From runoff to resilience: exploring multifunctional nature-based solutions for sustainable urban stormwater management

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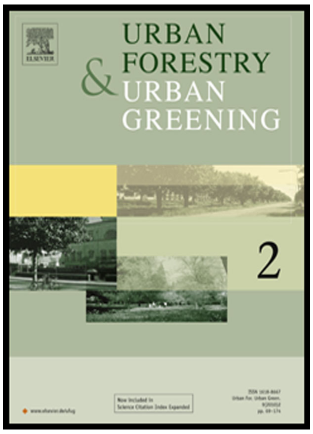

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Urban stormwater, Nature-based solutions (NbS), Social-Ecological-Technological Systems (SETS), Ecosystem Services, InVEST modeling

Abstract

Climate change and rapid urbanization intensify stormwater-related challenges in cities, particularly in compact urban environments. Traditional grey infrastructure often fails to address these risks in a flexible and adaptive manner. Nature-based solutions (NbS) offer a multifunctional and resilient complement to traditional grey infrastructure. This study presents a Social-Ecological-Technological Systems (SETS)-framed methodology for evaluating urban risks, feasibility, and the multifunctional performance of NbS at the city scale. Using a GIS-based framework, we assess NbS feasibility across social, ecological, and technological domains, simulate stormwater retention under different scenarios, and quantify co-benefits including heat mitigation, water storage, water quality, habitat provisioning, and recreation. Applied to Barcelona, the study finds that implementing NbS (including green roofs, rain gardens, urban parks, and permeable pavements) over 160 hectares in Scenario 1 (S1), aligned with the city's greening strategy, and 2,498 hectares in Scenario 2 (S2), which maximizes NbS feasibility, could reduce city-scale flood volume by up to 4.6% for T1 events, increase water storage capacity by 43%, improve habitat quality by 36%, and reduce the proportion of the population underserved by urban nature by nearly 50%, compared to the current land use and land cover (S0). While the reduction in runoff volume is moderate, especially for high-intensity storm events, our findings highlight the substantial additional value of NbS through the provisioning of co-benefits and risk reduction for vulnerable urban communities. Although the assumptions and simplifications of the numerical models used in this study may influence the results, our findings underscore the importance of integrating NbS not only as technical solutions for stormwater management but also as strategic tools for enhancing urban resilience, equity, and climate adaptation, while unlocking their transformative potential to reconfigure urban systems towards more sustainable and inclusive futures.

1 Introduction

Urban areas, where most of the global population resides, face increasing challenges due to climate change (CC) and rapid urbanization (UN DESA, 2022). Climate-related hazards threaten citizens' health and wellbeing and compromise urban infrastructure (IPCC, 2022). Cities have long relied on grey infrastructure solutions to face environmental challenges. Such infrastructure is typically designed to perform a single function, such as storing rainwater during storm events before conveying it to wastewater treatment plants (Kremer et al., 2016; Dhakal & Chevalier, 2017; Raymond et al., 2017). These systems are traditionally built to withstand known or predicted conditions (Gordon and Roudavski, 2021). However, such approaches do not always yield reliable solutions in the context of uncertainties like CC (Dong et al., 2017). CC is expected to alter precipitation and temperature patterns, thereby disrupting the hydrologic cycle (Kourtis and Tsihrintzis, 2021). In many older European and North American cities, urban drainage infrastructure was constructed under stationary climate assumptions, which limits its capacity to accommodate increasing rainfall intensities and growing climatic uncertainty (Zhou et al. 2012). Projections of intensified rainfall across multiple regions further highlight the limitations of traditional design practices in a non-stationary climate context (Bayazit, 2015; Kourtis and Tsihrintzis, 2021). In response, CC adaptation planning is increasingly shifting toward approaches that emphasize flexibility, resilience, and multifunctionality under evolving climate conditions.

Nature-Based Solutions (NbS) have emerged as a versatile and multifunctional approach to tackle pressing socio-environmental challenges, complementing existing grey urban infrastructure (McPhearson et al. 2015). According to the United Nations, NbS are defined as "*actions to protect, conserve, restore, sustainably use and manage natural or modified terrestrial, freshwater, coastal and marine ecosystems which address social, economic and environmental challenges effectively and adaptively, while simultaneously providing human well-being, ecosystem services, resilience and biodiversity benefits*" (United Nations, 2022). Compared to the concept of green infrastructure, NbS are often praised for their multifunctionality, as they encompass a broader range of co-benefits (Venkataramanan et al., 2019, Meerow 2019). A key obstacle in advancing NbS is the insufficient availability of reliable, empirical data that can quantify their co-benefits in various settings (Hanson et al., 2020). Although the theoretical advantages of NbS are widely acknowledged, there is a notable absence of uniform methods for assessing and comparing outcomes like enhanced mental health, urban heat regulation, or increased biodiversity. Gap in standardized evaluation techniques limits ability to fully understand and communicate the multifaceted value of NbS interventions (IPCC, 2022; Dunlop et al., 2024). Moreover, assessing the spatial distribution of NbS and their site-specific synergies and trade-offs at the city scale remains under-investigated (Haase et al., 2014; Kremer et al., 2016; Penning et al, 2023).

One of the ways to analyze the diverse benefits provided by NbS is through the concept of Ecosystem Services (ES). ES are the direct contributions of ecosystems to human wellbeing, for example, stormwater infiltration, flood buffering, or opportunities for recreation (Fisher et al., 2009; Cohen-Shacham et al., 2019). The spatial distribution of ES is crucial, as it determines the accessibility and availability of these benefits across urban landscapes (Fisher et al., 2009; Wolff et al. 2015). Spatial variability often results in urban areas with deficits in ES provision (Langemeyer et al., 2020), underscoring the importance of strategically planning NbS to address specific deficits while enhancing urban resilience and equity (Basnou et al., 2020; Langemeyer and Connolly, 2020).

Prior studies, such as those by Alves et al., 2024 and Camacho-Caballero et al., 2024, highlight the need for comprehensive frameworks in NbS planning that address key challenges, envision future outcomes, and assess potential impacts. At the same time, resilience-oriented planning has been criticized for relying on overly simplified assumptions about social conditions and for insufficiently engaging with the historical and socio-political processes that shape vulnerability (Weichselgartner and Kelman, 2014). As a result, such frameworks risk failing to adequately capture the complexity of interrelated actions, values, and meanings. Addressing these limitations requires breaking the sectoral barriers to infrastructure planning by integrating diverse forms of knowledge, recognizing nature's multiple values, and adopting more inclusive ecosystem management practices. Although this need has been widely recognized in theory (Paul et al., 2018; Muñoz-Erickson et al., 2017), practical approaches remain essential to overcome these limitations (Ramsey et al., 2019).

To address these challenges, an interdisciplinary approach is crucial. The Social-Ecological-Technological Systems (SETS) framework (McPhearson et al., 2016) provides a valuable basis for fostering this integration. By synthesizing insights across disciplines, SETS promote a more holistic understanding of the complex interplay between social, ecological, and technological factors, thereby enhancing the planning and application of NbS to address both environmental and community needs (Keeler et al. 2019; McPhearson et al. 2022). SETS conceptualizes these domains as interconnected components of a unified urban system rather than independent subsystems (Chester et al., 2023). Understanding interactions within and between these domains is crucial for promoting sustainable urban transformations, as it strengthens synergies and minimizes trade-offs (Pickett et al., 2021). The versatility of the SETS framework is reflected in its diverse applications, from resilience assessment to guiding urban planning strategies. For instance, Chang et al. (2021) advocate using SETS to plan flood management transitions, moving beyond approaches focused solely on technological solutions. These considerations are particularly urgent in dense, compact cities, where demand for cultural and provisioning ecosystem services often exceeds supply (Larondelle & Lauf, 2016). This imbalance highlights the need for strategies that balance urban density with green space and carefully navigate trade-offs among ecosystem services. Despite growing attention to sustainable urban development, there is still a lack of concrete approaches for effectively integrating green and compact city concepts (Artmann et al., 2019).

To address these gaps, this study introduces a spatially explicit, interdisciplinary framework that integrates urban risks and feasibilities to evaluate the planning of NbS in dense urban environments. By jointly assessing climate adaptation and urban development objectives and systematically capturing NbS co-benefits for both communities and ecosystems, the framework provides an evidence-based tool to prioritize interventions and guide decision-making. Applied to a compact context such as Barcelona, it represents a first step toward strategic planning for city-wide NbS expansion, analyzing how such interventions can be planned to reduce stormwater-related risks while advancing urban resilience, equity, and sustainability.

2 Methodological framework:

The methodological framework (Fig.1), developed using a GIS-based approach and drawing from the work of Langemeyer (2016) and Langemeyer et al. (2020), implements a four-step analysis (Fig.1). The first step follows the SETS vulnerability approach (McPhearson et al., 2016, Chang et al., 2021) to assess urban risks. This step involves identifying areas within the city that are most vulnerable to CC hazards and where NbS have the potential to mitigate CC-related risks (Khromova et al. 2025). The second step involves scenario development based on feasibility assessment, evaluating the potential for future NbS integration based on developed system of SETS indicators and categorizing areas from fully feasible to non-feasible. The third step evaluates the performance of NbS by analyzing runoff reduction and assessing how this integration can reduce risks identified in the first step. Finally, the fourth step evaluates the additional co-benefits that NbS can provide by applying several models to analyze changes in heat mitigation, recreation, water storage, habitat provisioning and water purification parameters. This research advances the planning of multifunctional NbS in urban areas by jointly addressing local risks and spatial feasibility. The approach is demonstrated through a case study of Barcelona and can be adapted to other urban contexts by tailoring the framework to local planning guidelines, data availability, and policy priorities.

