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Integrating risk and feasibility in the spatial planning of nature-based solutions: a cross-city analysis of Barcelona, Boston, and Rotterdam

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Urban areas increasingly turn to nature-based solutions (NbS) to adapt to climate-related risks, which require integrated and systemic planning evaluating risks and feasibility of implementation. Here, we develop a transferable, SETS-based decision-support framework that spatially analyzes multi-hazard climate risk and feasibility for four NbS types: green roofs, permeable pavements, rain gardens, and urban parks, across Barcelona, Boston, and Rotterdam. Integrating spatial and statistical analyses, we identify where different kinds of NbS are both most needed and most feasible for mitigating urban flooding and heat stress. Results reveal strong spatial clustering of risks and feasibility across all cities, with heat risk showing the highest spatial autocorrelation. Across cases, green roofs and permeable pavements consistently exhibit high feasibility in dense, heat-prone urban areas, whereas rain gardens and urban parks are constrained by land availability and underground infrastructure. The comparative analysis highlights how urban morphology, governance structures, and socio-economic factors shape feasibility for NbS implementation. Overlaying risk and feasibility identifies priority high risk–high feasibility zones for rapid implementation and flags high-risk/low-feasibility neighborhoods where infrastructure deficits and vulnerability may constrain adaptation, supporting more justice-oriented, context-sensitive NbS planning.

Urban areas face an increasingly complex array of risks and challenges. Rapid urbanization places mounting pressure on natural ecosystems, exacerbating environmental degradation, and intensifying climate-related hazards[1]. Consequently, the UN International Strategy for Disaster Reduction highlights the growing vulnerability of cities to climate change, which poses significant threats to public health, disrupts critical services, and strains essential infrastructure[2]. Moreover, the intricate interdependence of urban systems amplifies these vulnerabilities, underscoring the need for strategic and integrative approaches to adaptation planning[3]. The dense interconnectedness of critical infrastructures means that climate-induced shocks in one domain, such as flooding, can cascade across transport, health, energy, and other essential services[4]. Yet, as hubs of population, infrastructure, and economic activity, cities are also at the forefront of climate change adaptation, serving as dynamic arenas where strategies are developed, tested, and refined[5,6].

Many cities are turning to urban greening as a response to the complex challenges of climate change[7]. Along these lines, interest and investment in nature-based solutions (NbS) are steadily growing, as they are among the most frequently proposed strategies for mitigating climate-related hazards while simultaneously delivering sustainability and resilience co-benefits[8]. 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*"[9]. In contrast to single-function gray infrastructure, NbS are valued for their ability to deliver

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multiple benefits, including reduced runoff, mitigation of daytime temperatures during heatwaves, enhanced biodiversity, and provision of recreational spaces[10,11]. Despite the particular importance of multifunctionality in dense urban environments, it remains insufficiently integrated into urban infrastructure transition planning[12,13].

The risk-mitigating benefits provided by NbS have received different levels of attention. For example, existing research places greater emphasis on stormwater management than on heat mitigation, reflecting a larger and more mature body of literature and more established methodological approaches[7]. Arguably, this divergence stems from disciplinary silos that often treat climate adaptation strategies in isolation[14], overlooking the NbS potential to address multiple challenges simultaneously[10]. This fragmented approach complicates efforts to plan and implement NbS in an integrated, multifunctional manner and undermines holistic urban resilience improvements. Evaluating multi-hazard applications is crucial for capturing the broad value of NbS, moving beyond isolated measures to a more comprehensive understanding of their impacts[15].

The hazards mitigation potential of NbS are inherently localized, meaning that the placement of interventions directly shapes which areas and which residents' benefit[7]. Existing research suggests that the cooling effects of urban parks tend to diminish with distance, pointing to potential environmental justice implications in the spatial distribution of NbS[16]. Despite this, efforts to incorporate both social and ecological benefits into city-wide NbS planning remain limited. There is a clear need for practical, integrated tools to support such planning[17]. NbS have been assessed through their ecological functions. While research is increasingly incorporating social outcomes, the ways NbS interact with urban technologies and infrastructures remain underexplored. This persistent gap limits both theory and application, often leading to piecemeal implementation, variable effectiveness, and weak arrangements for long-term maintenance and governance[18–21].

Addressing these limitations requires system-based approaches capable of capturing the complexity and interdependence of urban climate adaptation challenges[8]. The social–ecological–technological systems (SETS) framework conceptualizes cities as entangled systems where social, ecological, and technological domains are understood as tightly coupled rather than as separated subsystems[22]. By integrating insights across disciplines, SETS provides a holistic lens for understanding urban systems and enhances the planning and deployment of NbS to address both environmental and societal needs[14,18]. This perspective helps anticipate cascading effects and avoid maladaptation. Without such systems thinking, even well-intentioned NbS can undermine the very goals they seek to achieve. For example, poorly sited rain gardens designed to manage runoff may fragment or degrade habitats for amphibians and other sensitive fauna, weakening local ecological resilience. Likewise, flood-risk restoration projects that overlook meaningful engagement with affected residents can trigger social displacement, concentrating vulnerabilities among already marginalized communities[23].

This study addresses the described research and planning gaps by applying a SETS lens (a) to identify spatial needs for NbS integration through a risk-based approach[2] and (b) to explore spatial opportunities through an NbS feasibility analysis. In this study, feasibility is understood as a screening-level measure of spatial suitability and theoretical land-use convertibility, rather than as a direct estimate of immediate implementation readiness. The approach is applied across three coastal cities, Barcelona (Spain), Boston (USA), and Rotterdam (Netherlands). These cities represent diverse climatic zones, urban morphologies, and governance structures, providing a robust comparative basis. The framework integrates spatial indicators of hazard, exposure, and SETS vulnerability to map flood and heat risks. It combines them with indicators of feasibility across four NbS types: green roofs, permeable pavements, rain gardens, and urban parks. Using spatial and statistical analyses, including correlation and clustering metrics, we explore how risks and opportunities for NbS implementation align or diverge across contexts. This study makes three key contributions. (1) It introduces an integrated risk–feasibility framework that bridges social, ecological and technological dimensions of NbS planning. (2) It provides one of the few cross-city, multi-hazard comparative analyses of NbS potential, revealing both generalizable and place-specific adaptation patterns. (3) It offers a replicable, decision-support approach for planners to identify where NbS are simultaneously most needed and most feasible, supporting equitable and multifunctional urban adaptation.

