Nature's integration in cities' hydrologies, ecologies and societies

D4.1 Integrated assessment framework

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1 Summary

The research focuses on the development of an integrated multi-criteria decision analysis framework to evaluate nature-based solutions (NBS) scenarios in urban areas, specifically addressing conflicting social preferences, environmental risks, and ecosystem services (ES) provisioning. The report summarizes the integration of results from WP2 and WP3, focusing on the evaluation of risk assessment, creation of NBS scenarios, and assessment of their capacity to reduce risks, as well as the provisioning of ES.

The framework was then tested and refined within the core NICHES case-study cities: Barcelona, Boston, and Rotterdam, providing essential insights for developing transition pathways (T4.3) and ensuring the effective application of NBS in urban water management systems.

2 List of abbreviations

EU	European Union
NBS	Nature-based solutions
ES	Ecosystem services
SETS	Social-Ecological-Technological Systems
CC	Climate Change

3 Introduction

Urban areas, where the majority of the global population resides, face increasing challenges due to climate change (CC) and rapid urbanization (UN-Habitat, 2022). Climate-related hazards threaten citizens' health and wellbeing while compromising urban infrastructure (IPCC, 2022). Traditionally, urban systems have relied on grey infrastructure, designed to address a single function per system (Kremer et al., 2016; Dhakal & Chevalier, 2017; Raymond et al., 2017), but these solutions often fail to account for uncertainties, such as those introduced by climate change. To address these challenges, Nature-Based Solutions (NBS) have emerged as a promising approach to enhance urban resilience (McPhearson et al., 2015). NBS offer a range of benefits, including enhancing biodiversity, improving resilience, and addressing environmental and social challenges (UN, 2022). Compare to the concept of green infrastructure, NBS are often praised for their multifunctionality, as they extend beyond a narrow set of benefits, particularly those related to stormwater and flood management (Venkataramanan et al., 2019, Meerow 2019). One core concept of NBS, the provision of co-benefits remains underexplored (Hanson et al., 2020). Understanding the more complex picture of needs, opportunities, and synergies of these co-benefits is essential for effective urban planning (Haase et al., 2014; Kremer et al., 2016; Penning et al., 2023).

This study presents an integrated multi-criteria decision analysis framework, emphasizing spatially explicit analyses of urban needs, opportunities, and constraints for integrating NBS in sustainable stormwater management at the city scale. The framework was developed and tested in the core NICHES case study cities: Barcelona, Boston, and Rotterdam.

4 Conceptual framework

Overcoming the persistent sectoral divides that dominate spatial infrastructure planning is critical, particularly for integrating diverse knowledge systems. Although numerous scholars have highlighted the importance of breaking these barriers in theory (Paul et al., 2017; Muñoz-Erickson et al., 2017), the translation of such ideas into practical methodologies remains a significant challenge (Ramsey et al., 2019). Addressing these limitations requires an interdisciplinary approach that bridges gaps across disciplines and sectors.

The Social-Ecological-Technological Systems (SETS) framework (Fig.1), proposed by McPhearson et al. (2016), serves as an effective tool for achieving such integration. SETS are framed as an interconnected system of social, ecological, and technological domains (Chester et al., 2023), where interactions between and within these domains are considered "couplings." Recognizing these interdependencies is key to fostering sustainable urban transformations that maximize synergies, minimize trade-offs, and account for cascading impacts (Helmrich et al., 2023). For example, the capacity of use of NBS as a tool for urban adaptation is heavily moderated by social, ecological and technological factors (McPhearson et al., 2022).