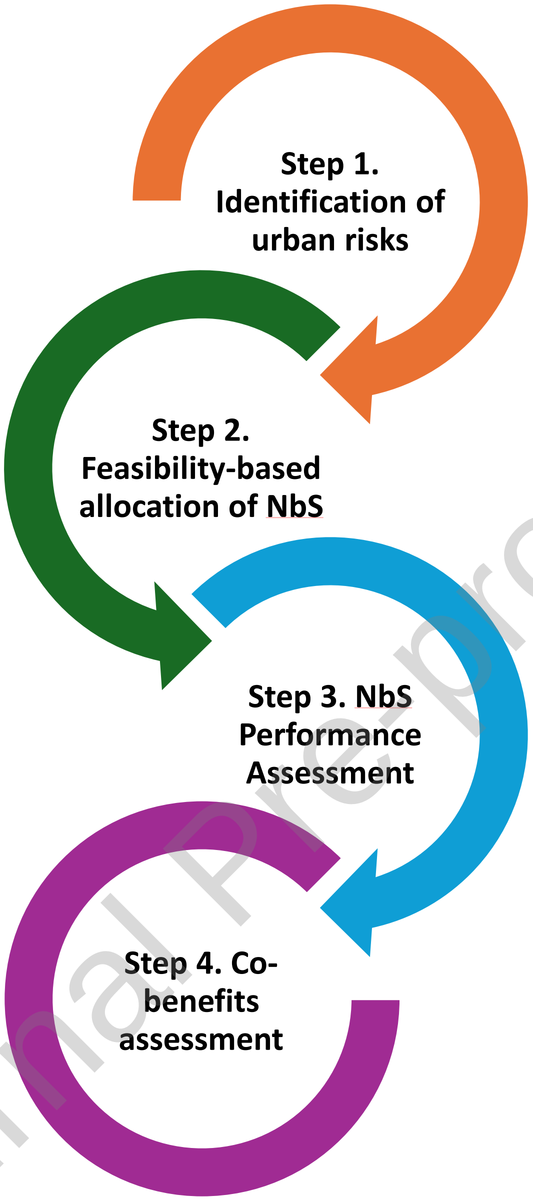


Figure 1. Conceptual and methodological framework.

2.1 Case study of Barcelona's hydrological systems:

Barcelona (Fig.2), the capital of Catalonia, Spain covers an area of approximately 101 km² and is inhabited by around 1.6 million people (2023), characterized by high compactness and population density (16,339 residents /km^2) (IDESCAT, 2023). The region receives around 600 mm/year of rainfall annually with heavy storms typical of the Mediterranean climate, leading to flooding and combined sewer overflow (CSO) events (BCASA, 2020). The region experiences severe flood events with return periods exceeding 100 years, as well as frequent minor flood events each year, primarily driven by convective and localized precipitation during late summer and autumn (Llasat et al., 2022; Cortès et al., 2018). According to the

Meteorological Service of Catalonia, the frequency of 50mm rain events is expected to increase by 15% by the middle of the century in Barcelona (BCASA, 2020). Another study carried out by the Climate Research Foundation within the framework of the European project RESCCUE estimates that the rains that occur in a return period of 100 years will increase between 20% in the middle of the century and 40 % at the end of the century (Russo et al., 2020). This is just one of the challenges posed by the climate emergency, and the need to increase efforts to deal with the climate crisis is becoming more and more evident (SUDS commission, 2020).

Addressing these challenges posed by CC, the Barcelona Nature Plan 2030 outlines a goal of providing 1m² of green space per resident by 2030, translating to the creation of 160 hectares of new green areas to the already existing 3,659 ha. In addition to expanding green spaces, the city has also set a target to increase the coverage of green roofs. The Municipal Urban Ecology Agency aims to extend green roof areas to 22,000 m² by 2030, as part of a broader strategy to scale up NbS across the city (BCNecologia, 2014). The spatial framework proposed in this study can contribute to these efforts by guiding decision-making and helping prioritize the implementation of NbS across the city. Additionally, it assesses whether the expansion of NbS in a compact urban environment like Barcelona can be further scaled, and how this integration may influence stormwater-related hazards while also providing additional co-benefits.

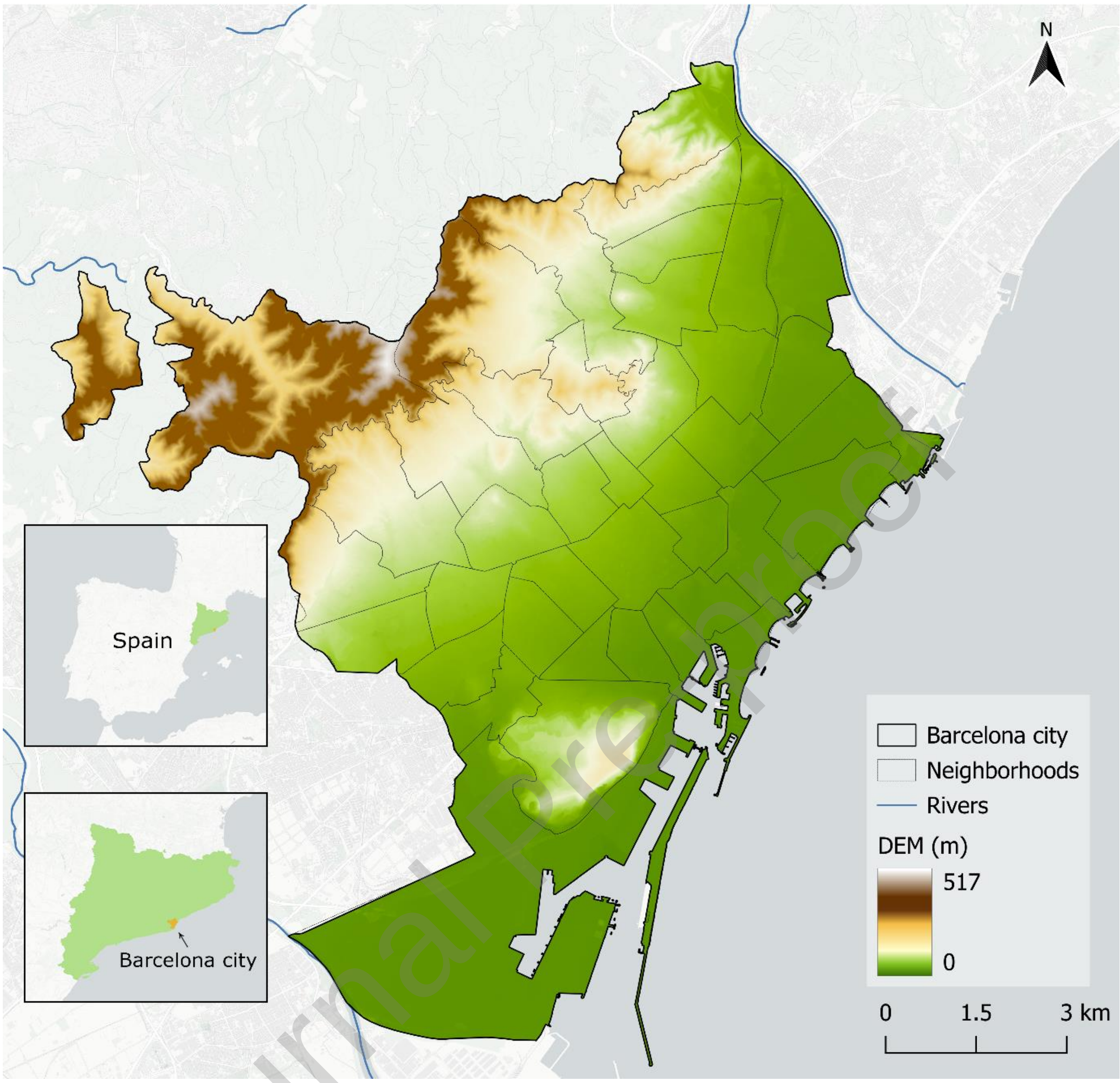


Figure 2. Topographical and Neighborhood Map of Barcelona City (DEM-Digital Elevation Model).

2.2 Identification of urban risks.

To identify the urban risks for NbS integration and assess urban communities' risk to stormwater-related hazards at the census tract scale, the methodology developed in Khromova et al. (2025) is applied. This approach follows the IPCC (2012) risk framework, which defines risk as a function of hazard, exposure, and vulnerability, with vulnerability conceptualized as the interplay of social, ecological, and technological (SETS) domains. Hazard is understood as the potential to cause extensive damage to infrastructure, disrupt essential services, jeopardize public safety, and inflict economic losses on communities. It is represented by runoff generation and retention, modeled using InVEST® Urban Flood Risk Mitigation module version 3.14.2 (Natural Capital Project, 2023). Exposure is defined by the presence of people within the affected area, as individuals may face risks such as being swept away, property damage, injury from debris or vehicles, or transportation disruptions. It is measured through population density. Social vulnerability is assessed based on susceptibility factors such as age, income level, and language barriers, with equity considerations central to understanding how these factors intersect to create disproportionate impacts from hazards and shape unequal opportunities for adaptation. Ecological vulnerability considers ecosystem characteristics that influence water retention and runoff mitigation, while technological vulnerability accounts for landscape features such as impervious surface area, sewer capacity deficits, and terrain slope, which impact the effectiveness of stormwater management solutions.

3 Feasibility-based allocation of NbS

Four types of NbS are selected to assess optimal location based on a literature review highlighting their relevance for stormwater management, namely green roofs, rain gardens, porous pavement, and urban parks.

Definition of various types of NbS:

1. Green Roofs

Green roofs are vegetated layers installed on top of building rooftops that capture and retain rainfall, slowing runoff while promoting evapotranspiration (Berghage et al. 2009; Bonilla Iglesias, 2014; Raji, Tenpierik, Van Den Dobbelsteen, 2015; Sims et al., 2016; Bosch et al., 2023)

2. Rain Garden

Rain gardens are shallow, landscaped depressions designed to capture, filter, and infiltrate stormwater runoff from impervious surfaces such as roofs, streets, and sidewalks. (Feldman et al., 2019; Majidi et al.,2019).

3. Porous Pavement

Porous pavement is a permeable surface that allows stormwater to percolate through it into the ground rather than running off into drains. It is used in place of traditional impervious surfaces like asphalt or concrete (Majidi et al. 2019).

