

Article

Local-Scale Assessment of Urban Resilience and the Role of Nature-Based Solutions and Stormwater Modelling

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Abstract

Although urban resilience is a complex concept, several initiatives have made it more tangible. Urban public authorities and policymakers are of utmost importance, as they influence multiple neighbourhoods, stakeholders and aspects of urban resilience. Nevertheless, the role of individual facilities—such as sports fields—should not be overlooked. While their impacts are smaller in scale, they can significantly enhance local resilience and serve as inspirational pilots for broader initiatives. To assess resilience at the facility scale, an existing assessment framework was adapted, aligned with ESG (environmental, social and governance) criteria and climate action pillars and valuing ecosystem services. In the sports field case study, stormwater was reframed from a burden into a resource and integrated with other scheduled resilience-enhancing interventions: water conservation, installation of photovoltaic panels, enhanced tree shading, and circularity through sports equipment reuse. Together, these interventions strengthen urban sustainability, resilience, and climate adaptation while delivering ecological and social benefits. The stormwater drainage system was modelled to simulate naturalization actions. The assessment framework is described, and its application at both neighbourhood and facility scales is discussed. Comparisons between the existing and improved situations show clear resilience gains, and opportunities for extending these measures to the city scale are explored.

Keywords: drainage; ecosystem services; flooding; Lisboa; neighbourhood; resilience assessment framework (RAF); upscaling



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1. Introduction

1.1. Urban Resilience

Although urban resilience is complex and multi-dimensional, various initiatives sought to make the concept more tangible to academia, policymakers, managers, and citizens. The concept has evolved from the ability to return to a previous state after disturbance, to the capacity to absorb shocks while maintaining core functions, and finally to a social view of disturbances as opportunities for renewal and adaptation [1–3]. In urban contexts, a set of systems ensures the essential societal functions. Public authorities, policymakers and utilities managers are particularly relevant as their decisions about these systems shape the resilience of multiple neighbourhoods, guiding resource allocation and

affecting the city's social, economic, and environmental dimensions. Their strategies often determine how urban systems respond to shocks and stresses, from climate-related hazards to social and economic disruptions. At the same time, the contribution of neighbourhoods or individual facilities—e.g., educational campuses, healthcare facilities, or sports complexes—should not be underestimated. While with smaller scope, targeted measures enhance local resilience, such as energy efficiency, water management, emergency preparedness, or community engagement. Importantly, they can function as demonstrators or pilot projects, displaying innovative approaches that can be scaled up or replicated across neighbourhoods, districts, or the wider metropolitan area. By fostering experimentation and generating concrete results, these smaller-scale initiatives bridge policy and practice and promote effective innovation, providing a bottom-up complement to top-down resilience planning [4].

Urban environmental resilience is strongly water-related. In Europe, recognizing water as a basic need and a critical resource, the European Water Resilience Strategy aims to make water systems secure, sustainable, and resilient, balancing environmental protection, public health, social equity, and economic competitiveness amid pressures like climate change (CC), pollution, droughts, floods, and overuse [5]. In line with the revised European Directive on Urban Wastewater Treatment [6], major efforts will focus on controlling polluted discharges. For larger agglomerations, discharges must not exceed 2% of the annual wastewater load, alongside objectives like integrated wastewater planning, rainwater harvesting, and implementation of nature-based solutions (NBSs). Therefore, to meet these guidelines, efficient water use, water and energy savings, safe water reuse and adequate stormwater source control are required. In this context, appropriate stormwater management plays an essential role for sustainable and climate-resilient cities by handling rainfall and runoff while protecting people, property, and the environment and by supporting long-term ecological balance, urban liveability, and climate adaptation. Current stormwater management faces multiple challenges, including flood control, water quality and pollution management, water reuse, urban climate adaptation, groundwater recharge, and support to ecosystems and biodiversity.

Another CC concern relates to heatwaves, which have significant impact on cities, as temperatures tend to be higher than in surrounding areas due to the urban heat island effect [7]. This hazard affects human health, agriculture, energy, wildfire risk, and infrastructure. In the next decades, the frequency, intensity, duration, and spatial extent of heatwaves are expected to increase in Europe, with the highest values in central and southern regions [8,9]. Urban environments that do not consider adaptive design aggravate liveability challenges during extreme heat conditions [4]. Regarding the greenhouse effect, the European Climate Law [10] sets a binding target of at least 55% net greenhouse gas (GHG) reduction by 2030 (baseline 1990) and a legal framework for climate neutrality by 2050. The Energy Efficiency Directive [11] mandates reducing and using energy more efficiently. Renewable energy technologies are recognized as relevant contributors.

Resilience assessment systems have been developed and applied, and a recent review is presented in [12,13].

1.2. Relevance of NBSs for Resilience

Natural spaces are vital for CC mitigation and adaptation. They include large reserves, forests, dunes, urban parks, or NBSs, like infiltration basins or green roofs and walls, which mimic natural processes to address environmental, social, and health issues [14]. Beyond their targeted functions (from an engineering or urbanistic perspective), NBSs provide ecosystem services—such as providing food and water, regulating extreme weather events and erosion, improving air quality, supporting biodiversity and cultural

services [15]—crucial for achieving 2030 goals for CC [16]. Even in dense urban areas, NBSs can provide these several ecosystem services (ESs), being essential for the resilience of socially vulnerable groups who are often more exposed to CC impacts [17] and to green gentrification. Natural areas enhance urban sustainability and climate resilience by improving preparedness, reducing exposure and vulnerability to extremes (e.g., wind gusts, peak flows, water volumes), providing resource autonomy and redundancy (e.g., urban farming, stormwater reuse), and mitigating CC (e.g., carbon sequestration, urban heat island reduction). Specific NBSs contribute to enhance resilience at different scales (e.g., urban, city, neighbourhood, building) and sectors (e.g., education, transportation, health, tourism) [18,19].

Resilience and sustainability matter at multiple scales. ESG criteria (environmental, social, governance) assess sustainability, ethics, and long-term resilience, being quite relevant at company and organization scales [20]. Environmentally, key aspects include GHG emissions, energy efficiency, waste and pollution control, water and land use, and biodiversity protection. From a social perspective, considerations involve relationships with communities and employees (health and safety, diversity and inclusion, human rights, and labour conditions). Governance focuses on transparency, accountability, and ethical practices. The ESG criteria strongly relate to resilience: environmental sustainability strengthens physical resilience by reducing GHG emissions, protecting ecosystems, and providing buffers against climate impacts; social responsibility builds community resilience; and good governance ensures transparent and accountable decision-making, contributing to institutional resilience.

Sustainability is also a European Union priority, reflected in regulations like the Nature Restoration Law [21] and the European Taxonomy regulation [20]. The latter defines sustainable economic activities as those that substantially advance one or more environmental objectives (climate, water, circularity, pollution, biodiversity) without significantly harming others (DNSH principle—Do No Significant Harm), for example, planting native trees while avoiding invasive species. The Nature Restoration Law calls on Member States to maintain current urban green space per capita levels by 2030 and promote urban naturalization (ecological corridors, green roofs, NBSs).

Ecological restoration [22] emerges as a major contribution to enhance sustainability and resilience by protecting (preventing further degradation), mitigating (reducing unavoidable impacts), remediating (eliminating or neutralizing contaminants), rehabilitating (partially restoring ecological functions) or completely restoring ecosystems (maximum recovery of structure and function). Action at any stage or scale of ecological restoration enhances environmental outcomes and resilience. Increased biodiversity strengthens ecosystems against pests, diseases, and climate change. Restoring ecological processes reactivates natural cycles (water, nutrients, carbon), boosts self-regulation, and reduces reliance on external inputs. Restored areas are less vulnerable to erosion, runoff, desertification, and overuse, while native vegetation improves infiltration, protects soils, and stabilizes the microclimate. The European Union Biodiversity Strategy for 2030 [14] also highlights the roles of neighbourhood and local scales—cities above 20,000 inhabitants should have urban biodiversity plans by 2030, promote green roofs and walls, urban ecological corridors, and accessible and restored natural spaces.

1.3. City and Local Scales

Traditionally, decarbonization and adaptation practices in cities are carried out on a project-by-project basis, usually described in climate action plans. The transition to a strategic approach is therefore essential, anchored in robust projects linked to the development of supporting policies [23]. This approach involves identifying the barriers hindering

appropriate solutions and addressing them across different levels and sectors, integrating stakeholders to create an enabling environment for climate neutrality [24].

Cities must rethink how all urban systems (e.g., urban water cycle and waste management, mobility, buildings, and the natural environment) can contribute to reducing emissions and enhancing climate resilience. At the same time, citizens and other stakeholders (e.g., already-mentioned educational campuses, healthcare facilities, or sports complexes) interact with these systems, actively building the city's resilience through their daily decisions and behaviours and conditioning their carbon footprint. Effective governance and engagement of civil society, businesses, and local, metropolitan, regional and national authorities are essential for achieving the EU targets [4]. Given the complexity of urban interactions, technology alone cannot achieve neutrality. Updated urban planning and social innovation are also crucial for improving quality of life. This approach links to multiple socio-environmental benefits, especially at the neighbourhood level. Focusing on piloting and prototyping in neighbourhoods leverages their role in problem-solving, attracting investment, and driving climate innovation, providing insights for potential city-wide implementation [25] while also benefiting from broader city initiatives, like mobility management and stakeholder agreements.