Results

General overview

The Results section presents first the spatial distribution of flood and heat risk, then the spatial feasibility of different NbS types, and finally the statistical relationships among risk, feasibility, and their underlying indicators. Flood and heat risk are calculated following the IPCC risk framing[24] as the interaction of hazard, exposure, and SETS vulnerability. SETS vulnerability integrates social, ecological, and technological indicators that condition vulnerability of urban communities. The full methodological procedure is described in the methods section, with indicator definitions, data sources, and formulas provided in Supplementary Section A and Supplementary Table S2. NbS feasibility is calculated separately for each NbS type using NbS-specific social, ecological and technological indicators. The full procedure is described in the methods section, with classification criteria, thresholds, formulas, and indicator rationales provided in Supplementary Section B and Supplementary Tables S3–S6.

Spatial analysis

Figures 1–5.

Statistical analysis

Spatial autocorrelation analysis using Moran's I (Table 1) revealed strong and statistically significant positive spatial autocorrelation (Moran's I between 0.5 and 1.0; $p < 0.01$), confirming that both climate risk exposure and NbS feasibility are spatially clustered rather than randomly distributed. The accompanying Z-scores, which quantify the degree to which the observed patterns deviate from spatial randomness, are exceptionally high across all indicators, further reinforcing the robustness of these clustering effects. Heat risk shows the strongest clustering (Moran's I = 0.9–1.0), particularly pronounced in Rotterdam, where values approach a near-continuous spatial field due to large homogeneous zones. Barcelona and Boston also exhibit strong heat-risk clustering, though with slightly more internal variation. Flood risk displays moderately strong clustering (Moran's I = 0.6–0.8), with Rotterdam again showing the most spatial concentration, while Barcelona and Boston present more localized flood-risk hotspots. Feasibility metrics show moderate to strong clustering in all cities (Moran's I = 0.5–0.7), reflecting spatially coherent patterns.

Cross-case Pearson correlation analysis revealed distinct yet converging patterns in how socio-environmental and technological drivers shape climate-related risks across Barcelona, Boston, and Rotterdam. Vulnerability indicators (Table 2), particularly social vulnerability and SETS vulnerability, show strong linear correlations with exposure ($r = 0.73$ and $r = 0.77$, respectively) and with heat risk ($r = 0.61$ and $r = 0.69$) in Rotterdam. In Boston, moderate correlations are observed between social vulnerability and exposure ($r = 0.30$), as well as between social vulnerability and heat risk ($r = 0.43$). For Barcelona, moderate linear relationships are found between heat hazard and exposure ($r = 0.53$), and between flood hazard and flood risk ($r = 0.57$), while the relationship between heat hazard and heat risk is comparatively stronger ($r = 0.63$).

Socioeconomic indicators (Table 3), especially living below the poverty line, emerged as critical determinants of climate risk, with Rotterdam again standing out due to strong correlations with both flood ($r = 0.63$) and heat risk ($r = 0.73$). Technological factors such as impervious surfaces were highly predictive of heat-related risks in Barcelona ($r = 0.79$) and Rotterdam ($r = 0.60$), underscoring the influence of urban morphology. Ground slope consistently showed negative correlations with risk and exposure, particularly in Barcelona, suggesting its mitigating role in hazard intensity. Linguistic barriers and age-related demographics showed moderate but

