



Index-based Approach to Evaluate City Resilience in Flooding Scenarios

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Abstract

Intense rainfall events combined with high tide levels frequently result in urban floods in riverine or coastal cities. Their increasing variability and uncertainty demand urgent but sustained responses. Thus, resilience-driven approaches are emerging in contrast to the traditional technical-economic frameworks, as urban resilience reflects the overall capacity of a city to survive, adapt and thrive when experiencing stresses and shocks. This paper presents a simplified index-based methodology for the evaluation and quantification of urban resilience to flooding, based on the works developed in the EU H2020 RESCCUE project. A set of five indicators are proposed to compute the Integrated Urban Resilience Index (IURI), allowing to classify resilience according to a proposed range of rankings. This methodology considers simultaneously a multisectoral approach, reflecting services interdependences, and a sectorial approach, applying 1D/2D computational modelling of the urban drainage network. It was applied to the study case of Lisbon downtown, involving the analysis of interdependencies between 124 infrastructures of 10 urban services. Two scenarios were considered, respecting the current and future situations, considering climate changes. Results enhance the usefulness, practicability, and potential of the proposed approach, and improvement opportunities were also identified for future developments.

Keywords: City Resilience; Cascade Effects; Urban Flooding; Resilience Assessment; 1D/2D Drainage Modelling.

1. Introduction

City resilience reflects the overall capacity of a city (individuals, communities, institutions, businesses and systems) to survive, adapt and thrive no matter what kinds of chronic stresses or acute shocks they experience [1]. This capacity may be acquired through adopting structural and non-structural solutions and/or introducing knowledge and intelligence in the management of city infrastructures [2].

In recent years, society has become increasingly aware of the climate-related risks. Climate changes increase the pressure posed by these risks, namely due to sea level rise, irregularity in rainfall frequency and intensity, droughts, and heat waves [3]. This pressure demands a rapid but also informed, sustainable and cohesive response from several stakeholders. In fact, the growing diversity of hazards, increasing complexity of cities, and uncertainty associated with climate changes, globalization and rapid urbanization have contributed to introduce urban resilience into a critical agenda [1], reinforcing the need to make cities and human settlements more inclusive, safe, resilient and sustainable [4].

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Furthermore, there is a need to increase the knowledge on urban services interconnectedness and to have models and tools capable to reliably assess its behaviour. This demand requires multisectoral approaches, considering the city as a system of systems, in order to increase city’s sustainability and resilience [5].

Under the scope of climate changes and urban resilience, urban flooding poses a current challenge for riverine or coastal settlements, with high potential for worsening, increasing the urgency of analyzing this issue and finding methodologies that can support decision makers [6]. Several multidimensional and multisectoral urban resilience assessment frameworks have been developed considering climate change, mainly in the last decade, although stormwater systems, as urban service, have been poorly addressed [7, 8]. Other works have been developed at a more sectorial level, mainly by using 1D or 1D/2D modelling to simulate the performance of the sewerage network, in the first case, or of the sewerage network and surface flows, in the second case. These works highlight the usefulness of using dynamic modelling to quantify the resilience of urban drainage systems through sets of more or less complex indicators, which also enable to compare different adaptation strategies (for example [9-13]). Although urban resilience requires a comprehensive overview of the cities and its services as a whole [1], sectorial approaches are of utmost importance as they provide sectorial expertise contributions to this broad theme. These different approaches, *i.e.*, holistic vs. sectorial, are part of the current scientific discussion regarding urban resilience and the choice of one or another generally reflects the scope of the institution and authors developing the assessment approaches [1].

the present paper is based on the works developed in the project Resilience to Cope with Climate Change in Urban Areas (RESCCUE), funded by EU’s Horizon 2020 Programme [14]. The paper proposes a straightforward index-based approach to evaluate city resilience in flooding scenarios, based on the evaluation of five indicators. Additionally, a simplified and innovative process to integrate the inlets efficiency in the simulation process is developed. After this introductory chapter, the proposed methodology is described on Chapter 2, and applied to a study case in Lisbon downtown on Chapter 3. Conclusions and improvement suggestions are presented on Chapter 4.

2. Research Methodology

2.1. General Description

The proposed methodology focuses on evaluating urban resilience to flooding, in result of extreme precipitation events and high tide levels, on a multisectoral approach, considering services’ interdependences and cascading effects, and is developed four main steps. Figure 1 presents the main methodology steps and required data for its application. These four steps are described in the following paragraphs.

