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Development of Resilience Framework and Respective Tool for Urban Stormwater Services

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Abstract: Resilience theory has gained significant traction in various urban fields, including natural disasters and risk management or climate change adaptation, and at different organizational levels, including academics, practitioners, and policymakers. It should be considered a complementary approach to sustainable development that enhances cities' capacity to endure future uncertainties and promote rational urban development. However, the lack of a generally accepted definition of resilience hampers understanding and practical implementation in urban services like stormwater management. Conventionally, stormwater services aimed to minimize the impact of rainfall through fail-safe approaches. The resilience approach, on the other hand, embraces a holistic "safe-to-fail" perspective. The existing literature offers diverse approaches to measure flood and stormwater resilience. Still, there is room for the development and improvement of standardized but flexible frameworks for operationalizing resilience in urban drainage and flood management. To address this, a comprehensive resilience framework for urban stormwater services is proposed, entitled RESILISTORM. This framework incorporates a Strategic Dimension and a Performance Dimension, providing segmented and overall resilience ratings that enable utilities to address critical aspects undermining the service's resilience. An open-source digital tool (RESILISTORM-tool) is also introduced to expedite answering, data integration, and visualization analysis of results.

Keywords: climate change; disaster risk; integrated management; stormwater; urban floods; urban resilience; resilience framework; sustainable development

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1. Introduction

Under the urban scope, resilience theory has become very popular in the last two decades [1,2], 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 [1–4].

Three mainstream resilience conceptual focuses are found in the literature: engineering resilience, ecological resilience, and socio-ecological resilience [2,4].

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 [5].

The work of the ecologist Holling in 1973 [6] is frequently cited in the literature (e.g., [2,4,7]) 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 [6]. 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 [8]. 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 [9].

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 [9]. 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 [10]. 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 [11].

Angeler et al. [5] point out that despite such different conceptual approaches, these are not mutually exclusive, and Meyer [12] 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 [8].

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 [4]. 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 [4]. Examples of such projects include the Making Cities Resilient Campaign, launched in 2010 by UNISDR (United Nations International Strategy for Disaster Reduction) [13]; the 100 Resilient Cities campaign, launched in 2013 and pioneered by The Rockefeller Foundation [14]; the City Resilience Profiling Program, announced in 2012 by UN-Habitat [15]; or the RESCCUE Project (2016–2020), the first large-scale urban resilience-related project funded by the European Union under the Horizon 2020 framework [16]. 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 [2,17], making planning, operationalizing, and measuring resilience challenging [1]. Additionally, it is essential to keep in mind that resilience and sustainability are not mutually exclusive developmental rationales [18]. Instead, complementary approaches that enhance cities' capacity to endure future uncertainties and promote rational urban development should be considered [19,20]. 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 [21].

Many organizations and stakeholders still poorly understand the resilience concept [22–24], 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 [2], and that the complexity of urban systems and different players' responsibilities, objectives, and concerns creates confusion among stakeholders makes resilience-oriented management a challenging task [24].

Blanco-Londoño et al. [25] refer to two types of methodologies found in the literature to assess flood and stormwater resilience: 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; 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. [23] 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. [26] use resistance, absorption, and recovery as characteristics to compare the resilience of different urban design features. Valizadeh et al. [27] 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. [28] 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. [29] 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. [30], Miguez and Veról [31], Bertilsson et al. [32], and Rezende et al. [33] 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 a set of 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. [34] 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. [35] follows the same concept but uses the complete range of values in the curve—both concepts recurring in 1D models. Barreiro et al. [36] 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, 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. [28] analyzed 14 urban resilience assessment frameworks for climate change; only 2 frameworks considered stormwater as an urban service/sector. The previously mentioned RAF, developed by Cardoso et al. [28] for both the city and several urban services and assets (including the stormwater service), would benefit from a deeper assessment of the infrastructure performance during a disruptive event. In addition to theoretical discussions, Lhomme et al. [22] highlight that decision-makers need tools that help them operationalize such methodologies and decide how to tackle critical infrastructures under different disruptive scenarios.

The current paper aims to respond to this gap by presenting the development of a resilience framework for urban stormwater services—RESILISTORM. After the current introductory chapter, stormwater management is contextualized as an urban service to better support the framework scope. RESILISTORM incorporates qualitative and quantitative metrics, providing segmented and overall resilience ratings that enable management entities to address critical aspects undermining the service's resilience. A digital tool (RESILISTORM-tool) is also introduced to expedite answering, data integration, and results visualization and analysis.

