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Assessing Urban Resilience in Complex and Dynamic Systems: The RESCCUE Project Approach in Lisbon Research Site

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Abstract: Urban environments are challenged with unprecedented anthropogenic and natural pressures, the latter being accelerated by the growing awareness of the consequences of climate change. The concept of urban resilience has been growing in response, since it allows us to understand city behaviour as a system of systems, improving its response to extreme climate-related events. This paper presents the EU H2020 Resilience to Cope with Climate Change in Urban Areas (RESCCUE) project approach in Lisbon's research site, regarding the Hazur® resilience assessment methodology. This methodology focuses on the interdependencies between services and infrastructures, and on the recovery times needed to restore its normal functionalities. This approach allows the integration of several work packages of the RESCCUE project, from climate change projections to adaptation strategies selection. The assessment was conducted for 19 services and 146 infrastructures, including water (supply and drainage systems), power, mobility, waste, telecommunication, environment, and the social sector. The principal climate-related hazard analysed at the Lisbon research site was urban flooding. The main result consists of a deep understanding of the relations between different services and the consequent cascade effects triggered by flooding events. Stakeholders' involvement, beyond the project consortium, was fundamental for the success of the methodology implementation.

Keywords: cascading effects; climate change; urban flooding; urban resilience; urban services

1. Introduction

The importance of cities performance in the global context of rapid urbanisation is undoubted. In 2050, 68% of the population will be living in cities [1]. Decision-makers are confronted with too many challenges: from societal disparities or economic instability to climate change and climate-related hazards. Only by understanding the behaviour and dynamics of cities, being aware of its complexity as systems of systems, can decision-makers respond promptly and efficiently to these challenges. Additionally, efforts must be made towards understanding the magnitude of the hazards and risks posed by these challenges, considering its inherent uncertainty [2].

As a response, the resilience system thinking has increased significantly since the beginning of the XXI century [3,4], although its conceptual definition and focus has neither been consensual nor converging to a single common approach [4,5]. Resilience approaches tend to vary across disciplines, and interpretations from governments and organisations are diverse across global, national, municipal, and community scales [6]. Nevertheless, regarding cities, contemporary approaches have been often "revolved around the abilities of urban environments to absorb disturbances, to recover from shocks, for self-organization, and for adaptation and transformation" [3].

Urban resilience aims at understanding the dynamic behaviour of systems on different timescales and optimise both preparedness and recovery capabilities [7]. Programmes that target sectorial urban aspects separately do not enhance a city's overall resilience properly [6]. As the dynamic behaviour is increasingly determined by interdependencies, new methods are needed to model cities as systems of systems, connected both within and beyond its boundaries, and carry out comprehensive resilience assessments [6,7]. The urban resilience assessment shall fit the local needs and be capable of clearly informing stakeholders and decision-makers in order to be integrated into the planning system [8].

In urban areas, climate change impacts are expected to result in more frequent urban flooding events, as a result of intense rain and sea level rise [9]. The occurrence of floods may be aggravated by lack of adequate planning and resilience programs [10]. In many cities, the organisational capacity required to address climate resilience with further sustainability targets may not be available [11].

The present paper focuses on the approach followed at the Lisbon research site regarding the application of an holistic resilience assessment methodology, the Hazur® methodology [12,13], with the acquisition, centralization, and compatibility of different types of data to produce useful outcomes regarding the city performance and the resilience improvement. This work was developed under European Horizon 2020 project Resilience to Cope with Climate Change in Urban Areas (RESCCUE—a multisectoral approach focusing on water) [14]. This project proposes a roadmap able to assess urban resilience focusing on water related services and hazards and comprises several work packages, from climate change projection, hazard and risk assessment, and definition of adaptation strategies, to the development of a Resilience Action Plan.

After this introductory section, Section 2 presents the overall methodology of the RESCCUE Project (Section 2.1), the Holistic Resilience Assessment methodology (Hazur® methodology) used in the project (Section 2.2), and contextualises the Lisbon research site (Section 2.3). Section 3 describes the Hazur® methodology application steps in the Lisbon research site. Discussion of the obtained results is undertaken is Section 4, followed by final remarks (Section 5).

2. Methodology

2.1. RESCCUE Project Overview

The RESCCUE project (initiated in May 2016 and ending in November 2020) aimed at helping cities around the world to become more resilient, going beyond conventional approaches to "build and improve urban resilience" by delivering a forward-looking, multi-scale, multisectoral, and multi-hazard methodology. The consortium is led by Aquatec—SUEZ Advanced Solutions—and consists of 17 partners, including the three city councils of the research sites (Barcelona, Bristol, and Lisbon), the United Nations agency UN-Habitat, several urban services companies, research centres, universities, and small and medium enterprises (SMEs), all of them with a key role on resilience management in the three research sites [14]. Along with the project implementation, other relevant stakeholders were involved, namely urban services management bodies and operational teams [15], enriching the project results beyond the consortium limits.

The focus of the project is the water sector, i.e., urban water utilities, and interdependencies with other crucial urban services, such as energy, transports, solid waste, green infrastructures, receiving water bodies, and telecommunications.