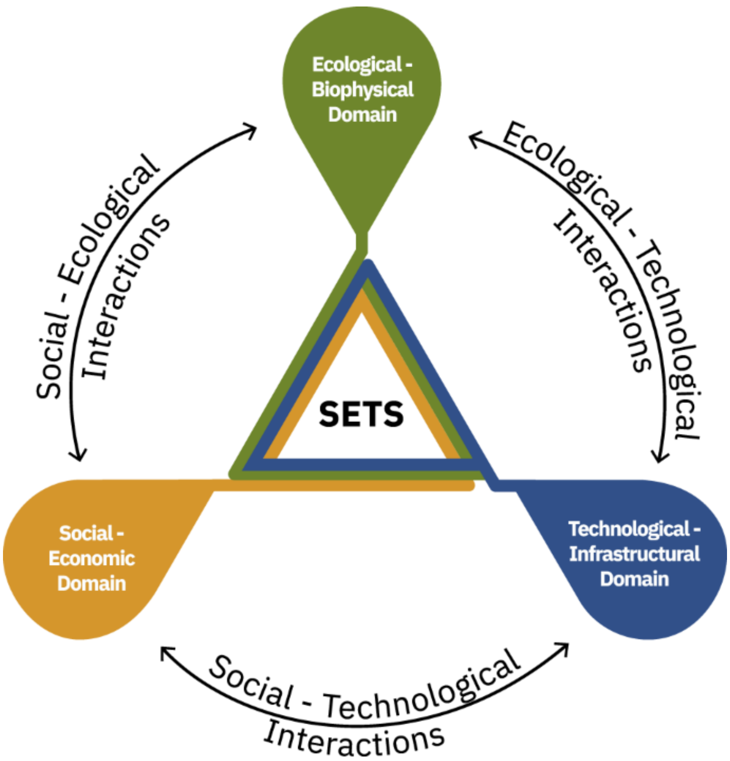


Figure 1. Conceptual framework (adapted from McPhearson et al. 2021)

Building on the SETS framework, the integrated assessment approach for NBS in urban planning connects policy analysis with transitioning pathways by enabling a holistic evaluation of social, ecological, and technological interactions. Beyond the technical planning and evaluation of NBS, it is essential to understand the role of existing policy structures in their successful implementation, identifying current patterns and potential opportunities. Integrated assessment plays a central role in the NICHES project by bridging the gap between policy analysis and the practical implementation of NBS (Fig. 2). Building on policy analysis findings, integrated assessment offers a systematic framework for evaluating the social, ecological, and technological implications of NBS scenarios. This approach is vital for co-defining transition pathways, which involve large-scale changes in system properties, infrastructures, and overall system structure, with the potential to use external forces like policies to achieve the desired goals of urban adaptation strategies. By incorporating spatially explicit analyses of urban needs, opportunities, and constraints for integrating NBS in sustainable stormwater management at the city scale, integrated assessment ensures that transition pathways are not only feasible but also socially and environmentally sustainable.

Figure 2. Task framing withing NICHES project workflow

5 Methodological framework

The methodological framework (Fig.1) developed for this study employs a GIS-based approach, drawing on the work of Langemeyer (2016) and Langemeyer and Baró (2021). It follows a four-step analysis to assess the potential of nature-based solutions (NBS) in urban areas.