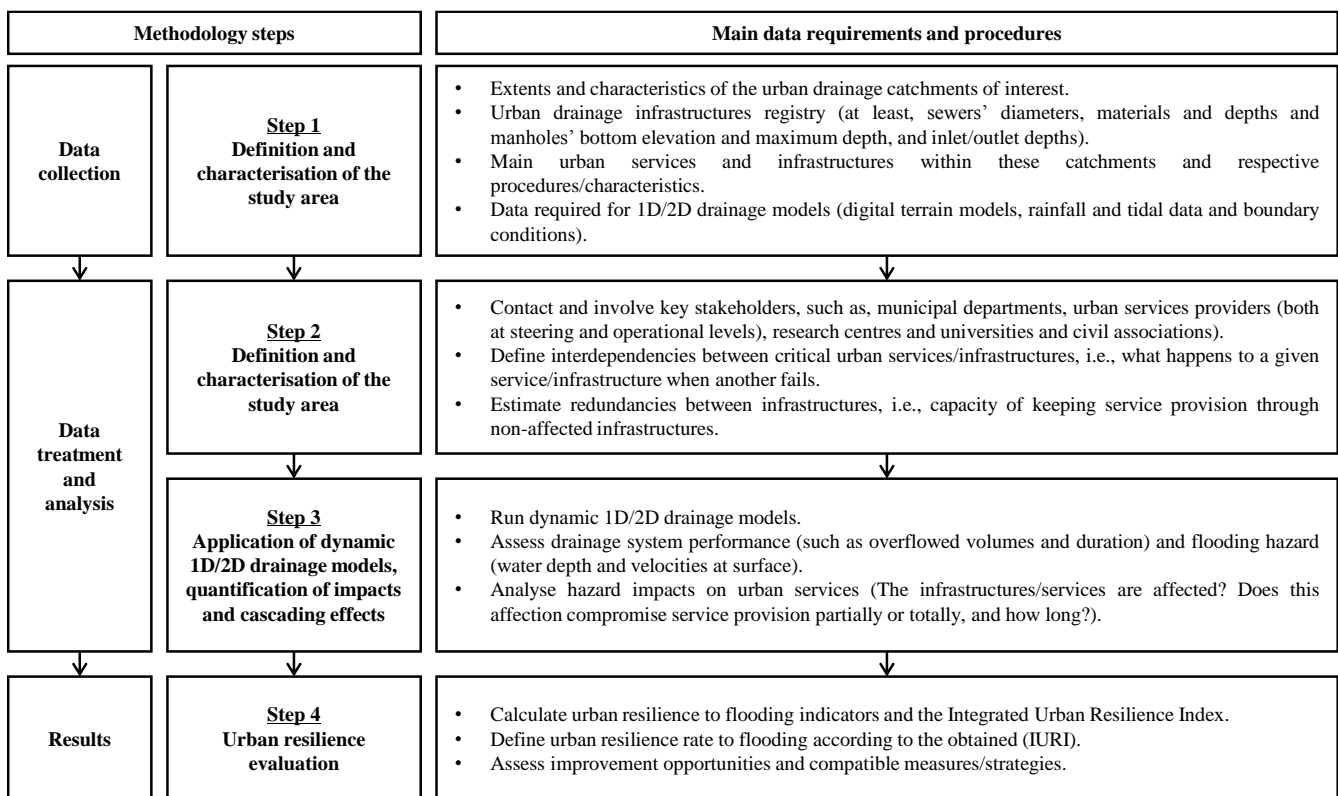


Figure 1. Proposed methodology steps, main data required and procedures

2.2. Step 1 - Definition and Characterisation of the Study Area

The definition of the study area constitutes an initial phase that aims to provide a base point from which the study is developed. As the main purpose of this study is to evaluate urban resilience in flooding scenarios, the definition of the study area is delimited by the drainage catchments most susceptible to floods.

The characterisation implies the definition of critical infrastructures and services. This stage also includes the study of operating procedures, during normal and extraordinary conditions, and physical or human resources that can be activated in an emergency situation to restore the normal state of operation. The number of critical infrastructures should neither be excessive nor too scarce, allowing a realistic analysis of the system without an increasing degree of complexity that might compromise the results. A special focus should be placed on the characteristics of the drainage system and on the collection of data to be used on dynamic 1D/2D drainage models.

2.3. Step 2 - Identification of Interdependencies and Redundancies

Considering the selected services and infrastructures, interdependencies and redundancies between services and infrastructures should be identified. The involvement of stakeholders is fundamental at this stage. Cross-functional workshops and interviews must be held involving diverse stakeholders, including political administration, managerial senior officers and technical operators, from different services. These workshops intend to define resilience objectives, interdependencies between services and infrastructures, redundancies between infrastructures, as well as the operational routines of response to a given disruptive event. In this phase the average recovery time of the services after the occurrence of a given disruptive event should also be established.

The proposed cross-functional workshops also enable the identification of potential improvements and facilitates the definition of crisis management protocols. The main objective is to break down the barriers between the different actors responsible for urban metabolism (*e.g.*, public or private companies, institutions) and arise critical issues, which ultimately should lead to a sounder management of the city as a system of interconnected systems.