2. Resilience Framework for Urban Stormwater Systems (RESILISTORM)

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 [37].

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 [29], 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 [38]. Several approaches, with similar conceptual ideas but different terminologies, have been adopted worldwide since then [39]: 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 [40]. 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 [41]. Consequently, the urban stormwater spatial/infrastructural domain spreads beyond the underground infrastructures. It tends to be considered a composition of two systems: the minor and the major systems, also referred to as dual-drainage systems [42]. 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 [43,44].

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 [44] (see Figure 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.

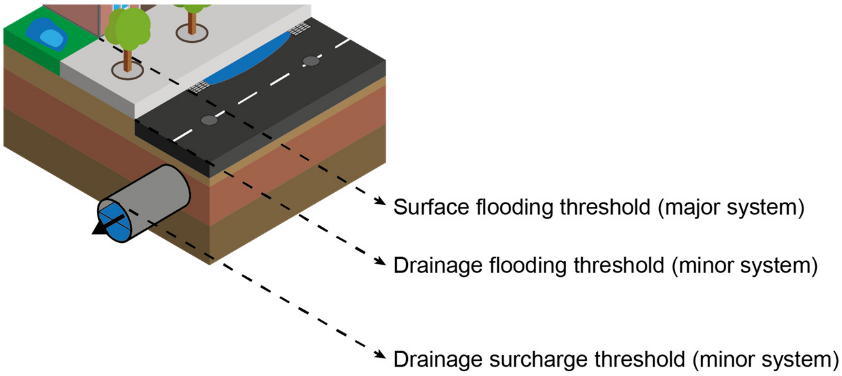

Figure 1. Stormwater flooding design thresholds.

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 [32]. Urban floods must be understood as human problems with natural but also social, economic, and political causes [45]. 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), 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. 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 [24]. 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 [27].

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 [24]. 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 [34,45], enhancing the ability to cope with and recover from flooding, especially when considering future risks and related uncertainties [46,47].

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 [36]. 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 [48]. 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 [49].

Such events affect the performance of several urban services that rely mostly on public space for operation [48,49]. Typically, affected services include mobility (buses, trams, etc.) and dependent services (e.g., municipal waste collection and the population itself due to mobility constraints) [29], tertiary activities (shops, offices, restaurants, etc.), and power distribution (although with a low probability of service failure [47]). Naturally, urban flooding impacts are singular in each city, 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 and nursing homes), and power supply infrastructures [47]. 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 [49]. Figure 2 depicts a generic cascade chain in case of failures of stormwater systems and consequent urban flooding impacts.

