to function correctly and minimize negative impacts on the city. Encompassing two objectives, *P1. System performance resilience* and *P2. System performance consequences*, this dimension focuses on service performance in response to rainfall events, assessed through performance indicators derived from the results of 1D and 1D/2D drainage models. Thus, the service is evaluated not only based on its intrinsic performance but also on the consequences of this performance on the city, a necessary condition for assessing its resilience.

The structure of the developed framework makes the assignment of varying weights to criteria, objectives, and dimensions possible, enabling the calculation of a singular indicator, the Urban Stormwater Resilience Index. Naturally, allocating different weights influences the outcomes and requires self-critique capacity by utilities aiming to conduct a meaningful resilience assessment. While applying equal weights to various criteria or objectives might contravene the established goals of the service, this allocation must also avoid bias, ensuring that seemingly less relevant criteria or objectives are not overlooked. In this regard, it is also crucial to examine the different approaches proposed for evaluating the Strategic Dimension and the Performance Dimension. Can a stormwater service be deemed resilient with a low-performance level but a strong strategic component? Despite the inherent subjectivity, it is hypothesized that the Performance Dimension might typically carry more weight, as it mirrors the effective results of a successful strategic service management. Conversely, an exclusive focus on the performance dimension risks undermining the adaptability and transformation capacities essential for coping with future climate conditions, which will significantly impact the ability of urban stormwater services to fulfill their mission effectively. These considerations highlight the significance of context in assessing and managing the resilience of urban stormwater services, underscoring the necessity to acknowledge the impact of contextual variations to improve stormwater management practices and bolster resilience.

The efficacy and adaptability of the framework were corroborated through its application in two pivotal drainage catchments in Lisbon: the Historic downtown catchment, notable for its central significance in the urban landscape, and the Alcântara catchment, the largest catchment of Lisbon, involving tributary areas of two neighbor municipalities. Although within two basins of the same city, this implementation was established on differing assumptions and aimed to explore the potentialities and vulnerabilities of the presented framework and its indicators. It is generally observed that the Strategic Dimension can pinpoint management issues that predominantly impact the capacity for acquiring and consolidating essential knowledge for improving urban stormwater drainage services. The indicators of this dimension were intentionally designed to be uncomplicated, both in interpretation and response options, employing domain-specific terminology yet subtly steering towards critical and innovative thinking about concepts such as systemic thinking within urban services and integration with other urban utilities (encompassing notions like interdependencies, autonomy, and redundancy). This also includes the effective capability to ascertain the real-time performance of the infrastructure without necessitating an urban flood event to acknowledge that the service is likely to fail and that proactive measures must be taken to address this uncertainty. On another note, it is recognized that the employment of 1D/2D modeling is still incipient in the field and is somewhat ahead of many stormwater utilities' current capabilities. However, this can be viewed as a challenge that encourages these entities to enhance their digital modeling competencies, which adds significant advantages in terms of decision-making concerning both routine maintenance activities and adopting more complex strategies. Additionally, resorting to this type of modeling aligns with the trend of managing urban stormwater systems from a dual perspective, incorporating not only conventional and underground grey infrastructures but also the urban surface and blue and green infrastructures, acknowledging the significance of urban design in transforming stormwater from a perceived trouble to a valuable asset for the city.

The framework exhibits a non-rigid structure, wherein context emerges as a pivotal factor for its application, particularly concerning the performance dimension and corresponding indicators, enabling its applicability in diverse contexts and extending to other urban consequences.

The development of open-source digital tools that assist in implementing the developed framework also stands out as a distinguishing effort. The creation of the RESILISTORM-tool aims to facilitate a deeper understanding of the RESILISTORM roadmap through its application. It enables the expedited completion of indicators, aggregation of indicator results, and automatic computation of metrics/indicators, criteria, objectives, and dimensions ratings for the Urban Stormwater Resilience Index. A significant advantage of being an open-source tool is its capacity for ongoing refinement and enhancement by the community. Challenges and novel developments can be tackled within the online repository structure, promoting continuous improvement, nurturing a collaborative attitude in addressing new issues, and enriching the tool. The inclusion and availability of tools that allow the calculation of the indicators related to the minor and major systems emerges as another contributory factor to the ease of applying the developed framework.