2.4. Step 3 - Application of Dynamic 1D/2D Drainage Models, Quantification of Impacts and Cascading Effects

Dynamic 1D/2D models were developed and used to simulate the drainage system behaviour, estimating the impact of extreme rain events with different return periods. The models identify the surcharge nodes, quantify the runoff volumes and contribute to delimitate the flooded areas and the height of accumulated water at the surface, thus allowing a further analysis on the impacts of each event.

In the current study, this goal is achieved by combining two existing simulation tools: Storm Water Management Model (SWMM), developed by the United States Environmental Protection Agency (US EPA) [15], and Basic Simulation Environment (BASEMENT), developed by the Laboratory of Hydraulics, Hydrology and Glaciology of the ETH Zürich [16]. A combined model SWMM+BASEMENT (CMSB) was developed [17], integrating the results of both models, which takes into account the efficiency of the stormwater interception devices (inlets). An efficiency parameter was defined (α parameter), reflecting the catchment average inlet efficiency. This parameter acts on the useful precipitation (P_{useful}) hyetograph, resulting in an attenuated precipitation hyetograph which is introduced on SWMM to simulate the drainage system. The remaining useful precipitation hyetograph is converted to surface runoff and simulated on BASEMENT. Additionally, the volumes resulting from overflows in the SWMM nodes are also considered as flow input on BASEMENT. The overall concept of this combined model is shown in Figure 2.

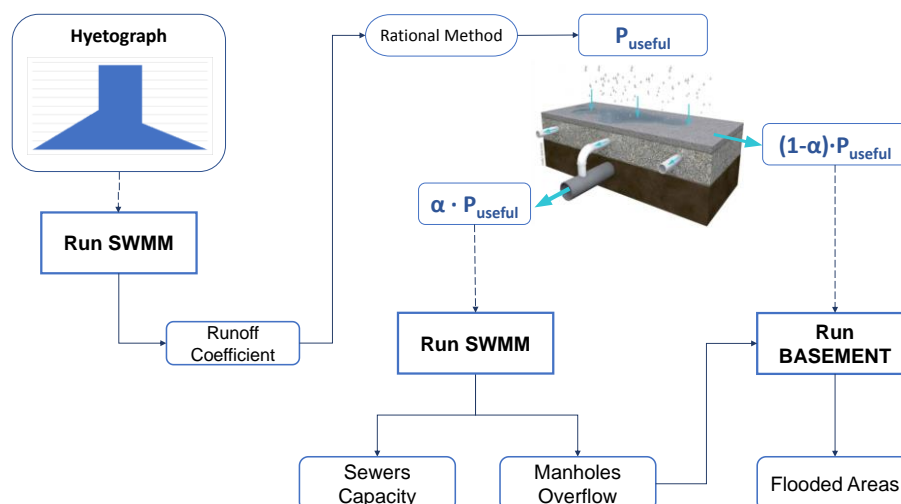


Figure 2. Conceptualisation and procedure of the application of the CMSB [17]

2.5. Step 4 - Urban Resilience Evaluation

The city performance to flooding may be evaluated considering the proposed dimensionless indicators presented on Table 1 [17]. These indicators are simple and can be computed considering the outputs of 1D/2D models, for rainfall events with different return periods.

Table 1. Proposed urban resilience to flooding indicators [17]

Indicator	Description	Computation
I1 - Volume overflowed	Measures the degree of affectation of the drainage system and its contribution to the aggravation of the urban flood.	$I1 = \frac{\text{Volume overflowed by drainage system}}{\text{Total volume entering the drainage system}}$
I2 - Flooded Area	Measures the extent, in area, of public space that is affected by flood.	$I2 = \frac{\text{Flooded area}}{\text{Total area}}$
I3 - Flood Duration	Measures the extent, in time, of public space that is affected by flood.	$I3 = \frac{\text{Duration of flooding}}{\text{Duration of precipitation event}}$
I4 - Buildings Affected	Measures the extent of potentially affected buildings.	$I4 = \frac{\text{Number of affected buildings}}{\text{Number of total buildings}}$
I5 - Services Affected	Measures the extent of services potentially affected by flooding.	$I5 = \frac{\text{Number of services affected}}{\text{Total number of services}}$

Considering these five resilience indicators, an integrated urban resilience index (IURI) can be determined using Equation 1:

$$IURI = 1 - \frac{\sum_i^n I_i}{n} \quad (1)$$

Where I_i is the value of the indicator i (dimensionless) and n the total number of indicators.

The IURI index allows the evaluation of city resilience accordingly to the following criteria:

- For IURI higher than 0.90, the urban resilience is considered excellent.
- For IURI between 0.75 and 0.90, the urban resilience is considered good.
- For IURI between 0.50 and 0.75, the urban resilience is considered acceptable.
- For IURI between 0.30 and 0.50, the urban resilience is considered insufficient.
- For IURI lower than 0.30, the urban resilience is considered unacceptable.