4. Urban Parks

Urban parks are multipurpose green spaces in cities that provide ecological and social benefits. They can also contribute to stormwater management by integrating other NbS types, such as rain gardens, bioswales, and permeable pathways. Furthermore, parks can play a greater role in stormwater management through floodable designs that store, capture, and channel runoff, serving as multifunctional elements that enhance and complement existing infrastructure (Martín Muñoz et al, 2024; Matos Silva and Costa, 2016).

3.1.1 Feasibility assessment

The feasibility assessment involves analyzing the city's landscape through a multidisciplinary lens, incorporating social, ecological, and technological aspects. Social indicators include institutional capacity, the existing regulatory framework, and support for pro-environmental political parties. Ecological indicators include factors such as infiltration capacity and topography. Technological indicators focus on the characteristics of built-up areas. The selection of indicators is summarized in Table 1. Detailed information on the classification and justification for the choice of indicators can be found in Appendix A.

Table 1: Suitability of indicators for different NbS (✓ -suitable, x- not suitable)

	Indicators	**Metric Description**	**Green Roofs**	**Rain garden**	**Porous pavement**	**Urban parks**
Social	Existing zoning policies	Map of planned parks (PDU); areas outside plans scored lower (Zuniga-Teran et al., 2020)	x	✓	x	✓
	Current land use	Feasibility assigned per land use type (Johns, 2019; Everett et al., 2018)	x	✓	✓	✓
	Support for pro-environmental political parties	Voting data from 2023 Barcelona elections; neighborhoods with >38% green-party support scored higher	✓	✓	✓	✓
	Administrative suitability	Land registry / rooftop ownership; private/industrial/under-construction areas scored lower (Johns, 2019; Matzing et al., 2017)	✓	x	x	x
Ecological	Ground Slope	Raster slope map; areas <6° feasible (Comissió de SUDS, 2020)	x	✓	✓	x
	Soil Permeability	Soil drainage data; well-drained soils scored higher	x	✓	x	x
	Polluted water for land use	Buffer >60 m from major roads feasible (to prevent polluted water infiltration)	x	✓	x	x
Technological	Distance Buildings	>3 m buffer feasible (Comissió de SUDS, 2020)	x	✓	x	✓
	Underground Structures	Presence of underground infrastructure scored non-feasible	x	✓	x	x
	Rooftop slope	Measured slope <15° feasible, 15–45° intermediate (Comissió de SUDS, 2020)	✓	x	x	x
	Rooftop stability	Year of construction / load-bearing capacity; built after 1965 feasible (L’Agència d’Ecologia Urbana, 2010)	✓	x	x	x
	Rooftop area	Measured area of rooftops; >5 m² feasible (CobertesVerdes, AMB)	✓	x	x	x

ArcPro version 3.32 is used for this assessment. Spatially explicit data for each indicator is collected (see Table 1) and converted into raster format, classifying each area into three categories: 0, 0.5, or 1. A suitability value of 0 denotes non-feasible areas for implementing the considered NbS type, 0.5 represents areas where implementation is feasible, but requires significant site modifications, and 1 indicates areas that are both feasible and well-suited for NbS implementation. A detailed explanation and justification of the threshold values are provided in Appendix A.

The next step aggregates the indicator rasters into final feasibility maps for each NbS type using geometric mean aggregation. This operator is used because it preserves zero values (i.e., hard constraints remain non-feasible) and reduces the influence of extreme values, thereby limiting the impact of outliers (Joint Research Centre, 2008), which is consistent with screening-level feasibility logic for multi-constraint urban planning.

$$Fs(R) = \sqrt[n]{I1 * I2 * I3 \dots In} \quad (1)$$

Where Fs(R) - rescaling feasibility score, and $I1 * I2 * I3 \dots xn$ – indicators used for each type of NbS.

The final maps identify NbS implementation feasibility based on a 0-1 scoring. A score of 0 represents no feasibility and 1 indicates the highest feasibility for NbS implementation. The scale was divided into five equal quantile groups.

3.1.2 Scenario Development

Based on the feasibility assessment, two scenarios are developed alongside the current land use scenario (S0). In Scenario 1 (S1), target numbers from city planning are integrated to align with the existing urban goal of providing 1m² of green space per resident by 2030, translating to the creation of 160 hectares of new green areas (Barcelona Nature Plan 2030). The allocation of NbS within this scenario is implemented in the ArcGIS version 3.32 environment through a custom Python script, which calculates polygon areas, orders them by suitability score, and iteratively selects spatial units until the cumulative target area is reached. This procedure ensures that the most feasible locations are prioritized while maintaining transparency and reproducibility. The Python code used for this allocation is made openly available in the project Dataverse (Khromova et al., 2025).

In Scenario 2 (S2), the four selected NbS are implemented in areas where the previous analysis indicates very high SETS feasibility, prioritizing the first out of five respective feasibility groups. In cases where the implementation of two or more NbS is deemed highly feasible in the same location, the NbS type associated with the highest capacity to mitigate stormwater (i.e., the highest curve number) is prioritized (Muche et al., 2019).

3.2 NbS performance assessment

3.2.1 Rainfall-runoff modelling

We use the InVEST® Urban Flood Risk Mitigation module version 3.14.2 (Natural Capital Project, 2023) to estimate runoff generated and retained within the watershed. This model applies the widely used SCS-CN method (Muche et al., 2019) for flood estimation across various spatial scales. Stormwater retention at the catchment outlet is calculated by summing pixel-level contributions. Required inputs included rainfall (mm; Table 2, Appendix B), a raster of land use/land cover (LULC) categories, a table of curve number (CN) values for each LULC category, and a raster of soil hydrologic groups. Curve numbers were then assigned to each LULC type, as detailed in Table 3 (Appendix B). Further information on the input parameters, their sources, and references is provided in Table 1 (Appendix B). All model input data are publicly available in Dataverse (Khromova et al., 2025).

3.2.2 Impact on risk

NbS provide numerous social and community benefits, making them particularly valuable for prioritization in disadvantaged or vulnerable communities. In this study, risk scores (Step 1) for stormwater-related hazards at the census-tract scale for scenarios S1 and S2 are compared to the baseline scenario (S0) developed in the first step using ArcGIS version 3.32. The results are visualized through maps illustrating percentage changes in risk scores for census tract groups, with calculations performed using the field calculator tool in the attribute table of ArcGIS version 3.32.

3.3 Co-benefits provided by NbS

The list of relevant co-benefits was selected in alignment with climate projections and predictions for various climate-change impacts in Barcelona (Fundación de Investigación del Clima), as well as with the goals outlined in the city's urban development and climate adaptation program, like Pla Natura (Ajuntament de Barcelona, 2021).

3.3.1 Heat mitigation

Heat mitigation was assessed using daytime air temperature (°C) between 13:00 and 16:00 for July 4–6, 2015. Temperature data were derived from four meteorological simulations using the Weather Research and Forecasting model (WRF-Comfort v4.3.3; Skamarock et al., 2019;

Martilli et al., 2024). Simulations covered extreme heat and dry conditions from 00 UTC on June 20 to 00 UTC on July 25, 2015, with the first five days used for model spin-up (Segura et al., 2021). The model was configured with four two-way nested domains, with the innermost domain at 333 m resolution covering the Metropolitan Area of Barcelona. The physical configuration followed Segura et al. (2021). Inputs included land-use maps, urban fractions, building and street morphology, and irrigation maps. Corine Land Cover data (Büttner et al., 2017) were remapped into 16 MODIS IGBP classes following Pineda et al. (2004). Sedum was used as the green roof land-use class instead of grass, with an irrigation rate of 1.1 mm/day (Dutoit and Hermy, 2015). Results were mapped in ArcGIS v3.32, averaged over the three-day period, and aggregated to census tracts using zonal statistics. Detailed input parameters are provided in Table 3 (Appendix B), and all input data are available in Dataverse (Khromova et al., 2025).

Barcelona projected increases in the frequency and intensity of heat waves (Ríos-Cornejo and del Río, 2012) and the city's identification of heat vulnerability as a priority issue (AMB, 2018). NbS proposed in this study, except for permeable pavement, incorporates a vegetation component, which plays a crucial role in moderating temperatures during heat waves by absorbing solar energy, facilitating transpiration, and providing shade (Shao and Kim, 2022).

3.3.2 Water Storage

Water storage was assessed using the Urban Stormwater Retention module of InVEST v3.14.2 (Natural Capital Project, 2023). The model estimates runoff coefficients and percolation ratios for each land use and land cover (LULC) type, representing potential groundwater recharge. Required inputs included LULC raster, soil hydrologic group raster, precipitation raster, and a biophysical table defining runoff and percolation coefficients for each LULC class. Detailed input information is provided in Table 4 (Appendix B), and all data are available in Dataverse (Khromova et al., 2025).

Barcelona has experienced a significant increase in drought occurrences linked to an accelerated hydrological cycle (Russo et al., 2020), leading to irrigation restrictions and associated socio-environmental impacts (Forero-Ortiz et al., 2020). While groundwater is not widely used for domestic supply due to quality constraints, it represents a viable alternative for irrigation (AMB, 2023). Most NbS evaluated in this study (except green roofs) promote infiltration and aquifer recharge, making water storage a relevant co-benefit in this context.

3.3.3 Water purification

Water purification was assessed using the InVEST Nutrient Delivery Ratio (NDR) model (Natural Capital Project, 2023), following Benez-Secanho and Puneet Dwivedi (2019). The model estimates relative nutrient export and retention under different land-use scenarios by computing a long-term nutrient mass balance based on diffuse nutrient sources associated with LULC and landscape retention characteristics along flow paths. Nutrient export at the catchment outlet is calculated as the sum of pixel-level contributions (InVEST 3.14.2 user guide). Required inputs included a digital elevation model, LULC raster, nutrient runoff proxy raster, watershed boundaries, biophysical tables, threshold flow accumulation, and the Borselli K parameter. Input details are provided in Table 5 (Appendix B), and all data are available in Dataverse (Khromova et al., 2025).