To support cities' socio-technical transitions toward climate neutrality, the 5UP vision-driven, strategy-based approach was developed to create connected, compact, net-zero neighbourhoods and has been applied in eleven cities [4]. Its thematic pillars [25] are carbon neutrality—reducing GHG, namely CO₂ emissions; climate resilience—enhancing cities' capacity to respond, adapt, or transform under climate change; and just transition—reducing socio-economic vulnerability during urban transformation.

This innovative approach combines prototyping at selected neighbourhoods (upgrading step) with city-wide impact through aligned governance arrangements, financial resources, and project portfolios (upscaling step). Upgrading enables innovative implementations of a variety of methods and tools [26]. For example, for resilience assessment, the RAF—Resilience Assessment Framework [12,27]—usually applied at city-wide levels, can be tailored for neighbourhood or facility scales to identify local resilience, evaluate the effect of local actions, and estimate potential city-wide impact if scaled.

Additional methods, such as urban drainage modelling, can further enhance these local assessments. By replicating real or hypothetical conditions of a system, mathematical modelling of urban drainage systems simulates its performance under operational day-to-day conditions or under stress conditions, contributing to assessing resilience and identifying improvement needs. Such models calculate the catchments' surface runoff and simulate water flow through pipes, channels, or operational devices, outputting velocity, water level and flood occurrences. This type of model shows where and when flooding or system failures are most likely under different rainfall or climate-related scenarios, revealing capacity bottlenecks and providing information to exposure and vulnerability assessments. They also constitute a valuable tool to test and inform systems' adaptive and recovery capacities by simulating solutions such as green infrastructure, permeable surfaces, larger pipes, or retention basins [28]. This applies at any scale, such as the facility, neighbourhood, city, metropolitan area, or regional scale. However, it is important to note that in very small urban catchments, uncertainty in input data—ranging from sewer parameterization to local soil parameters—can propagate and influence model outputs [29,30].

This paper's objective is to assess resilience at the neighbourhood and facility scales and align it with climate action concerns. Specifically, the paper presents an innovative downscaling application of the RAF [12,27], applied at broader scales up to now (e.g., cities, metropolitan areas or regions), while addressing the mentioned thematic pillars of climate action of the UP2030 project—carbon neutrality, climate resilience and just transition [25].

A case study of a Portuguese neighbourhood and a sports facility allowed for testing the application at these scales, both to assess the initial resilience and the contributions of planned interventions, such as water conservation (water saving, rainwater harvesting), solar panels, tree planting, and sports equipment reuse. Given the importance of urban water management, an urban drainage model was developed for the sports facility. It was used to simulate naturalization options and water reuse, delivering information for the assessment. The application of the RAF and further assessment of ESG criteria and ecosystem services revealed potential benefits and opportunities to upscale these measures, from the facility to the neighbourhood and city scales.

2. Materials and Methods

2.1. Overall Approach

The context behind the proposed methodology and the steps taken to implement it are shown in Figure 1, aiming to downscale the RAF to the local level (neighbourhood and facility scale) and provide inputs to the city scale. One software package is used, SWMM (Storm Water Management Model, SWMM, v5.2; [31,32]).

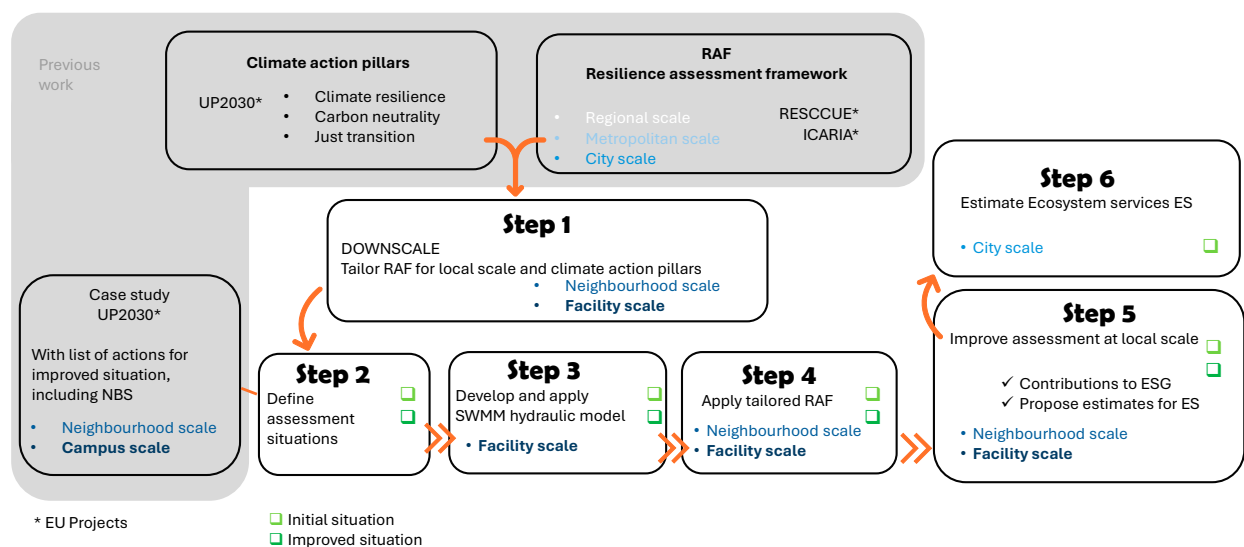


Figure 1. Overall step-by-step approach: previous work, development activities, spatial scales, and assessment situations.

In Figure 1, a grey background highlights prior activities—namely, identification of climate action pillars, existing applications of the RAF from city to regional scales, and case study development. Steps developed herein include the following:

- Step 1: tailor the RAF to local scale and climate action pillars;
- Step 2: define the initial and improved situations;
- Step 3: develop and apply the stormwater system model in SWMM;
- Step 4: apply the tailored RAF to the initial and improved situations;
- Step 5: improve assessment at the local scale: identifying contributions to ESG criteria and estimating specific ecosystem services;
- Step 6: estimate ecosystem services at the city scale.

Most steps (1, 2, 4, and 5) were applied at both neighbourhood and facility scales, while Step 3 targeted only the facility scale. Step 6, however, was applied exclusively at the city scale to upscale the results, thereby completing the cycle of downscaling from city to local and upscaling back. Two assessments were considered, initial and improved situations (except for Step 6).

2.2. Case Study

Lisbon aims to become a sustainable, resilient, inclusive, and climate-neutral city by 2030, reinforcing its climate leadership at European and global levels. This vision is outlined in the Lisbon Climate City Contract 2030 [33]. Lisbon is also one of eight European cities in the UP2030 project, whose objectives align fully with this vision. At the city scale, Lisbon is actively enhancing multi-functional public spaces, promoting healthier lifestyles, and advancing climate neutrality goals. Over the past decade, numerous trees and horticultural parks, playgrounds and seating areas were added. A key challenge is measuring interventions benefits when expanding green and blue infrastructure while reclaiming space from cars.

Following the 5UP approach, the Alvalade neighbourhood is the UP2030 Lisbon pilot. With 30,000 inhabitants in 230 ha, it is a landmark mid-20th-century Portuguese urban project. The original layout has eight blocks and a hierarchy of roads interwoven with public spaces. Pedestrian and cycle paths cross the blocks, providing efficient mobility. Each block centres on key amenities—a school, a market, a church—and includes other facilities like large open spaces, university and research campuses, cinemas, and sports areas, serving residents, workers and tourists. However, Alvalade faces significant climate, social and cultural vulnerabilities. Climate concerns include risk of flooding, wildfires, and extreme heat. Resistance to change, low engagement, and inequalities that hinder participation are some social barriers. Alvalade is planning for extended improvement measures focused on various facilities open to the public.

The São Miguel Rugby Club (CRSM, acronym in Portuguese) (Figure 2) is a neighbourhood pillar and one of the four facilities with planned or implemented actions in the Alvalade pilot. The Alvalade neighbourhood and the CRSM facility form the case study analyzed herein.



Figure 2. Case study location (adapted from [34]).

Generally, the actions carried out at the Alvalade neighbourhood scale focus on improving knowledge and information on energy and water efficiency, mobility, circularity and waste, the environment, NBSs, and social inclusion and justice.

CRSM is a sports organization that has been promoting rugby and other sports since 1970. It has long been a reference in the training and development of Portuguese rugby, focusing on youth and low-income communities. The club has about 330 athletes and offers weekly training for local primary school students. Social events throughout the year attract and impact a wider community. Covering 2.17 ha, it includes a rugby field,

two football fields, unpaved grounds, spectator stands, flowerbeds, some tree beds and other vegetation. Buildings feature changing and physiotherapy rooms, laundry, a guest house, and a restaurant [35].