Additionally, the development of the coupled 1D/2D SWMM/Land model, presented in Chapter 4, represents an innovative leap, given the scarcity of such models within the community. Although this model was not applied to the thesis case studies, its testing in the lower zone of Albufeira city yielded promising results, considering the complexity of the involved processes. Moreover, developing this open-source model enables utilities or researchers to perform 1D/2D modeling of urban drainage systems without needing proprietary models and software. The availability of such tool may thus contribute to a greater understanding of the performance of urban drainage systems, a critical factor in developing their resilience.

In general terms, this thesis evolved to meet the established objectives and provides a reference framework concerning the resilience of urban stormwater drainage services and their contribution to city resilience. The framework applies to traditional gray stormwater systems based on underground infrastructure, systems established on blue and green Nature-Based Solutions, or hybrid systems with gray and blue-green solutions. Thus, RESILISTORM emerges as a potent contributor to the paradigm shift in managing urban stormwater services, incorporating resilience as an innovative and transformative factor that empowers stormwater utilities and stakeholders to tackle present and future challenges proactively. This endeavor will aid in ensuring the uninterrupted operation of urban services while safeguarding the population and assets. Moreover, it can bolster urban sustainable development through improved planning to evolve into a water-wise city.

7.2. FUTURE DEVELOPMENTS

This thesis presents a resilience framework for urban stormwater services, which, by definition, encompasses a wide range of characteristics and properties to be considered, especially since there are various management models, and a framework that can fully integrate into all of them will inevitably have much greater complexity. However, it is believed that the value of a relatively synthetic framework, like the one presented, can be an advantage by identifying aspects that undermine the resilience of services and, thus, lead them toward adopting more specific assessment strategies about them.

Nevertheless, within the scope of the Strategic Dimension, the indicators presented could be better consolidated and developed by applying RESILISTORM to different cities and with different contexts. Consequently, the Performance Dimension could also benefit from this by including other indicators related to service performance and its consequences for the city.

The increasing pressures placed on the performance of urban stormwater drainage systems go beyond their capacity to respond to stormwater flows, with a trend for this demand to strongly grow towards controlling the quality and quantity/frequency of stormwater overflows in combined systems, as well as increasing the integration of green, blue, and hybrid solutions. Although the framework includes indicators related to this issue, they should be further deepened in both proposed dimensions.

Finally, an important step was taken by presenting the developed tools, both the RESILISTORM-tool and associated calculation tools, and the coupled SWMM/Land model. Naturally, any tool or model requires continuous improvement so that its application is, on the one hand, more expedited and practical and, on the other, more flexible and adaptable. The most desired development is RESILISTORM to be an initial version of a possible future dashboard for managing the resilience of urban stormwater services, including monitoring and real-time predictions of the performance component.

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ANNEXES

Annex 1. Potential flood exposure and affection/cascade effects on urban services

Table A1. Summary of potential flood exposure and affection/cascade effects of/on several urban services on Barcelona, Bristol, and Lisbon research sites in the case of urban flooding (adapted from Vela, 2018)

Urban service	Subsystem	Critical elements	Potential Exposure	Potential affection/cascade effects
Power and Electricity	Power generation	Main station of power generation	○	-
		Station of distributed generation		
	Electric Transportation	Substation	●	The exposure to flooding of such critical elements can interrupt the power supply, triggering critical cascade effects on several key urban services with power dependencies. At the distribution level, infrastructure potential for flood exposure is higher, leading to more affected assets, although at smaller scales due to the affection of specific substations.
		Overhead lines	○	
		Underground cables	●	
	Electric Distribution	Substation	●	
		Overhead lines	○	
		Underground cables	●	
Telecommunication	Network	Antennas	●	Communication assets can be exposed to rain/flood. There is a dependence of several key urban services on communications, mainly regarding monitoring and telemetry systems. Usually, critical security and emergency services are equipped with redundant communication equipment.
		Telecommunication network		
	Nodes	Operational centers		
Urban water cycle	Water supply	Distribution network	○	-
	Urban drainage	Sewer network	●	Stormwater inlets can have low efficiencies, leading to higher surface runoffs. Sewer networks with limited conveyance capacity can surcharge, leading to manholes' overflow (flood aggravation) with the potential of fecal contamination on the surface. Storm weirs will operate leading to CSO. Bathing on receiving water bodies can be compromised.
		Pumping stations	●	Excessive inflows lead to bypass and discharge of untreated flows into receiving water bodies. Bathing on receiving water bodies can be compromised. Electromechanical and control systems can be flooded, leading to low or total failure of the pumping capacity and overflow to the surface (flood aggravation and potential fecal contamination on the surface).