Stormwater pollution remains a major concern in Barcelona and limits the reuse of runoff for augmenting water supplies, as urban runoff is typically contaminated (Björklund et al., 2018). Evaluating nutrient retention highlights the potential of NbS to reduce nitrogen and phosphorus exports in the urban environment.

3.3.4 Habitat Quality

Habitat quality was assessed using the InVEST Habitat Quality and Rarity module (Natural Capital Project, 2023), following Terrado et al. (2016). The model estimates habitat extent and degradation based on land cover and spatially explicit threats, accounting for habitat sensitivity and proximity to pressures such as roads, railways, industrial zones, and built-up areas. Required inputs included current and future land-cover rasters, threat and sensitivity tables, and a half-saturation constant. Detailed input information is provided in Table 6 (Appendix B), and all data are available in Dataverse (Khromova et al., 2025).

Newly constructed areas in Barcelona provide limited biodiversity services (Zhang and Ramírez, 2019), underscoring the need to expand multifunctional green spaces and assess the ecological co-benefits of NbS.

3.3.5 Recreation

Recreational benefits were assessed using the InVEST Urban Nature Access module v3.14.2 (Natural Capital Project, 2023), following Hamel et al. (2021). The model estimates population access to urban nature based on LULC, population density, per capita demand for green space, and identification of LULC classes representing urban nature. Input details are provided in Table 7 (Appendix B), and all data are available in Dataverse (Khromova et al., 2025).

Barcelona's dense urban structure and limited green space result in high demand for accessible recreational areas, which are essential for physical and mental well-being (Baró et al., 2016; Triguero-Mas et al., 2015).

4 Results

4.1 Identification of urban risks

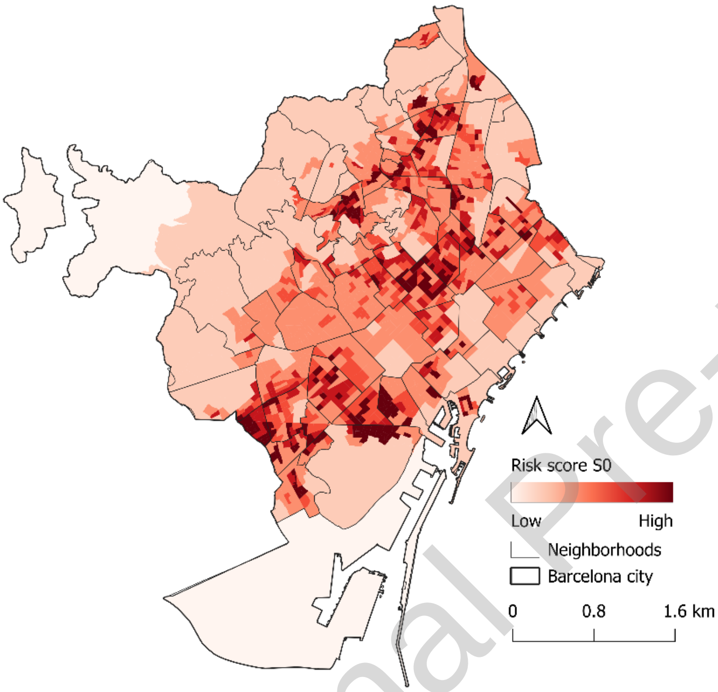


Figure 3. Spatial distribution of stormwater risk scores.

The risk assessment of the existing urban development (Fig. 3) identified the city center, as well as the western and northern parts of the city, as areas with the highest risk scores. It is important to note that this analysis reflects runoff generation for specific land parcels, rather than capturing the more complex dynamics of runoff distribution within the collector and sewer systems.

4.2 Feasibility-based allocation of NbS

This component of the study integrates a spatially explicit feasibility assessment for various types of NbS with scenario development. First, the study identified NbS that mitigate runoff, focusing on the most commonly used NbS in urban spaces for stormwater management. These were employed to demonstrate the proposed methodology. Second, it involved developing a system of indicators tailored to each NbS type, adopting a SETS perspective. Using these indicators, feasibility maps were generated for each NbS type, resulting in four feasibility maps (Fig. 4).

Green Roofs: The city center, southwest, and northeast areas exhibit the highest feasibility for green roof implementation.

Rain Gardens: In this study, rain gardens were considered exclusively within existing or planned green spaces aligned with city development strategies. The areas with the highest feasibility scores include the southwest, city center, and various locations across the northeast and east of the city.

Permeable Pavement: Permeable pavement was deemed applicable only to existing roads and parking lots. The highest feasibility scores were observed in the southwest, west, and northeast areas of the city.

Urban Parks: Urban parks were excluded from placement within existing urban green spaces and parks. The areas with the highest feasibility scores include the southwest, as well as regions in the east and northeast.

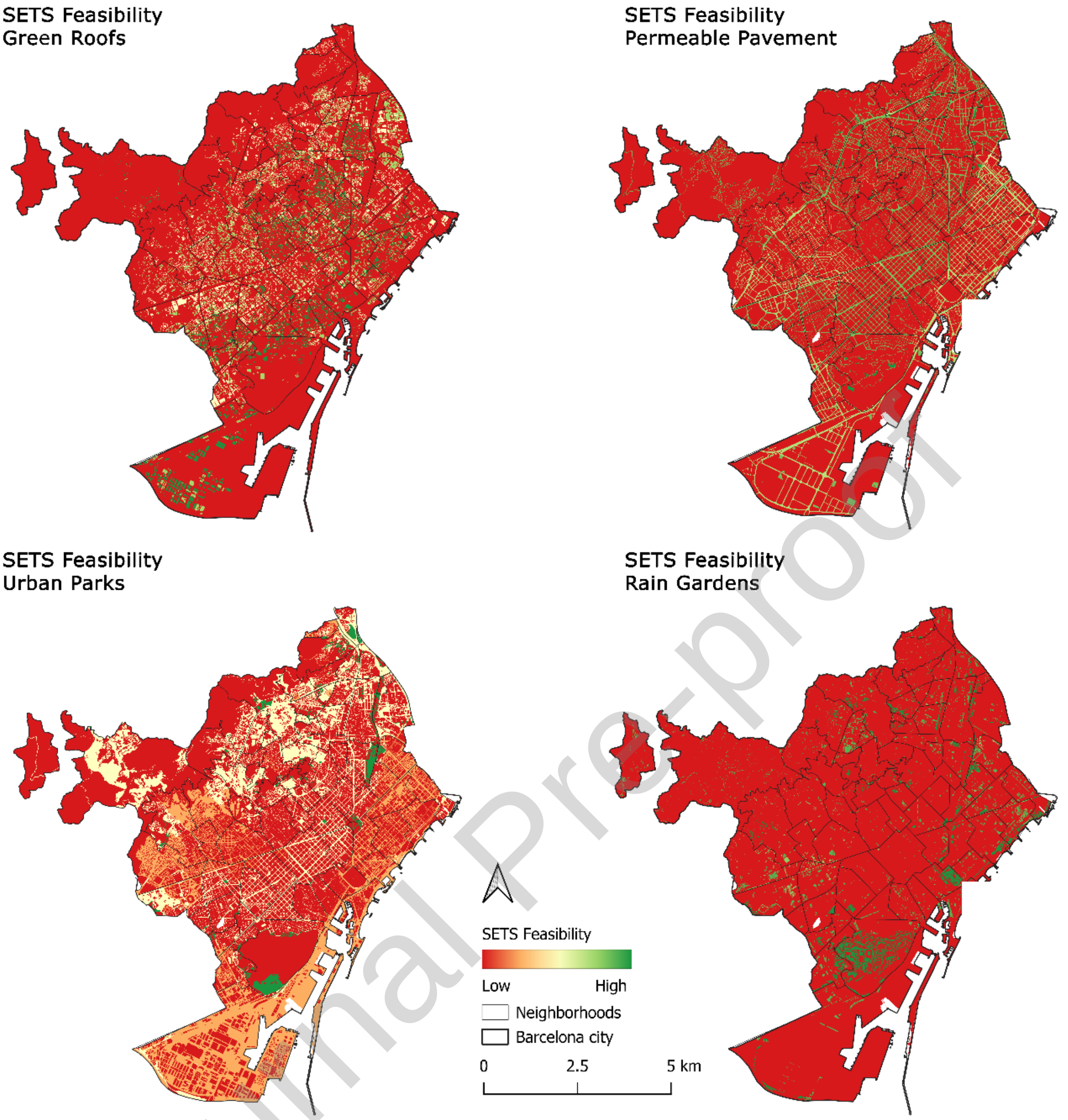


Figure 4. Combined maps with SET feasibility for each type of NbS.

Following the feasibility assessment, two NbS scenarios were developed, with total implementation areas of 160 hectares for Scenario 1 (S1, current policy goal) and 2,498 hectares for Scenario 2 (S2, maximizing feasibility) (Fig. 4).