The project comprises a set of eight work packages (WP). WP1 to WP6 is where the technical work is focused, whereas WP7 deals with communication and exploitation, and WP8 is related to project management. The progress of RESCCUE work does not follow a typical straightforward path, being developed with two approaches (Figure 1) characterised by a different level of detail, allowing to understand the functioning of the city as a whole:

- Detailed approach: From climate change projections and extreme events prediction, using downscaling techniques, 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 extreme weather events (WP2). Then, the analysis of the impacts on services and infrastructures was achieved via the use of loosely coupled models and tools (integrated models), using the outputs of one as inputs of the other (WP3). Later, adaptation strategies and measures were proposed and prioritised 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 to assess resilience through the study of 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 for the reestablishment of the normal operation of the urban services and infrastructures.

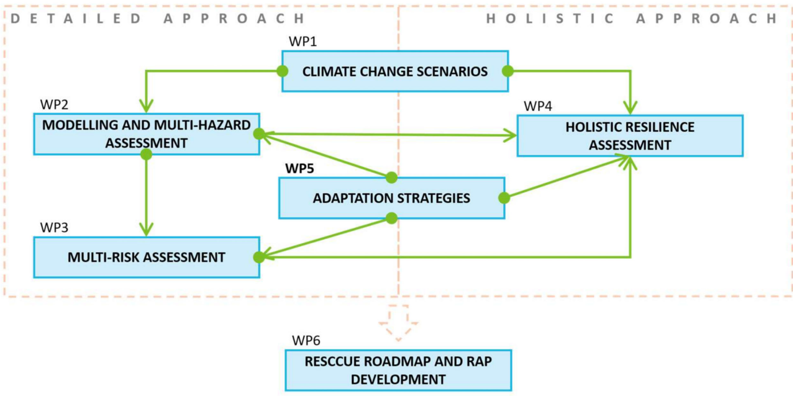

Figure 1. Summary of the Resilience to Cope with Climate Change in Urban Areas (RESCCUE) dual-level approach [14].

Additionally, a Resilience Assessment Framework was developed (WP6) with the objective of [16]:

1. Directing and facilitating a structured resilience diagnosis of the cities and of 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 the development of cities' resilience action plans by supporting decision-making in the selection of resilience measures and the development of 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.

A specific Resilience Action Plan for each research site was developed, presenting the current resilience status of the city and the strategic lines, fed with concrete measures, to be applied to solve specific problems.

2.2. Hazur® Methodology

Hazur® methodology [12] was developed taking into account Hazard Identification Studies (HAZID) techniques, the methodology of strategic analysis from business management [17] and the methodology of the Industrial Security Auditing service. This methodology can be organised in four main steps: (1) definition of scope and objectives and stakeholder's engagement; (2) selection and characterisation of critical services and infrastructures; (3) assessment of interdependencies and redundancies between services and infrastructures; (4) quantification of direct impacts due to selected disruptive events and analysis of cascade effects and quantification of potential improvements due to strategies application. The implementation of the Hazur® methodology was supported by an online platform, which allowed the implementing partner, Hidra, Hidráulica, e Ambiente (HIDRA), to upload and store data, and the remaining project partners and stakeholders to analyse, validate, and visualise results all along the process, making it possible to visualise interdependencies and cascading effects among services and infrastructures under different situations and scenarios, showing the city as a system of systems [18].

The objective of this analysis is to assess the city resilience in a broader sense (holistic approach), improving knowledge regarding the services and infrastructures interdependencies. The main goal is to better understand where to act and how to better operate the city as a whole, increasing the quality of life of the citizens and ensuring a continuous and fluent adequate performance of the services.

2.3. Lisbon Research Site

Lisbon, the capital city of Portugal, is located in the northern riverside of the Tagus river estuary and is one of the 18 municipalities that constitute the Lisbon Metropolitan Area, Portugal's largest urban expanse, as presented in Figure 2. The city urbanisation is diverse, with an historical medieval centre, neighbourhoods developing along the main axes of circulation and more recent developments, following a process of rapid urbanisation and consequent urban sprawl [19]. The council has a continental area of 85.8 km^2 and a submersed area of 14.2 km^2, resulting in a total area of circa 100 km^2.

Figure 2. Lisbon geographical location: European (**left**) and Lisbon Metropolitan Area (**right**) framing (data from [20]).

The Municipal Strategy for Climate Change Adaptation [21] emphasises the main climate trends, highlighting the decrease in the average annual precipitation and rainy days; the increase in the average annual temperatures (with hot days, tropical nights, and frequent heat waves); the mean sea level rise; and the increase in the frequency of extreme events, such as intense rainfalls, storm surges, and wind gusts.