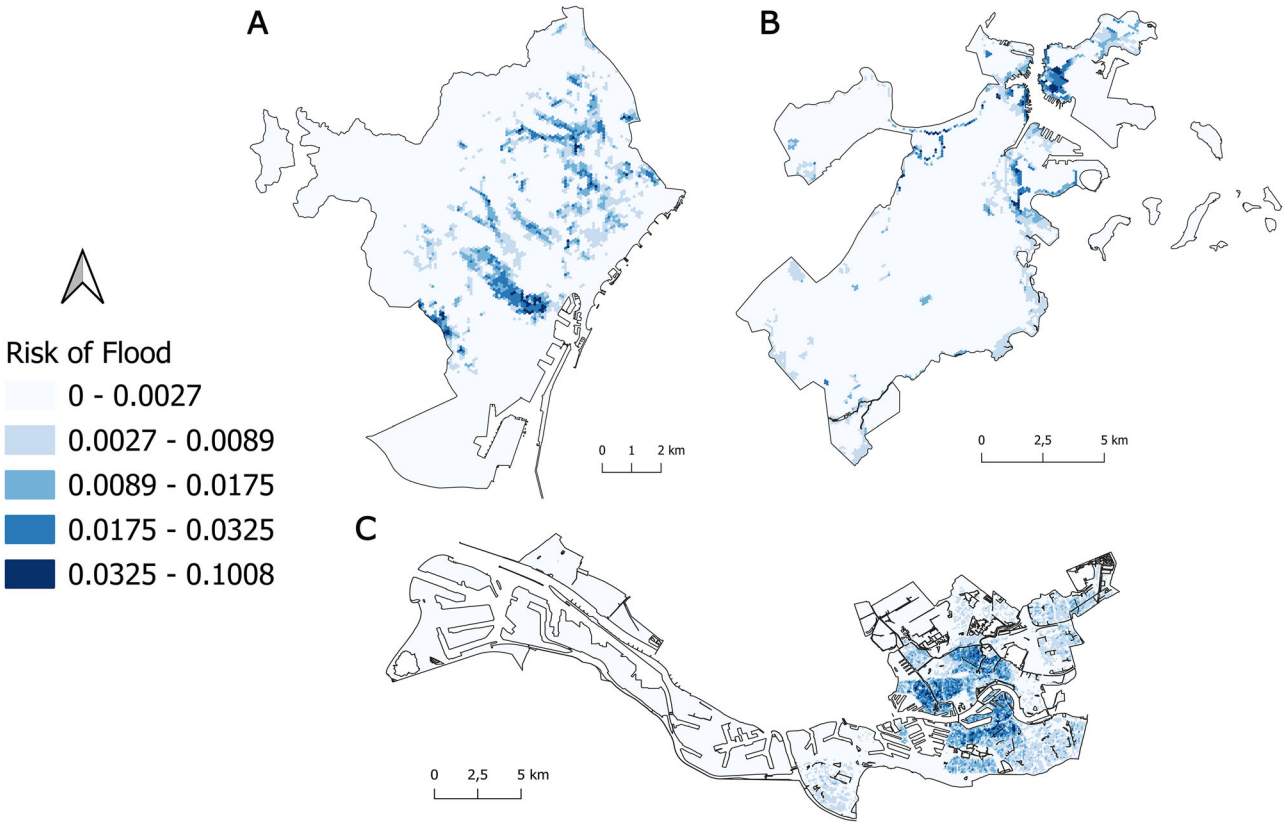


Fig. 1 | Spatial distribution of pluvial flood risk across case studies based on the IPCC 2012 hazard–exposure–vulnerability framework. A Barcelona, **B** Boston, **C** Rotterdam. Flood risk was calculated for each 100 × 100 m grid cell as the geometric mean of three components: hazard (1-in-100-year pluvial flood depth, mm), exposure (population density), and social–ecological–technological systems (SETS) vulnerability, which combines social, ecological, and technological indicators (see Methods). Risk scores are displayed using a five-class graduated color scale from pale blue (lowest risk) to dark blue (highest risk), with class breaks determined by natural (Jenks) breaks and shown in the legend (range 0–0.1008). a) Barcelona: high-risk cells (dark blue) are concentrated in the central, central-west, and north-east districts, following the downhill fluid dynamics of pluvial runoff from the surrounding hills toward the coast. b) Boston: high-risk cells are concentrated in the northern coastal areas, with additional clusters in the central-east and central-west, and smaller hotspots in the south. c) Rotterdam: high-risk cells are concentrated in the central-east part of the city, outside the port area, which shows negligible risk (pale blue) throughout.

variable associations across cities, with language difficulties positively correlated with risk in all cases, and senior population linked to increased heat hazard and risk in Barcelona.

Correlation analysis of NbS feasibility and risk and associated indicators revealed distinct patterns (Table 4), with notable differences in how climate-related risks align with implementation potential for specific solution types. Green roofs showed the strongest and most consistent positive correlations with exposure and heat-related risks, particularly in Barcelona ($r = 0.62$ with exposure, $r = 0.61$ with heat risk, $r = 0.60$ with heat hazard), suggesting their suitability in densely built, heat-prone urban areas. Permeable pavement also demonstrated moderate to strong positive associations across all cities, especially with exposure and heat hazard in Boston and Rotterdam ($r = 0.43$–0.39), indicating its relevance in mitigating surface runoff and urban heat. In contrast, rain gardens and urban parks exhibited weak or negative correlations with most risk indicators, especially in Rotterdam, where feasibility was negatively associated with both flood and heat hazards ($r = -0.25$ to -0.41), reflecting spatial constraints across SET domains.

Correlation analysis between NbS feasibility scores and their associated indicators (Table 5) revealed strong structural dependencies across cities and solution types. Land use emerged as the most consistently influential factor, showing high positive correlations with all NbS types across all cities (e.g., $r = 0.91$–0.98), confirming its central role in spatial suitability. For green roofs, feasibility in Barcelona was strongly driven by roof slope ($r = 0.97$) and administrative suitability ($r = 0.94$). In contrast, in Rotterdam, land use remained dominant ($r = 0.90$), while other indicators showed minimal influence. Permeable pavement feasibility was similarly shaped by land use across all cities, with moderate contributions from ground slope in Barcelona ($r = 0.54$) and Rotterdam ($r = 0.27$). Rain gardens and urban parks exhibited more complex and variable patterns: feasibility was moderately correlated with proximity to buildings and underground structures in Boston and Rotterdam (e.g., rain gardens and distance to buildings in Boston, $r = 0.52$), while social acceptance showed weak or inconsistent influence across all NbS types.

Site-specific and cross-case consistent patterns of risk and feasibility

Cross-case analysis reveals both converging and diverging tendencies in how SETs shape climate-related risks and the feasibility of NbS. Across Barcelona, Boston, and Rotterdam, both climate-related risks and NbS feasibility are highly spatially structured rather than random, with statistically significant positive spatial autocorrelation for all indices (Moran's I = 0.5–1.0; $p < 0.01$). Heat risk is the most clustered outcome (Moran's I = 0.9–1.0), reaching near-continuous spatial fields in Rotterdam, while flood risk shows moderately strong clustering (Moran's I = 0.6–0.8) and more localized hotspots in Barcelona and Boston. Feasibility patterns are also clustered (Moran's I = 0.5–0.7), indicating that both climate risks and feasibilities for NbS tend to concentrate in particular parts of each city.

The drivers of risk show a mix of cross-case consistency and site specificity when decomposed through the SETS lens. Rotterdam stands out for the strength social vulnerability and SETS vulnerability; they correlate strongly with exposure ($r = 0.73$ and $r = 0.77$) and with heat risk ($r = 0.61$