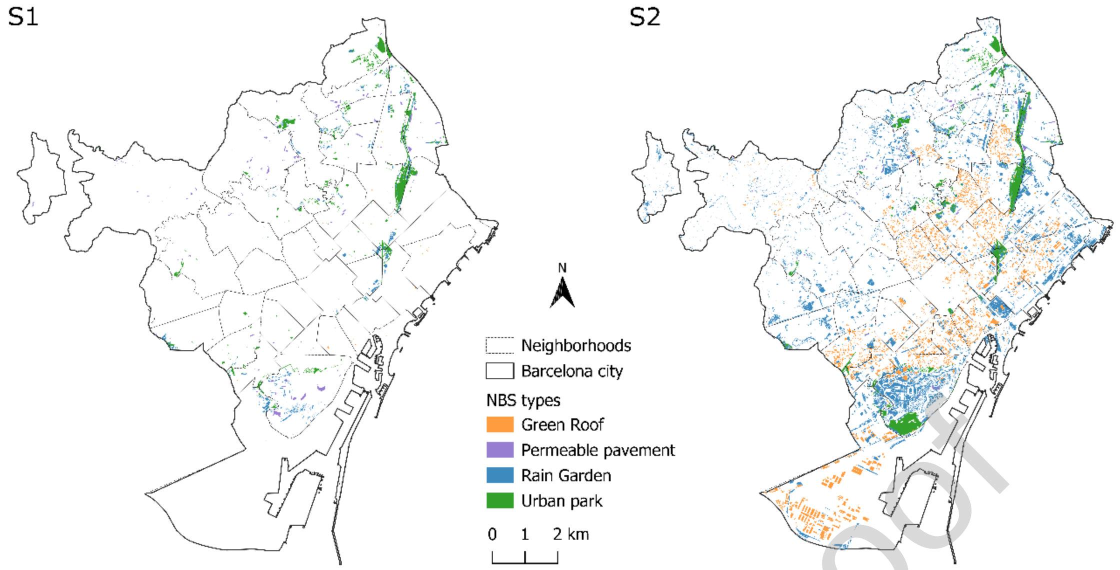
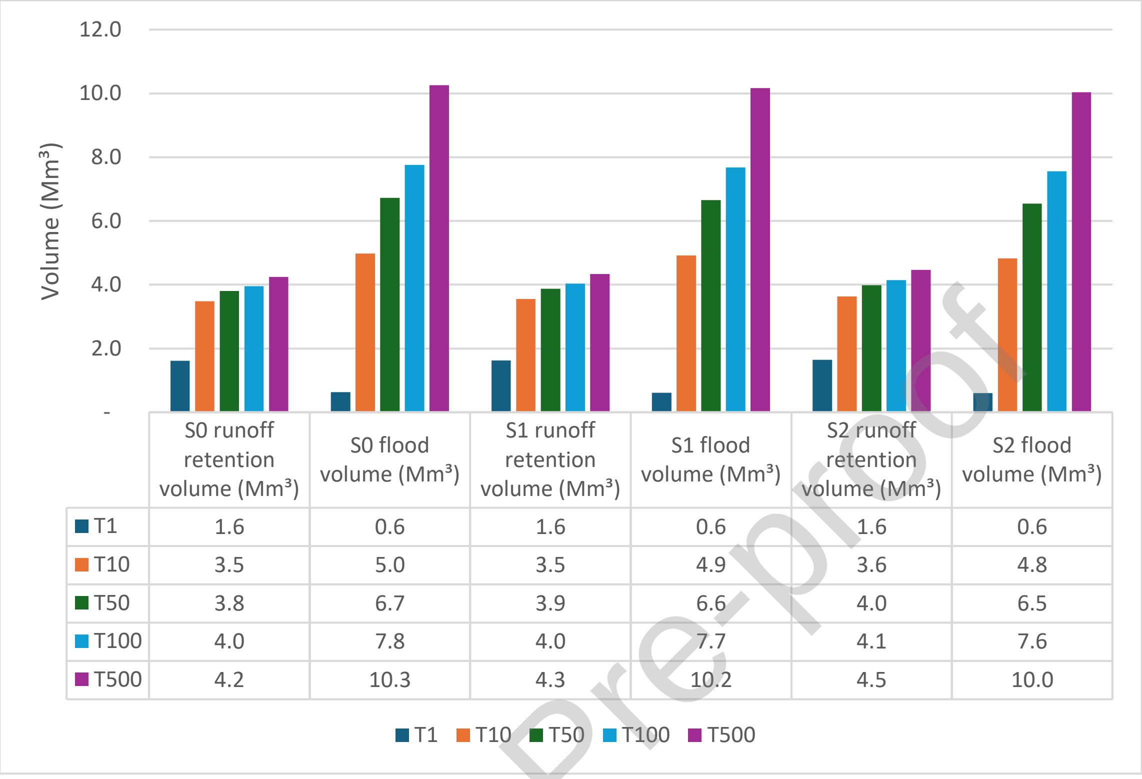


Figure 5. Scenario 1 and scenario 2 maps of NbS distribution.

4.3 NbS performance assessment

The performance assessment of stormwater management was based on InVEST model outputs, which utilized the following metrics. The stormwater retention volume is defined as the amount of precipitation from a given storm event that is retained, stored, or infiltrated within the landscape and therefore does not contribute to flood flow. In contrast, the flood volume represents the portion of storm precipitation that is not retained and thus becomes surface runoff. Both stormwater retention volume and flood volume were calculated at the watershed scale for the current LULC configuration (S0) as well as for two alternative scenarios (S1 and S2) and were evaluated across design storms corresponding to return periods (T) of 1, 10, 50, 100, and 500 years (Table 2). In addition to these watershed-scale indicators, the model also computes runoff at the pixel level. This spatially explicit runoff output illustrates the changes in runoff for NbS scenarios S1 and S2 in comparison with the current LULC configuration (S0) under a design storm with a 100-year return period and is presented in Figure 6.

Table 2. Performance assessment results for retention and flood volumes (calculated for rainstorms with return periods (T) of 1, 10, 50, 100, and 500 years)



	S0 runoff retention volume (Mm³)	S0 flood volume (Mm³)	S1 runoff retention volume (Mm³)	S1 flood volume (Mm³)	S2 runoff retention volume (Mm³)	S2 flood volume (Mm³)
T1	1.6	0.6	1.6	0.6	1.6	0.6
T10	3.5	5.0	3.5	4.9	3.6	4.8
T50	3.8	6.7	3.9	6.6	4.0	6.5
T100	4.0	7.8	4.0	7.7	4.1	7.6
T500	4.2	10.3	4.3	10.2	4.5	10.0

The retention volume and flood volume for scenarios S1 and S2 were compared to the current LULC (S0) by calculating the percentage of reduction (Table 3). A gradual decrease in the percentage reduction of flood volume relative to S0 was observed across return periods from 1 to 500 for both S1 and S2, ranging from -2.4% to -0.9% and -4.6% to -2.2%, respectively. Conversely, both S1 and S2 showed an increase in retention volume relative to S0, ranging from 0.9% to 2.1% for S1 and from 1.8% to 5.2% for S2. This corresponds to a reduction in runoff volume of between 15,134 m³ and 221,043 m³

Table 3. Performance assessment results expressed as percentage changes in S1 and S2 relative to S0.

	T1	T10	T50	T100	T500
🟩 %S1 retention volume to S0	0.9	1.8	2.0	2.0	2.1
🟪 % S1 flood volume to S0	-2.4	-1.3	-1.1	-1.0	-0.9
🟦 % S2 retention volume to S0	1.8	4.3	4.7	4.9	5.2
🟩 % S2 flood volumes to S0	-4.6	-3.0	-2.7	-2.5	-2.2

The reduction in runoff is much more pronounced in Scenario 2 (S2) compared with the baseline (S0), underscoring the spatially heterogeneous impact of NbS interventions (Fig. 5). In several districts, particularly in the northeastern, southern, southeastern, western, and southwestern parts of Barcelona, runoff generation decreases by up to ~35%, reflecting the concentration of high-capacity interventions such as rain gardens, permeable pavements, and large urban parks.

To account for uncertainty in key model inputs, a deterministic uncertainty propagation analysis was conducted by varying rainfall depth (±10%) and curve number values (±5 units). While absolute flood and retention volumes varied across return periods, the relative performance of scenarios remained consistent, with S2 showing the greatest runoff reduction and S0 the highest runoff across all design storms. This indicates that the reported reductions in runoff and increases in retention volume associated with NbS are robust to plausible uncertainty in model inputs (Appendix D).

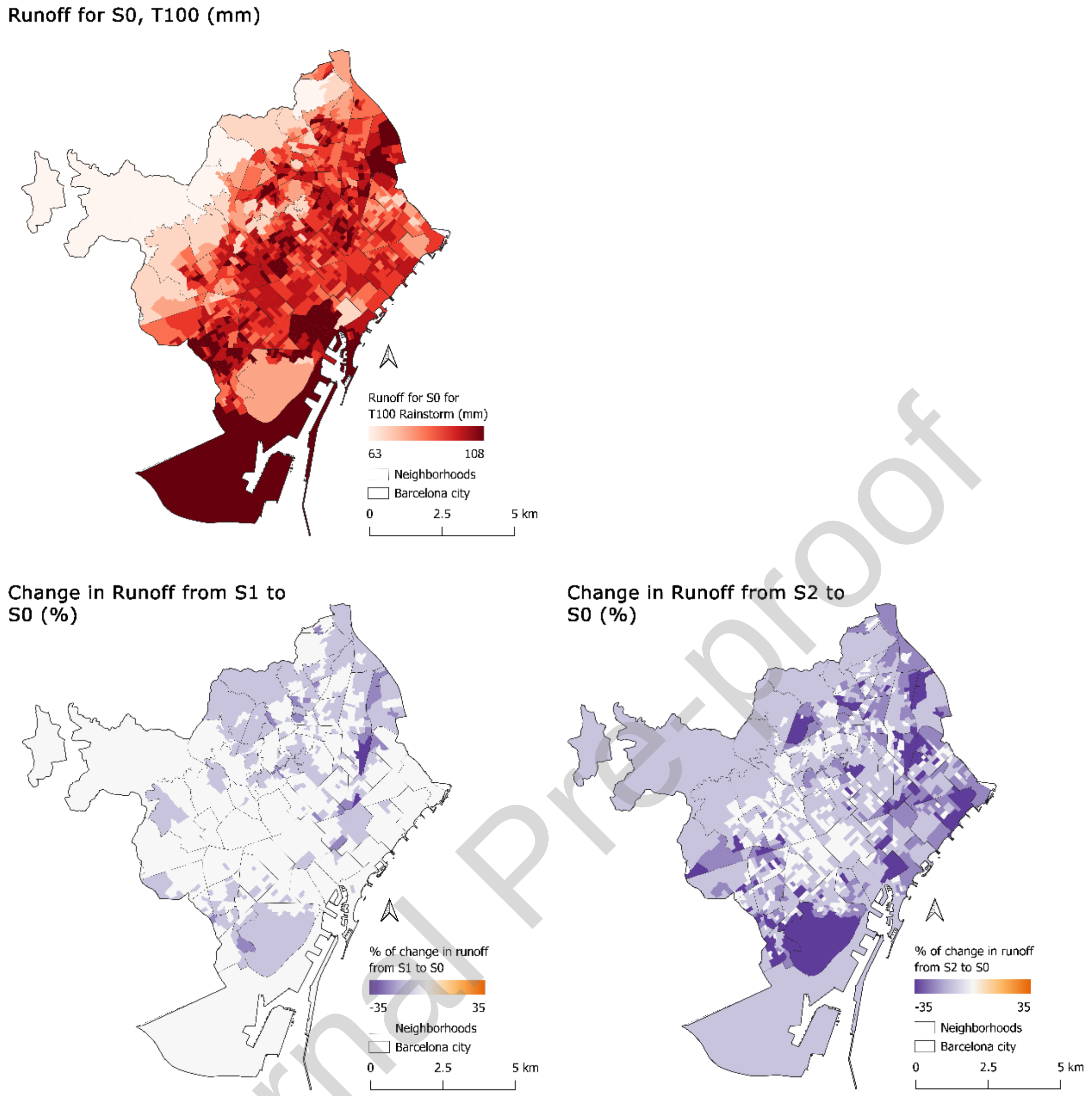


Figure 6. Spatially explicit performance assessment results of change in runoff.