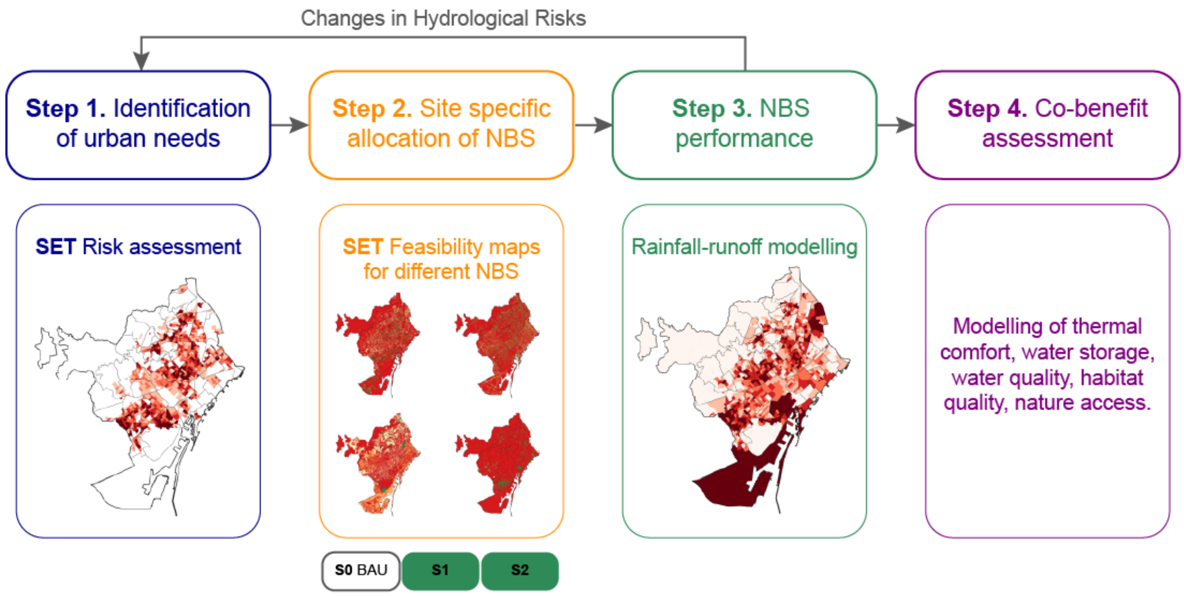


Figure 3. Example of methodological framework applied to the Barcelona Municipality

The first step utilizes the SETS-framed (McPhearson et al., 2016; Chang et al., 2021) risk assessment developed in T3.1 “Community vulnerability assessment” to identify urban areas most vulnerable to stormwater-related hazards with the identify area with higher potential for NBS integration for mitigating existing risk.

The second step focuses on T2.3, NBS scenario development, assessing the feasibility of integrating NBS into the urban landscape. This evaluation is based on a system of SETS indicators, which are used to categorize areas from fully feasible to non-feasible for NBS implementation.

In the third step, based on T2.4, the performance of NBS is evaluated by analyzing runoff reduction and assessing how NBS integration can reduce the risks identified in the first step.

The final step involves evaluating the additional co-benefits provided by NBS, such as improvements in thermal comfort, recreation, water storage, habitat provisioning, and water quality.

This delivery specifically demonstrates the application of the framework using the case study of Barcelona.

5.1 Case study of Barcelona

Barcelona, the capital of Catalonia, Spain spans approximately 101 km² and is home to around 1.6 million residents (2021), making it one of Europe's most densely populated cities (Baró et al., 2014). The city experiences a Mediterranean climate with annual rainfall of about 600 mm, often concentrated in intense storms that contribute to flooding and combined sewer overflows (Llasat et al., 2022; Cortès et al., 2018). Projections indicate a 15% increase in extreme rainfall events by mid-century, with century-scale storm intensities rising by 20–40% (SUDS Commission, 2020).

To address these climate challenges, the Barcelona Nature Plan 2030 aims to provide 1m² of green space per resident, adding 160 hectares of new green areas, alongside an expansion of green roof coverage to 22,000 m² (Municipal Urban Ecology Agency). This study's spatial framework supports these efforts by guiding NBS implementation, assessing their scalability in a dense urban environment, and evaluating their role in mitigating stormwater-related hazards while delivering additional co-benefits.

5.2 Changes in hydrological risks

This step advances a previously developed methodology and theoretical framework for assessing stormwater-related hazards and their impacts on urban communities (D3.1). It is intended to complement T2.1 by mapping vulnerabilities of urban communities to stormwater related hazards like pluvial flood and combined sewer overflow within socio-ecological-technological systems. All detailed explanations of methodology, indicators selection and justification could be found in deliverable 3.1 and Khromova et. al (forthcoming).

5.3 Feasibility assessment and scenarios development

This step refines a previously developed methodology for NBS allocation (D2.3), selecting five NBS types relevant to stormwater management. Green roofs, rain gardens, porous pavement, and urban parks were assessed based on social, ecological, and technological indicators. Feasibility maps were generated using spatial data and geometric mean aggregation, categorizing areas by suitability. All detailed explanations of methodology, indicators selection and justification could be found in deliverable 2.3 and Khromova et. al (forthcoming).

Two NBS implementation scenarios were developed: Scenario 1 (S1) aligns with Barcelona's Nature Plan 2030, adding 160 hectares of green space, while Scenario 2 (S2) prioritizes high-feasibility areas from previous step.