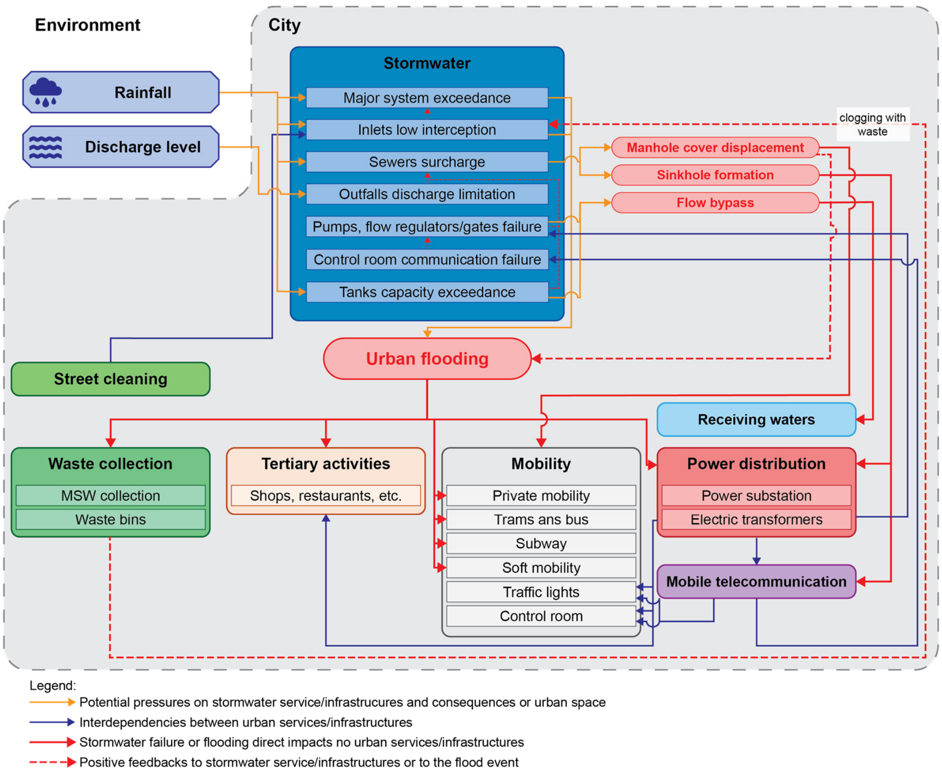

Figure 2. Generic cascade chain and feedbacks for urban stormwater system failure.

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 [11]. Thus, the framework intends to contribute to the general domain of urban resilience by deepening the understanding of the stormwater service resilience and its contributions to the 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.» [1]. 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.

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 [10]. This property represents the resilience "continuum" that allows cities and services to better prepare for new floods [45]. It confers to resilience a double behavior as a system's property and as 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 [10,24] (Figure 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.

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 metrics. For the Performance Dimension, the objectives are assessed through context-dependent indicators that rely on quantitative and model-based metrics.

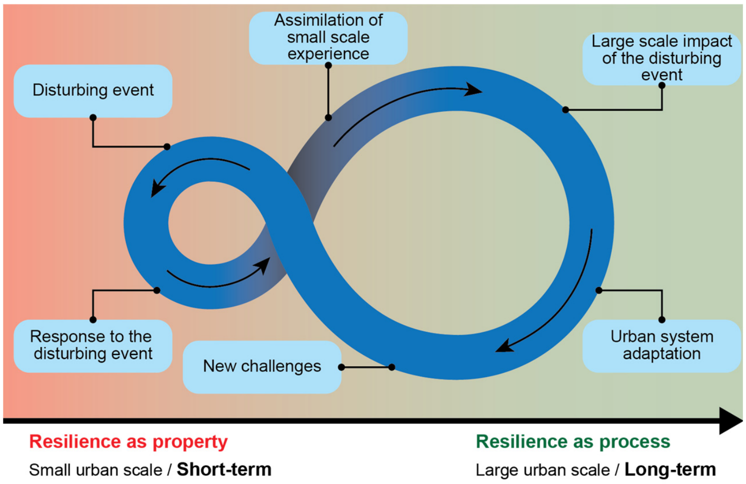

Figure 3. Panarchy adapted to stormwater service resilience (adapted from [24]).