Whilst a greater IURI represents a better resilience, the indicators refer to undesirable situations and are computed inversely, *i.e.*, the greater the indicator value, the worse the situation.

3. Lisbon Downtown Study Case

3.1. Study Area

The proposed methodology was applied to a critical area of Lisbon, Portugal. The study area is defined by two main catchments, J (Avenida da Liberdade) and L (Avenida Almirante Reis), which drain high level zones to the lower riverside catchment (KJL), located in Lisbon downtown. These catchments have more than 600 ha, 140 km of combined sewers with limited capacity and serve almost 76 400 inhabitants [18] and were selected since they comprise areas that register an average of 5 to 8 flooding events per decade [19]. Historically critical prone to flooding areas are Rossio, located at downstream of both avenues, and Terreiro do Paço, located in the river side. The study case area (Figure 3) represents nearly 7.5% of the municipality and concentrated, in 2011, about 14% of its inhabitants, 68% of tourist accommodations, 30% of buildings and monuments of public interest and 30% of commercial activities [20].

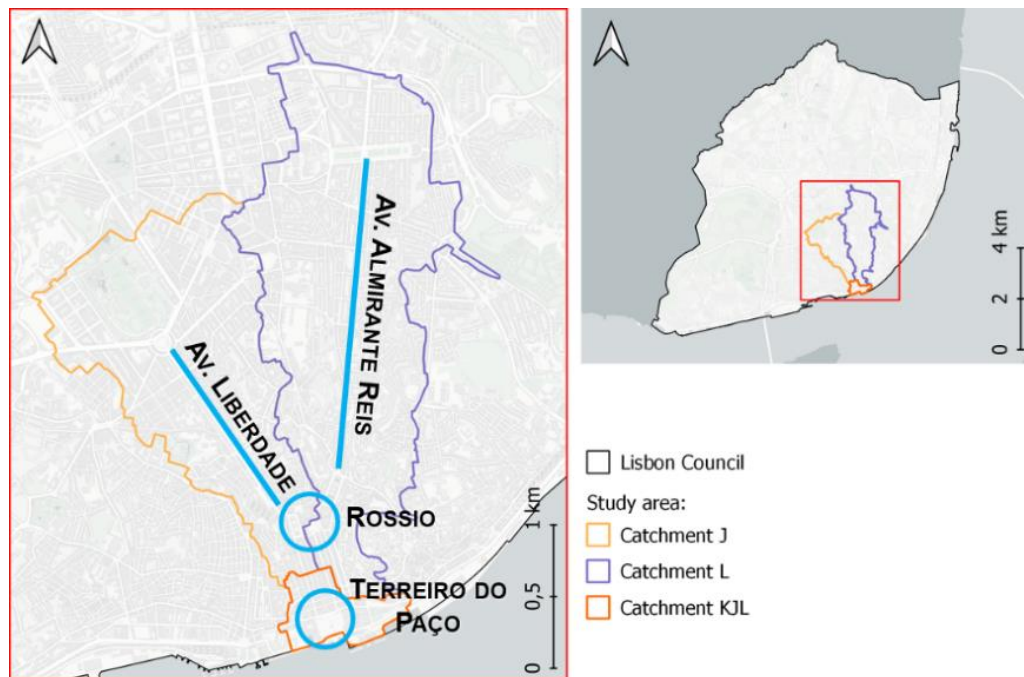


Figure 3. Lisbon study area: drainage catchments J, L and JKL

The list of services and infrastructures considered for the analysis is presented in Table 2. Water, power, mobility, waste, telecommunication, environmental and social sectors were included, and the total number of analysed infrastructures is 124. The services directly affected by floods are located within the flooded areas. However, other services might be affected due to interdependencies and, therefore, should be considered. An example of these are the services that require overland transports that might be partially compromised by the traffic interruptions related to floods.

Table 2. Services and Infrastructures analysed, located within the study area

Sector	Service	Infrastructure	Nr
Water	Water Distribution	District Metering Areas	37
	Urban Drainage	Wastewater Pumping Stations	1
		Overflows	3
Power	Power Distribution	Power substation	31
	Subway	Subway stations	15
METRO Power Substation		2	
Control Room		1	
Mobility	Bus	Bus Routes	19
	Traffic Management	Traffic Control Room	1
Waste	Municipal Solid Waste Collection	Routes	13
Telecommunication	Mobile Telecom (analysed only as a service provider)	-	-
Environmental	Receiver Waters	Tagus River	1
Social	Citizens	-	-

3.2. Interdependencies and Redundancies

For the establishment of the interdependencies in the study area, an effort was placed to produce results at infrastructure level, when possible. Therefore, practical results and acknowledgments about the services can be inferred from this assessment. This approach allowed to extrapolate the results, at service level, to Lisbon City. Figure 4 shows the interdependencies between the services analysed (A → B implies that when service A fails, a failure of some degree is triggered on service B).