5.4 Rainfall-Runoff Modeling

For performance assessment, we used InVEST® Urban Flood Risk Mitigation (version 3.14.2) to model runoff in the watershed, applying the SCS-CN method (USDA, 1972; Muche et al., 2019). Runoff retention at the catchment outlet was calculated using rainfall, land use data, and soil hydrologic groups (Natural Capital Project, 2023).

5.5 Impact on Risk

NBS were evaluated for their potential risk reduction, focusing on vulnerable census tracts. Using the methodology developed in deliverable 3.1, also showcased in Khromova et al. (forthcoming) and Langemeyer et al. (forthcoming), we calculated risk scores for different scenarios (S0, S1, S2), comparing the percentage changes in risk with ArcGIS.

5.6 Co-benefits of NBS

5.6.1 Water Storage

NBS promotes groundwater recharge, supporting drought contingencies (Russo et al., 2020). InVEST's Urban Stormwater Retention module was used to model aquifer recharge from NBS, with input data on LULC, soil groups, and precipitation.

Indicator	Type	Spatial Scale / Value	Year	Source/ Reference
Map of average annual precipitation	geotif			Average annual precipitation (mm) 1991-2020 Servei Meteorològic de Catalunya
LULC categories	geotif	0.75m	2019	LULC estimation based on NDVI
Biophysical Table of runoff and percolation coefficients	csv		2024	Estimation based on Muche et al, 2019 (CN), NRCS-USDA 2004, InVEST user guide
Soil hydrologic groups	geotif	250m	2018	Global Hydrologic Soil Groups (HYSOGs250m) for Curve Number-Based Runoff Modeling

Table 1. Indicators used as an input for urban stormwater retention module

5.6.2 Water Quality

NBS were assessed for nutrient retention (nitrogen and phosphorus), using InVEST's NDR module (Björklund et al., 2018). The model calculates nutrient export and retention based on land use, slope, and flow paths (InVEST, 2023).

Indicator	Type	Spatial Scale / Value	Year	Source/ Reference
Digital Elevation Model	geotif	0.5m	2017	Institut Cartogràfic i Geològic de Catalunya
LULC categories	geotif	1m	2018	Institut Cartogràfic i Geològic de Catalunya
Nutrient runoff proxy	geotif		2024	Average annual precipitation (mm) 1991-2020 Servei Meteorològic de Catalunya
Table with biophysical properties	csv			U.S. Environmental Protection Agency (EPA) estimations
Threshold flow accumulation	number			1000 (InVEST user guide)
Borselli K parameter	number			2 (InVEST user guide)

Table 2. Indicators used as an input for nutrient delivery ratio (NDR) module

5.6.3 Habitat Quality

Biodiversity services were assessed through InVEST's Habitat Quality module, which evaluates habitat sensitivity and threats (Zhang & Ramírez, 2019). This model uses land cover data and threat proximity to estimate habitat degradation.

Indicator	**Type**	**Spatial Scale / Value**	**Year**	**Source/ Reference**
Current LC categories	geotif	1m	2018	Institut Cartogràfic i Geològic de Catalunya
Future LC categories	geotif	1m	2024	Elaboration based on developed S1 and S2
Threats table	csv			Adapted from Wu et al. 2021, INVEST user guide
Sensitivity table	csv			Estimations based on InVEST user guide
Half-saturation constant	number	0.05		default value from InVEST user guide

Table 3. Indicators used as an input for habitat quality and rarity module

5.6.4 Nature Access

Given Barcelona's limited green space (Baró et al., 2014), InVEST's Urban Nature Access module assessed both supply and demand for recreational areas, critical for residents' well-being (Triguero-Mas et al., 2015). The model uses population density, LULC data, and nature demand per capita.