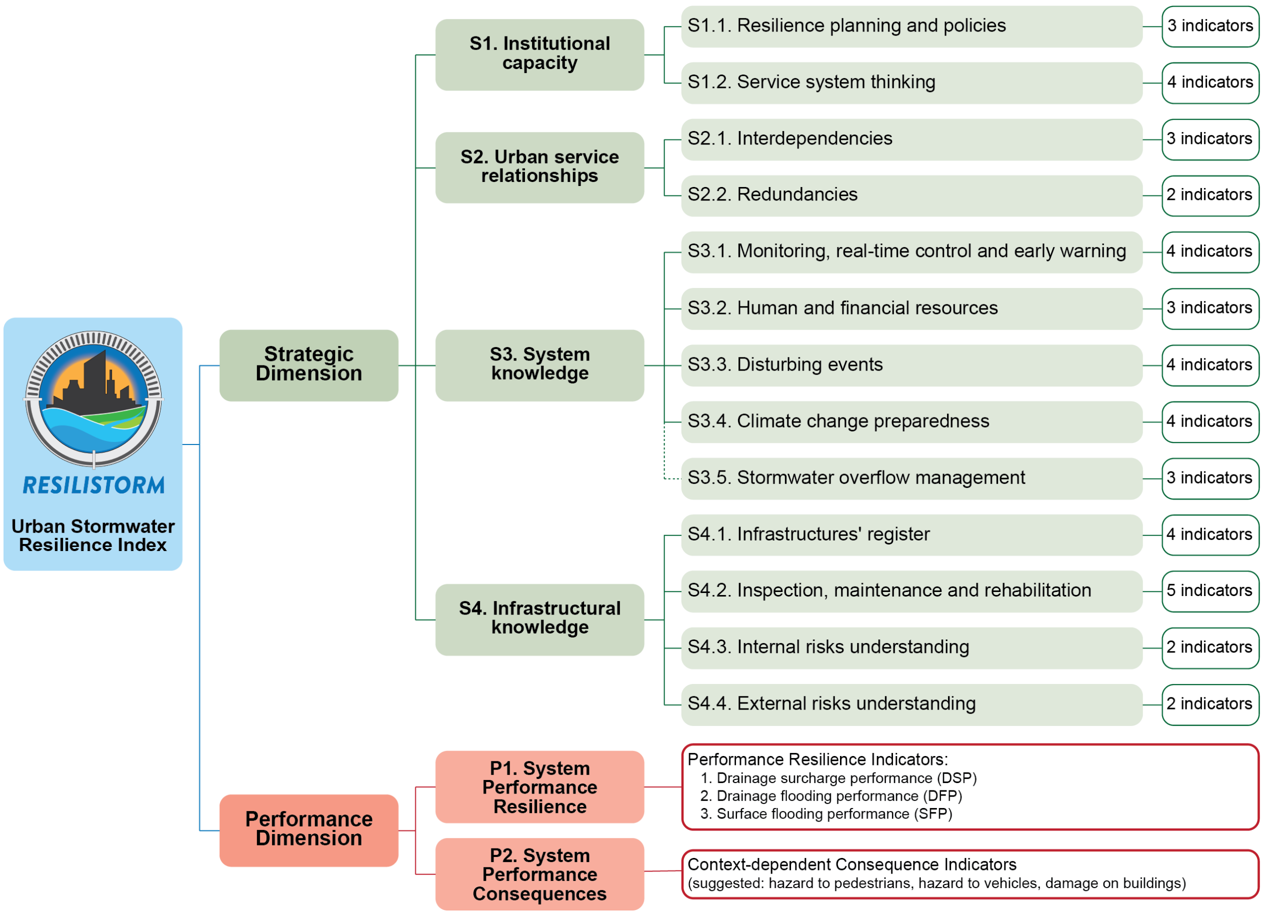

Figure 4. Resilience Framework for Urban Stormwater Systems: dimensions, objectives, and criteria.

The development of RESILISTORM is aligned with the Resilience Assessment Framework (RAF) developed on the H2020 project RESCCUE [16]. 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) [28]. 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.

2.4. Objectives, Criteria, and Metrics

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

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 *S3.3. 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 [50] 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 metrics consisting of questions that integrate, mostly, qualitative multi- or single-choice answers. All metrics answers are rated between 0 (worst case) and 1 (best case). The complete list and descriptions of the Strategic Dimension's metrics are included in the supplementary material (Table S1), including source references [28,51]. In this sense, each criterion is rated as the average of the respective metric answers, according to Equation (1):

$$CR_j = \frac{1}{n}\sum_{i}^{n} RM_i \tag{1}$$

where CR_j is the rating of the criterion j, RM_i is the rate of the metric answer i, and n is the number of metrics of the criterion j.

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 that result 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 [52]. 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 an analysis of the system's reaction during a disruptive event. There are some interpretations and naming variations on the main characteristics and variables of these curves when applied to stormwater systems [34,35,53], 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.

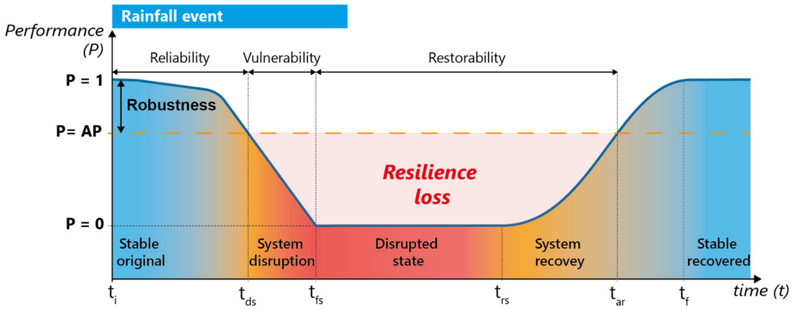

Figure 5. Theoretical generalized performance curve for stormwater systems.

This performance curve concept is used for the assessment of objective *P1. System performance*, varying the admissible performance thresholds and the failure threshold. The performance curves are obtained by normalizing, between 0 and 1, a state variable of the system through its maximum admissible value and the analysis time (see Figure 6 and Table 1). The state variable performance 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 thresholds; when the failure threshold is reached, the system enters failure mode. 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.

Table 1. Equations for state variable performance (left) and normalized performance curve (right).