Lisbon municipality has been tackling climate change in recent decades by joining and renewing international initiatives and partnerships and developing local plans and strategies, both on mitigation and adaptation perspectives, leading to a continuous improvement process. At the international level, several initiatives stand out: the signing of the Covenant of Mayors in 2008 and of the Covenant of Mayors for Climate and Energy in 2016 [22]; the development of a Sustainable Energy Action Plan in 2012 [23] and of a Sustainable Energy and Climate Action Plan in 2018 [24]; the admission in the 100 Resilient Cities in 2014 [25] and in the C40 Cities Network in 2019 [26]; the development of Lisbon's Resilience Action Plan [27] in 2017 under United Nations Office for Disaster Risk Reduction (UNISDR)"Making Cities Resilient Campaign"; and the European Green Capital 2020 award [28]. Additionally, the municipality has been partnering EU H2020 climate and resilience-related projects, namely Realising European Resilience for Critical Infrastructure (RESILENS) [29], from 2015 to 2018, Bringing Innovation to Ongoing Water Management—a Better Future under Climate Change (BINGO) [30] from 2015 to 2019, and RESCCUE from 2016 to 2020. At a local level, the Municipal Strategy for Climate Change Adaptation [21], in 2017, and the Metropolitan Plan for Climate Change Adaptation [31], in 2019, are highlighted.

In the Lisbon research site, the Portuguese RESCCUE team involved researchers of the Laboratório Nacional de Engenharia Civil (LNEC), Câmara Municipal de Lisboa (CML), EDP Distribuição (EDP D), Águas do Tejo Atântico (AdTA), and Hidra, Hidráulica, e Ambiente (HIDRA), being the latest the responsible for the Hazur® implementation in Lisbon.

3. Approach in Lisbon Research Site

3.1. Definition of Scope and Objectives and Stakeholder's Engagement

One of the main concerns regarding Hazur® implementation in Lisbon was the requirement to meet the city council needs and to produce useful results to the city management. Thus, the first task was to define a clear goal for the Hazur® implementation in Lisbon, assumed by the city council: "the overall objective of the Hazur® implementation in Lisbon is to understand the city performance as a system of systems, and, from there, to answer to the city and actors' needs, integrating public participation, to increase the overall city resilience level. At a broader sense, the ultimate goal is to increase the quality of life in the city, ensuring a continuous and fluent performance." [18].

Having this goal in mind, Hazur® implementation was developed at two different levels of detail. Firstly, a detailed analysis was focused at the service and infrastructure level, selecting a critical and representative area of Lisbon. From this, a broader and citywide analysis was made, at the service level, based on the knowledge of the city and on the conclusions drawn from the detailed analysis, with more generic results. This strategy allowed for much more targeted work, oriented to critical areas of the city.

The detailed implementation of Hazur® was focused on a crucial and critical areas corresponding to the drainage catchment basins J and L, as well as its confluence area (catchment basin KJL), of the Lisbon Drainage Masterplan [32], as presented in Figure 3. This area was selected due to its high importance for the city daily life, being the centre of its economic and touristic activities and the core of its urbanistic and demographic development (Table 1). Since this specific area overlaps with the old and historical centre of Lisbon, it is vulnerable to many risks such as flooding, tidal effects, slope movements, earthquakes, and tsunamis; most of these are expected to be aggravated by climate change.

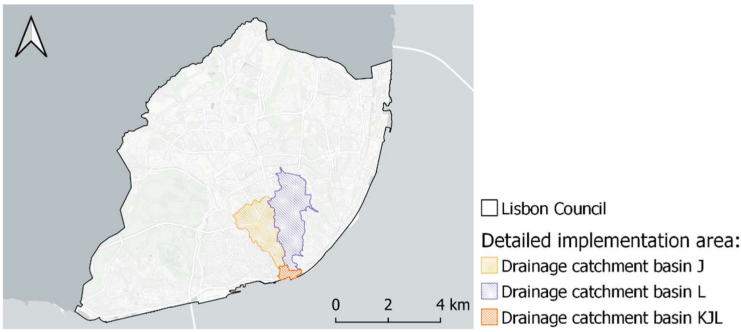

Figure 3. Lisbon Council and detailed implementation area (data from [20] and [32]).

Table 1. Lisbon Council and catchment basins J and L indicators (data from [33]).

Indicator	Catch. Basins J and L	Lisbon Council	% Over Lisbon Council	Density (per km^2)	
				Catch. Basins J and L	Lisbon Council
Area (km^2)	6.3	85.9	7.3	–	
Inhabitants	76,400	547,733	13.9	12,137	6436
Dwellings	48,142	322,981	14.9	7648	3760
Buildings	7966	52,496	15.2	1265	611
Accommodations (hotels and aparthotels)	100	148	67.6	15.9	1.7
Buildings and monuments of public interest	88	319	27.6	14.0	3.7
Commercial activities	5277	17,200	30.6	838.3	200.2

The detailed implementation and results covered services and infrastructures that were not located within this area, due to the interdependencies of infrastructures that spread beyond these catchments. It was considered that the specific analysis of this area was fundamental and a priority for managing Lisbon's resilience, to help expand the results citywide. It also worked as a starting point to assess interdependencies and cascade effects.