Today the campus is mostly impermeable, with paved car routes and parking spaces and synthetic grass sports fields. Spectator stands are uncovered, and unpaved ground is compact and left unattended.

Opportunities for community engagement, resources use and naturalization actions, with several social, well-being and environmental co-benefits, are considered in the planned measures for the coming years in CRSM (Table 1), which are to be assessed in the project's improved situation (Step 2, Figure 1).

Table 1. Planned improvement measures in the case study.

Measure	Actions
Increase water and energy efficiency	- Continuous monitoring of water and electricity consumption - Retrofitting lighting systems to LED - Installing water-saving devices on showers and taps - Using alternative water sources for irrigation (water reuse and rainwater use) - Assessing solar energy production potential - installing photovoltaic system - Obtaining the Climate Ready certification (B-WaterSmart project) - Using digital tools (B-WaterSmart project) aimed at smart urban water allocation (fit-for-purpose), safe reuse and efficiency, and the quantitative and qualitative matching of water supply to demand
Improve climate resilience	- Naturalizing water cycle: enhance hydrological functions (e.g., infiltration, retention), store rainwater for local uses, reduce peak outflows to public drainage system - Planting more trees: improve shadowing, carbon sequestration, evapotranspiration, and water infiltration; provide shelter and food for birds and insects; restore derelict areas; provide natural space for cultural activities, health and well-being
Adopt a circular mindset	- Reusing sports equipment - Implementing waste separation (paper, glass, plastic and metal) - Composting
Promote soft mobility	- Installing one of the city's public bicycle-sharing station in front of the facility - Installing an electric car-charging station
Engage stakeholders with climate neutrality	- Adopting the city's Climate Neutrality 2030 Factsheet, characterizing actions that shape the climate neutrality pathway - Committing to the city's action on carbon neutrality - Participating in adaptation and inclusion actions
Implement sustainable events	- Adhering to the city's guidelines on sustainable events (e.g., eliminating plastic bottles, paper flyers) - Implementing actions for awareness and more inclusive community (e.g., solidarity actions and awareness-raising activities at festivals and championships)

2.3. Resilience Assessment

Resilience assessment exploited the RAF framework from the European projects H2020 RESCCUE (<https://toolkit.resccue.eu/>, (accessed on 27 February 2026) focused on city and key strategic urban services [12], and HE ICARIA (<https://icaria.lnec.pt/accounts/login/>, accessed on 27 February 2026), expanding to regional assessment and natural areas as a service [27]. The RAF app is its freely available tool, enabling resilience

assessment to CC with particular focus on the urban water cycle and interdependences among services (water supply, wastewater, stormwater and waste management, electrical energy distribution, mobility, and natural areas). Assessment has a tree structure through resilience Objectives–Criteria–Metrics, covering all resilience capacities and governance, environmental, social, technical, and economic aspects, presenting strong alignment with the UP2030 pillars, and covering ecosystem services [15] and concerns of ESG criteria [14] and UWWTD [6]. With more than 700 metrics, each metric offers a set of answers, scored 0–3, assigning a resilience development level: incipient (<1), progressing (1–2) or advanced (2–3). Intuitive graphs support result interpretation.

Resilience assessment was grounded in the previously described framework and implemented through a sequence of methodological steps, as illustrated in Figure 1 (presented above). The local-scale RAF application is innovative (Step 1, Figure 1). Metrics were analyzed for applicability and relevance at both neighbourhood and facility scales and for alignment with UP2030 pillars—carbon neutrality, climate resilience, just transition, determined for sub-city scales.

Resilience was assessed for the initial and improved situations at both scales (Step 4, Figure 1). Information related to solutions is presented in Table 1; some data is provided from mathematical modelling (Step 3, Figure 1).

For the selected metrics, contributions to ESG criteria (environmental, social and governance—closely related to the facility scale) were identified, along with those enabling ES quantification (Step 5, Figure 1), important for recognition of upscaling NBS effects. Required data for ES metrics were analyzed against Lisbon GIS open data, with the minimum necessary date identified. This information was collected, for each neighbourhood, from GIS data and local inputs (Step 6, Figure 1).

Metric selection and determination were conducted in collaboration with local stakeholders.

2.4. Stormwater Drainage Modelling

At the facility scale, a mathematical model was developed using the Storm Water Management Model (SWMM, v5.2; [31,32]) to simulate the stormwater drainage. Metrics were proposed and calculated (Step 3, Figure 1), informing on the system behaviour for different situations and facilitating comparisons. SWMM was applied to CRSM's drainage system to assess both the initial and improved situations. The model simulates runoff generation, conveyance, and temporary storage across CRSM and adjacent paved areas, reflecting real geometry and topography. The dynamic wave method was used for runoff routing to capture pressurized flow and backwater effects. Variable computational stepping was used with no ponding allowed.

Due to the absence of sewer hydraulic data, the model could not be calibrated or validated. Adequacy was checked by keeping computational continuity errors below 1%, with some simulations using a 2 min timestep.

Precipitation records from the nearby Gago Coutinho station (Portuguese Institute for Sea and Atmosphere IPMA) were available in the utility for the 1998–2022 period at 10 min intervals. From a series of rain events with return periods from below 2 to 100 years that had been characterized by Lisbon Municipality (CML), five were modelled, from moderate to extreme, in a range of intensities and return periods (Table 2).

The model used the Green–Ampt method for infiltration with site-specific parameters per sub-catchment (e.g., saturated hydraulic conductivity, suction head, initial moisture deficit), based on field observations and the literature for compacted sports-field soils [31].

Table 2. Modelled rain events (CML data).

Event	Date	Duration	Return Period (Years)	Total Precipitation (mm)	Maximum Precipitation Intensity (mm/h)
P1	7 December 2022 00:00–8 December 2022 23:50	47 h 50 min	100	58.9	73.8
P2	29 October 2010 00:00–30 October 2010 02:10	26 h 10 min	50	30.9	41.4
P3	13 October 2014 00:00–14 October 2014 02:30	26 h 30 min	20	23.8	75.6
P4	26 November 2014 00:00–27 November 2014 01:30	25 h 30 min	10	16.5	49.2
P5	6 April 2020 00:00–7 April 2020 07:00	31 h 00 min	<2	20.20	32.4

Key model components—sub-catchments, junctions, conduits, storage units, and streets—were parameterized by area, slope, width, imperviousness, and roughness from surveys and design specifications. Hydraulic elements were characterized by their lengths, diameters, elevations, and materials. Streets and inlets were included to capture overland–underground flow interactions.

To represent this complexity—stormwater across courts, flowerbeds, unpaved grounds, stands, tree beds and other vegetation, along with sewer channelled flow—multiple SWMM components and special devices were used, as follows:

- Sub-catchments: Drainage basins, some with LID controls (vegetated swales or bioretention cells to represent flower and tree beds). Each one links to a rain gauge, for rain event representation, allowing for simulation of runoff to downstream nodes or other basins. SWMM computes subsequent hydrologic processes (infiltration, evapotranspiration, surface accumulation, and flow conveyance).
- Nodes: Junctions and outfall, including normal (with surface exchange allowed) and sealed manholes (auxiliary nodes when connections occur at intermediate sewer sections, with overflow restrained by high internal pressure thresholds).
- Links: Conduits between nodes to compute sewer hydraulics. Variables such as manhole depths were estimated when registry data was missing.
- Streets and inlets: Route surface runoff to conduits and simulate surcharge or bypass. Specific basins were associated to streets, the runoff of which is captured by inlets to the conduits or bypasses it to the streets if inlet capacity is exceeded. Different street cross-sections were defined.

Flow propagation through the drainage network enables dynamic calculation of discharge, water depth, flow velocity, and potential flooding along the simulation period for each element of the system. Outputs were extracted at key junctions and storage units, including hydrographs (flow and depth), cumulative runoff and infiltration volumes, storage use, and surcharge/flooding frequency.

Some units can enable water storage or retention, such as sports fields or flowerbeds, while others can overflow to the surface, such as manholes. An intervention aimed at increasing the perviousness of sports fields is envisaged, consisting of a multilayered

system with subsurface drainage conveyed to a perforated pipe. This design is intended to enhance infiltration capacity, prevent soil compaction, and ensure the long-term persistence of hydraulic conductivity. Within SWMM, explicit representation of this solution would require specification of multiple hydraulic and soil parameters [36]. Therefore, a simplified modelling approach was adopted, whereby the intervention was represented by reducing the percentage of impervious area.

Assessing each model shows each unit's effectiveness. Comparing the models for the two situations (initial and improved) highlights the overall impact of improvement measures, both on CRSM system performance and on the public stormwater sewer along Av. Brasil, outside the campus. Additionally, this analysis supports CRSM overall resilience assessment, providing information to the RAF. These results will input resilience metrics, i.e., the exact numerical output of the model (e.g., 5 manholes were flooded) is subsequently mapped to predefined categorical ranges (e.g., less than 10 or between 10 and 20 manholes) for decision-making purposes.