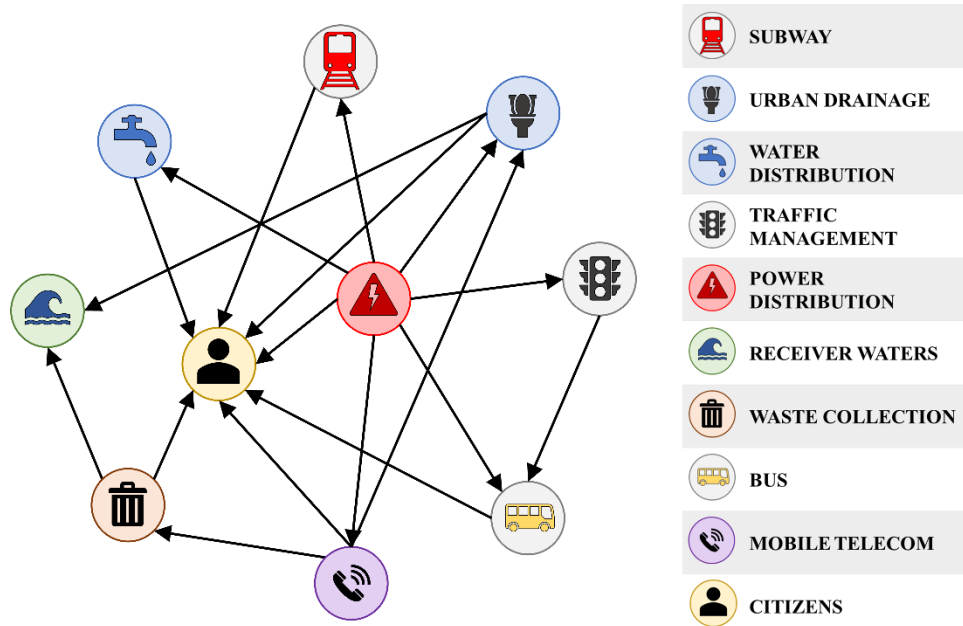


Figure 4. Services interdependencies in the case study area

Redundancies were found in the services which infrastructures are organized as a mesh/network, namely, power distribution, water distribution and buses. Redundancy is an important property that allows infrastructures of a given service to ensure service continuity when another infrastructure fails.

3.3. CMSB Application

The CMSB was applied considering the Portuguese design hyetograph with a duration of 4 hours [9], for a 10-year return period rainfall. Two scenarios were considered:

- Current situation (CS): maximum tide level of 1.95 m [18], and intensity-duration-frequency (IDF) curve estimated for IGIDL rainfall station [21].
- Climate changes at the end of the century (CC): maximum tide level aggravated of 2.81 m [22] and IDF curve magnified 15% [23].

Figure 5 presents the IDF curves and design hyetographs considered for each scenario.

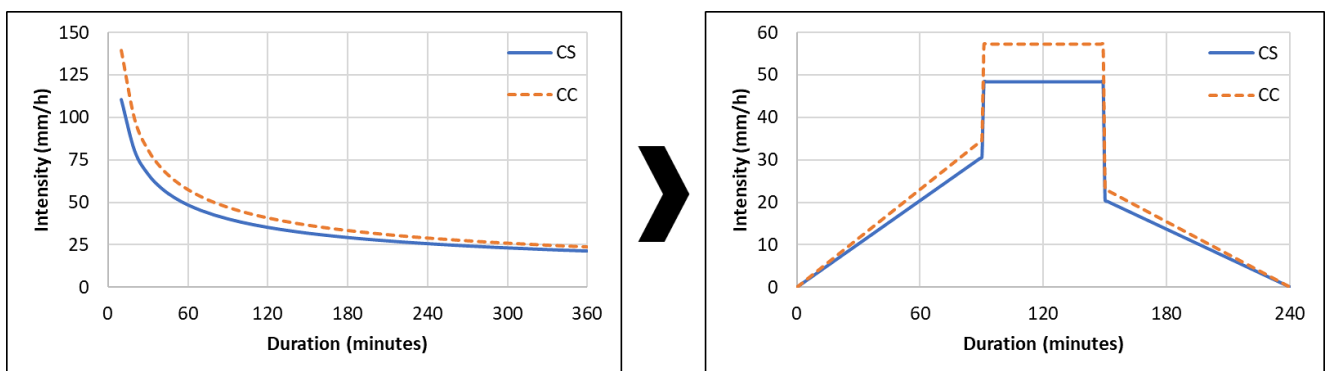


Figure 5. IDF curves (left) and design hyetograph (right) for 10-year return period rainfall for current situation (CS) and climate changes (CC) scenarios

The α parameter was established to reflect as faithfully as possible the real interception capacity of the drainage system inlets (including curb, gutter, and combination inlets). A set of α parameters was defined for each sub-catchment, throughout the duration of the rainfall event, considering a uniform distribution of inlets in each sub-catchment. Figure 6 presents the different α parameter values for the Current situation's 10-year return period rainfall, for the sub-catchments analysed. As observed, the inlets' capacity decreases with the increase of the precipitation intensity.