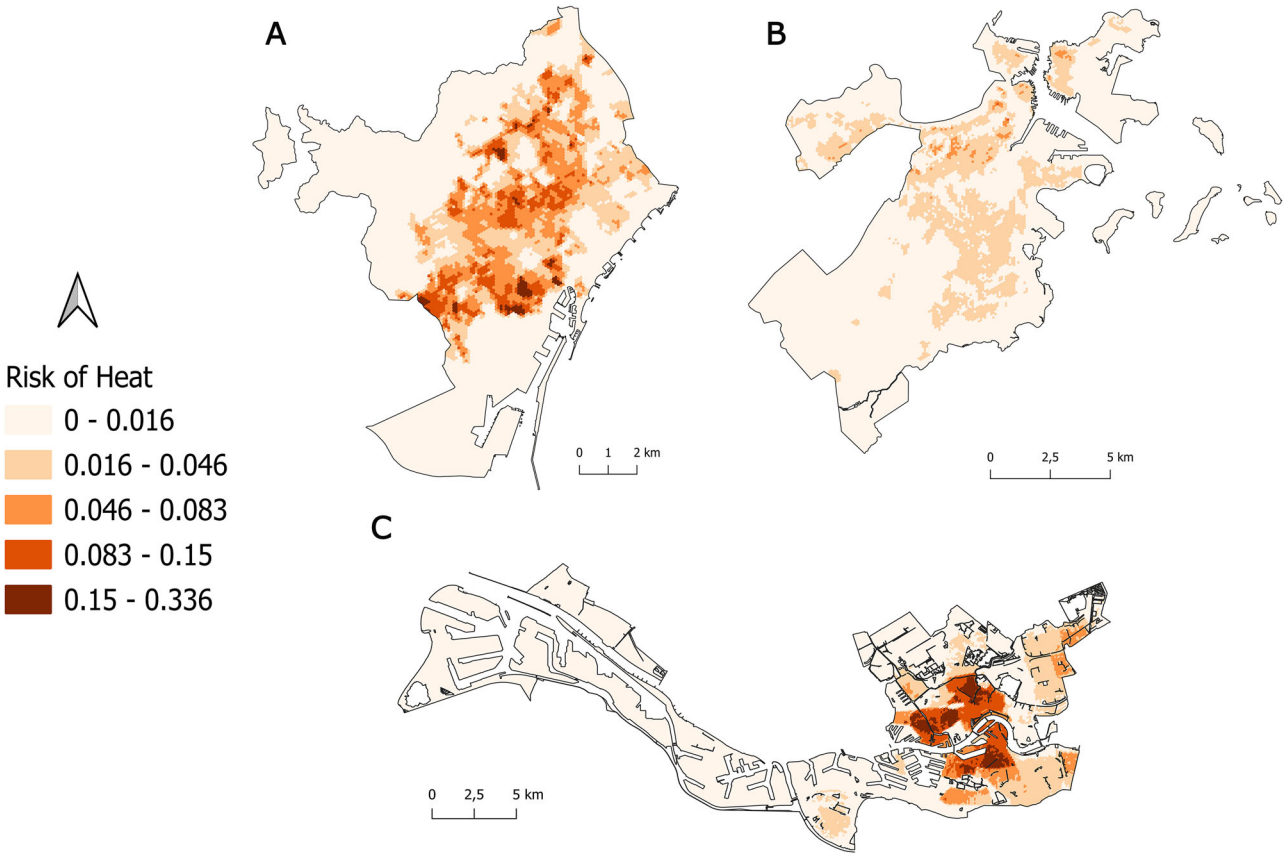


Fig. 2 | Heat risk distribution across the case studies, based on the IPCC 2012 hazard–exposure–vulnerability framework. A Barcelona, **B** Boston, **C** Rotterdam. Heat risk was calculated for each 100 × 100 m grid cell as the geometric mean of hazard (daytime air temperature, °C, during a documented historic heatwave event in each city), exposure (population density), and social–ecological–technological systems (SETS) vulnerability (see Methods). Risk scores are displayed using a five-class graduated color scale from pale cream (lowest risk, 0–0.016) through orange to dark brown (highest risk, 0.15–0.336), with class breaks determined by natural (Jenks) breaks. a) Barcelona: high-risk cells (dark orange/brown) are concentrated in the central, central-west, and central-north districts, corresponding to the most densely built parts of the city. b) Boston: high-risk cells are concentrated in the northern areas, with moderate-to-lower risk in the south. c) Rotterdam: high-risk cells are concentrated in the central-east part of the city, outside the port area. Across all three cities, heat risk is more spatially widespread than flood risk (Fig. 1), reflecting the broader footprint of urban heat exposure compared with the more localized, drainage-dependent pattern of pluvial flooding.

and $r = 0.69$). In Boston, these relationships are present but weaker (e.g., social vulnerability with exposure $r = 0.30$; with heat risk $r = 0.43$). In Barcelona, heat risk is more tightly associated with hazard and technological structure: heat hazard correlates more strongly with heat risk ($r = 0.63$), and impervious surfaces are highly predictive of heat-related outcomes (r = 0.79 for heat risk; $r = 0.62$ for heat hazard), consistent with a morphology-driven heat signal. At the indicator level, Rotterdam again shows a clear equity signal: social vulnerability indicators such as difficulties with local language and living below poverty line correlate strongly with both flood risk ($r = 0.32$–0.63) and heat risk ($r = 0.38$–0.73), whereas technological vulnerability indicators like impervious surface coverage played a more dominant role in Barcelona ($r = 0.35$ for flood risk and $r = 0.79$ for heat risk). These findings reinforce arguments that urban adaptation processes must be grounded in place-based realities, even when informed by shared conceptual frameworks[25].

The feasibility analysis offers a spatially explicit lens for prioritizing NbS implementation, revealing clear typological and locational opportunities. Green roofs show the clearest and most consistent alignment with heat-related need where assessed: in Barcelona, feasibility correlates strongly with exposure ($r = 0.62$), heat risk ($r = 0.61$), and heat hazard ($r = 0.60$), indicating that areas with high heat exposure are also places where roof-based interventions are structurally plausible. Permeable pavements exhibit moderate positive relationships with exposure and heat indicators across the cases (e.g., exposure $r \approx 0.43$ in Boston; heat hazard $r \approx 0.39$ in Rotterdam), suggesting they can be deployed in dense settings without the land take required by larger green spaces. In contrast, rain gardens and urban parks show weak or negative associations with risk in several instances, most notably in Rotterdam, where feasibility is negatively associated with flood and heat hazards (approximately $r = -0.25$ to -0.41), which supports an interpretation: the places with the highest hazard intensity are not necessarily the places with sufficient available space, compatible land use, or subsurface conditions for these typologies. These findings align with strategic NbS planning approaches that advocate for matching solution types to local physical and administrative contexts[26,27].

The reasons behind these feasibility differences are also reflected in the underlying indicator patterns. Land use is the dominant feasibility determinant across all cities and NbS types ($r = 0.91$–0.98), indicating that zoning and existing land functions largely gate where NbS can be considered in the first place. For green roofs in Barcelona specifically, feasibility is strongly driven by roof slope ($r = 0.97$) and administrative suitability ($r = 0.94$), underscoring that feasibility is not only a physical question but also an institutional/regulatory one in this case. For rain gardens and urban parks, feasibility is more contingent on constraints such as proximity to buildings and underground structures (e.g., rain gardens vs. distance to buildings in Boston, $r = 0.52$), which helps explain why these typologies decouple from hazard hotspots in some contexts.

Sensitivity analysis

The one-at-a-time (OAT) sensitivity analysis (Supplementary Tables S7–S12) shows that the composite risk and feasibility indices are