From an initial assessment of the main exposed assets to climate-related hazards [34], taking into account past occurrences, some sectors and services were initially identified as important to be considered in the Hazur® assessment (Table 2), also allowing us to predict that the stakeholders would be engaged. The data collection and validation phase, which demands a stronger involvement with the stakeholders, was carried out between February and June 2017, at different levels. In total, 12 meetings were conducted with different actors/partners; 1 RESCCUE local workshop was held, with a wider range of participants; and 5 Portuguese RESCCUE team follow-up meetings occurred.

3.2. Selection and Characterisation of Critical Services and Infrastructures

Concerning the services to be analysed, a set of mandatory services related to the water sector was agreed upon at the beginning of the project, as a starting point for all the three research sites of the project. These services include water sourcing and transportation, water treatment, water storage, water distribution, urban drainage, and wastewater treatment. Through discussions among Lisbon stakeholders, and linking to the previously identified hazards, a more comprehensive list of services was selected and analysed in order to have a more complete, broad, and structured representation of the city's reality. The complete list of services analysed is presented in Table 3. Additionally, this table lists the infrastructures studied during the detailed Hazur® implementation, presented in Figure 4. The analysed infrastructures are the ones considered critical or fundamental to the respective service or the ones that best represent the service's operation.

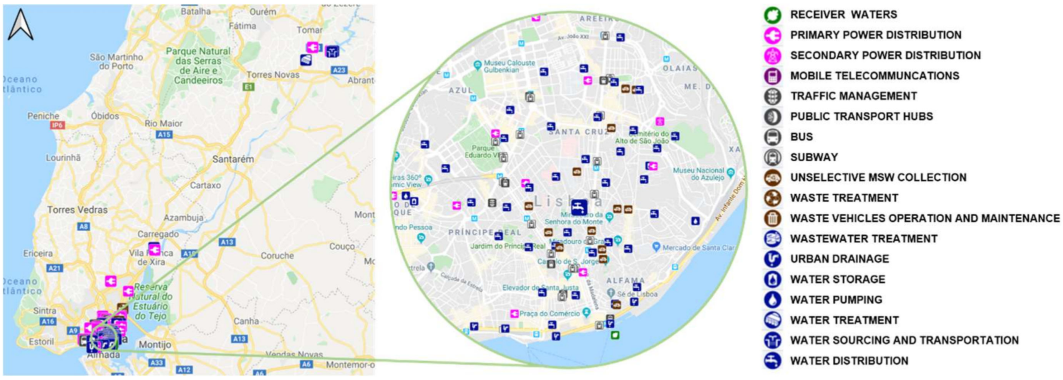

Figure 4. Location of the considered infrastructures in Lisbon [35].

Table 2. Summary of Lisbon matrix of assets exposure to climate-related hazards adapted from [34].

Service	Cycle	Subsystem	HW	SLR	F	W
Energy	Electricity	Power generation	○	○	○	○
		Electric Transportation	⊗	⊗	⊗	⊗
		Electric Distribution	⊗	⊗	⊗	⊗
Telecommunication	-	Network	⊗	○	⊗	⊗
		Nodes	○	○	○	○
Urban water cycle	Water Supply	Water Distribution	○	○	○	○
	Urban Drainage	Sewers system	○	⊗	⊗	○
	Wastewater Treatment	Wastewater Treatment Plant	○	⊗	⊗	○
Waste	Solid waste	Urban Solid Waste Collection	○	○	⊗	○
		Cleaning	○	○	⊗	⊗
		Treatment	○	○	○	○
Transport	Roadways	Roadways	○	⊗	⊗	⊗
	Rail and Metro	Rail and Metro	○	⊗	⊗	⊗
Green infrastructures	-	Trees	○	○	○	⊗
Urban equipment	Urban equipment	Various components	○	○	⊗	⊗

Legend: HW—heat waves; SLR—sea level rise; F—flooding; W—wind; ○—not exposed or not considered; ⊗—exposed.

The services and infrastructures were analysed and characterised regarding main operation routines, failure causes, reestablishment routines, critical hazards, physical characteristics of infrastructures, among others.

3.3. Assessment of Interdependencies and Redundancies between Services and Infrastructures

The definition of the interdependencies between services and infrastructures is the core of the Hazur® assessment methodology. It is crucial to set, a priori, to what extent these interdependencies should be explored. In the case of Lisbon, this extent was clearly defined and only interdependencies between the agreed set of services and infrastructures were considered. However, during the process, interdependencies with other services were identified, such as fuel supply or health care facilities. For the establishment of the interdependencies, efforts were made to produce results as specific as possible, i.e., at infrastructure level. This way, more practical results and acknowledgments about the services can be inferred from this assessment. This approach also allowed us to extrapolate the results, at service level, to Lisbon City.

Table 3. Services and infrastructures analysed under Hazur® in Lisbon.