The defined metrics (Table 3) regard water storage, volume retention, overloaded nodes and conduits, and downstream peak flow and runoff volume (detailed in the Supplementary Material, Table S4), affecting the public system.

Table 3. Metrics using SWMM model information.

Perspective	Model A: Initial Situation	Model B: Improved Situation with NBSs
Unit effectiveness	Storage capacity (%) Volume retention (%)	NBS Storage capacity (%) NBS Volume retention (%)
CRSM stormwater drainage performance		Variation in surcharged nodes (%) Variation in flooded volume (%) Variation in surcharged pipes (%)
Av. Brasil public sewer performance		Reduction in output flow peak Reduction in output flow volume

3. Results

3.1. Resilience Assessment Metrics for Local Scale

For resilience assessment at the local scale (Step 1, Figure 1), the metrics in Table 4 were selected from the whole RAF to assess the facility and neighbourhood as per UP2030 pillars. The alignment with each pillar is provided. The metrics contributing to the facility's alignment to ESG criteria and enabling quantification of ecosystem services are also identified (Step 5, Figure 1). The Supplementary Material (Table S1) describes each metric, regarding the question and set of possible answers.

Table 4. RAF resilience assessment metrics applicable at local scales (F: facility, N: neighbourhood) with alignment with UP2030 pillars (C: carbon neutrality, R: climate resilience; J: just transition), contributing to facility ESG criteria (E: environmental; S: social; G: governance; -: none) and quantification of ESs (Y: yes; -: N: no).

Resilience Metrics	Scale	Alignments		
		UP2030	ESG	ES
Co-ordination with other government bodies	N	R	-	-
Multi-stakeholder collaboration	F, N	J	G, S	-
Collaboration mechanisms	F, N	J	G, S	-
Status when addressing contribution to climate change	N	C	-	-

Table 4. *Cont.*

Resilience Metrics	Scale	Alignments		
		UP2030	ESG	ES
Design solutions that increase resilience	N	R	-	-
Implemented design solutions to increase resilience	F, N	R	E	-
Mitigation of perceived social detrimental effects of natural areas	N	J	-	-
Use of design solutions to improve the resilience of the area	F, N	R, C	E	-
Other contributions to city resilience	F, N	R	E	-
Infrastructural measures to address CC mitigation and adaptation	F, N	R, C	E	-
Infrastructural measures to address CC mitigation and adaptation of natural areas	F, N	R, C	E	-
Integration with other neighbouring natural areas	F, N	R, J	E	-
Natural areas' autonomy from other services according to CC scenarios	F, N	R	-	-
Availability of green and blue infrastructures in the location per inhabitant	N	R, C	-	-
Ecosystem services	F, N	R, J, C	E	-
Natural areas' alignment with ecosystem services	F, N	R, J, C	E	-
Health and well-being co-benefits	F, N	J	S	-
Biodiversity enhancement	F, N	R	E	-
Undesired species	F, N	R	E	-
Aesthetical and recreational importance	F, N	J	S	-
Regeneration of abandoned areas	F, N	J	E	-
Land slide and erosion prevention	F, N	R	E	-
Temperature reduction for local climate regulation	F, N	R, J	E	Y
Air quality improvement	F, N	R, J	E	Y
Carbon sequestration and storage	F, N	C	E	Y
Groundwater recharge	F, N	R	E	-
Estimated infiltration enhancement	F, N	R	E	Y
Estimated water retention enhancement	F, N	R	E	Y
Estimated evapotranspiration improvement	F, N	R	E	Y
Water uses	F, N	R	E	-
Water sources	F, N	R	E	-
Water reuse	F, N	R	E	-
Collected stormwater uses	F, N	R	E	-
Rainwater use	F, N	R	E	-
Rainwater uses	F, N	R	E	-
Stormwater management	F, N	R	E	-
Variation in drinking water consumption	F, N	R	E	-
Flooding incidents—rainfall-related	F, N	R	E	-
Alternative energy sources	F, N	C	E	-
Energy sources	F, N	C, R	E	-
Renewable energy production	F, N	R, C	E	Y
Public transport spatial coverage	N	J	-	-
Public transport daily coverage	N	J	-	-
Alternative mobility	N	J, C	-	-
Location mobility solutions	N	J, C, R	-	-
Modal split for location road based solutions	N	R, J	-	-
Waste separation	F, N	R	E	-

3.2. Stormwater Drainage and NBS Models

3.2.1. Definition of Modelling Situations

Given the planned improvement measures for CRSM (Table 1), two assessment situations, i.e., initial and improved (Step 2, Figure 1), were modelled and simulated in SWMM:

Model A: initial situation, representing the existing drainage system;

Model B: improved situation, incorporating hydraulic improvements and NBSs aimed at increasing infiltration, attenuating peak runoff, and promoting sustainable drainage.

In Model B, the following NBSs were implemented:

- Naturalized rugby and tennis fields, enhancing infiltration capacity and storage.
- Forestated derelict western area, increasing pervious surface, interception and evapotranspiration.
- Partially forestated lower western area, improving infiltration and reducing surface runoff.
- Collected water in existing large planters as shallow storage zones for temporary retention and delayed discharge.
- Added linear tree beds above spectator stands and in the parking lot, providing distributed infiltration and increased surface roughness.
- Rehabilitated permeable pavement above spectator stands, modelled by increased pervious area and adjusted Green–Ampt parameters, for restored infiltration performance.

Specific details on the inclusion of NBSs in SWMM Model B are presented in Table 4.

3.2.2. Model Development and Results

The SWMM model was developed for both situations (Step 3, Figure 1). Figures 3 and 4 illustrate the configuration and interconnection between special devices (streets, inlets, storage units), as detailed in the Supplementary Material, Table S3.

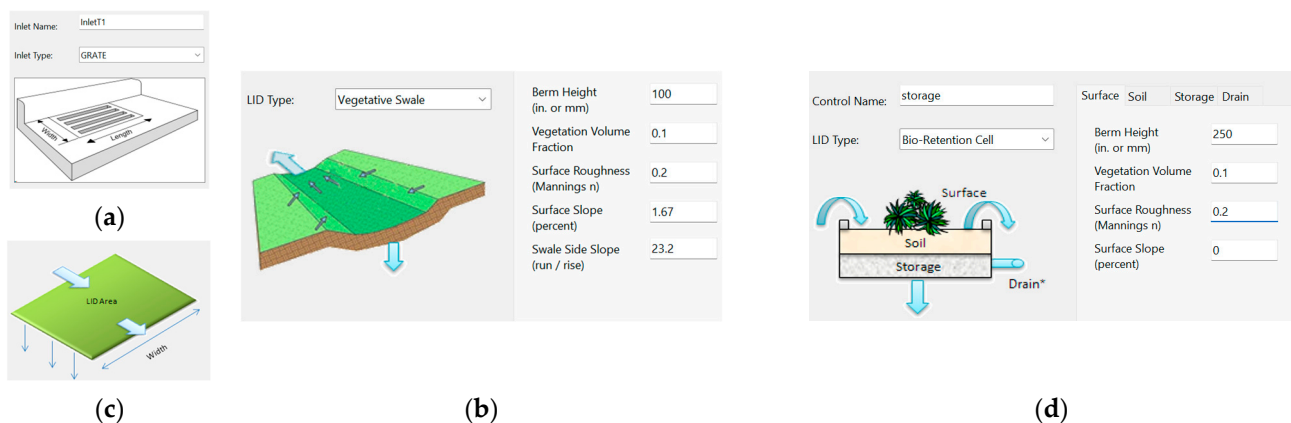


Figure 3. SWMM special device configurations: (a) inlet; (b) “storage tree” LID control; (c) vegetative swale; (d) “storage” bio-retention cell LID control [31].

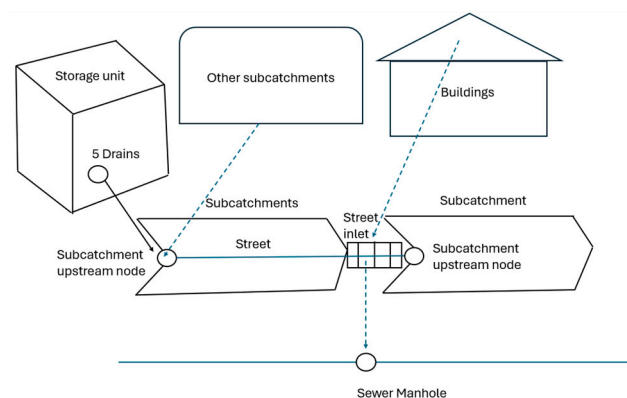


Figure 4. Interconnections defined between SWMM special devices.