4.4 Impact on risk

Risk scores for stormwater-related hazards at the census tract scale decreased by up to 55% in both S1 and S2 scenarios compared to the baseline (S0), particularly in areas where NbS interventions, such as rain gardens and large urban parks, were implemented (Fig. 7). This trend is especially evident in the northeastern, southern, southeastern, western, and southwestern areas of Barcelona. It is important to note that this reduction reflects the effect of NBS on runoff generation for specific land parcels, rather than capturing the more complex dynamics of runoff distribution within the collector and sewer systems.

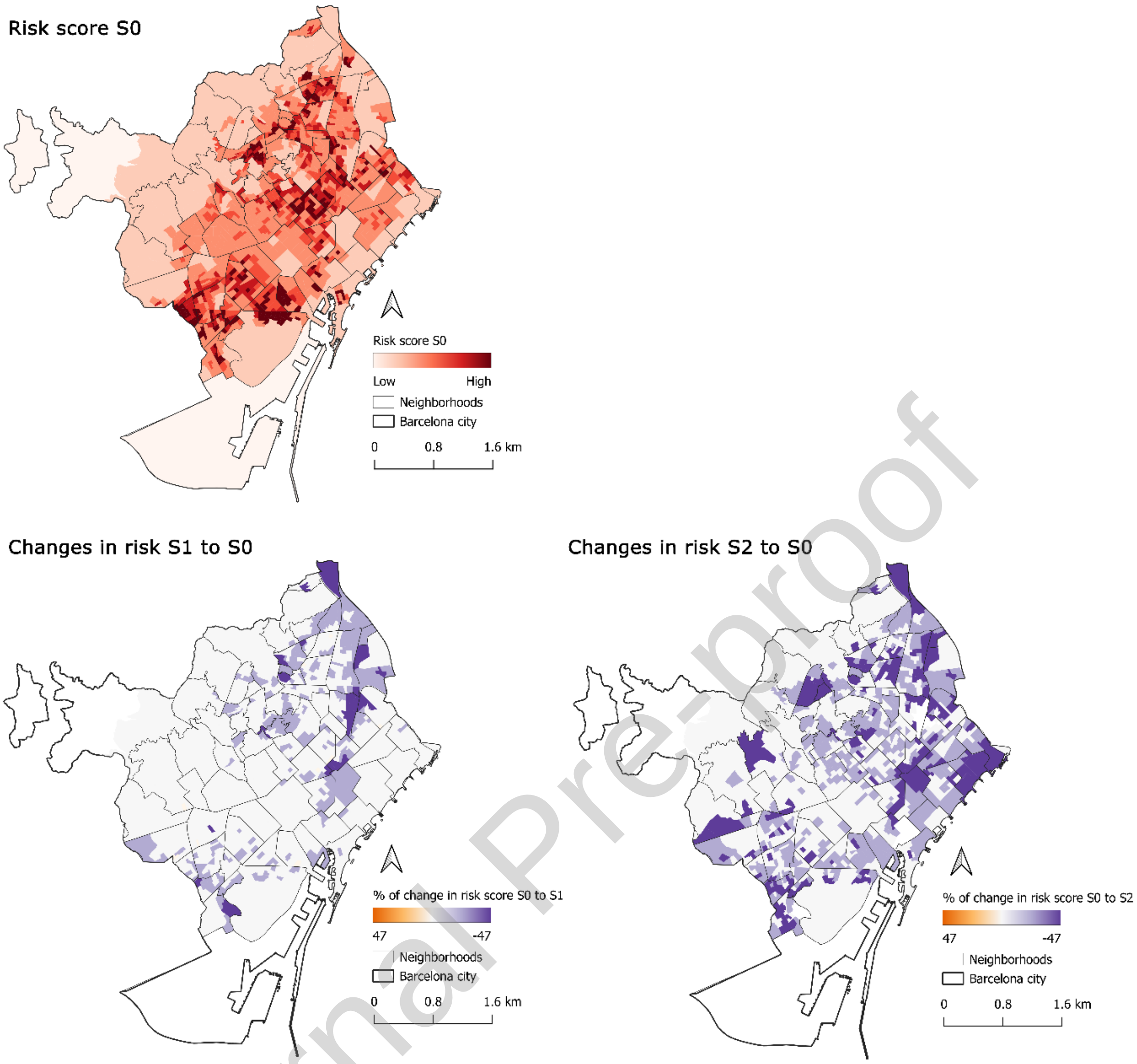


Figure 7. Changes across scenarios S1 and S2 compared to S0 in spatial distribution of risk.

4.5 Co-benefits provided by NbS

Table 4. Modeling outputs for different co-benefits provided by NbS.

Co-benefit type	**Assessment Indicator**	**S0**	**S1**	**S2**	**% S1 to S0**	**% S2 to S0**
Heat Mitigation	Mean temperature for heatwave event (°C)	34.4	34.3	33.9	-0.3	-1.5

Water Storage	Total percolation volume (m^3/year)	2996350	3123932	4287556	4.25	43.09
Habitat Provisioning	Mean value for quality of ecosystems	0.0029	0.0030	0.0042	3.6	36.2
Water Purification	N surface load (kg/ year)	113947	111698.7	105599.4	-1.9	-7.3
	N surface export (kg/ year)	31497.26	30689.4	28154.8	-2.5	-10.6
	P surface load (kg/ year)	15692.03	15411.28	14609.06	-1.7	-6.9
	P surface export (kg/ year)	4036.063	3937.71	3628.548	-2.4	-10.1
Recreation	Population undersupplied with urban nature	262.6	226.5	131.4	-13.7	-49.9

4.5.1 Heat mitigation

Heat mitigation, assessed via mean daytime temperature during a heatwave, improved in both S1 and S2 scenarios, with a noticeable reduction in temperatures compared to the baseline.

Specifically, the mean midday temperature (13:00–16:00) during the 2015 heatwave reduced by up to 0.3% for S1 and 1.5% for S2 compared to the baseline scenario (Tab.4). At the census tract scale (Fig.7), temperature reductions of up to 2.5°C were observed in the city center, as well as in the northeastern, southeastern coastal, and southwestern areas.

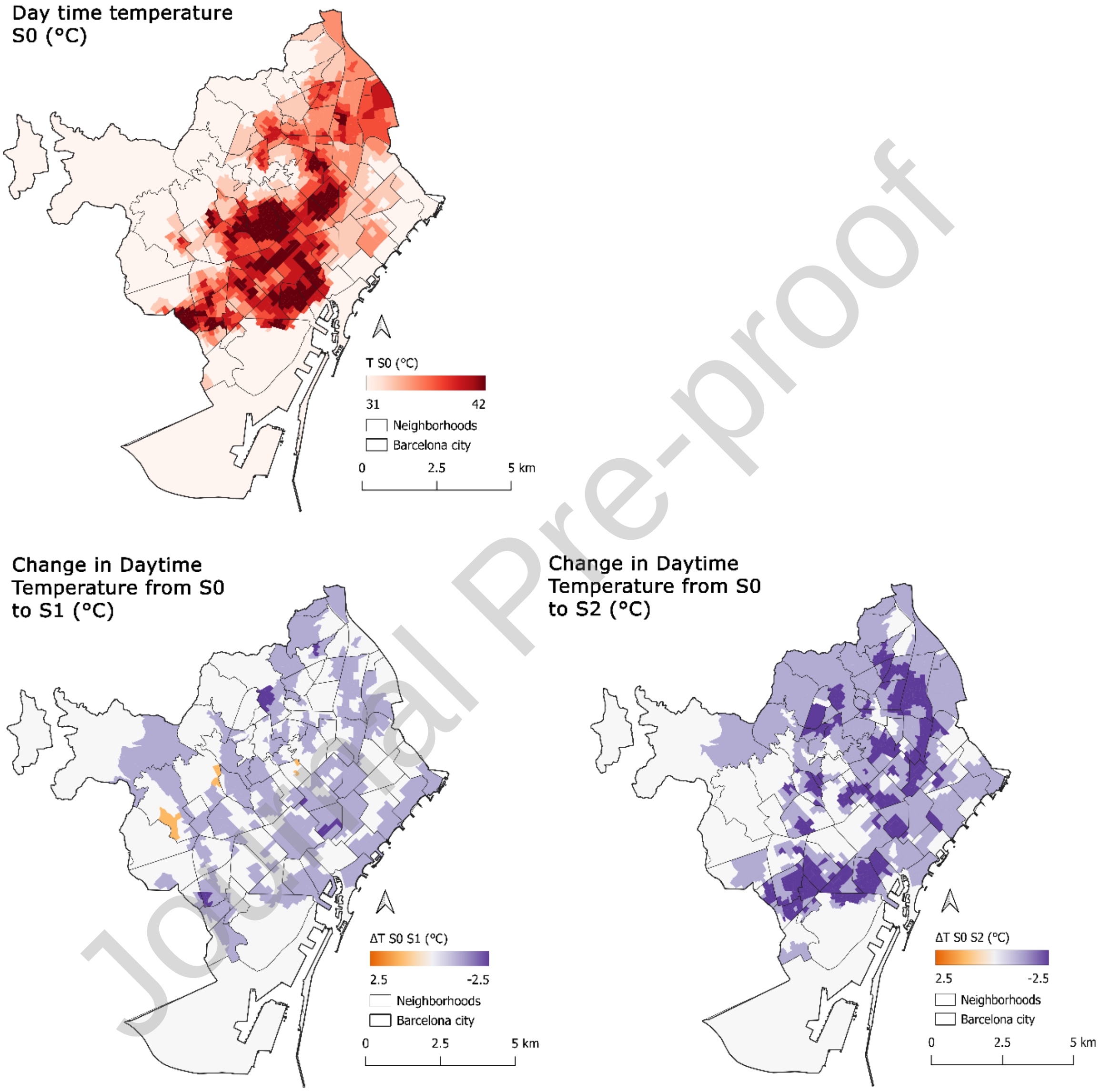


Figure 8. Changes across scenarios S1and S2 compared to S0 in spatial distribution of daytime temperature.