Indicator	Type	Spatial Scale / Value	Year	Source/ Reference
LULC categories	geotif	1m	2018	Institut Cartogràfic i Geològic de Catalunya
Table with LULC codes	csv			Radiuses suggested in Ta et al, 2022 and Claron et al, 2022
Population density	csv	Census tract	2021	INE Población por sexo, Sección y edad (grupos quinquenales). (ine.es)
Per capita demand for urban nature (m^2)	number	9m2		Target recommended by the WHO
Administrative Boundaries	shp			Barcelona city boundaries
Search radius Mode	parameter			300 m (walking distance)
Decay Function	parameter	Exponential		A distance-weighted exponential decay function, where people are more likely to visit the nature closest to them, with likelihood falling off exponentially out to the maximum radius.

Table 4. Indicators used as an input for urban nature access module

All detailed information, input data and references for all modules are available in Khromova et. al (forthcoming).

6 Results and discussion

Following the feasibility assessment (D 2.3), two NBS scenarios were developed (Fig. 4):

- Scenario 1 (S1): This scenario integrates city planning targets, aligning with the Barcelona Nature Plan 2030 goal of providing $1m^2$ of green space per resident by 2030. This translates to the creation of 160 hectares of new green areas.
- Scenario 2 (S2): This scenario prioritizes areas with the highest feasibility, selecting all NBS from the first of five feasibility groups. This approach results in a total implementation area of 2498 hectares.

While scenarios for assessing the effectiveness of NBS often focus on ecological and technological feasibility, we put forward the argument that explicitly including social factors promoting or limiting certain developments can lead to more in-depth results. In doing so, we aim to do justice to Anguelovski and Cobera's (2023) call for rigorous assessment of the capacity of NBS to deliver benefits.

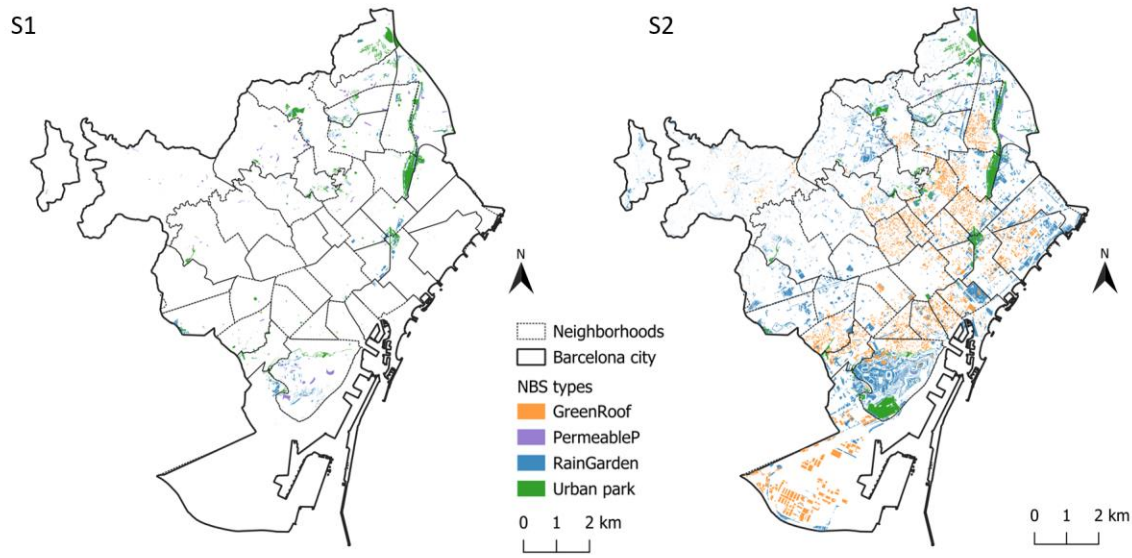
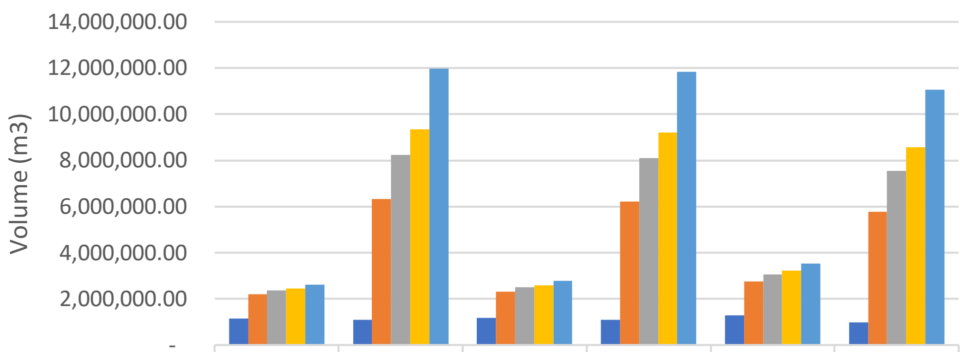