State Variable Performance Curve	Normalized Performance Curve	
$R_0 = (FD - AD)\left(t_f - t_0\right)$	$R_0{}^P = AP$	(2)
$R_L = \int_{t_0}^{t_f} d(t) - AD$ $being\ d(t) = \begin{cases} AD & if \quad d(t) \leq AD \\ d(t) & if \quad AD < d(t) \leq FD \\ FD & if \quad d(t) \leq FD \end{cases}$	$R_L{}^P = \int_0^1 AP - P(t)$ $being\ P(t) = \begin{cases} AP & if \quad P(t) \geq AP \\ P(t) = 1 - \frac{d(t)}{FD} & if \quad PF < P(t) \leq AP \\ PF = 0 & if \quad P(t) \leq FD \end{cases}$	(3)
$R = R_0 - R_L$	$R^R = R_0{}^P - R_L{}^P$	(4)
$R_N = 1 - \frac{R_L}{R_0}$	$R^R{}_N = 1 - \frac{R_L{}^P}{R_0{}^P}$	(5)

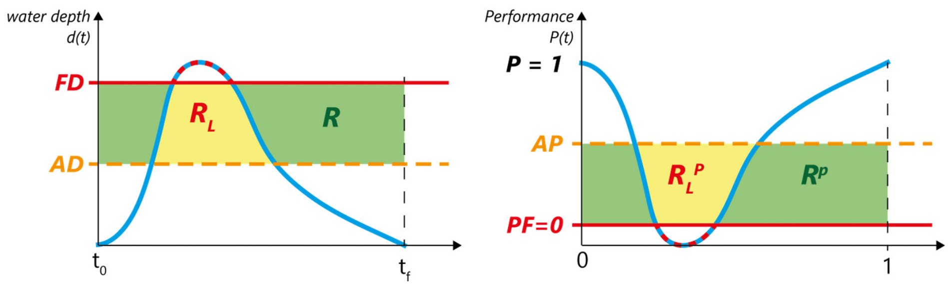

Figure 6. State variable performance (**left**) and normalized performance curve (**right**).

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 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.

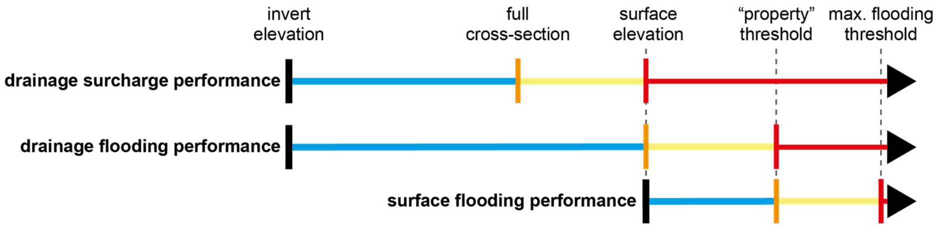

Figure 7. Reference and threshold values of stormwater performance curves.

Regarding the minor system, each node is weighted as a function of the maximum flow capacity of the linked sewers as in Equation (6):

$$NW_j = \frac{max(Q_i, \ldots, Q_n)_j}{\sum NW} \tag{6}$$

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. The performance curves are obtained from the results of 1D hydrodynamic models, such as the widely used EPA-SWMM [54], 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., [55–58]) and licensed software (e.g., [59–61]). 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 and 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.

Aiming to assess the impact of system performance on the urban space and services, objective *P2. Failure consequences* is strongly context dependent on identified dependencies or infrastructure/services that are vulnerable or exposed to flooding. A suggestion of indicators for such is presented in Appendix A.

2.5. Urban Stormwater Resilience Index

Each objective is rated as the weighted sum of the respective criterion rate, as expressed in Equation (7):

$$OR_j = \sum_i^n CW_i \times CR_i \tag{7}$$

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 (8)).

$$DR_j = \sum_i^n OW_i \times OR_i \tag{8}$$

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 (9)) and is also categorized in resilience ranges [36], as depicted in Figure 8.

$$USRI = SDW \times SDR + PDW \times PDR \tag{9}$$

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

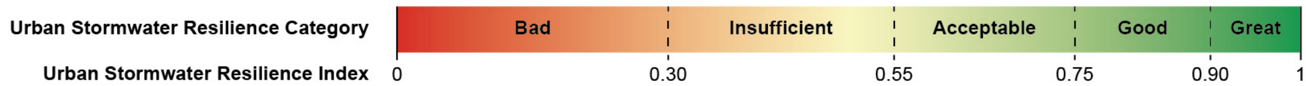

Figure 8. Resilience normalized rating and categorization ranges.