Sector		Service	Infrastructures	Nr
Water	Water Supply System	Water Sourcing and Transportation	Water Intake Tower Collected Water Pumping	1 1
		Water Treatment Water Storage Water Pumping Water Distribution	Water Treatment Plant Reservoirs Water Pumping Stations District Metering Areas	1 6 4 37
	Wastewater Drainage System	Urban Drainage	Wastewater Pumping Stations	11
		Wastewater Treatment	Wastewater Treatment Plant	1
Power		Primary Power Distribution Secondary Power Distribution	Switching station Power substation	5 31
Mobility/Transports		Subway	Subway stations METRO Power Substation Control Room	15 3 1
		Bus	Control Room Stations	1 4
		Public Transport Hubs Traffic Management	Hubs Traffic Control Room	6 1
Waste		Unselective Municipal Waste Collection	Routes	13
		Waste Vehicles Operation and Maintenance	Maintenance Garage Parking Space	1 1
		Waste Treatment	Mixed Solid Waste Treatment Plant	1
Telecommunication		Mobile Telecom (analysed only as a service provider)	–	-
Environment		Receiver Waters	Tagus River	1
Social		Citizens (analysed only as a service receiver)	–	-
Total Sectors = 7		**Total Services = 19**	**Total Infrastructures = 146**	

The analysis of the interdependencies consists of the assessment of the consequences of a given service/infrastructure failure (the "giver") in a given service/infrastructure (the "receiver"), by filling the "Interdependencies Matrix". Under Hazur® methodology, there are three possibilities to define an interdependency: (i) the failure of the giver has no effect on the receiver (no dependency); (ii) the failure of the giver has some effect on the normal functioning of the receiver, without completely compromising its functionality; (iii) the failure of the giver triggers the complete failure of the receiver. Additionally, it is also possible to assign an autonomy time, i.e., the time that the receiver can keep its functionality, even with the giver failure, by means of intrinsic characteristics/equipment or through the activation of external backup teams and equipment (e.g., if a given infrastructure is dependent on electricity and a power failure occurs, if that infrastructure is equipped with an emergency generator, that equipment provides an autonomy time before failing). "Critical infrastructures" can also be stipulated, i.e., infrastructures, failure of which implies a total failure of the service. Figure 5 presents and excerpt of the Interdependencies Matrix obtained for Lisbon. The green tag, as "none", represents no dependence of the receiver on the donor; the yellow tag, as "affected", represents a partial affection of the receiver when the giver fails; and the red tag, as "down immediately", represents a total failure of the receiver when the giver fails. Additionally, the blue-filled circles open the "critical infrastructures setup"; the blue circles crossed in white mean that interdependencies are set at infrastructure level; and the purple circles open the "redundancies setup" of the respective service, where redundancies are defined.

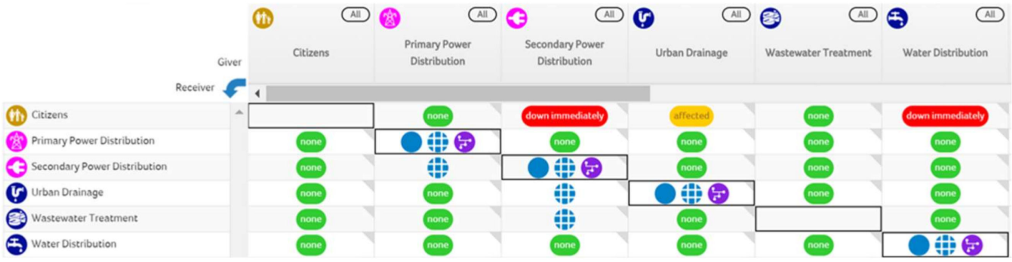

Figure 5. Excerpt of the Interdependencies Matrix for Lisbon at service scale [35].

The Resilience Map (Figure 6) presents a visual overview of the global interdependencies at the service level, or a close-up at a given interaction on a selected set of services or infrastructures. Connections between services/infrastructures represent an interdependency at least of one from another. Blue lines are presented when interdependencies are defined at a more detailed level, yellow lines represent a partial failure of the receiver, and red lines represent a complete failure of the receiver in case of the giver failure.