4.5.2 Water Storage

Water storage, measured as total percolation volume representing potential annual aquifer recharge in Barcelona, increased under both S1 and S2 scenarios. Specifically, the total percolation volume increased by up to 4.25% for S1 and 43.09% for S2 compared to the baseline scenario (Tab.4).

4.5.3 Habitat Provisioning

Habitat provisioning, assessed through ecosystem quality at the administrative unit level, improved in both S1 and S2 scenarios, with increases of 3.6% and 36.2%, respectively (Tab.4).

4.5.4 Water purification

Water quality modeling results for nitrogen (N) and phosphorus (P) surface load and export per watershed showed reductions across all indicators. Compared to the baseline (S0), reductions ranged from 1.9% to 2.5% in S1 and from 6.9% to 10.6% in S2 (Tab.4).

4.5.5 Recreation

Urban nature access model indicates a significant reduction in the population underserved by green space at the administrative unit level, 13.7% in S1 and 49.9% in S2 compared to the baseline (S0) (Tab.4).

5 Discussion

Using Barcelona as a case study, this research assesses the role of NbS in sustainable stormwater management, focusing on stormwater risk reduction and the expansion of urban greening. The results show that NbS implementation reduces local stormwater risk when comparing S1 and S2 to current land cover, with neighborhood-scale reductions of up to 35% in runoff and 47% in risk. At the city scale, however, runoff reductions remain modest, averaging 1–5%, indicating limited hydrological effectiveness at larger scales.

Despite the modest city-scale runoff reduction achieved by NbS, the results demonstrate substantial and policy-relevant co-benefits, particularly under the ambitious S2 scenario, which assumes implementation in all areas of very high SETS feasibility. Compared to the baseline (S0), S2 reduces mean air temperature during heatwave events from 34.4 °C to 33.9 °C (−1.5%), while total annual percolation increases from 3.0 to 4.3 million m^3/year (+43.1%), indicating a sizeable enhancement of urban water storage capacity. This increase is directly relevant to municipal water management, given that Barcelona's upgraded groundwater network targets a reduction of approximately 115,000 m^3/year of potable water used for irrigating parks and gardens, suggesting that NbS-supported percolation can meaningfully contribute to easing pressure on potable supplies (Ajuntament de Barcelona, 2021). Habitat quality also improves markedly, with the mean ecosystem quality index increasing by 36.2%, reflecting spatial upgrading of ecological conditions consistent with municipal biodiversity and greening objectives.

In terms of water quality, S2 reduces nitrogen and phosphorus surface exports by 10.6% and 10.1%, respectively, representing a clear reduction in diffuse nutrient pressures and a direction of travel aligned with EU Water Framework Directive objectives to achieve or maintain good ecological status in urban and downstream water bodies. Social co-benefits are equally pronounced: the population underserved by urban nature decreases from 262.6 to 131.4 thousand inhabitants (−49.9%), highlighting a substantial improvement in equitable access to green space. Finally, the spatial feasibility analysis indicates that NbS-compatible green space could expand up to 15 times beyond current development patterns, demonstrating that even compact, densely built cities like Barcelona retain significant untapped potential for ambitious, multifunctional NbS implementation.

Stormwater mitigation capacity of NbS:

Results from the InVEST Urban Flood Risk Mitigation model indicate a maximum flood volume reduction of 4.6% when comparing S0 with S1 and S2. While this reduction is modest relative to the scale of interventions in S2, it reflects the constraints of Barcelona's drainage system, which is frequently overwhelmed and experiences a high frequency of combined sewer overflow (CSO) events (BCASA, 2020). The system operates near capacity and has extremely low renovation rates, averaging 0.5% per year, meaning that conventional expansion mainly shifts problems downstream rather than resolving them. NbS interventions modeled in this study retain between 0.9% and 5.2% of runoff, corresponding to volumes of 15,134–221,043 m^3. When combined with existing underground reservoirs (470,000 m^3 capacity) and the sewer network's storage volume (2,209,400 m^3), NbS might contribute meaningfully to reducing CSO events and pluvial flooding, particularly during lower-intensity storms. However, hydraulic modelling under the PDISBA framework (BCASA, 2020) shows that SUDS alone are insufficient to meet flood safety and environmental standards. These findings reinforce the need to integrate NbS with upgrades to conventional drainage infrastructure, as well as hybrid grey–green–blue solutions and smart technologies that optimize system performance (Ortiz et al., 2021).

NbS planning tool.

A central contribution of this study is methodological rather than predictive. The framework integrates spatial feasibility, stormwater risk, and multiple co-benefits within a single SETS-informed assessment, thereby supporting strategic NbS planning at the city scale. Existing approaches often examine vulnerability, ecosystem service provision, or feasibility separately.

By contrast, the framework developed here links demand- and supply-side considerations in one spatial workflow, making it possible to identify not only where NbS may be beneficial, but also where they are more likely to be feasible under current social, ecological, and technological conditions.

The Barcelona case study shows that NbS scenarios generate differentiated spatial patterns of risk reduction and co-benefits, highlighting the context dependence of their performance. The framework is grounded in local planning and technical conditions rather than generic indicators, and it explicitly incorporates feasibility constraints that reflect current governance and implementation realities. At the same time, these feasibility conditions should not be treated as fixed. They are shaped by institutional priorities, planning rules, and political choices, all of which may change over time. For this reason, the framework should be understood as a first-stage screening and prioritization tool for strategic planning, not as a substitute for site-scale design, hydraulic modelling, or implementation sequencing.

NbS as a hybrid solution for stormwater mitigation

Green-blue infrastructure offers a broad range of mitigation functions against multiple disturbances but remains vulnerable to environmental stressors. NbS can be conceptualized as hybrid, semi-autonomous, and mutually reinforcing layers of protection that complement traditional grey infrastructure around cities. In this context, integrating NbS should be viewed as a valuable enhancement to existing and planned grey infrastructure interventions for CC adaptation. Our findings emphasize the importance of prioritizing NbS as a flexible and multifunctional approach that provides extensive co-benefits for both people and ecosystems. However, it is crucial to recognize its limitations and ensure that its role is clearly defined within broader adaptation strategies.

Further research is needed to deepen the understanding of NbS hybridity and its capacity to integrate into broader traditional infrastructure networks, enhancing adaptability and resilience. While NbS remains an engineered solution, its strong co-benefits provisioning component offers unique opportunities for dynamic infrastructure planning. For instance, studies on drainage systems highlight the advantages of decentralized or semi-decentralized solutions, which maintain functional connectivity while outperforming both centralized and point-source approaches (Flynn and Davidson, 2016). However, the potential synergies between green-blue and grey infrastructure, particularly in hybrid NbS solutions, remain underexplored (Whelche et al., 2018). While differences between green-blue and grey infrastructure pose integration challenges, they also introduce diversity, which can be leveraged to build multiple layers of resilience (Andersson et al., 2022).

Single hazard vs multiple hazards prioritization

This work studies the effectiveness of NbS in addressing a specific hazard, runoff reduction, while serving as a reference for constructing scenarios to assess additional co-benefits. Although the results demonstrate the multifunctionality of NbS, focusing on a single hazard cannot constitute a comprehensive strategy for managing complex urban challenges. The concept of polycrisis (Lawrence et al. 2024) underscores how tightly interconnected global systems act as conduits for transmitting the causes and effects of cascading crises. In the context of urban CC-related hazards, the connections between wildfires, droughts, and the future occurrence of floods (Alamanos et al. 2023, Brunner, 2023) highlight how risks traditionally treated as isolated are, in fact, deeply interconnected. For effective mitigation, however, it is critical to underscore the cascading effects of hazards and highlight the importance of integrated approaches in CC adaptation strategies. Building on this, future research should aim to explore multi-hazard interconnections through the lens of polycrisis, while also advancing understanding of governance and social dimensions that shape the implementation and effectiveness of NbS.