Figure 4. Combined maps of NBS distribution for S1 and S2.

6.1 NBS performance assessment

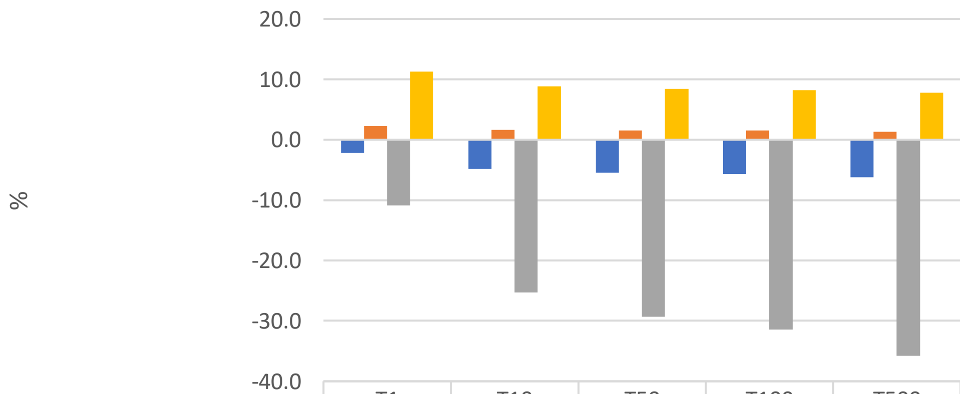
The performance assessment of runoff retention volume and flood volume for the current LULC (S0), S1, and S2, as well as the flood volume for storms with return periods of T1, T10, T50, T100, and T500, is presented in Table 2.



	S0 runoff retention volume (m3)	S0 flood volume (m3)	S1 runoff retention volume (m3)	S1 flood volume (m3)	S2 runoff retention volume (m3)	S2 flood volume (m3)
T1	1,149,670	1,106,404	1,175,182	1,080,893	1,274,123	981,953.0
T10	2,197,887	6,321,698	2,304,950	6,214,632	2,754,661	5,764,901
T50	2,369,829	8,228,737	2,498,360	8,100,221	3,065,056	7,533,502
T100	2,450,785	9,334,311	2,590,415	9,194,686	3,220,414	8,564,666
T500	2,607,305	11,986,45	2,770,343	11,823,41	3,539,015	11,054,75

Table 5. Performance assessment results.

The runoff 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 T1 to T500 for both S1 and S2, ranging from 2.3% to 1.4% and 11.2% to 7.8%, respectively. Conversely, an increase in the percentage of retention volume compared to S0 was noted for both S1 and S2, ranging from -2.2% to -6.3% and -10.8% to -35.7%, respectively.



	T1	T10	T50	T100	T500
%S1 retention volume to S0	-2.2	-4.9	-5.4	-5.7	-6.3
% S1 flood volume to S0	2.3	1.7	1.6	1.5	1.4
% S2 retention volume to S0	-10.8	-25.3	-29.3	-31.4	-35.7
% S2 flood volumes to S0	11.2	8.8	8.4	8.2	7.8

Table 6. Performance assessment results.

The InVEST Urban Flood Risk Mitigation model results show a maximum flood volume reduction of 11.2% between scenarios S0, S1, and S2 during storm events (T1, T10, T50, T100, T500) (Table 3). While this reduction seems modest, it reflects the strain on the existing drainage system, which frequently faces CSO events. NBS interventions could improve runoff retention by 1.4% to 11.2%, reducing runoff volumes by up to 931,707 m^3. Combined with existing flood mitigation infrastructure (e.g., underground reservoirs and sewer pipes), these interventions could help reduce CSO events and mitigate flooding during low-intensity storms.