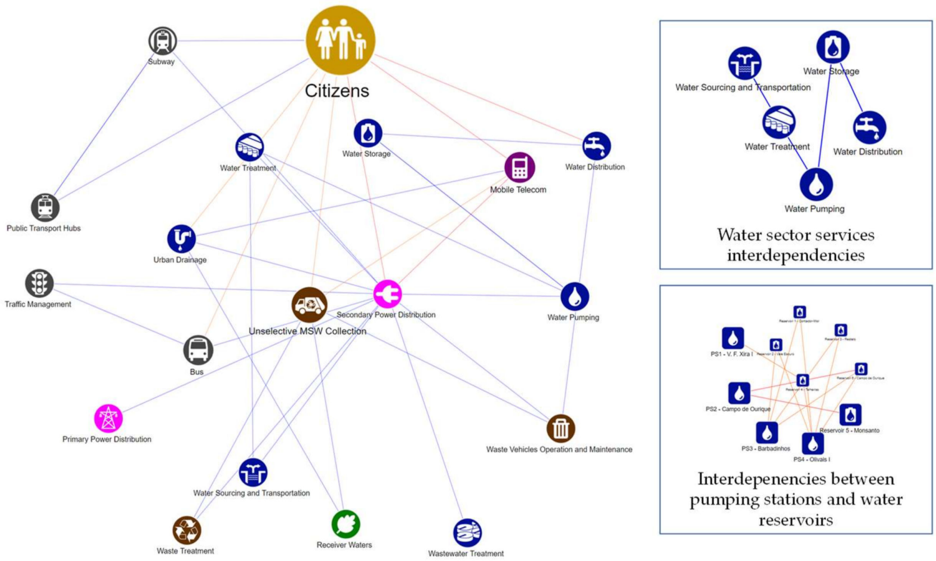

Figure 6. Resilience map for Lisbon and examples of specific interactions at service scale (**left** and **top right**) and at infrastructure scale (**bottom right**) [35].

One advantage of making the analysis at the infrastructure level is the possibility of assessing its redundancies, i.e., cases where a given infrastructure can ensure the continuity of the service when another infrastructure fails. In Hazur®, the redundancies are established between infrastructures of the same service, although, in reality, redundancies can happen between different services and infrastructures of different services. For instance, if there is a subway service failure, the redundancy found by the users is to use a different transportation service, such as the bus. Moreover, some services can present internal redundancies, which are not necessarily between infrastructures. An example is the case when the waste collection is not possible at a given moment or a certain area, and the redundancy can be achieved by making the waste collection at a different shift or round. From the analysed services, redundancies were found in the power distribution substations, water distribution metering areas, water storage reservoirs, and subway power substations. Those redundancies rely on the network or grid organisation of these services' infrastructures, granting them an important resilient characteristic.

3.4. Quantification of Direct Impacts Due to Selected Disruptive Events, Analysis of Cascade Effects, and of Potential Improvements Due to Strategies Application

As previously mentioned, under the RESCCUE scope, in the Lisbon Research Site, the main hazard analysed was urban flooding, which is of extreme importance for the city due to the frequent occurrence of flooding events that result from the combination of extreme rainfall events and high estuarine tide levels, leading to socio-economic and environmental damages, affecting services and citizens (including tourists).

The characterisation of the impacts of a given disruptive event is made by the indication of the failure status, as in the interdependencies matrix (Section 3.3), and of the recovery time, i.e., the time that the service/infrastructure remains in that failure status before recovering from the disruption, in a new matrix, the "Direct Impacts" matrix. The recovery time definition is difficult due to the great number of factors (internal and external) that may affect the response of the services or infrastructures, such as the time of day or the time of the year that the event occurs, the expectation and preparedness for the event, the severity of the event, among others. Additionally, it was clear that there was no systematic report procedure for extreme event occurrences. The available data are scarce and dispersed on registers with distinct formats, depending on the responsible body (social media, fire department, civil protection, municipal departments, universities, etc.), making it difficult to systematically analyse past events' impacts.

For the flooding hazard, in the cases analysed, the impact on the services/infrastructures was defined depending, at least, on: (a) the service/infrastructure exposure; for example, water pressurized systems in Lisbon are not affected by flooding, but if a pipe rupture occurs within a flooded area, its repairment can only occur after the flooding; (b) the water height; for instance, buses may still operate during flooding events if the water level is low; (c) the duration of the flooding; that depends mainly on the duration and intensity of the rainfall and on the sea level. Additionally, due to its uncertainty, the recovery times presented are only indicative, based on average simulation results and records of past events, and intend to be representative of the impact degree of different flooding events. For most of the services that do not fail, but have their routine operation affected, it was assumed that these may recover by the time the flood ends (or the level of water is compatible to the routine operations). It was also considered that, on average, the areas stayed flooded during 1 to 3 h (reported time from previous events).

The impact quantification procedure was supported by the 1D/2D modelling performed on WP2 for the current situation (CS), as baseline; future situation (business as usual—BAU), considering climate change drivers and that no strategy is implemented; and future situation with the implementation of climate adaptation strategies (CAS). For WP2 purposes, three adaptation strategies were modelled, namely: CAS1—adaptation of green infrastructure; CAS2—peak flow attenuation through the construction of two retention basis; and CAS3—construction of new components in drainage system (including a large interception tunnel and improvements in the inlets to the sewer network) [2]. The strategy CAS3 is the most important strategy identified in the Municipal Drainage Master Plan 2016–2030 [32] and was the only strategy simulated through 1D/2D modelling in the drainage catchments J and L. For this reason, this strategy was selected to be considered in the Hazur® implementation. Table 4 summarises the main direct impacts due to flooding events considered in the current analysis. Due to confidential and sensible information, the specific infrastructures are not mentioned.

As presented, most of the services and infrastructures affected by flooding events (from the set considered in the Hazur® implementation) do not fail completely, although they might have their normal procedures affected. Additionally, most of the affected services are "end-of-chain" services, leading to short cascading effects, as presented in Figure 7 for business as usual (BAU) situation.