Urban service	Subsystem	Critical elements	Potential Exposure	Potential affection/cascade effects
	Wastewater treatment	WWTP	●	Excessive inflows lead to bypass and discharge of untreated flows into receiving water bodies. With higher inflow rates and dilution, treatment efficiencies tend to decrease.
Municipal Solid Waste	MSW Collection	Pneumatic collecting plants	○	-
		Pneumatic collecting network	○	-
		Waste vehicles	●	High flood levels can impede the passage of collection vehicles.
		Solid waste containers	●	Containers can be damaged, displaced, and overturned, leading to waste spreading on the surface. Clogging of stormwater inlets is a critical cascade effect.
	MSW Treatment	Waste treatment plant	○	-
		Cleaning stations	○	-
Mobility	Roadways transport	Road's network	●	Floods can cause interruption of roadway traffic and displacement of parked vehicles. Cascade effects are expected on any service with dependencies on roadway transport.
		Traffic signals		Although potentially exposed, its failure is more probable due to the affection of power assets.
	Railway and subway transport	Surface rail and metro network	●	Surface rail and subway infrastructures can be compromised due to food depths, leading to service interruption.
		Surface rail and metro stations		
		Underground rail and metro network		Underground rail and subway infrastructures are less prone to flooding. However, surface runoff can reach such assets by pedestrian accesses and ventilation grates. Higher flood depths are typically required to lead to service interruption.
		Underground rail and metro stations		
		Traffic signals		Although potentially exposed, its failure is more probable due to the affection of power assets.
Green infrastructures	Trees	Trees	○	Green infrastructures are generally not affected by floods. However, intense rainfall events can lead to the falling of leaves and small branches. Clogging of stormwater inlets is a critical cascade effect.

Annex 2. RESILISTORM Strategic Dimension

Table A2. Objectives, criteria, and indicators of RESILISTORM Strategic Dimension

Objective	**S1 - Institutional capacity**	
Criteria	**S1.1 - Resilience planning and policies**	**Ans. rate**
Indicator	**S1.1.1 - Stormwater Strategic Plan**	
Source	Adapted from RESCCUE RAF	
Ans. type	Single choice	
Question	**Does the service have an implemented Drainage/Stormwater Plan with adequate monitoring and review?**	
1)	The strategic plan does not exist.	0.00
2)	The strategic plan exists but is not implemented (outdated/unmonitored).	0.33
3)	The strategic plan is implemented but considers only a technical component.	0.67
4)	The strategic plan is implemented and considers technical and non-technical components.	1.00
Indicator	S1.1.2 - Plan alignment with the City Master Plan	
Source	Adapted from RESCCUE RAF	
Ans. type	Single choice	
Question	Is the plan aligned and complying with the City Master Plan?	
1)	No.	0.00
2)	Partially.	0.50
3)	Yes.	1.00
Indicator	S1.1.3 - Plan alignment with Resilience system-thinking	
Source	-	
Ans. type	Single choice	
Question	Does the plan have an explicit resilience-oriented view?	
1)	No.	0.00
2)	Partially or indirectly.	0.50
3)	Yes.	1.00
Criteria	**S1.2 - Service system thinking**	
Indicator	**S1.2.1 - Service management inclusion in city planning and strategic involvement**	
Source	-	
Ans. type	Single choice	
Question	**Is the stormwater service included in the city's strategic planning?**	
1)	No strategic involvement.	0.00
2)	Yes, but indirectly, marginally, or sporadically.	0.50
3)	Yes.	1.00
Indicator	**S1.2.2 - Knowledge exchange with other urban services**	
Source	Adapted from RESCCUE RAF	
Ans. type	Single choice	
Question	**Does the service have knowledge exchange procedures with other urban services (partnerships, participation in conferences, etc.)?**	
1)	No explicit knowledge exchange procedures are in place.	0.00
2)	Yes, but informally or unofficially.	0.50
3)	Yes.	1.00