While runoff reduction is a useful metric, it doesn't fully capture the spatial distribution of water in the drainage system, limiting its assessment of stormwater risk. However, NBS still show a positive impact on water retention and flood volume (Table 2, Table 3), potentially improving stormwater management in vulnerable areas. While these results can't predict future conditions with certainty, they offer valuable insights for informed urban water management decisions.

6.1.1 Impact on risk

Regarding the impact on risk scores, a significant reduction of up to 55% relative to S0 is observed for both S1 and S2, particularly in areas influenced by NBS interventions such as rain gardens and large urban parks (Fig. 5). 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.

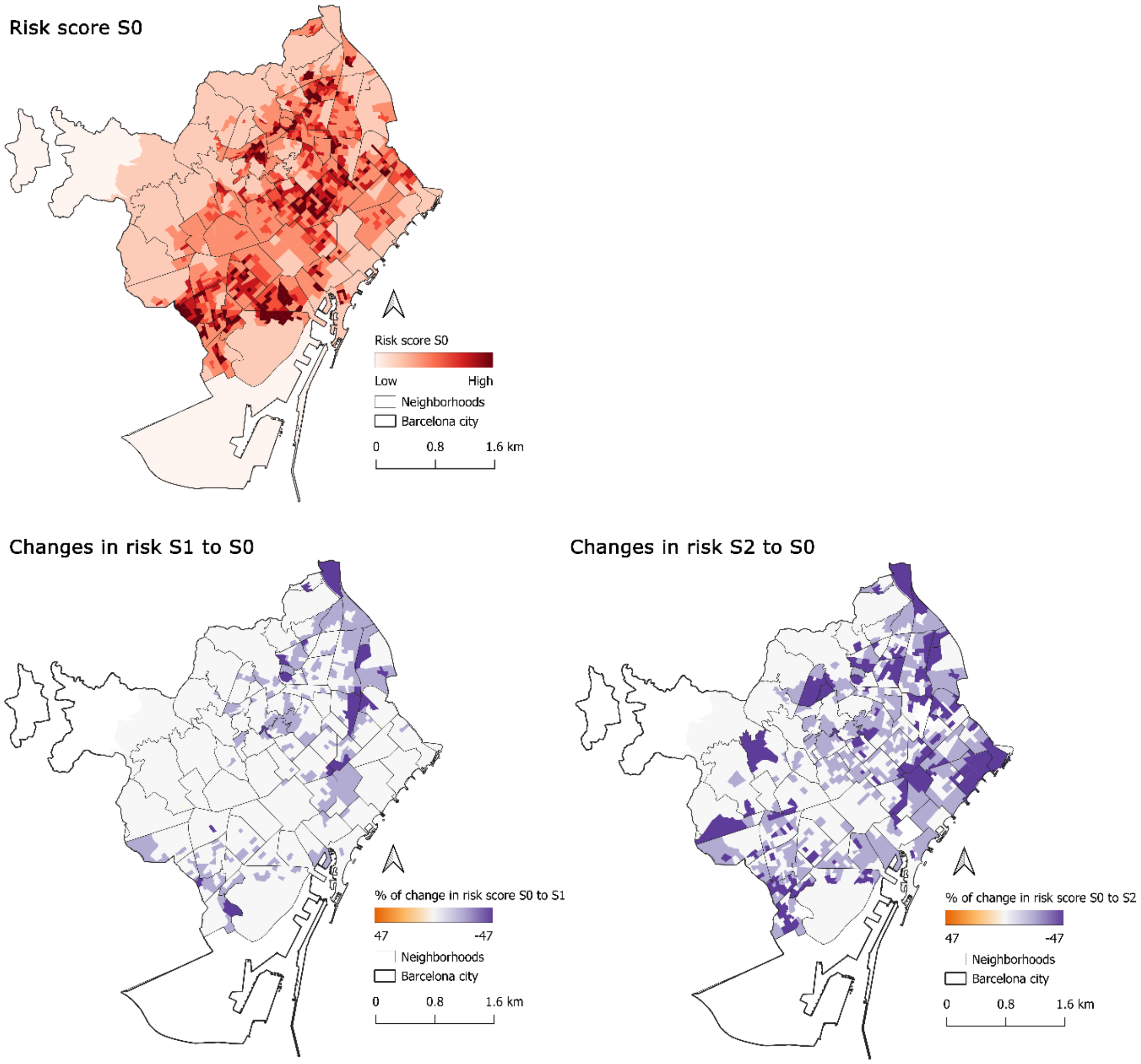


Figure 5. Changes across scenarios S1 and S2 compared to S0 in spatial distribution of risk of stormwater related hazard.

6.2 Co-benefits provided by NBS

6.2.1 Water Storage

Regarding water storage, measured as the total percolation volume, representing the potential aquifer recharge within the study area (Barcelona city) over a given time period (one year), an increase was observed for both S1 and S2. Specifically, the total percolation volume increased by up to 8.8% for S1 and 58.4% for S2 compared to the baseline scenario (S0).

	S0	S1	S2	% S1 to S0	% S2 to S0
Total percolation volume (m^3/year)	3,206,250	3,490,291	5,079,064	-8.8	-58.4

Table 7. Water storage modelling outputs.

6.2.2 Habitat Provisioning

Regarding the habitat provisioning modeling outputs for ecosystem quality per administrative unit, an increase is observed for both S1 and S2, with improvements of 3.6% and 36.2%, respectively.

	S0	S1	S2	% S1 to S0	% S2 to S0
Mean value for quality of ecosystems	0.0029	0.0030	0.0042	-3.6	-36.2

Table 8. Habitat provisioning modelling outputs.

6.2.3 Water quality

Regarding the water quality modelling outputs for nitrogen (N) and phosphorus (P) surface export and surface load per watershed, a reduction is observed across all indicators. The reduction ranges from 1.9% to 2.5% when comparing S0 and S1, and from 6.9% to 10.6% when comparing S0 and S2 for all indicators.