The SWMM models (Figure 5) consist of 31 nodes (including the outlet), 30 conduits (9 representing streets), and 38 sub-catchments, covering 2.17 ha. A main sewer conveys

runoff from upstream of the rugby field (node 11) to the outlet outside the campus on Av. Brasil (outlet 1). Along this line, node CP9 receives inflow from two lateral sewers (CP5–CP9 and node 3–CP9), and node CP10 collects additional inflows from both sides of the field. Though not fully registered, these alignments were verified in the field. A secondary outlet, on the west side of the campus, is represented schematically by conduits between nodes 12 and 13. Node 12 collects excess runoff from the parking area, nearby streets, and the western open fields.



Figure 5. SWMM model schematic representation.

CRSM sub-catchment boundaries were mapped in GIS (Figure 6a). In Model B, NBS interventions are distributed across the campus (Figure 6b, Table 5). For example, to further increase local infiltration and distributed retention, “storage with trees” units were implemented in several sub-catchments in Model B (permeable pavement 1 and unpaved ground 1, 2 and 3). These distributed units collectively enhance the campus storage capacity, delay runoff peaks, and mitigate pressure on the downstream drainage system.



Figure 6. CRSM sub-catchments (a) and planned interventions in Model B (b).

Table 5. NBSs in initial (Model A) and improved situations (Model B).

NBS	Model A: Initial Situation	Model B: Improved Situation with NBSs
Naturalization of rugby and tennis fields, with potential for collecting infiltrated volumes	%Imperv set to 80% for both rugby and tennis fields.	%Imperv modified to 10% to simulate naturalization
Forestation of derelict western area	%Imperv set to 90% and 80% of the area (unpaved ground)	%Imperv adjusted to 20% for both cases, LID type “storage with trees” incorporated, covering 100% of the area
Partial forestation of lower western area	%Imperv set to 90% in the lower western area	%Imperv adjusted to 20%, LID type “storage with trees” incorporated, covering half the area
Collection of water in existing large planters	No water collection considered	Water collection considered
Implementation of linear tree beds above the spectator stands	%Imperv set to 80% in the area	%Imperv adjusted to 20%, LID type “storage with trees” incorporated, covering 100% of the area
Implementation of linear tree beds in the parking lot	Only the pre-existing tree-covered area was considered, occupying a small fraction of the area	LID type “storage with trees” incorporated, covering a more significant area of the parking lot
Rehabilitation of permeable pavement west to the spectator stands	%Imperv set to 80% in the area	%Imperv modified to 50%

%Imperv: SWMM parameter representing the percentage of each sub-catchment’s area considered impervious, i.e., surfaces that do not allow infiltration.

The impact of uncertainty in model parameters on resilience metrics was not significant. Simulations showed clear differences between initial and improved situations across the five rain events. Under the initial situation (Model A), the system experienced frequent surcharge and limited infiltration, especially during high-intensity events. Impermeable sports fields and limited storage caused rapid runoff and high downstream flows. In contrast, the improved configuration (Model B) improved hydraulic performance for all events. Added infiltration areas and increased storage substantially reduced runoff volumes and peak flows. Detailed information and a discussion are provided in the Supplementary Material.

A highlight is made for the runoff that decreased by 25–40% for moderate events and 15–25% for intense events (Table S4 in the Supplementary Material). Infiltration and water storage increased accordingly, confirming the effectiveness of the NBSs in Model B.

Surcharging events also decreased, with fewer overloaded conduits and flooded junctions. Maximum water depths in the main conduits remained below critical thresholds for all but the most extreme events.

Regarding the different units’ effectiveness, storage effectiveness and water retention (see Tables S4 and S5 in the Supplementary Material) varied with the rain event, as expected. Permeable pavements increased storage effectiveness from around 20% (Model A) to 50–90% (Model B). Unpaved grounds showed the largest gains (10–100%). Flowerbeds remained 100% efficient but with low retained volume (0.4%). Rugby and tennis fields improved significantly: rugby field, 20–93% effectiveness, 8–37% volume; tennis field, 20–90% effectiveness, 2–8% volume. Large open areas benefited most from NBS storage and infiltration enhancements.

During the extreme event P1 (T100), four nodes flooded (CP1, CP6, 3, 11) in Model A, while only node (11) flooded in Model B. NBSs reduced flooding, mitigated local overloading, and redistributed flows via upstream retention, delaying downstream impacts. Figure 7 shows the water profile in a surcharge event.

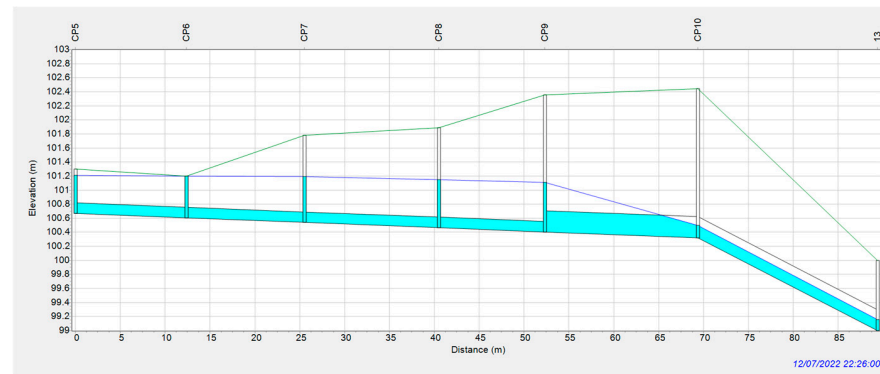


Figure 7. SWMM water elevation profile for event P1 (T100) in Model A, sewer CP5–CP10, during flooding in node CP6.

Hydrographs at critical nodes (Figure 8) show lower peak flows and delayed peak timing in the improved scenario, indicating a more gradual system response. As an example, the hydrographs for event P1 in Figure 8 show that water depth and rainfall rose almost simultaneously in Model A (Figure 8a), given a fast runoff response and limited storage capacity; in Model B (Figure 8b), the water peak was lower and occurred slightly later. NBSs attenuated the hydraulic response, spreading runoff over a longer period and reducing peaks. Figure 9 illustrates, for the same event, Model A's maximum flooding and link maximum capacity.

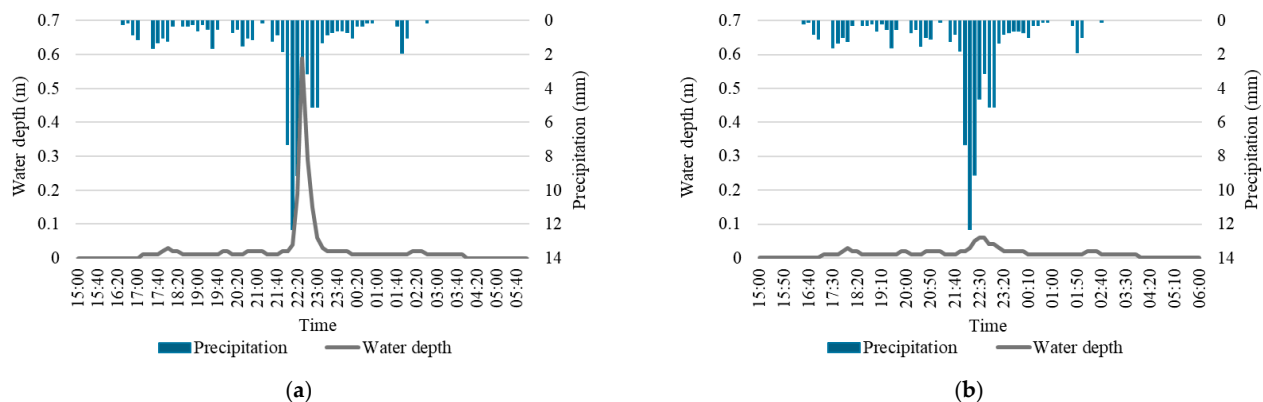


Figure 8. SWMM precipitation (event P1, T100) and water depth (node CP6): (a) Model A; (b) Model B.

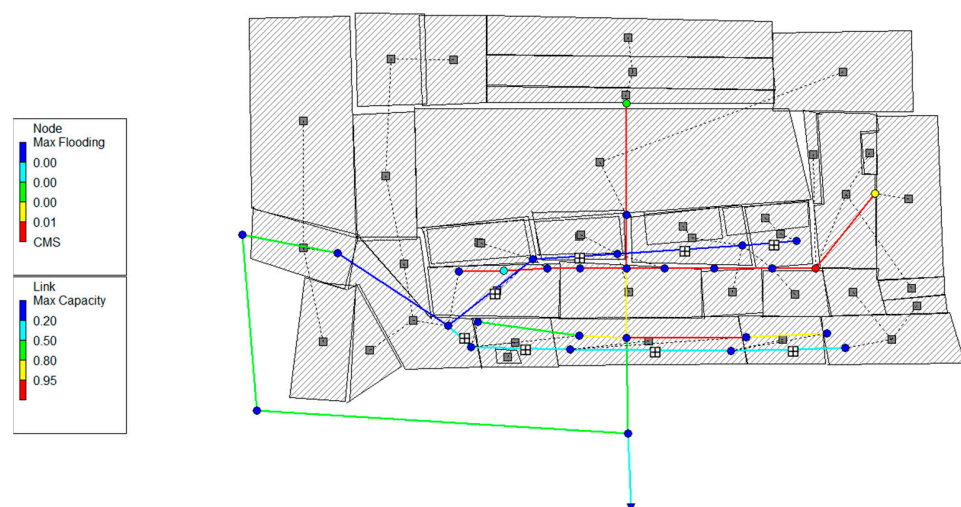


Figure 9. SWMM maximum flooding and link maximum capacity, event P1 (T100), Model A.