Indicator	**S1.2.3 - Service involvement in R&D activities**	
Source	-	
Ans. type	Single choice	
Question	**Is the service involved in R&D or other innovation activities or projects?**	
1)	No involvement in the last 5 years.	0.00
2)	Yes, in the last 5 years, but not at the moment.	0.50
3)	Yes, at the moment or up to the next 5 years.	1.00
Indicator	**S1.2.4 - Service contribution to societal change**	
Source	-	
Ans. type	Single choice	
Question	**Does the service provide opportunities for public engagement and participation?**	
1)	Not explicitly.	0.00
2)	Only when mandatory.	0.50
3)	Yes, regularly.	1.00

Objective	**S2 - Urban service relationships**	
Criteria	**S2.1 - Interdependencies**	
Indicator	**S2.1.1 - Stormwater service dependencies on other urban services**	
Source	Adapted from RESCCUE RAF	
Ans. type	Single choice	
Question	**To what extent are dependencies on other services known?**	
1)	No knowledge or formal understanding of dependencies.	0.00
2)	Minor understanding of dependencies.	0.33
3)	Critical dependencies are known.	0.67
4)	The entire map of dependencies is depicted.	1.00
Indicator	**S2.1.2 - Urban services dependencies on Stormwater service**	
Source	Adapted from RAF RESCCUE	
Ans. type	Single choice	
Question	**To what extent are dependencies from other services known?**	
1)	No knowledge or formal understanding of dependencies.	0.00
2)	Minor understanding of dependencies.	0.33
3)	Critical dependencies are known.	0.67
4)	The entire map of dependencies is depicted.	1.00
Indicator	**S2.1.3 - Autonomy capacity**	
Source	-	
Ans. type	Single choice	
Question	**Do infrastructures that are dependent on other services have any degree of autonomy?**	
1)	No	0.00
2)	Yes, but for short-term service disruptions	0.50
3)	Yes, including above-average service disruptions	1.00

Criteria	**S2.2 - Redundancies**	
Indicator	**S2.2.1 - Type of redundancies in place**	
Source	Adapted from RESCCUE RAF	
Ans. type	Multiple choice	
Question	**What type of redundancies are purposely in place?**	
1)	None.	0.00
2)	Meshed network (relief sewers)	0.14
3)	Oversized sewers (onsite storage)	0.14
4)	Storm tanks	0.14
5)	Multi-purpose flooding areas	0.14
6)	Alternative flow pathways	0.14
7)	Detention/Retention ponds	0.14
8)	Other NBS	0.14
Indicator	**S2.2.2 - Redundancies communication**	
Source	-	
Ans. type	Single choice	
Question	**Are redundancies communicated to the population?**	
1)	No.	0.00
2)	Yes, passively.	0.50
3)	Yes, actively.	1.00

Objective	**S3 - System knowledge**	
Criteria	**S3.1 - Monitoring, real-time control, and early warning**	
Indicator	**S3.1.1 - Monitoring equipment in place**	
Source	-	
Ans. type	Multiple choice	
Question	**What type of monitoring equipment is installed?**	
1)	None.	0.00
2)	Rain gauges	0.13
3)	Rainfall radar/satellite data	0.13
4)	Flow level in underground infrastructures	0.13
5)	Flow rate in underground infrastructures	0.13
6)	Flow quality in underground infrastructures/outfall	0.13
7)	Flow level at the surface	0.13
8)	Storm overflows	0.13
9)	Other(s)	0.13
Indicator	**S3.1.2 - Monitoring data treatment, usage and sharing**	
Source	-	
Ans. type	Multiple choice	
Question	**How is monitoring data used?**	**0.00**
1)	No specific treatment	0.25
2)	Real-time performance dashboard	0.25
3)	Early warning indicators	0.25
4)	Real-time control of equipment	0.25