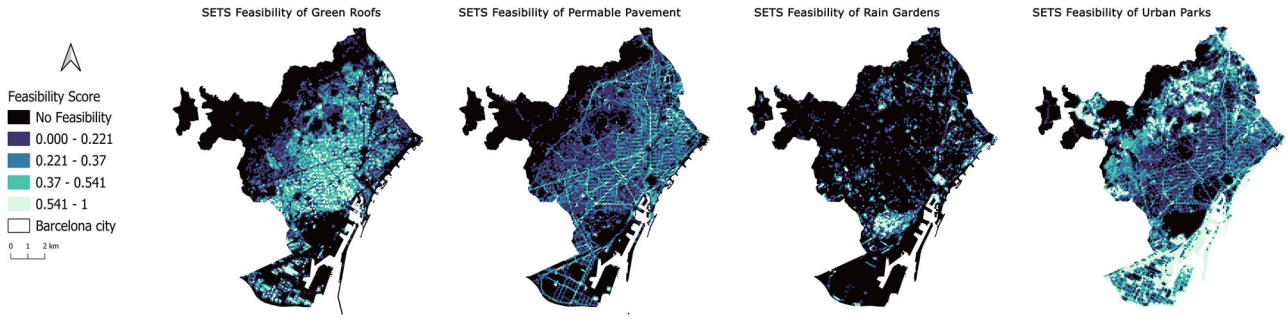


Fig. 3 | Social-Ecological-Technological Systems (SETS) feasibility of four nature-based solution (NbS) types in Barcelona: green roofs, permeable pavements, rain gardens, and urban parks. Feasibility was assessed independently for each NbS type on a 100 × 100 m grid, combining social, ecological, and technological indicators specific to each solution (see Methods and Supplementary Section B) using a geometric mean, and classified into five categories using natural (Jenks) breaks. Non-usable areas are shown in black ("no feasibility"); feasible areas are shown on a graduated scale from dark indigo-blue (lowest feasibility, 0.000–0.221) through medium blue and teal to pale mint-green (highest feasibility, 0.541–1). a) Green roofs: highest feasibility (pale green) is concentrated in the densely built central area, with additional hotspots in the south-west and north-east. b) Permeable pavements: feasible areas are relatively evenly distributed across built-up areas in the central part of the city. c) Rain gardens: feasibility hotspots occur within large parks, particularly in the north-west, central-east, and south-east. d) Urban parks: feasibility is dominant in the northern part of the city, with additional suitable areas in the south-east, central, and western districts.

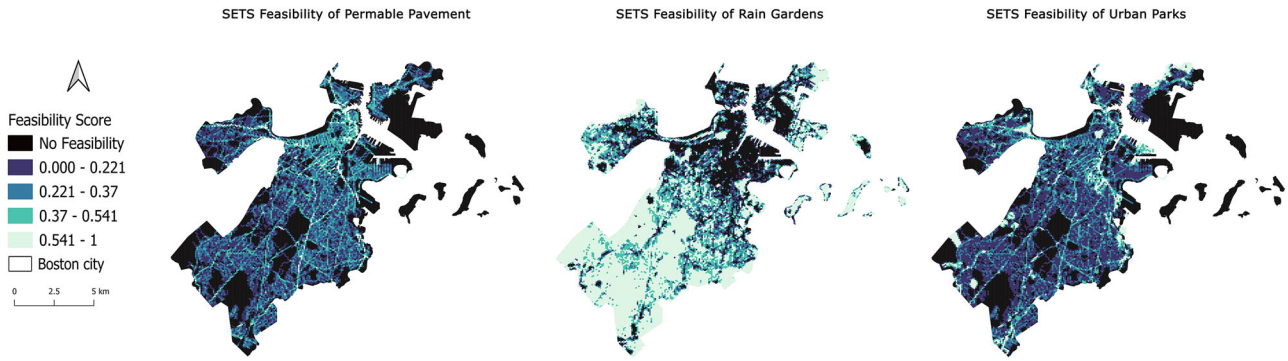


Fig. 4 | Social-Ecological-Technological Systems (SETS) feasibility of three nature-based solution (NbS) types in Boston: permeable pavements, rain gardens, and urban parks. Feasibility was assessed independently for each NbS type on a 100 × 100 m grid, combining social, ecological, and technological indicators specific to each solution (see Methods and Supplementary Section B) using a geometric mean, and classified into five categories using natural (Jenks) breaks. Non-usable areas are shown in black ("no feasibility"); feasible areas are shown on a graduated scale from dark indigo-blue (lowest feasibility, 0.000–0.221) through medium blue and teal to pale mint-green (highest feasibility, 0.541–1). Green roofs are not shown for Boston because spatially resolved empirical data required for this indicator were mostly unavailable at the city scale (see Methods). a) Permeable pavements: feasibility is relatively evenly distributed, with high-feasibility hotspots concentrated in the central-northern part of the city. b) Rain gardens: feasibility is primarily concentrated in the southern part of the city, an area dominated by residential land use and green space. c) Urban parks: feasibility is higher in the northern and central-eastern areas.

generally robust, with modest absolute deviations and consistent directional responses across cities. For heat-risk indices, perturbing individual indicators by ±10% produced small absolute changes (typically 0.006–0.013) and relative deviations of ~3.0–3.9%, with nearly symmetric effects for +10% and −10% perturbations. Barcelona's heat risk exhibited mean relative changes of 3.23 (+10%) and −3.45% (−10%), almost identical across heat hazard, exposure and SETS vulnerability, indicating similar influence from all three indicators. Flood-risk indices showed slightly higher sensitivity, particularly to exposure and SETS vulnerability, with relative deviations around 4.2–4.6% (+10%) and −4.5% (−10%) in Barcelona and Boston, and 3.6–4.1% in Rotterdam.

Feasibility indices showed more variability but remained well within an interpretable range. In Barcelona, feasibility for green roofs and rain gardens responded weakly to ±10% perturbations, with mean relative changes between 1.2 and 2.2%, while social acceptance exhibited a larger effect: 4.46% (+10%) and −4.61% (−10%). Urban-park feasibility was notably sensitive to land use and social acceptance, producing deviations of 2.7–3.7% across cities. Permeable pavement showed the largest feasibility responses overall, especially in Barcelona and Rotterdam, where ground slope and social acceptance produced relative changes of 3.5–3.8% (+10%) and up to −4.06% (−10%). Across all indicators and cities, changes remained below 5%, suggesting high stability of the composite indices under moderate perturbations.

For the test the robustness of the composite indices to aggregation assumptions (Supplementary Table S13), Rotterdam was the most robust case study, particularly for heat risk, which showed the smallest average score range across methods (mean range = 0.272). Barcelona showed intermediate sensitivity, with relatively similar average ranges across indices (0.510 for SET vulnerability, 0.515 for flood risk, and 0.516 for heat risk). Boston was the most sensitive overall, especially for flood risk (mean range = 0.990) and SET vulnerability (mean range = 0.882), indicating substantially greater dependence on the assumed aggregation logic. When the analysis was restricted to the standard averaging operators only (arithmetic, geometric, harmonic, quadratic and median), sensitivity decreased but the overall pattern remained unchanged: the average range for Rotterdam heat risk fell to 0.118, compared with 0.295 for Barcelona heat risk and 0.204 for Boston heat risk, while Boston flood risk remained the least robust (0.579). Taken together, these results suggest that the relative spatial patterns are reasonably stable under conventional aggregation rules, but that Boston, particularly for flood risk and SET vulnerability, remains more sensitive to changes in compensability assumptions and should therefore be interpreted with greater caution.