3.3. Resilience Assessment of the Case Study

The assessment results for the CRSM facility and Alvalade neighbourhood, for the initial and for the improved situations, are presented in Table 6 (Step 4 in Figure 1).

Table 6. Resilience assessment metrics applicable at neighbourhood and facility scales. Results for the CRSM facility and Alvalade neighbourhood for the initial and improved situations. Development level: advanced (A), progressing (P), incipient (I) or null (I₀).

Resilience Metrics	CRSM Facility *		Alvalade Neighbourhood *	
	Initial Situation	Improved Situation	Initial Situation	Improved Situation
Co-ordination with other government bodies	-	-	P	P
Multi-stakeholder collaboration	A	A	A	A
Collaboration mechanisms	I	P	A	A
Status when addressing contribution to climate change	-	-	P	P
Design solutions that increase resilience	-	-	A	A
Implemented design solutions to increase resilience	I	P	I	I
Mitigation of perceived social detrimental effects of natural areas	-	-	A	A
Use of design solutions to improve the resilience of the area	P	A	A	A
Other contributions to city resilience	A	A	A	A
Infrastructural measures to address CC mitigation and adaptation	I ₀	A	A	A
Infrastructural measures to address CC mitigation and adaptation of natural areas	I	P	A	A
Integration with other neighbouring natural areas	-	I	P	P
Natural areas' autonomy from other services according to CC scenarios	I ₀	P	P	P
Availability of green and blue infrastructures in the location, per inhabitant	-	-	A	A
Ecosystem services	I ₀	A	P	A
Natural areas' alignment with ecosystem services	I ₀	P	P	P
Health and well-being co-benefits	A	A	A	A
Biodiversity enhancement	P	P	A	A
Undesired species	P	P	P	P
Aesthetical and recreational importance	I	P	P	P
Regeneration of abandoned areas	P	A	I	I
Land slide and erosion prevention	-	-	I	I
Temperature reduction for local climate regulation	I ₀	I	I	I
Air quality improvement	I ₀	A	P	P
Carbon sequestration and storage	I ₀	P	P	P
Groundwater recharge	I ₀	A	A	A
Estimated infiltration enhancement	I ₀	P	I	I
Estimated water retention enhancement	I ₀	A	I	I
Estimated evapotranspiration improvement	I ₀	P	I	I
Water uses	I ₀	I	I ₀	I
Water sources	I ₀	A	I	A
Water reuse	I ₀	I	I ₀	I
Collected stormwater uses	I ₀	P	I ₀	I
Rainwater use	I ₀	P	I ₀	I
Rainwater uses	I ₀	A	I ₀	I
Stormwater management	I ₀	A	P	P
Variation in drinking water consumption	-	-	I	I
Flooding incidents—rainfall-related	A	A	I	I

Table 6. Cont.

Resilience Metrics	CRSM Facility *		Alvalade Neighbourhood *	
	Initial Situation	Improved Situation	Initial Situation	Improved Situation
Alternative energy sources	A	A	A	A
Energy sources	A	A	A	A
Renewable energy production	I ₀	I	I	I
Public transport spatial coverage	-	-	A	A
Public transport daily coverage	-	-	P	P
Alternative mobility	-	-	P	P
Location mobility solutions	-	-	A	A
Modal split for location road-based solutions	-	-	A	A
Waste separation	P	A	A	A

* No development (I₀) or incipient (I), progressing (P), advanced (A).

Figure 10 summarizes the assessment results for the CRSM facility (left) and the Alvalade neighbourhood (right), indicating the percentage of metrics at each resilience development level. The inner donut depicts the initial situation, and the outer donut depicts the improved one.

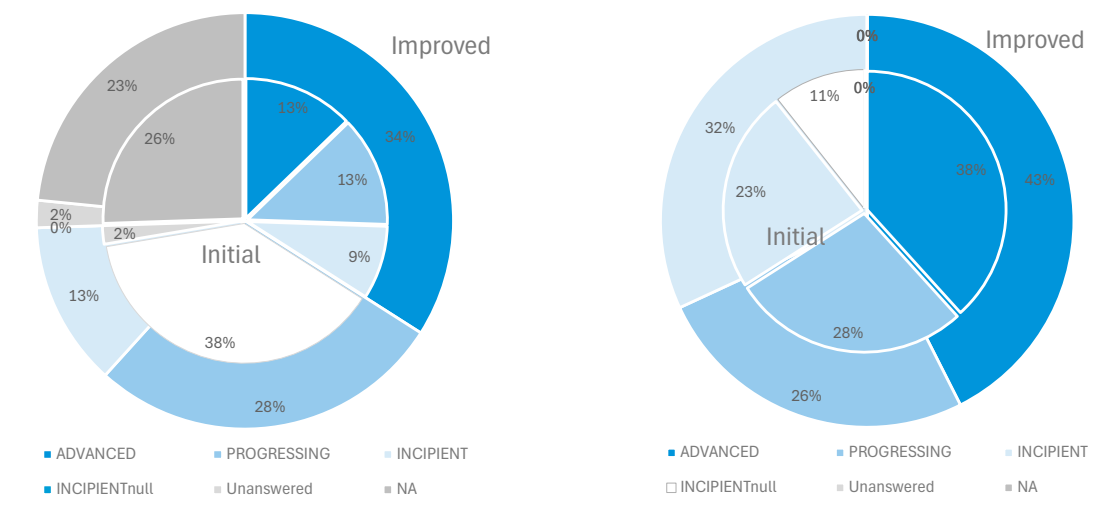


Figure 10. Resilience assessment of CRSM facility (**left**) and Alvalade neighbourhood (**right**), in initial (inner donut) and improved situations (outer donut). Percentage of metrics in each resilience development level (advanced, progressing, incipient or null).

Globally, the results in Table 3 and Figure 10 evidence a notable resilience enhancement, more evident in CRSM. Resilience enhancement is less noticeable at the neighbourhood scale for two main reasons:

- The Alvalade neighbourhood had already started its path for resilience some time ago; further advancement demands substantially greater effort to generate perceptible change; on the contrary, for locations in early resilience stages, even small efforts can lead to visible improvement.
- Many planned measures are designed for the facility scale; they can have clear effects locally, which tend to fade when viewed across the whole neighbourhood.

Overall, initially, the CRSM (Figure 10, left) has about 13% of the assessed metrics at an advanced level and another 13% in progress. There remains significant room for improvement, given that 46% of the metrics are still incipient and 38% show no action yet.

Alvalade (Figure 10, right) is already benefiting from its earlier vision for resilience. In the initial situation, about 38% of the assessed metrics are at an advanced level and 28% are progressing. However, there remains significant room for improvement, given that 23% of the metrics are still incipient and 11% show no action yet.

Regarding the alignment with UP2030 pillars, in the CRSM facility (Figure 11, left), globally, there are currently several challenges to overcome, with carbon neutrality and social justice a bit more advanced than climate resilience, where a higher percentage of aspects are still currently not covered. With the improvement measures, most of these challenges are addressed, with all aspects covered in every pillar. They are expected to be progressing or advanced for over 50% of the metrics for climate resilience and carbon neutrality and a bit lower for social justice.

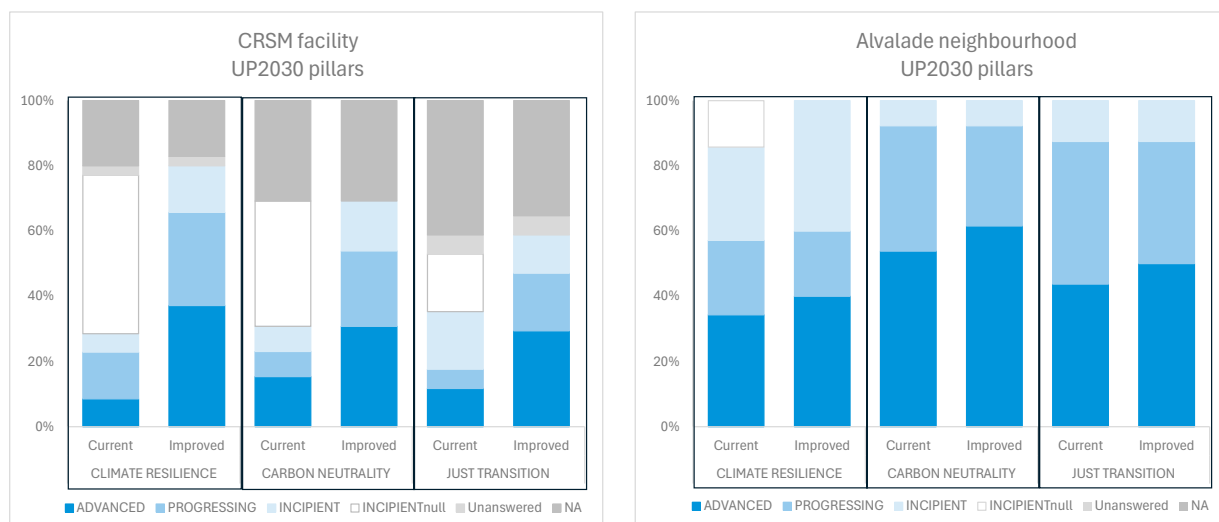


Figure 11. Resilience assessment of the CRSM facility (left) and Alvalade neighbourhood (right) per UP2030 pillar in the initial and improvement situations. Percentage of metrics in each resilience development level (advanced, progressing, incipient or null).