Indicator	**S3.1.3 - Real-time control equipment in place**	
Source	-	
Ans. type	Single choice	
Question	**Is there real-time controlled equipment installed?**	
1)	No	0.00
2)	Yes	1.00
Indicator	**S3.1.4 - Early warning procedures**	
Source	Adapted from RESCCUE RAF	
Ans. type	Single choice	
Question	**Are there forecasts and/or early warning procedures?**	
1)	No	0.00
2)	Yes, with an internal early warning only	0.50
3)	Yes, internal and public early warning procedures exist	1.00
Criteria	**S3.2 - Human and financial resources**	
Indicator	**S3.2.1 - Human resources adequacy for service cover**	
Source	Adapted from RESCCUE RAF	
Ans. type	Single choice	
Question	**Does the service have adequate human resources?**	
1)	No	0.00
2)	Yes, for normal conditions	0.50
3)	Yes, for normal conditions and emergencies	1.00
Indicator	**S3.2.2 - Financial plan and budget allocation**	
Source	Adapted from RESCCUE RAF	
Ans. type	Single choice	
Question	**Does the service have a financial plan with a dedicated budget for resilience building/disaster risk reduction (DRR)?**	
1)	There is no clear financial plan.	0.00
2)	The financial plan indirectly includes resilience building/DRR, but budgets are not ring-fenced.	0.50
3)	The financial plan directly considers resilience building/DRR, and budgets are ring-fenced.	1.00
Indicator	**S3.2.3 - Service material resources in case of failure**	
Source	-	
Ans. type	Single choice	
Question	**Does the service have adequate material resources?**	
1)	No	0.00
2)	Yes, for normal conditions	0.50
3)	Yes, for normal conditions and emergencies	1.00
Criteria	**S3.3 - Disturbing events**	
Indicator	**S3.3.1 - Response protocol for disturbing events**	
Source	-	
Ans. type	Single choice	
Question	**Does the service have a standard protocol for emergencies?**	
1)	No formal/informal protocol exists.	0.00
2)	Protocol exists, but informally (based on past occurrences and available resources)	0.33
3)	Protocol exists formally but is not integrated/aligned with a city-wide emergency plan	0.67
4)	Protocol exists formally and is integrated/aligned with a city-wide emergency plan	1.00

Indicator	**S3.3.2 - Recording procedures for disturbing events**	
Source	-	
Ans. type	Multiple choice	
Question	**Are recording procedures implemented in the case of a disruptive event?**	
1)	No recording procedures are implemented.	0.00
2)	Emergency/civil protection calls.	0.17
3)	Flood duration is measured/estimated.	0.17
4)	Flood hazardousness (e.g., depth) is measured/estimated.	0.17
5)	Flooded area is measured/estimated.	0.17
6)	Infrastructure failure is registered.	0.17
7)	Other(s)	0.17
Indicator	**S3.3.3 - Adaptation capacity after disturbing events**	
Source	-	
Ans. type	Single choice	
Question	**Does the service have cases of adaptation measures/strategies taken due to past disruptive events?**	
1)	No	0.00
Indicator	**S3.3.4 - Transformability capacity after disturbing events**	
Source	-	
Ans. type	Single choice	
Question	**Does the service have cases of transformational measures/strategies taken due to past disruptive events?**	
1)	No	0.00
2)	Yes	1.00
Criteria	**S3.4 - Climate change preparedness**	
Indicator	**S3.4.1 - Commitment to CC mitigation (%GHG reduction)**	
Source	Adapted from RESCCUE RAF	
Ans. type	Single choice	
Question	**Is the service committed to CC mitigation through the reduction of GHG emissions?**	
1)	No commitment.	0.00
2)	Yes, but the target is lower than 20% or is not defined.	0.33
3)	Yes, with a 20 - 49% reduction target.	0.67
4)	Yes, with a minimum 50% reduction target.	1.00
Indicator	S3.4.2 - Existence of local/downscaled CC scenarios	
Source	-	
Answer type	Multiple choice	
Question	Which relevant climate variables/events are there agreed CC scenarios/local projections?	
1)	None.	0.00
2)	Sea level rise	0.33
3)	Rainfall intensities	0.33
4)	Storm surges or coastal overtopping	0.33