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 better understand the RESILISTORM framework roadmap through its application. It allows for the expedited answering of the metrics, aggregate indicators' results, and automatic calculation of the metrics/indicators, criteria, objectives, and dimensions ratings of the 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 a comparison of 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 metrics (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 metrics 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).

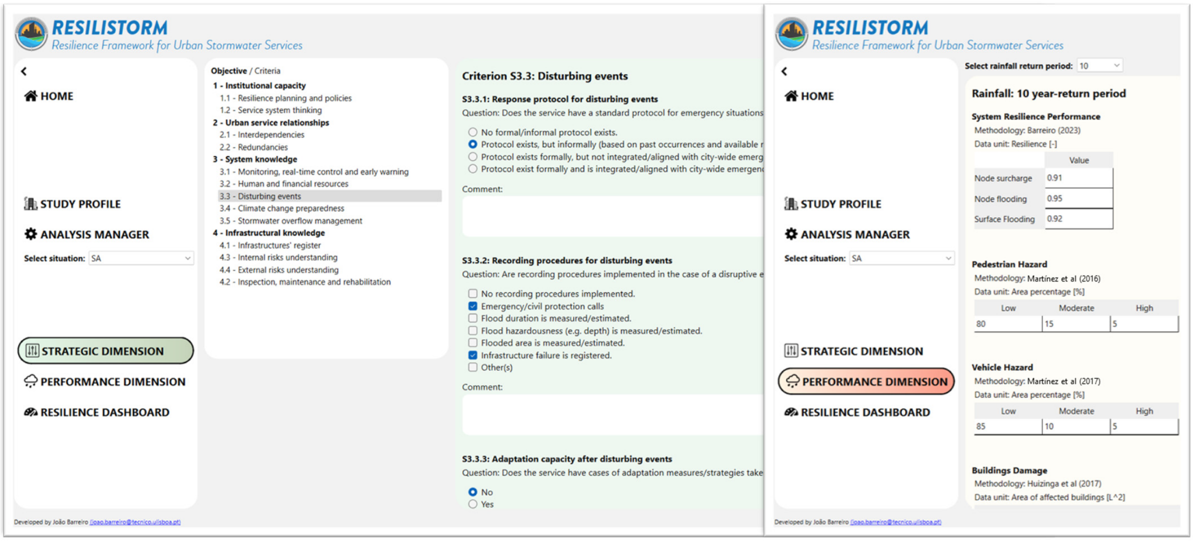

Figure 9. RESILISTORM-tool: examples of the Strategic Dimension (**left**) and Performance Dimension (**right**) answering [58,62–64].

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

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 an incipient practice within the urban stormwater field, although examples can be found in the literature (e.g., [55,56,58,65–67]). 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 metric. Additionally, assigning weights to dimensions, objectives, and criteria introduces an inherent level of subjectivity. 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, 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 can be incorporated into specific applications of the framework and tool. The framework can be used for traditional gray stormwater systems based on buried infrastructure, for systems based on blue and green NBS, or by 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.

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 may involve 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.

Supplementary Materials: The following supporting information can be downloaded at: https://www.mdpi.com/article/10.3390/su16031316/s1, Table S1: Strategic Dimension objectives, criteria, and metrics. https://github.com/JoaoBarreiro/RESILISTORM-tool (accessed on 20 December 2023), RESILISTORM-tool open-source code repository.

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Appendix A. Suggested Indicators for Objective *P2. System Performance Consequences*

Appendix A.1. Indicator of Hazard to Pedestrians (IHP)

The methodology proposed by the Department of Environment, Food, and Rural Affairs of the UK Environmental Agency [68] is suggested to evaluate the pedestrian hazard resulting from a flood event. It is based on the hydraulic characteristics of surface flow, including velocity and height. The degree of flood hazard for pedestrians is calculated according to Equation (A1),

$$HR = d \times (v + 0.5) + DF \tag{A1}$$

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, as presented in Table A1.

Table A1. Hazard classification for pedestrians [68].