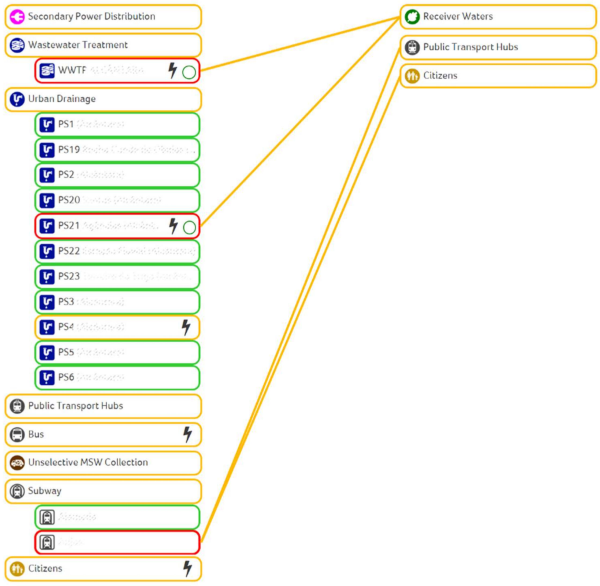

Figure 7. Visualisation of flooding cascading effects triggered for business as usual (BAU) [35].

Table 4. Direct impacts for flooding events (adapted from [18]).

Service	Impact Description
Secondary Power Distribution	There is a specific substation located in an area prone to flooding that has already been affected due to flooding events in the past. The recovery time considered is greater than the rainfall event due to the implemented procedures to restore the service and no significant changes are predicted for the BAU. With the implementation of the CAS3, the flooding probability in this location is highly reduced. Therefore, it is considered that this substation will no longer be affected in this scenario.
Public Transport Hubs	There is a specific hub located at the downstream of the drainage catchment, where is expected a high-water volume convergence. Since this infrastructure is close to the Tagus River level, higher tides will contribute to the harshness of the flooding conditions. The recovery time was set between 2 to 3 h, average estimated times for the water level to decrease to low levels so that the transports and citizens can resume their routes and daily life. With CAS3 implementation, the risk is minimised.
Citizens	From the simulation results developed under WP2, direct consequences of flooding on citizens were estimated by calculating the hazard for pedestrians (dependent on the water height on the streets and of the surface water velocity). Since the water level for BAU is expected to be slightly higher than for CS, the recovery time for BAU was set higher than for CS. The recovery time is estimated as the time needed for the water level on the streets to reach a level of low risk for pedestrians. When CAS3 is implemented, there will still be some areas prone to flooding (low depression areas) where the water level might still have an impact on citizens. However, it is considered that the recovery time is lower than for the CS.
Bus	The service does not fail completely due to flooding, but when the water level reaches a certain height, the buses must find alternative routes, and citizens may need to go to different stops. The recovery times for CS and for BAU was set to 1.5 and 2.5 h, respectively, based on the average estimated time for the water level to decrease to safe levels for buses to resume their routes. However, the citizens may be affected longer than this due to the level and velocity of the water and might need to resort to other bus stops. If CAS3 is implemented, the probability of routes being affected is minimized in the downtown area.
Subway	Most of the subway stations have retaining walls on the entrance staircases. Nonetheless, there is a tendency for the superficial runoff to flow through the entrance stairs, possibly flooding the station atriums and platforms. In some stations, the recovery time was set to between 2 and 3 h due to the possible need for cleaning and repairment works.
Urban Solid Waste Collection	In some specific routes, located in areas prone to flooding, water heights might reach levels that prevent waste collection vehicles from collecting waste. This situation is particularly important at night, when most waste collection procedures occur. The recovery time in this case is the time estimated for the water level on the streets to reduce to a level that poses no risks for the trucks' circulation.
Wastewater Treatment	The flows that reach the Wastewater Treatment Plant (WWTP) are higher than the design flows, and the excess wastewater is diverged by a bypass infrastructure and discharged downstream into the river. Nevertheless, the treatment service does not fail per si (the WWTP continues to treat the design flow). The recovery time is estimated to 3 h, the average time needed for the event to dissipate.
Urban Drainage	The flows in the drainage system are high, causing the surcharge of the conduits, promoting discharges of wastewater into de surface through manholes and pumping systems' bypass activation, discharging wastewater into the Tagus estuary. The recovery time is such that allows the cleaning, maintenance, and repair works.

4. Discussion

Despite the complexity and necessary data for Hazur® implementation, in the Lisbon research site, efforts were made to apply the methodology in the most straightforward way possible, keeping it simple to implement and to understand, but still representative of the city behaviour. The assessment for the Lisbon research site was mainly focused on analysing the interdependencies and cascading effects between the considered services and infrastructures on a critical area of the city, the catchment basins J and L, with the purpose of extrapolating the results, at service level, to the whole city. Although some particular and local relations might be reflected, it is consensual that most of the relations studied in the detailed area are applied in a broader sense to the city.