Indicator	**S3.4.3 - Current performance with future conditions**	
Source	-	
Ans. type	Single choice	
Question	**Has the current system's performance been evaluated based on known CC scenarios?**	
1)	No	0.00
2)	Yes, for the minor system	0.50
3)	Yes, for the minor and major systems	1.00
Indicator	**S3.4.4 - In place or planned CC adaptation measures**	
Source	Adapted from RESCCUE RAF	
Ans. type	Multiple choice	
Question	**What type of measures has the service implemented/planned to address climate change mitigation and adaptation?**	
1)	None.	0.00
2)	Stakeholder or public engagement or awareness	0.11
3)	Strengthening relationships between (inter)dependent services	0.11
4)	Improvement of information collection and analysis	0.11
5)	Development of emergency or contingency plans	0.11
6)	Implementation/improvement of green infrastructure	0.11
7)	Implementation/improvement of grey infrastructure	0.11
8)	Power generation in drainage infrastructures (e.g., turbinating)	0.11
9)	Energy consumption reduction (service fleet, pumping station optimization, etc.)	0.11
10)	Other(s)	0.11
Criteria	**S3.5 - Stormwater overflow management**	
Indicator	**S3.5.1 - Stormwater overflow control**	
Source	-	
Ans. type	Single choice	
Question	**Are stormwater overflows controlled with adequate equipment?**	
1)	No adequate equipment exists for stormwater overflow control.	0.00
2)	Stormwater overflows are partially controlled with adequate equipment.	0.50
3)	Stormwater overflows are globally controlled with adequate equipment.	1.00
Indicator	**S3.5.2 - Stormwater overflow monitoring**	
Source	-	
Ans. type	Single choice	
Question	**Are stormwater overflows monitored with adequate equipment?**	
1)	No adequate equipment exists for stormwater overflow monitoring.	0.00
2)	Stormwater overflow frequency and/or volumes are partially monitored.	0.50
3)	Stormwater overflow frequency and/or volumes are globally monitored.	1.00
Indicator	**S3.5.3 - Stormwater overflow discharge**	
Source	-	
Ans. type	Single choice	
Question	**Are stormwater overflow outfalls identified?**	
1)	No.	0.00
2)	Yes, partially.	0.50
3)	Yes, globally.	1.00

Objective	**S4 - Infrastructural knowledge**	
Criteria	**S4.1 - Infrastructures' register**	
Indicator	**S4.1.1 - Infrastructures' register existence and completeness**	
Source	-	
Ans. type	Single choice	
Question	**Are the infrastructures adequately identified and mapped?**	
1)	No structured register of infrastructures exists.	0.00
2)	Global infrastructures' register exists with low detailed level	0.33
3)	Detailed infrastructure' register exists for critical areas	0.67
4)	Global and detailed infrastructure' register exists	1.00
Indicator	**S4.1.2 - Infrastructures' register update**	
Source	-	
Ans. type	Multiple choice	
Question	**How frequently is the infrastructure register updated?**	
1)	No update routines/criteria	0.00
2)	Updated but with no defined frequency or other criteria.	0.33
3)	Updated periodically.	0.33
4)	Updated when infrastructures have any modifications.	0.33
Indicator	**S4.1.3 - Infrastructures' register format**	
Source	-	
Ans. type	Single choice	
Question	**In what format is the infrastructure register kept?**	
1)	Sketched-based register (CAD or similar)	0.00
2)	GIS attribute-based (shapefiles or similar)	1.00
Indicator	**S4.1.4 - Infrastructures' register sharing**	
Source	-	
Ans. type	Multiple choice	
Question	**What is the infrastructure's register-sharing policy?**	
1)	Detailed sharing with other municipal services	0.33
2)	Unrefined sharing with the public	0.33
3)	Detailed sharing with the public	0.33
Criteria	**S4.2 - Inspection, maintenance and rehabilitation**	
Indicator	**S4.2.1 - Inspection procedures**	
Source	-	
Ans. type	Multiple choice	
Question	**How are inspection procedures implemented?**	
1)	No inspection routines are implemented	0.00
2)	Locally, when issues are reported	0.50
3)	Periodic inspection of critical assets	0.50
Indicator	**S4.2.2 - Maintenance of inlet devices**	
Source	-	
Ans. type	Single choice	
Question	**Are there inlet devices' maintenance procedures?**	
1)	No maintenance procedures	0.00
2)	Maintenance is the responsibility of an external player	0.33
3)	Yes, with no established criteria (arbitrary)	0.67
4)	Yes, regularly and with established criteria	1.00