Regarding the alignment with UP2030 pillars in the Alvalade neighbourhood (Figure 11, right), globally, for the initial situation, carbon neutrality and social justice are more advanced or have higher progress compared to climate resilience, where a higher percentage of incipient metrics are observed, including some aspects not yet covered. With improvement measures, again, all aspects are covered, and notably, the main developments are related to climate resilience, where all relevant aspects are planned for action. Both carbon neutrality and social justice also improve and are now more advanced or show higher progress.

3.4. Improved Assessment at the Local Scale—ESG and Ecosystems Services

Regarding the contribution to ESG criteria (Step 5, Figure 1), in the CRSM facility (Figure 12, left), initially, there are several challenges to overcome in the Environmental criteria, with some actions to be taken, which clearly benefit from improvement measures. As mentioned, Social and Governance criteria are hardly represented by these metrics, yet still, improvement is noted.

The estimation of the ESs (Figure 12, right) is quite incipient in the initial situation and is undoubtedly improved with the planned measures in the CRSM facility. For Alvalade, the changes are not visually noticeable, as the development levels remain the same. However, the estimated metrics' results indicate that change has indeed occurred. By simply implementing the NBSs in the CRSM facility, a slight measurable effect on the entire Alvalade

neighbourhood was observed: temperature reduction, air quality improvement, carbon sequestration and storage, and evapotranspiration increased by more than 0.5%; infiltration rate and water retention rose by 1.8% and 4.5%, respectively. Given the complexity of these ESs, which should account for the specific species, their age and root systems, and even the season, the statistical significance of these results is marginal. While not enough to shift to a higher development level, the improvement was nonetheless discernible and indicates the potential benefits that could be achieved through broader, city-wide implementation of these measures.

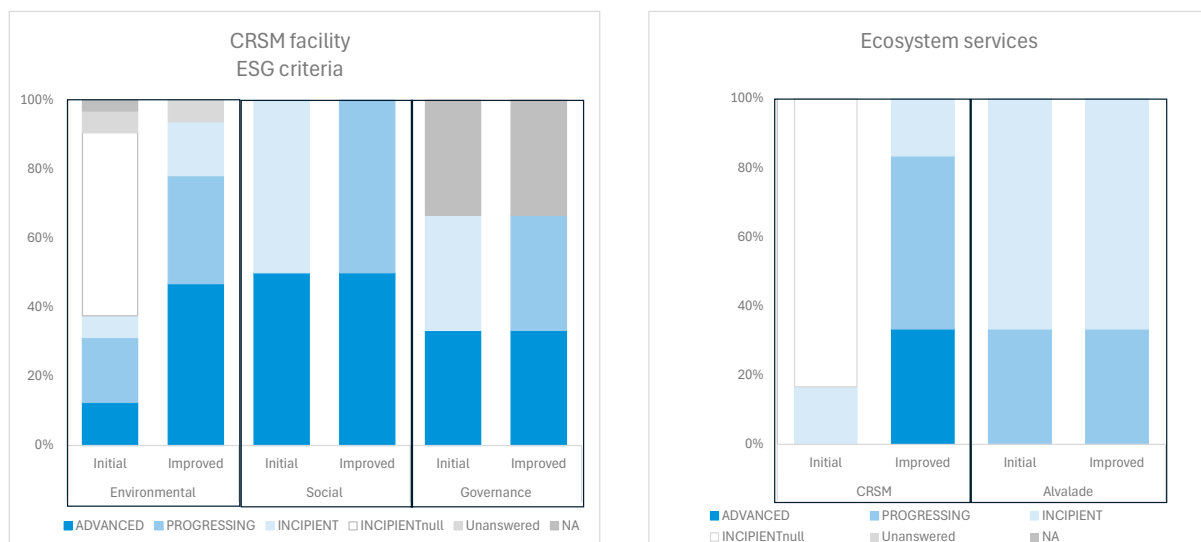


Figure 12. Assessment of the CRSM facility regarding alignment with ESG criteria (left) and quantifiable ecosystem services, ESs, of the CRSM facility and Alvalade (right) in the initial and improved situations. Percentage of metrics in each resilience development level (advanced, progressing, incipient or null).

3.5. Contribution to the Resilience Assessment Related to Ecosystem Services at the City Scale

For the city ecosystem services that can be estimated at the neighbourhood scale (Step 6, Figure 1) and using readily available data, the following green-area-related metrics (selected from those listed in Table 6) were calculated: temperature reduction for local climate regulation; air quality improvement; carbon sequestration and storage; estimated infiltration enhancement; estimated water retention enhancement; estimated evapotranspiration improvement.

The details required for calculating these metrics can be found in [27]. Diverse information is required for a more accurate estimation, regarding soil (texture, permeability, hydraulic conductivity, contents) and vegetation characteristics (vegetation cover, plant type, e.g., trees or shrubs, age, root system, canopy size and leaf area), among others.

With a lack of detailed data, estimations might be simplified based on the following: vegetation size (trees, shrubs or herbaceous cultures); green area size (below 0.25 ha; between 0.25 and 2 ha; between 2 and 8 ha; above 8 ha); and green area type of soil (percentage of sandy soils, silty sands, sandy clay loams and clayey soils). The metrics were estimated for all 24 neighbourhoods within the Lisbon municipality for the initial situation (Supplementary Material, Table S2). Table 7 presents some examples for a few neighbourhoods with some contextual information.

The results show notable differences across Lisbon's neighbourhoods, indicating where targeted measures could address ecosystem service gaps.

Table 7. Resilience metrics related to ecosystem services of green areas (estimates). Examples for distinct Lisbon neighbourhoods. Development level: advanced (**A**), progressing (**P**), incipient (**I**) or null (**I₀**).

Resilience Metrics	Lisbon's Neighbourhoods (Examples)		
	Ajuda	Misericordia	Olivaís
	High green area, Lisbon's largest park, silty sands and clays	Old town, densely urbanized; few, small, scattered green areas	Several green corridors; large trees; clayey soils
Temperature reduction for local climate regulation	A	I	P
Air quality improvement	A	I	P
Carbon sequestration and storage	A	I₀	P
Estimated infiltration enhancement	P	I₀	I₀
Estimated water retention enhancement	P	I₀	I
Estimated evapotranspiration improvement	P	I₀	I

Although biodiversity was not specifically addressed in this study, simple examples of regenerative practices, adaptable to several business and community areas, are advisable for the detailed design of the improvement measures, e.g., planting with native and climate-adapted species; reducing intensive lawns and replacing them with biodiverse meadows; applying selective pruning instead of radical cuts; or installing biodiversity islands (with shrubs, rocks, wood stumps, and wildflowers).

4. Discussion

Regarding the applicability of the assessment metrics at the local scale, all metrics in the RAF tailored for UP2030 are applicable at the neighbourhood scale, even if some are not at the facility scale. This is expected, since aspects involving broader coordination, transversal services (e.g., mobility), or metrics assessed per inhabitant are hardly addressed within a facility context, as their scope is the urban area or public services.

For those applicable at the facility scale, most contribute to understanding the facility sustainability, as in the ESG criteria, particularly in the Environmental criterion but not so much in the Social and Governance criteria. For a broader alignment to these last criteria, the full RAF must be considered.

Looking at the CRSM stormwater drainage and Av. Brasil sewer performance (Table S6, Supplementary Material), an improvement is evident with the implementation of the NBSs, where the estimated magnitude (%) of the improvement depends on the event. Namely, there was a decrease in surcharged nodes (39–69%), flooded volume (7–25%), and surcharged pipes (50–92%). For the Av. Brasil sewer, total output volume and peak flows fell (53–69%). Overall, NBSs effectively limited the flood extent and improved stormwater control even in extreme events.