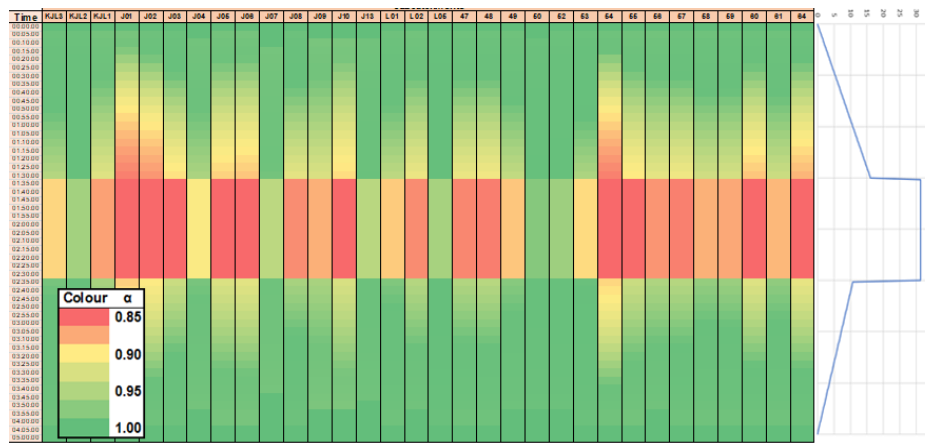


Figure 6. α parameter values for a 10-year return period precipitation event in the sub-catchments considered

Figure 7 illustrates the CMSB results, focusing on the downtown area (Rossio and Terreiro do Paço). The stormwater accumulated on the surface results from the low efficiency of inlet devices and from the drainage system’s lack of capacity to properly convey the incoming flows (mainly due to downstream constraints caused by high tide levels). The latter results in surcharge of the sewers and manholes’ overflow. In both scenarios, the most critical situation occurs approximately 2h40 after the rain event start, coinciding with the highest tide level and precipitation intensity. The results denote a significant surface water accumulation leading to floods in the downtown area, as expected. For the current situation, water heights of about 60 cm and 20 cm are observed in Rossio and Terreiro do Paço, respectively. Considering the climate changes scenario, with aggravated precipitation intensity and tidal levels, the situation is slightly worse, mainly in the streets located between Rossio and Terreiro do Paço (flat streets) and in Terreiro do Paço, with the enlargement of flooded areas and water heights.

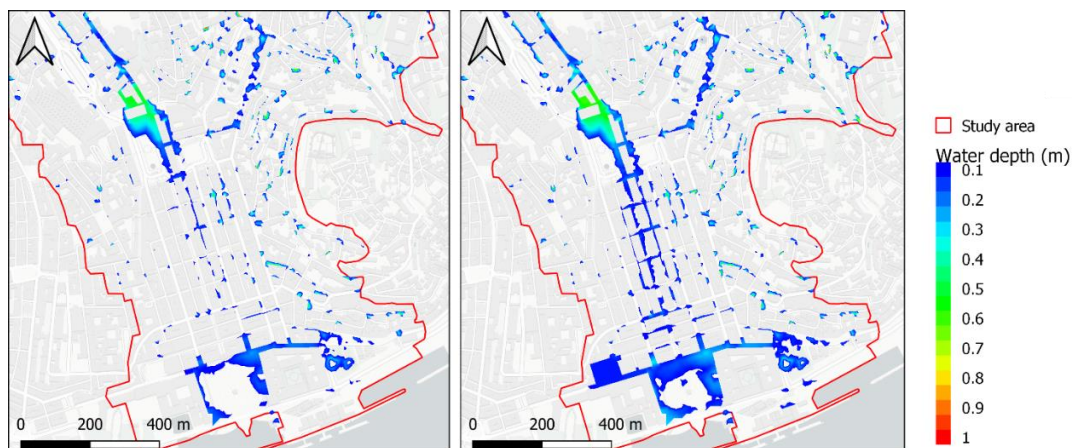


Figure 7. CMSB results for 10-year return period rainfall: current situation (left) and considering climate changes (right)

3.4. Cascade Effects Resulting from Flooding

The cascading effects resulting from flood events can be determined taking into account the services interdependencies and its reactions during the event: which services/infrastructures will fail, in what degree, and how long will it take for its recovery, if proper measures are taken. The potential services and infrastructures affected were selected based on past events, data collected on workshops and results from CMSB. It should be pointed out that the location of infrastructures within the flooded areas is not a sufficient criterion. The degree to which infrastructures are potentially affected depends on its physical properties (such as flood gates and walls, existence of pumping systems, raised positioning of vulnerable assets, among others), and on the flood severity, mainly regarding water depths.