Indicator	**S4.2.3 - Maintenance of electromechanical equipment**	
Source	-	
Ans. type	Single choice	
Question	**Are there electromechanical equipment maintenance procedures?**	
1)	No maintenance procedures	0.00
2)	Yes, with no established criteria (arbitrary or when needed)	0.50
3)	Yes, regularly and with established criteria	1.00
Indicator	**S4.2.4 - Rehabilitation of sewers/open channels**	
Source	Adapted from ERSAR [51]	
Ans. type	Single choice	
Question	**What is the average annual percentage of storm sewers/open channels with more than 10 years rehabilitated in the last 5 years?**	
1)	Less than 4.0	0.00
2)	Between 4.0 and 20.0	0.50
3)	More than 20.0	1.00
Indicator	**S4.2.5 - Coverage of expenditure with inspection, maintenance, and rehabilitation**	
Source	Adapted from RESCCUE RAF	
Ans. type	Single choice	
Question	What is the ratio between rehabilitation, operation, and infrastructure management expenditure and last year's annual operating budget?	
1)	Less than 0.9 or more than 1.2	0.00
2)	More than or equal to 0.9 and less than 1.0 or more than 1.1 and less than or equal to 1.2	0.50
3)	More than or equal to 1.0 and less than or equal to 1.1	1.00
Criteria	**S4.3 - Internal risks understanding**	
Indicator	**S4.3.1 - Known internal risks**	
Source	Adapted from RESCCUE RAF	
Ans. type	Multiple choice	
Question	**Which of the following physical internal risks are currently assessed?**	
1)	None.	0.00
2)	Structural conditions of sewers and manholes	0.25
3)	Electromechanical equipment failure	0.25
4)	Inlets' capacity available	0.25
5)	Storm overflows frequency	0.25
Indicator	**S4.3.2 - Mapping of internal risks**	
Source	Adapted from RESCCUE RAF	
Ans. type	Single choice	
Question	**Are the physical internal risks mapped?**	
1)	No	0.00
2)	Partially, not covering all the risks or all the infrastructure	0.50
3)	Yes (if suitable)	1.00

Criteria	**S4.4 - External risks understanding**	
Indicator	**S4.4.1 - Known external risks**	
Source	Adapted from RESCCUE RAF	
Ans. type	Multiple choice	
Question	Which of the following physical external risks are currently assessed?	
1)	**None.**	**0.00**
2)	Electromechanical equipment's exposure to flooding	0.20
3)	Equipment's exposure to tides	0.20
4)	Sewers' exposure to tides	0.20
5)	Inlet devices' exposure to clogging	0.20
6)	Sewers' exposure to silting up and deposition of sediments	0.20
Indicator	**S4.4.2 - Mapping of external risks**	
Source	-	
Ans. type	Single choice	
Question	**Are the physical external risks mapped?**	
1)	No	0.00
2)	Partially, not covering all the risks or all the infrastructure	0.50
3)	Yes (if suitable)	1.00