Role of NbS in systemic changes

Following the analysis of the role of different NbS in driving systemic changes necessary to enhance ecological resilience and biodiversity, notable differences emerge between various solutions. While Porous pavement, as well as many grey and "green-grey" solutions, offer a practical and cost-effective approach, their transformative potential remains limited. Transformative potential, in this context, refers to an NbS's capacity to go beyond immediate functionality and incremental improvements, actively reshaping urban ecosystems, fostering novel socio-ecological relationships, and enabling regenerative and self-sustaining processes (Palomo et al. 2021). These installations are effective in mitigating surface runoff and providing immediate, tangible benefits for urban stormwater management, aligning well with existing human-centric infrastructure. Porous pavement is designed to maintain the status quo in terms of urban land use and accessibility, making it an attractive option for municipalities seeking to address flooding and drainage issues without significant disruptions to urban spaces. However, from a more-than-human perspective (Gordon and Roudavski, 2021) and an ecosystem services provisioning perspective, permeable pavers fail to address the underlying, systemic causes of environmental degradation and do not facilitate the expansion of additional ecological functions. They may alleviate symptoms, but they do not fundamentally challenge the broader patterns of ecological imbalance and loss of biodiversity. In contrast, NbS such as constructed wetlands, urban forests, raingardens, green roofs. These interventions not only manage stormwater but also restore habitat connectivity, enhance soil and water quality, support pollinators and other wildlife, and may foster community engagement in ecological stewardship. By integrating multiple ecological, social, and hydrological functions, these solutions help restructure urban landscapes in ways that promote long-term regenerative processes and resilience, going beyond mere symptom alleviation to address the systemic drivers of environmental degradation.

Modelling limitations:

The estimated runoff reduction provides a first-order indication of how alternative land use and land cover (LULC) configurations influence hydrological responses at the city scale. Consistent with the intended application of InVEST models, designed for strategic planning and scenario comparison rather than detailed hydraulic prediction, the results highlight the relative contribution of NbS to stormwater retention and reductions in total flood volume (Tables 2 and 3). These outcomes should therefore be interpreted as indicative trends rather than precise estimates of flood risk mitigation. Model performance is strongly conditioned by the quality and resolution of input data, including LULC, precipitation, digital elevation models, and soil properties, with uncertainties in these inputs propagating directly into model outputs, particularly in dense and heterogeneous urban environments. In addition, the model relies on a limited set of biophysical parameters, making results sensitive to parameter selection. In this study, biophysical values were primarily drawn from the literature due to limited availability of locally calibrated parameters for Barcelona, introducing additional uncertainty in absolute estimates.

Several process-level simplifications further constrain confidence in localized results. The model does not explicitly represent local surcharging, drainage capacity bottlenecks, or backwater effects, which reduces reliability for street-scale flooding patterns. Soil saturation dynamics during multi-day or compound storm events are also simplified, increasing uncertainty under extreme rainfall conditions. Moreover, the absence of an explicit urban drainage network likely biases the spatial distribution of flooding, although catchment-scale runoff volumes are expected to remain directionally robust. Accordingly, this framework is not intended to replace hydraulic or design-level modelling, which would require detailed sewer network data, continuous rainfall series, calibration datasets, and site-specific NbS designs. Instead, the analysis functions as a screening-level tool to explore spatial patterns, compare scenarios under consistent assumptions, and identify areas with higher potential for NbS deployment. Despite these limitations, the results provide a comparative basis for evaluating alternative NbS pathways at the city scale and support early-stage decision-making by guiding strategic investment and prioritization. Future work should integrate locally calibrated parameters, explicit uncertainty analysis, and coupling with dynamic hydrological models to support progression from strategic planning to detailed design.

Data limitations:

Limitations in data availability and quality significantly affected the application of this method, reflecting challenges widely reported in previous NbS and urban water studies. The accuracy of the results depends on the underlying datasets, which may contain uncertainties. It is therefore essential to transparently communicate data limitations and uncertainties, as well as the rationale for threshold selection (Appendix A).

A key constraint for fully integrated SETS assessments was the limited availability of technological data on urban drainage systems. The lack of open information on sewer network characteristics and operational rules prevented a transition from runoff-based estimates to system-performance-based flood and water quality assessments. Without such data, it is not possible to robustly simulate flow routing, storage dynamics, surcharge conditions, or combined sewer overflows. This limitation is not unique to Barcelona but represents a broader global challenge, as detailed drainage and flood modelling data typically require substantial institutional collaboration and resources. The absence of open technological datasets constrains methodological rigor, transparency, and accountability in urban water governance. Addressing this gap will require both expanded open-data policies and methodological innovation, including surrogate or reduced-complexity models, proxy drainage networks derived from open data, and hybrid approaches that combine city-scale screening with targeted subcatchment-level modelling.

Finally, uncertainties related to indicator weighting and feasibility assessment could be reduced through stakeholder engagement. Involving practitioners, planners, and communities in co-developing indicators and weights, through workshops or participatory GIS approaches, has been shown to enhance the legitimacy and contextual relevance of NbS assessments (Camacho-Caballero et al., 2024). Although this was beyond the scope of the present study, integrating participatory processes represents an important next step for strengthening the framework and aligning NbS planning with local priorities and governance contexts.

Conclusion

NbS have emerged as transformative approaches to enhance urban resilience by leveraging ES and addressing socio-ecological and socio-technical challenges. However, significant gaps persist in understanding the broader benefits of NbS, their spatial distribution, and their integration into urban planning at the city scale. Addressing these gaps is crucial for advancing CC adaptation in compact urban environments. This study introduces a four-steps SETS-framed integrated assessment, which provides a methodological and conceptual foundation for spatially explicit and interdisciplinary analysis of NbS implementation on the example of Barcelona. The framework is transferable to other urban contexts through adaptation to local planning guidelines, data availability, and policy priorities.

Results show that NbS can substantially reduce stormwater-related risk at local and neighborhood scales, with runoff reductions of up to 35% and risk reductions of up to 47% in highly feasible areas. At the city scale, however, runoff reduction remains modest (approximately 1–6%). Despite these hydrological limitations, NbS provide substantial and policy-relevant co-benefits. Under the ambitious implementation scenario (S2), NbS significantly increase urban water storage (+43%), improve habitat quality (+36%), reduce nutrient exports (≈10%), mitigate heat stress during heatwaves, and nearly halve the population underserved by urban green space. The spatial feasibility analysis further indicates that NbS-compatible green space could expand up to fifteenfold beyond current development patterns, revealing considerable untapped potential for multifunctional urban greening. These scenarios should not be interpreted as ready-to-implement plans or as substitutes for site-scale design, budgeting, or implementation sequencing; rather, they are intended to inform city-scale screening and strategic prioritization.

Methodologically, the proposed framework advances NbS planning by integrating spatial feasibility, risk, and multifunctional benefits within a unified SETS-based approach. While it is intended to support city-scale strategic prioritization and scenario comparison, rather than to identify parcel-level engineering siting for individual NbS interventions or exact pavement retrofits, it supports early-stage decision-making and highlights the importance of integrating NbS within hybrid grey–green–blue infrastructure systems and multi-hazard adaptation strategies to address interconnected urban risks.

Beyond the case-specific application, this work underscores the critical need for models that support multi-criteria spatial planning processes, enhance understanding of the multiple benefits provided by NbS, and facilitate their integration at the city scale. Recognizing transformative approaches in NbS, those that go beyond immediate functionality to actively reshape urban ecosystems and foster regenerative processes, emerges as a key enabler for experimenting with ambitious implementation scenarios and testing their potential systemic impacts (Frantzeskaki et al. 2025). Effective CC adaptation strategies must move beyond addressing individual hazards to consider the interconnected nature of risks, where the occurrence of one hazard, such as wildfire or drought, can increase the likelihood and severity of another, such as future flooding (Alamanos et al. 2023, Brunner, 2023). This perspective on polycrises emphasizes the cascading effects of hazards and highlights the importance of integrated approaches in CC adaptation strategies.

Policy and Urban Planning Recommendations

1. Position NbS as multifunctional planning instruments, not single-purpose flood controls

Our results show that while NbS alone deliver limited city-scale runoff reduction, they generate substantial co-benefits across heat mitigation, water storage, habitat quality, and access to green space. Urban policies should therefore prioritize NbS for their combined social–ecological value rather than judging their effectiveness solely through flood-volume reduction metrics.

2. Integrate NbS within hybrid grey–green–blue infrastructure strategies

Given the modest flood mitigation achieved under extreme rainfall, NbS should be embedded within broader infrastructure portfolios that include upgraded drainage networks, storage facilities, and smart control systems. Hybrid solutions can enhance system flexibility, reduce pressure on overburdened sewers, and improve performance under lower- to medium-intensity events.

3. Use spatially explicit feasibility assessments to unlock latent NbS potential

The finding that NbS-compatible green space could expand up to 15-fold highlights the importance of spatial feasibility analysis in dense urban contexts. Planning authorities should adopt feasibility tools, such as SETS-based MCDA approaches, to identify where NbS are both physically and institutionally implementable.

4. Prioritize NbS with higher transformative potential where space allows

Results indicate clear differences between NbS types: interventions such as urban forests, wetlands, raingardens, and green roofs deliver broader and more durable ecological and social benefits than primarily hydrological, green–grey measures (e.g., porous pavements). Planning frameworks should therefore differentiate between NbS that maintain the status quo and those capable of driving systemic ecological change.

5. Embed NbS planning within multi-hazard and polycrisis adaptation strategies

Focusing on single hazards risks underestimating cascading and compounding impacts. NbS strategies should be integrated into multi-hazard adaptation plans that explicitly consider interactions among flooding, heatwaves, droughts, and ecosystem degradation, thereby strengthening long-term urban resilience.

6. Improve data accessibility and participatory processes to strengthen NbS governance

The study highlights how limited access to drainage system data constrains model accuracy and accountability. Policymakers should invest in open data infrastructures for urban water systems and support participatory approaches that involve planners, practitioners, and communities in co-developing NbS priorities, indicators, and implementation pathways.

Data availability

The input data used in all fours steps of the analysis is openly available at Zenodo dataverse (https://doi.org/10.5281/zenodo.17659096).

Code availability

Source code for the InVEST software is available at: https://github.com/natcap/invest.

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Declaration of Competing Interest

The authors declare not to have any conflict of interest.

Highlights

- A SETS-based GIS framework evaluates NbS needs, feasibility, and performance
- Feasibility analysis shows potential to expand green area up to ninefold
- NbS assessed for runoff mitigation and five socio-ecological co-benefits
- In Barcelona, runoff reduction is modest, but co-benefits show strong value
- The proposed framework is transferable to other urban contexts