In fact, most of the services analysed in the study case do not fail completely due to flooding but may have their routine operations affected. The direct impacts identified on the services/infrastructures are presented in Table 3. The recovery times mentioned, meaning the time needed for the service to fully recover, are indicative and will vary if other rainfall events and tide levels are considered. When services do not fail completely but are affected at some degree, it was assumed that the recovery time might vary between 1 and 3 hours (average reported times), the time the flood takes to reach a water level compatible with the routine operation. As observed with the results presented in chapter 3.3, flooding severity is not substantially aggravated by the climate changes scenario considered. Thus, direct impacts and cascade effects are presented in an aggregate form for both scenarios studied.

Table 3. Direct impacts and cascade effects for flooding events in the study area

Direct Impacts				Cascade effects
Sector	Service	Infrastructure	Description	Services
Water	Urban Drainage	Wastewater Pumping Stations	Pumping systems' storage capacity is exceeded. For this reason, combined sewer overflows (CSOs) are activated, and the stormwater is discharged into the Tagus River. Manholes' overflow can be aggravated. Recovery time was estimated at 2h after the rainfall ending due to the possible need for maintenance or repair works.	→ Receiver water → Citizens
Mobility	Subway	Subway stations	Most of the subway stations have retaining walls near the entrances, but there is a tendency for the superficial runoff to flow through the entrance stairs, possibly flooding the station atriums and platforms. The recovery time was estimated at 3h after the rainfall ending due to the possible need of evacuation, maintenance, and repair works.	→ Citizens
	Bus	Bus Routes	Buses must find alternative routes to avoid high water heights. The recovery time was estimated at 1.5h, after the rainfall peak.	→ Citizens
Waste	Municipal Solid Waste Collection	Routes	Comparably to buses, when the water level reaches a certain height, the waste collection vehicles do not collect the waste at flooded areas. The recovery time was estimated at 1.5h, after the rainfall peak.	→ Receiver water → Citizens
Social	Citizens	-	Citizens are affected by floods mainly due to constraints in its mobility (pedestrian or vehicular) and due to hazard posed by water depth and velocity.	(none)

To summarize, the considered rainfall events result in urban flooding that affect mostly "end of the chain" services, *i.e.*, services that are mainly dependent on others and which service is addressed directly to the citizens. For this reason, significant cascade effects are not expected. However, the following considerations are highlighted:

- The performance of the drainage system results in the direct discharge of untreated effluents into the receiving waters and on flooding due to overflows.
- The mobility sector does not trigger cascade effects since it provides services directly to the population, resulting in the decrease of daily-life comfort and constraints in mobility of the citizens.
- Likewise, waste collection services might be temporarily affected but present no strong repercussions for other services. Ultimately, it can affect the population by reducing urban hygiene conditions.
- In the power sector, no significant cascading effects are expected due to the high service redundancy already installed. Additionally, in the study area, the power supply entity has already undertaken some measures to improve its capacity to ensure service continuity, namely, the reinforcement of pumping systems in underground facilities and the raising of flood protection walls near surface air circulation grids. If a disturbance occurs, it would be at a small-scale level, affecting temporarily services such as traffic lights or commercial activities (not directly considered in the current analysis).

3.5. Urban Resilience Evaluation

Accordingly to the proposed methodology, five urban resilience indicators were determined considering the outputs of 1D/2D models, for a 10-year return period rainfall, both for the present situation and for an aggravated scenario, considering climate changes. The Integrated Urban Resilience Index was also determined, as presented in Table 4. In the current study case, a minimum water depth threshold of 0.10 m was set to define flooded areas.

Table 4. Urban resilience evaluation for the study area

Indicator	Current situation	Climate changes
I1 - Volume overflowed	0.08	0.17
I2 - Flooded Area	0.12	0.13
I3 - Flood Duration	0.94	0.96
I4 - Buildings Affected	0.07	0.08
I5 - Services Affected	0.60	0.60
Integrated Urban Resilience Index	0.64	0.61

In the current situation, about 8% of the flow that is captured by inlets is overflowed through manholes, enhancing the lack of transport capacity of the drainage system. This situation is worsened when considering the climate changes scenario, with about 17% of the affluent flows being surcharged through manholes. Regarding the flooded areas and flood's duration, their similarity between scenarios is explained by the concentration of the flooded areas in Lisbon downtown and by the consideration of a synthetic hyetograph with the same duration. Consequently, the percentage of buildings and the percentage of services directly affected by flood are also similar. In fact, 6 of the 10 analysed services are potentially affected by the occurrence of a 10-year return precipitation event, for both scenarios. In general, it can be concluded that the capacity of the drainage systems and the topography of the city are the most conditioning factors for the occurrence of floods.