In general, NBSs significantly increased both the unit's effectiveness and retained volume, particularly for permeable pavements, unpaved grounds, and large open areas like sports fields. As for the public sewer outside the facility, NBSs provided clear benefits in reducing stormwater volumes, peak flows, and stress on the sewer network. The effectiveness was highest during moderate, frequent rain events where the infrastructure fully absorbed and retained rainfall-derived runoff, while extreme events still benefited, though to a slightly lesser degree. From a broader perspective, the simulations show that green and

permeable surfaces distributed storage, and vegetation-based retention areas improved local hydrological performance while providing co-benefits such as groundwater recharge, reduction in surface temperatures, and enhancement of urban biodiversity. This reinforces the multifunctional nature of NBSs, aligning hydraulic effectiveness with environmental and social value.

Overall, the results indicate that the improved situation provides a more resilient and sustainable drainage system that is capable of handling extreme rainfall with reduced flooding risk and improved retention performance.

The modelling outcomes also emphasize the importance of combining engineered and nature-based solutions in small urban catchments. While conventional systems tend to respond rapidly and generate high flow peaks, integrating permeable surfaces and distributed storage increases the system's capacity to absorb, retain, and gradually release stormwater.

From an operational perspective, the results support the potential for enhancing existing drainage systems through targeted retrofitting rather than complete reconstruction.

However, some limitations must be acknowledged. The SWMM model, while robust and widely applied, is constrained by the input data's accuracy and by the simplified representation of infiltration and surface flow processes. Heterogeneity of soil characteristics, compaction levels, and vegetation cover introduce uncertainty in infiltration estimates. Moreover, using design or historical rain events, while representative, does not fully account for uncertainty of future climate extremes. Calibration and validation using monitoring data are therefore essential next steps to refine predictive accuracy. Complementary information is provided in the Supplementary Material (Section B).

Urban drainage modelling is a powerful tool for improving local assessments and decision by simulating system performance for diverse operating conditions or alternative intervention solutions.

Following the resilience assessment at CRSM, the set of actions planned for the facility focus on improving knowledge and information, as well as on energy and water effectiveness, mobility, circularity and waste management, nature-based solutions, environmental quality, and social inclusion and justice. After considering these, CRSM appears to be following a robust path aligned with the vision of Alvalade and the city of Lisbon. In fact, in the improved scenario, a clear boost in resilience is observed: the share of advanced metrics has almost tripled, progressing metrics have more than doubled, and all relevant aspects are being addressed.

It can be anticipated that, through the adequate replication of similar measures in other facilities within the neighbourhood, overall neighbourhood resilience would improve significantly. Notably and conversely, certain aspects presently deemed not applicable at the facility scale will nonetheless influence CRSM in the context of improvement measures. Some of these aspects—such as integration with adjacent natural areas—are essentially addressed at the neighbourhood scale. However, since the CRSM facility actively participates in local initiatives, they also affect CRSM's improvement assessment.

Following the resilience assessment at the Alvalade neighbourhood, after considering the improvement measures, Alvalade is consolidating its path, as evidenced by a 5% increase in advanced metrics and the fact that all relevant aspects show some form of action. Nevertheless, further improvement is needed, particularly concerning the 32% of incipient metrics.

It can be anticipated that if similar measures are effectively replicated across other Lisbon neighbourhoods, a significant improvement in overall city resilience could be achieved.

The RAF was herein tailored to assess neighbourhood or facility scales in alignment with a city-wide scale assessment. This innovative application demonstrated its potential to

assess local resilience, evaluate the effect of local actions, and estimate potential city-wide impact if scaled.

Considering the innovative 5UP approach, presented in Section 1.3, RAF contributes to support the upgrading at prototype neighbourhood scale with upscaling to city-wide impact through aligned assessments.

5. Conclusions

A very complete resilience assessment framework—RAF—is publicly available, yet it was designed to be applied at regional and city scales. An innovative application at local scales (facility and neighbourhood) was made, highlighting alignment with carbon neutrality, climate resilience and just transition concerns. At both local scales, evidence was obtained for the resilience aspects still lacking attention and the benefits of improvement measures. At a smaller scale, within the CRSM facility, the improvement in resilience metrics is evident. At the Alvalade scale, the impact of the CRSM enhancements is more limited, yet it still demonstrates the benefits that could emerge from expanding these measures across the entire neighbourhood. It was demonstrated that the RAF provides information on the potential for replicating these measures across other Lisbon neighbourhoods, which is likely to lead to a significant increase in overall city resilience.

At the facility scale, mathematical modelling of stormwater drainage enabled the determination of some metrics related to the drainage system and to its performance in the face of NBS measures. This application showed how comprehensive stormwater management can transform stormwater from a risk source into a resource. The results confirmed the positive impact of integrating permeable surfaces, vegetation, storage units and other green infrastructure measures in the facility. This application did not intend to model each NBS's performance in detail; in future developments, the solutions adopted by SWMM (e.g., for the sports fields) could be upgraded by including the NBS complexities.

The results and the links to the ESG, at the facility scale, evidenced how such a management approach can strengthen urban sustainability, resilience, and climate adaptation while delivering ecological benefits. Social and governance benefits were not as evident, with the RAF assessment tailored for the local scale. The alignment of the ESG and the social and governance aspects of resilience require further refinement.

At the facility scale, stormwater discharge control, rainwater harvesting, and NBS implementation, are actions that significantly contribute to compliance with the UWWTD [6]. This, aligned with the enhancement of ESs at a smaller scale, demonstrates that actions at any stage of the ecological restoration process yield positive environmental results, contributing to compliance with the EU Biodiversity Strategy to 2030 [14] and its concern with urban biodiversity plans.

Estimation of ESs was a way to show the contribution of improvements at the local scale, which was quite clear at the facility scale, and this was used for evidencing the upscaling effect of the NBS measures at the neighbourhood scale. The procedure applied is a simplification, as the available data do not provide information on the specific plant species present, their leaf size, their age, or their root system characteristics. Accurate determination of ESs would require further developments. Estimation of these metrics for all the neighbourhoods in the city provides decision-makers with a clear roadmap for deploying NBSs where they can deliver the greatest impact, aiming at specific ecosystem services, simultaneously shaping a greener and more resilient city. The CRSM facility can be taken as a good example. By applying similar approaches across the city, neighbourhoods with sports fields that can be naturalized—like public schools or football grounds—and gardens with large planters that can be raised—such as in local parks or university facilities—can significantly improve water retention. Infiltration can also be further enhanced by creating

new parks in the sandy areas of the city, while, in space-limited locations, solutions like lowered tree beds, bioretention areas, or vegetated swales can make a real difference. Beyond water management, these interventions can generate multiple effects. Depending on vegetation type, size, and canopy cover, additional co-benefits can include reduced temperature, improved air quality, and increased carbon sequestration.

In the end, the authors believe that the presented work evidences that resilience assessment at local scale is a powerful tool to bridge policy and practice, providing a bottom-up complement to top-down resilience enhancement. Building urban resilience is fostered when city-scale strategies and local initiatives are aligned and complement each other, combining broad interventions with concrete, site-scale actions that inspire communities, test new approaches, and enhance the city's overall capacity to tackle a variety of challenges for a just transition to carbon-neutral and climate-resilient cities.

Supplementary Materials: The following supporting information can be downloaded at: <https://www.mdpi.com/article/10.3390/urbansci10040198/s1>, Table S1: Resilience assessment metrics; Table S2: Ecosystem services metrics related to green areas, determined in Lisbon neighbourhoods (estimates). Development level: advanced (A), progressing (P), incipient (I) or null (I₀); Table S3: Representation of CRSM special devices in SWMM; Table S4: Metrics for SWMM models; Table S5: Unit effectiveness: storage capacity (%) | volume retention (%). SWMM results for Model A and Model B, for each unit or NBS, for rain events P1–P5; Table S6: SWMM results for variation in surcharged nodes, flooded volume and surcharged pipes and reduction in output flow volume and flow peak (%); Figure S1: SWMM water elevation profile for event P1 (T100) in Model A situation for (a) nodes CP5–CP10 before (a), during (b) and after (c) flooding in node CP6; Figure S2: SWMM water depth and precipitation results for node CP6 for event P1 (T100) in (a) Model A and (b) Model B.

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Abbreviations

The following abbreviations are used in this manuscript:

B-WaterSmart	European H2020 project, accelerating the transformation to water-smart economies and societies in coastal Europe and beyond
CC	Climate Change

CML	Lisbon Municipality (acronym in Portuguese)
CRSM	São Miguel Rugby Club (acronym in Portuguese)
ES	Ecosystem Service
ESG	Environmental, Social, and Governance criteria for sustainability
GHG	Greenhouse Gas
ICARIA	European HE project, Improving ClimAte Resilience of crItical Assets
NBS	Nature Based Solution
RAF	Resilience Assessment Framework
RESCCUE	European H2020 project, RESilience to cope with Climate Change in Urban arEas
SWMM	Storm Water Management Model, EPA
UP2030	European HE project, Urban Planning and Design Ready for 2030
UWWTD	European Directive on Urban Wastewater Treatment

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