	S0	S1	S2	% S1 to S0	% S2 to S0
N surface load (kg/ year)	113947	111,698.7	105,599.4	1.9	7.3
N surface export (kg/ year)	31,497.26	30,689.4	28,154.8	2.5	10.6
P surface load (kg/ year)	15,692.03	15,411.28	14,609.06	1.7	6.9
P surface export (kg/ year)	4,036.063	3,937.71	3,628.548	2.4	10.1

Table 9. Water quality modelling outputs.

6.2.4 Nature Access:

Regarding the urban nature access modelling outputs for the total population within the administrative unit that is undersupplied (defined as areas where the demand for accessible green space exceeds the available supply) with urban nature, a significant reduction is observed. The reduction is 13.7% when comparing S0 and S1, and 49.9% when comparing S0 and S2.

	S0	S1	S2	% S1 to S0	% S2 to S0
Population undersupplied with urban nature	262.6	226.5	131.4	13.7	49.9

Table 10. Nature Access modelling outputs.

7 Conclusion

NBS are key for enhancing urban resilience by addressing socio-ecological and socio-technical challenges, but gaps remain in understanding their broader co-benefits and integration into urban planning. This study presents a five-step SETS-based framework for assessing NBS implementation in Barcelona, focusing on stormwater management and green development strategies.

Using Barcelona as a case study, the research shows that NBS can reduce stormwater-related risks by up to 55% in some areas. While runoff reduction is modest (1-10%), NBS demonstrate significant co-benefits, including a 49% improvement in recreational opportunities, a 58% increase in water storage, a 10% reduction in nutrient exports, and a 36% improvement in habitat quality.

The feasibility study indicates that areas with NBS could be expanded 15 times compared to current urban strategies, sparking a discussion on the potential for large-scale integration in dense urban environments like Barcelona. This research emphasizes 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. Effective CC adaptation strategies must move beyond addressing individual hazards to consider the interconnected nature of risks.

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9 Annex