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

The calculation of the respective indicator is performed by weighting the areas classified with different hazard levels, as shown in Equation (A2),

$$IHP = \sum_i A_{\text{affected}\,i} \times \omega_i \quad \text{where} \quad \omega_i = \begin{cases} 1.00 & if\ HC\ is\ low \\ 0.40 & if\ HC\ is\ moderate \\ 0.15 & if\ HC\ is\ high \\ 0.00 & if\ HC\ is\ very\ high \end{cases} \tag{A2}$$

where $A_{\text{affected}\,i}$ is the percentage of area classified with hazard degree i, ω_i is the weight of hazard degree i and HC is the hazard classification as in Table A1.

Appendix A.2. Indicator of Hazard to Vehicles (IHV)

The assessment of the hazard for vehicles was conducted according to the methodology described in [62]. This methodology allows for the consideration of different types of cars and models. For this purpose, the *Seat Ibiza* model was considered a reference for light passenger vehicles. Like the previous methodology, vehicle hazard classifications are defined based on flow characteristics, as presented in Table A2.

Table A2. Hazard classification for vehicles [62].

Flow Properties	Hazard Classification	Description
$d \leq 0.28$ and $M \leq 0.40$	Low	No damage to vehicles—regular traffic
$d \leq 0.28$ and $0.40 < M \leq 0.55$	Moderate	Low probability of damage to vehicles—traffic might be conditioned
$d > 0.28$ and $M > 0.55$	High	Considerable probability of damage to vehicles—traffic must be conditioned

Definitions: d is flow depth (m); $M = d \times |v|$ is the flow momentum (m^2/s); and $|v|$ is the flow velocity modulus (m/s).

The calculation of the respective indicator follows the same procedure as the IHP, as presented in Equation (A3),

$$IHV = \sum_i A_{\text{affected}\,i} \times \omega_i \quad \text{where} \quad \omega_i = \begin{cases} 1.00 & if\ HC\ is\ low \\ 0.40 & if\ HC\ is\ moderate \\ 0.00 & if\ HC\ \ is\ high \end{cases} \tag{A3}$$

where $A_{\text{affected}\,i}$ is the percentage of area classified with hazard degree i, ω_i is the weight of hazard degree i and HC is the hazard classification as in Table A2.

Appendix A.3. Indicator of Damage to Buildings (IDB)

The potential damage to buildings considers the number and typology of building uses according to the maximum water level reached at the facade. European curves of Damage Factor–Water Height for different building uses were considered [63]. Normalizing the damage factor curves allows for estimating a suitable weight for each building by use typology based on the water height reached. The original and normalized curves are presented in (Figure A1).

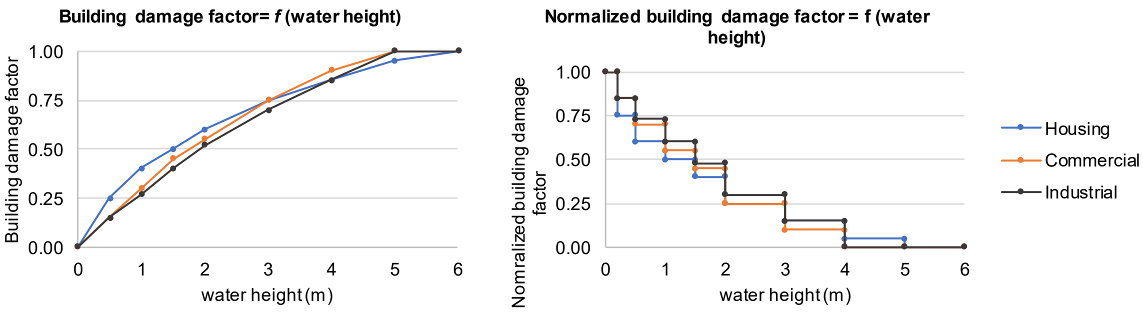

Figure A1. Curves of damage factor [63] and normalized damage factor to buildings.

The IDB is calculated by weighting the fraction of the number/area of affected buildings by use typology and water height class with the weight estimated from the damage curves, as represented in Equation (A4),

$$IDB = \frac{1}{K}\sum_u \sum_i K_{u,i} \times FD^N_{u,i} \tag{A4}$$

where K is the total number/area of buildings, u is the building by use typology, i is the class of maximum water height reached at the facade of the building, $K_{u,i}$ is the number/area of buildings by use typology u affected with maximum water height reached at the facade of the building of class i, and $FD^N_{u,i}$ is the normalized building damage factor to buildings by use typology u affected with maximum water height reached at the facade of class i.

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