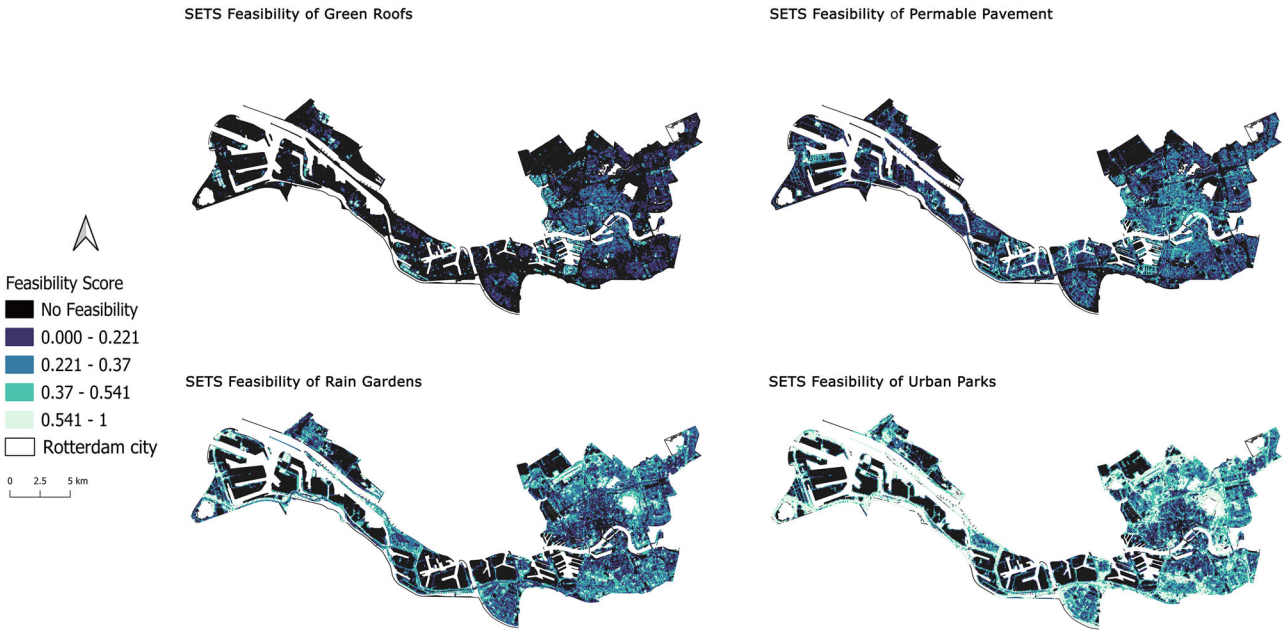


Fig. 5 | Social-Ecological-Technological Systems (SETS) feasibility of four nature-based solution (NbS) types in Rotterdam: green roofs, permeable pavements, rain gardens, and urban parks. Feasibility was assessed independently for each NbS type on a 100 × 100 m grid, combining social, ecological, and technological indicators specific to each solution (see Methods and Supplementary Section B) using a geometric mean, and classified into five categories using natural (Jenks) breaks. Non-usable areas are shown in black ("no feasibility"); feasible areas are shown on a graduated scale from dark indigo-blue (lowest feasibility, 0.000–0.221) through medium blue and teal to pale mint-green (highest feasibility, 0.541–1). a) Green roofs: high feasibility is concentrated in the central area of the city. b) Permeable pavements: feasibility is widespread across the city, without a single dominant cluster. c) Rain gardens: high-feasibility hotspots occur in the north-east, central, and south-east parts of the city. d) Urban parks: feasibility is higher in the northern, central, and south-eastern areas. Rotterdam's fragmented urban form, including the extensive port and industrial areas in the west, shows negligible feasibility for all four NbS types (black) and is visible across all four panels. The Rotterdam municipal boundary is outlined in white; a scale bar and north arrow are shown in the legend panel.

Table 1 | Results of Moran I spatial correlation for both risk and feasibility assessment

	Risk flood			Risk heat			Feasibility green roofs		
	BCN	**BOS**	**ROT**	**BCN**	**BOS**	**ROT**	**BCN**	**BOS**	**ROT**
Moran's index	0.7	0.6	0.8	0.9	0.9	1.0	0.6	NA	0.6
Z-score	129.0	121.3	195.8	167.0	178.3	253.1	133.6	NA	146.8
P-value	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	NA	<0.01
	Feasibility rain gardens			**Feasibility permeable pavement**			**Feasibility urban parks**		
	BCN	**BOS**	**ROT**	**BCN**	**BOS**	**ROT**	**BCN**	**BOS**	**ROT**
Moran's index	0.6	0.7	0.6	0.6	0.6	0.5	0.7	0.6	0.7
Z-score	103.6	156.2	162.3	103.6	119.6	133.8	130.6	135.5	189.6
P-value	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01

Discussion

Achieving social-ecological resilience in urban settings through NbS requires a fundamental transformation of current planning paradigms. This shift requires moving beyond approaches that focus solely on net ecosystem service gains and instead adopting a perspective that prioritizes the well-being of both urban communities and ecosystems[17]. In this study, we propose a framework for analyzing the needs and opportunities for NbS planning and applying it across multiple cross-continental case studies. This study introduces a framework for analyzing the needs and opportunities for NbS planning, which is applied in a cross-continental case study comparison. The framework recognizes the complexity and interdependence of urban systems by addressing community vulnerabilities, ecosystem capacities and constraints, administrative conditions, community readiness for NbS adoption, and the integration opportunities within the built environment. The discussion is organized into four sections: analysis of the differing dynamics of flood and heat hazards and their implications for NbS-based urban adaptation; synthesis of insights on strengthening urban resilience through NbS; and recommendations to guide future research to address the conceptual and methodological limitations identified in this study.