The obtained values for the integrated urban resilience index (between 50 and 75) indicate that the urban resilience of the studied area is considered acceptable, according to the ranged presented in chapter 2.5. Climate changes contribute to a slight decrease of IURI in relation to the current scenario, without corresponding to a worst classification of the study area urban resilience.

4. Conclusions

This paper presents a methodology to assess urban resilience to flooding considering simultaneously a multisectoral approach, reflecting services interdependences and cascading effects, and a sectorial approach, applying 1D/2D computational modelling of the urban drainage network. Urban resilience to flooding is evaluated through a set of five simple indicators, resulting in an Integrated Urban Resilience Index. Additionally, a simplified and innovative process to integrate the inlets efficiency in the simulation process was proposed and applied.

The methodology enhances the need of a dual approach, comprising a comprehensive level, with the involvement of several city stakeholders and services managers, and a technical level, with the development of sectorial urban drainage models. It is of utmost importance that cities improve the availability, adequacy, and updateability of data to produce reliable results that are clear to disseminate to non-technical stakeholders and decision makers. The current work contributes with a simple methodology that can be applied at different spatial scopes (from a neighbourhood, to a large urban drainage catchment or a whole city) and recurring to free computational tools, as exemplified in the study case.

The application of the proposed methodology to Lisbon downtown study case demonstrated its usefulness and potential of exploitation. Two scenarios were considered, the current situation (CS) and a climate changes scenario (CC). The IURI variability between these scenarios is small, although decreasing for the climate change scenario, and the resilience to urban flooding is classified as acceptable for both situations. Nevertheless, the application of this approach has arisen critical issues that contribute to a more sustainable management of the stormwater systems, guaranteeing that the remaining urban services, and the city, will maintain its essential functions when confronted with extreme rainfall events. In this context, Lisbon is already planning further approaches to implement important climate-adaptation measures to increase the city resilience to flooding, namely, the construction of two drainage tunnels (Monsanto-Santa Apolonia and Chelas-Beato), an antipollution basin and several retention basins. In addition, the "Monitoring and warning system plan of Lisbon drainage network" is also being implemented. Although not considered in the current paper, a future scenario considering such adaptation strategies could be considered allowing to assess the resilience improvement by comparing the IURI results.

The current work consists of an initial iteration regarding the proposed methodology, and the assessment of the results regarding its application to the study case allows to target improvements for future developments. Firstly, the small variability between scenarios enhances the need to adopt more detailed indicators. Although it is intended to be a simple and straightforward methodology, the consideration of different flooding severity levels (for instance, as function of water heights and flow velocities) shall allow to differentiate the hazards posed to urban services/infrastructures and citizens. It is also important to reflect the interdependencies at infrastructural level in the indicators, as the services directly affected by floods in a study area tend not to vary between scenarios. The inclusion of more services/infrastructures in the analysis is also recommended, namely, health care services (hospitals, health centers, nursing homes, etc.), emergency services (medical emergency response, fire brigades, civil protection, etc.), tertiary sector services (shops, restaurants, etc.) and, in the power sector, electric transformer stations (the most susceptible to flooding assets of the sector). This allows to expand the study of interdependencies and to better assess cascading effects. As previously mentioned, the consideration of scenarios regarding the implementation of adaptation strategies should be considered, allowing to compare different solutions on the perspective of resilience, instead of solely applying a traditional technical-economic evaluation.

It is important to keep in mind that methodologies as the one presented, constitute a novelty framework that enables to have a deeper understanding not only of the physical systems behaviour, at infrastructural level, but also of the managerial and decision-making process. Ultimately, urban resilience approaches contribute to broadening consensus and maximizing benefits for all the urban actors.

5. Declarations

5.1. Author Contributions

Conception or design, J.B., F.F.; Data collection and processing, J.B., R.L.; Analysis and interpretation of the data, J.B., F.F., J.S.M.; Writing - original draft preparation, J.B.; Writing - review and editing, J.B., R.L., F.F., J.S.M. All authors have read and agreed to the published version of the manuscript.

5.2. Data Availability Statement

Due to the nature of this research, the authors did not agree for some data to be shared publicly, namely regarding critical urban infrastructures, so supporting data is not available. Major case study data that support the findings of this study can be accessed at <https://toolkit.resccue.eu/city/lisbon/>.

5.3. Funding

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5.5. Conflicts of Interest

The authors declare no conflict of interest.

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