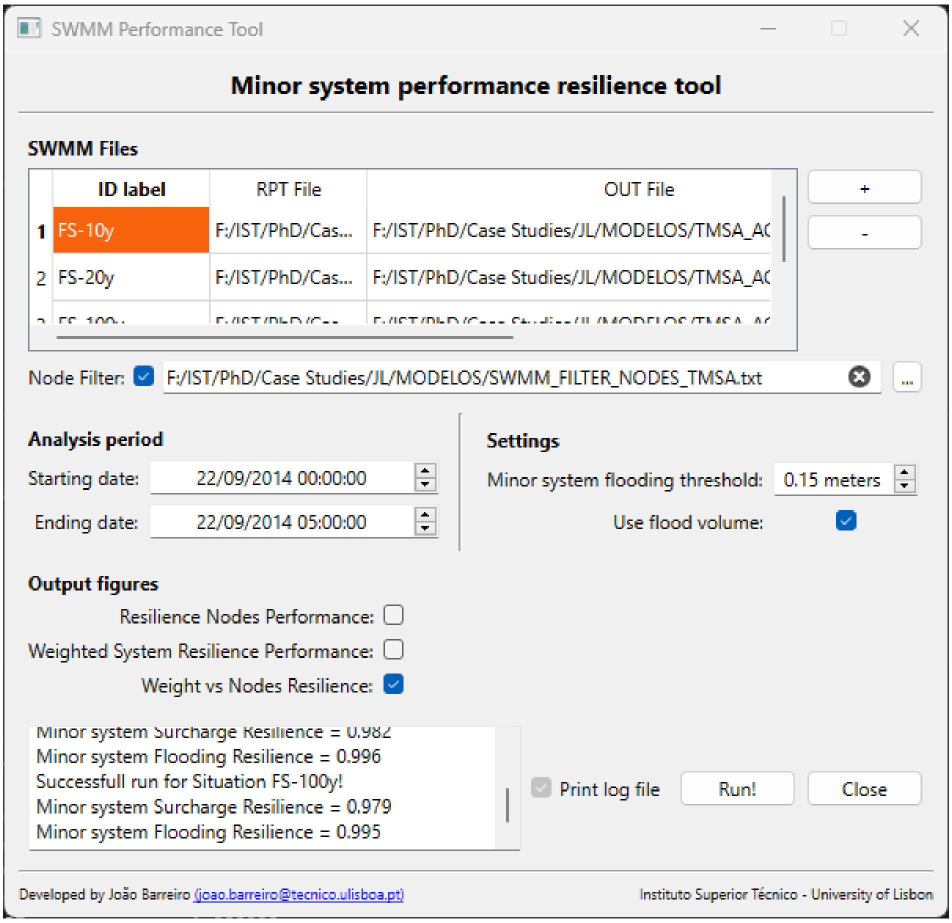

Figure A1. Screenshot of the SWMM/Minor System performance resilience tool GUI

This tool, integrated into the repository of the RESILISTORM-tool, allows the calculation of the minor system surcharge and minor system flooding indicators. If the SWMM model is set adequately regarding the ponding of the nodes, the major system flooding indicator can also be calculated atop the nodes.

The GUI of the tool is intuitive, and results are printed in the log area. Besides the indicators' results, the outputs comprise the performance curves for each node, the weighted performance curve for the whole system, and the plot of weight vs resilience of the nodes.

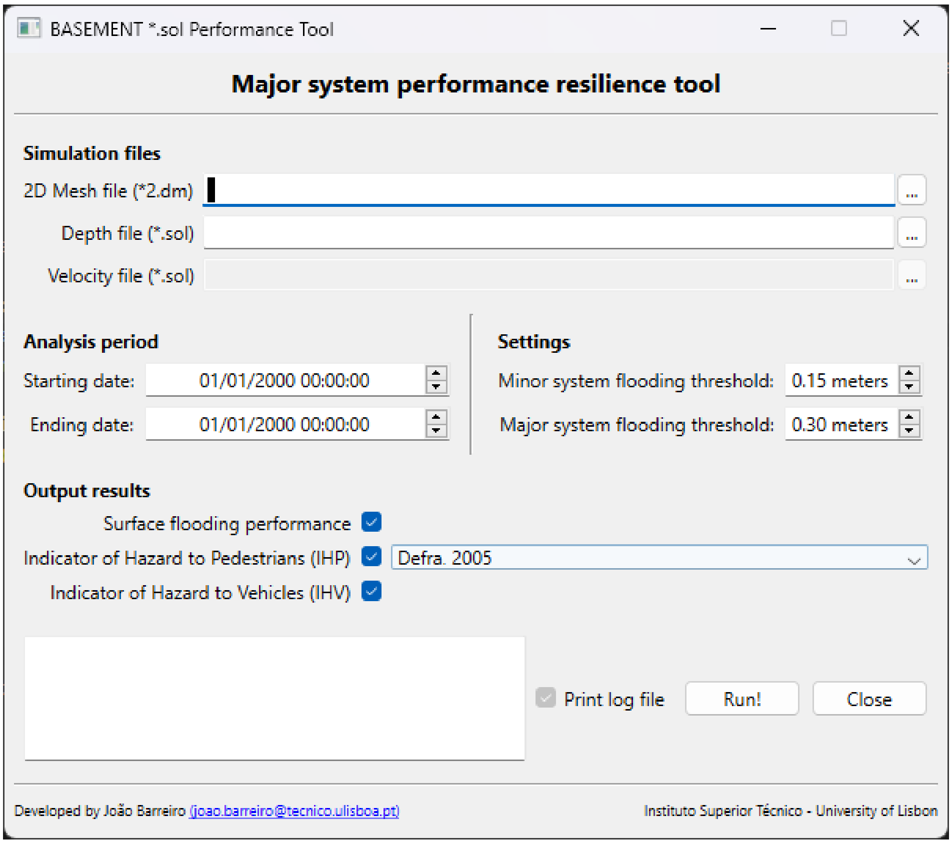

Figure A2. Screenshot of the BASEMENT/Major System performance resilience tool GUI

This tool, integrated into the repository of the RESILISTORM-tool, allows the calculation of the major system flooding indicator, along with the Indicator of Hazards to Pedestrians and Vehicles. The GUI of the tool is intuitive, and results are printed as a *.dat file constating a mesh dataset.