The results collectively provide a concrete basis for prioritization: high-risk and high-feasibility areas represent immediate opportunities for implementation, such as heat-exposed zones suitable for green roofs or permeable pavements. In contrast, high-risk but low-feasibility areas indicate locations where adaptation needs are significant, yet conventional NbS options face structural constraints. This pattern corresponds with strong socioeconomic–risk coupling, as observed in Rotterdam, where poverty and language isolation coincide with flood and heat risk. These areas are suitable candidates for alternative or hybrid interventions, such as gray–green combinations and require targeted governance and investment strategies. The primary constraint is not solely hazard intensity but also the underlying land-use and infrastructure conditions that determine feasibility. Empirical evidence indicates that NbS implementation frequently clusters in affluent

Table 2 | Results of Pearson correlation analysis between the risk index and associated indicators

	Social vulnerability			Ecological vulnerability			Technological vulnerability		
	BCN	BOS	ROT	BCN	BOS	ROT	BCN	BOS	ROT
Risk flood	0.03	0.11	0.53	0.14	−0.08	0.20	−0.01	0.10	0.20
Hazard flood	0.14	−0.22	-0.11	0.24	−0.22	0.18	−0.07	0.05	0.33
Exposure	−0.06	0.30[a]	0.73[b]	0.27	−0.15	0.18	0.16	0.29	0.16
Risk heat	0.03	0.43[a]	0.61[b]	0.27	−0.01	0.26	0.21	0.25	0.24
Hazard heat	−0.10	0.23	0.27	0.22	0.05	0.40[a]	0.06	0.08	0.60[b]
	SETS vulnerability			**Hazard flood**			**Hazard heat**		
	BCN	BOS	ROT	BCN	BOS	ROT	BCN	BOS	ROT
Risk flood	0.08	−0.01	0.59[a]	0.57[a]	0.45[a]	0.25	0.22	0.06	0.42[a]
Hazard flood	−0.11	0.36	0.02	NA	NA	NA	0.10	−0.25	0.30[a]
Exposure	0.13	0.04	0.77[b]	0.05	−0.26	−0.02	0.53[a]	0.26	0.46[a]
Risk heat	0.20	0.22	0.69[b]	0.03	−0.31[a]	0.06	0.63[b]	0.27	0.52[a]
Hazard heat	0.05	0.16	0.50[a]	0.10	−0.25	0.30[a]	NA	NA	NA

[a]$r = 0.30–0.59$: moderate linear relationship.
[b]$r = 0.60–0.79$: strong linear relationship.
[c]$r \geq 0.80$: very strong linear relationship.

Table 3 | Results of Pearson correlation for risk and single indicators used

	Minor population			Senior population			Difficulties with local language		
	BCN	BOS	ROT	BCN	BOS	ROT	BCN	BOS	ROT
Risk flood	−0.14	0.08	0.25	0.11	0.03	−0.01	0.04	0.18	0.32[a]
Hazard flood	0.03	−0.06	−0.19	0.01	−0.20	−0.17	0.09	−0.04	0.04
Exposure	−0.37[a]	0.11	0.40[a]	0.35[a]	0.11	0.06	−0.03	0.27	0.38[a]
Risk heat	−0.33[a]	0.17	0.27	0.25	0.16	−0.02	0.06	0.35[a]	0.38[a]
Hazard heat	−0.21	0.15	0.05	0.27	0.16	−0.20	−0.09	0.08	0.06
	Living below poverty line			**Ground slope**			**Impervious surfaces**		
	BCN	BOS	ROT	BCN	BOS	ROT	BCN	BOS	ROT
Risk flood	0.03	0.04	0.63[b]	−0.23	−0.02	NA	0.35[a]	0.09	0.20
Hazard flood	0.07	−0.04	−0.04	−0.28	−0.03	NA	0.14	0.21	0.33[a]
Exposure	−0.10	0.19	0.78[b]	−0.43[a]	−0.06	NA	0.78[b]	0.31[a]	0.16
Risk heat	0.00	0.22	0.73[b]	−0.37[a]	−0.02	NA	0.79[b]	0.03	0.24
Hazard heat	−0.17	−0.11	0.34[a]	−0.31	−0.07	NA	0.62[b]	−0.02	0.60[b]
	Green area								
	BCN	BOS	ROT						
Risk flood	−0.14	0.08	−0.20						
Hazard flood	−0.24	0.22	−0.18						
Exposure	−0.27	0.15	−0.18						
Risk heat	−0.27	0.01	−0.26						
Hazard heat	−0.22	−0.05	−0.40[a]						

[a]$r = 0.30–0.59$: moderate linear relationship.
[b]$r = 0.60–0.79$: strong linear relationship.
[c]$r \geq 0.80$: very strong linear relationship.

or regenerating districts, leaving disadvantaged communities underserved and perpetuating environmental inequity[28]. These spatial disparities point to the necessity for justice-oriented NbS planning that clearly incorporates social vulnerability and procedural inclusion into decision-making. Transformative NbS governance relies on institutional mechanisms that align ecological, social, and economic objectives[29], as well as participatory processes and targeted financing strategies to ensure equitable distribution of NbS benefits across urban populations[26].

The distinct spatial and functional dynamics of heat and flood hazards necessitate differentiated approaches to NbS design and implementation. Urban heat risk tends to be spatially persistent and concentrated in densely built environments with limited vegetation and extensive impervious surfaces. As our findings indicate, high NbS feasibility for green roofs correlates strongly with heat-related indicators, while feasibility for urban parks shows weaker or even negative associations with heat risk, reflecting land-availability and infrastructural constraints. This makes green roofs a

Table 4 | Results of Pearson correlation for feasibility and risk

	Feasibility green roofs			Feasibility permeable pavement			Feasibility rain gardens			Feasibility urban parks		
	BCN	BOS	ROT	BCN	BOS	ROT	BCN	BOS	ROT	BCN	BOS	ROT
Risk flood	0.27	NA	0.24	0.26	0.08	0.23	−0.02	−0.08	−0.03	−0.02	0.07	−0.12
Hazard flood	0.08	NA	0.08	0.21	−0.22	0.18	0.02	−0.03	−0.08	0.19	−0.04	−0.24
Exposure	0.62[b]	NA	0.25	0.43[a]	0.43[a]	0.25	−0.08	−0.37[a]	0.00	−0.11	0.15	−0.10
Risk heat	0.61[b]	NA	0.28	0.34[a]	0.40[a]	0.26	−0.12	−0.27	−0.06	−0.14	0.12	−0.15
Hazard heat	0.60[b]	NA	0.35[a]	0.28	0.26	0.39[a]	−0.16	−0.05	−0.25	−0.13	0.21	−0.41[a]

[a]$r = 0.30–0.59$: moderate linear relationship.
[b]$r = 0.60–0.79$: strong linear relationship.
[c]$r \geq 0.80$: very strong linear relationship.