The assessment was conducted for 19 services and 146 infrastructures, including water (supply and drainage systems), power, mobility, waste, and telecommunication, as well as the environment and social sectors. This number of services and infrastructures was appropriate for the Hazur® implementation, allowing us to understand the services' interactions and estimate an overall analysis of the city resilience. The main hazard considered was urban flooding, caused by heavy rainfall events and high tide levels.

Different climate change scenarios were taken into account. These scenarios were integrated in the urban flooding models and the results, namely flooded areas and water heights, were considered in the Hazur® implementation. These two variables helped to identify the affected infrastructures/services within prone to flood areas, as well as to infer if the water height at the surface is enough to cause an impact on a given the service/infrastructure.

Although, when comparing the current situation (CS) with the climate change scenario (BAU), there is an increase on the prone to flooding area and in the height of the water at the surface, in this particular case, the increase in the flooded area does not bare an impact on the number of infrastructures affected. The recovery time is aggravated due to the increase in water height, namely for the services/infrastructures where the decrease on this variable is the main factor contributing for the recovery of the service (e.g., citizens, public transport hubs, and bus and waste collection). However, some other recovery services do not depend as strongly on the flooding severity but on the procedures implemented when the event occurs, and that the recovery time is kept unchanged in these scenarios. Regarding the impact of flooding on "citizens", a detailed analysis on the risks for pedestrian, considering both water height and velocity, was set on WP2. Although more than 60% of the flooded area was categorized as a "low risk area", some streets, such as Avenida da Liberdade and Avenida Almirante Reis, and others located downtown, are considered to be at a high and very high risk, representing a potential problem for the most vulnerable groups, such as children, the elderly, and those with reduced mobility [2]. With the adoption of CAS3, both the prone to flooding areas and surface water level are reduced. Consequently, the number of infrastructures potentially affected and the recovery times diminished, and most of the previous affected services/infrastructures are no longer at risk of failure.

Considering that flooding impacts on the analysed services/infrastructures, it is important to highlight that most of the affected services do not produce strong cascade effects, and the citizens are mainly affected due to mobility restrictions. Given the importance of the electricity distribution in cities, it was expected that flooding events would trigger stronger cascade effects due to power failures. The analysis focused on the substation level, the assets that are most vulnerable to flooding. However, due to past occurrences, the power distribution company (EDP D) has adopted measures to decrease its assets vulnerability to flooding. Nowadays, this service is highly redundant, and electricity distribution is strongly ensured.

Additionally, the application of Hazur® methodology has suggested that, although service providers are aware of the existing interdependencies with other services, they typically do not allocate the resources and time into studying and deepening these relations, and collaborative emergency and response protocols are not always encouraged. Moreover, the resilience assessment has highlighted the need to assume sectoral failures and to combine institutional efforts in order to minimize cascade effects and its impacts to the citizens.

The implementation of the Hazur® methodology was performed under the RESCCUE project, meaning that the analysis performed in this study is limited by the project scope, namely in what regard services and infrastructures are analysed, geographical extent (herein focused on a critical area of the city), disruptive events considered (flooding, in the case), resilience assessment metrics (in this case based on the study of interdependencies and recovery times), and timeframe.

5. Final Remarks

Given the increasing pressures on cities, investment in assessing and improving urban resilience is key to ensure continuity and quality in services provision and citizens well-being. Climate change increases these pressures and requires city managers and basic services providers to embrace adaptation strategies and to implement specific measures to overcome the foreseen aggravation of climate-related hazards, on a race against time.

The RESCCUE project proposes a multi-level roadmap centred on the Hazur® methodology that allows us to integrate crucial, detailed, and scientific information, from climate change projections, sectorial models, risk analysis, and adaptation strategies. RESCCUE proposes a more understandable and clear methodology for stakeholders and decision-makers, allowing us to understand the reaction of the city as a system of systems, and to deal with the greatest issues effectively. Regarding urban flooding, it mainly affects services provided directly to citizens, resulting in a loss of comfort and safety for them. Additionally, although not part of the analysis carried out, it is important to take in consideration the impact of flooding on buildings, especially on their ground floor uses, which can be dominated by shops and other services, resulting in economic losses, namely damage to equipment and stocks.

The approach followed by Lisbon research site, considering Hazur® methodology, demonstrated the usefulness and potential of adopting this multisectoral and cross-functional method. The implementation of this approach with as much stakeholders involvement as possible was considered a crucial point by the Portuguese RESCCUE team, since it has arisen critical issues and fostered dialogue between them, which might endure beyond the RESCCUE timeline and, ultimately, will lead to a more sustainable management of water-cycle related hazards. The main goal is to ensure that the city and services are able to maintain its essential functions, identity, and structure, whilst preserving the capacity for adaptation, learning, and transformation. For this reason, the involvement of the city council is key to reach not only a successful resilience assessment, but also to integrate and enforce resilience-related goals in the local management and action plans. In addition, a resilience-based approach makes it possible to set up contact points between such plans, often decentralised. Only by assuring multisectoral cooperation among the managing entities of the city and increasing inter-institutional synergies (both at public/government and private levels) will the cities have an opportunity to ensure a safe, resilient, and sustainable environment for all.

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