Table 5 | Results of Pearson correlation for feasibility and associated indicators

	Feasibility green roofs			Feasibility permeable pavement			Feasibility rain gardens			Feasibility urban parks		
	BCN	BOS	ROT	BCN	BOS	ROT	BCN	BOS	ROT	BCN	BOS	ROT
Social acceptance	0.05	–	0.03	0.07	0.14	0.05	0.04	0.37[a]	−0.13	0.09	0.06	−0.05
Administrative suitability	0.94[c]	–	−0.01	–	–	–	–	–	–	–	–	–
Land use[a]	0.91[c]	–	0.90[c]	0.93[c]	0.98[c]	0.91[b]	0.43[a]	0.89***	0.78[b]	0.95[c]	0.88[c]	0.95[c]
Roof slope	0.97[c]	–	0.04	–	–	–	–	–	–	–	–	–
Ground slope	–	–	–	0.54[a]	0.10	0.27	0.10	−0.10	0.15	–	–	–
Distance to buildings	–	–	–	–	–	–	0.22	0.52[a]	0.19	0.31	−0.11	0.37[a]
Underground structures	–	–	–	–	–	–	0.08	0.11	0.07	–	–	–

[a]$r = 0.30–0.59$: moderate linear relationship.
[b]$r = 0.60–0.79$: strong linear relationship.
[c]$r \geq 0.80$: very strong linear relationship.

promising adaptation strategy for heat mitigation. By reducing surface and ambient temperatures through evapotranspiration, green roofs offer direct microclimatic benefits and should therefore be prioritized in areas with both high heat risk and high NbS feasibility[30]. In contrast, flood risk exhibits more complex behavior influenced by factors such as upstream runoff, sewer drainage capacity, and topography. While NbS can be tailored to highly flood-prone zones (e.g., permeable pavements and rain gardens in low-lying areas), their effectiveness often depends on broader catchment-scale interventions. Reducing runoff in upstream urban or peri-urban areas, through infiltration-based NbS such as rain gardens and urban parks, can alleviate pressure on sewer systems and mitigate downstream flooding. Therefore, while heat mitigation NbS can be effectively localized and site-specific, flood mitigation requires a more systemic and spatially integrated approach. These hazard-specific profiles intersect with social and political dimensions, since the distribution of risks and of feasible NbS options across neighborhoods and population groups raises questions of recognition and local legitimacy of interventions, as highlighted in recent work on locally grounded and justice-oriented NbS pathways (Benati et al., in preparation). Interpreting our cross-city results through this lens helps clarify where risk reduction and feasibility align to create synergies, and where they reveal potential tradeoffs between different hazards, NbS types and urban constituencies.

The findings contribute to the progressing discussion on urban resilience by showing how NbS can serve as multifunctional tools for climate adaptation when integrated within adaptive and inclusive planning frameworks. Consistent with previous research, NbS should be regarded not as isolated technical solutions but as socio-ecological-technological strategies whose effectiveness depends on integration within broader governance, planning, and social contexts[31]. From this perspective, the value of the risk–feasibility framework lies not only in identifying where NbS appear spatially suitable, but also in revealing where adaptation needs and implementation opportunities diverge.

A central implication of our results is that feasibility should not be interpreted as equivalent to implementation readiness. While flood and heat risk can be assessed through established hazard–exposure–vulnerability relationships, NbS feasibility is a relational planning construct. It depends on land-use compatibility, built-form constraints, ecological conditions, administrative rules, infrastructure conflicts, political legitimacy, and temporal horizons. In this study, feasibility identifies where selected SETS conditions are comparatively favorable for a given NbS type, but it does not determine whether implementation is legally, financially, politically, or socially secured.

The cross-city results show that incremental NbS often align more closely with dense, risk-prone urban areas. Green roofs and permeable pavements show comparatively strong suitability in built-up areas where heat risk, exposure, and imperviousness are high. This reflects their capacity to operate within existing urban surfaces rather than requiring substantial land-use change. In practical terms, such interventions may provide near-term adaptation opportunities when embedded in building retrofits, street redesign, resurfacing programs, stormwater upgrades, or heat-mitigation policies. However, their relative ease of integration should not be confused with system transformation capacity. Here, system transformation is understood as change that substantially alters existing structures, including institutional arrangements, norms, and rules[31,32]. NbS should therefore be understood along a gradient of transformative potential, depending on the extent to which they alter existing urban functions, such as land use, mobility, infrastructure configuration, public-space use, aesthetics, governance arrangements, and maintenance responsibilities.

Along this gradient, porous pavements and similar gray–green surface retrofits sit closer to the incremental end. They offer practical and cost-

effective benefits for stormwater management and heat mitigation, yet their transformative potential remains limited. While these interventions can reduce runoff and surface temperatures with minimal disruption to existing urban functions, they do not foster deeper socio-ecological change or support regenerative ecosystem processes. Designed primarily to maintain the status quo in land use and accessibility, they tend to appeal to municipalities seeking low-impact responses to flooding or heat stress. However, from both an ecosystem-services perspective and a more-than-human perspective[33], such approaches tend to address symptoms rather than the underlying drivers of environmental degradation, offering limited support for expanding ecological functions or reversing biodiversity loss.

Rain gardens and urban parks display a different planning logic and occupy more variable positions along this gradient. Small rain gardens may function as incremental interventions when inserted into existing open spaces or streetscapes, but larger or networked rain-garden systems can become more transformative when they require drainage redesign, redistribution of street space, or coordination across parcels and agencies. Urban parks sit closer to the transformative end of the gradient because their creation or expansion may require road-space reallocation, land acquisition, zoning change, infrastructure relocation, long-term maintenance commitments, and extensive public deliberation. Their weaker or negative association with high-risk areas in some cases does not indicate that they are less valuable as NbS. Rather, it reveals that the places where larger green interventions may be most needed are often those where land availability, subsurface infrastructure, dense built form, or existing land-use arrangements restrict implementation. Creating new or expanded parks may require road-space reallocation, land acquisition, zoning change, relocation of infrastructure, long-term maintenance commitments, and extensive public deliberation. For these more transformative NbS, feasibility analysis is best understood as an early-stage diagnostic tool: it identifies where spatial conditions may support future transformation, but it cannot replace political, institutional, and community-based planning processes.

The differentiated feasibility patterns observed across cities, together with the varying transformative potential of different NbS types, highlight the need for flexible and context-sensitive adaptation strategies. Rather than positioning NbS as a comprehensive solution, our findings emphasize their role as one component within broader urban resilience and sustainability transitions. As climate pressures intensify, integrating NbS alongside complementary policy, institutional, and infrastructural measures will be essential for advancing equitable and sustainable urban futures. While participatory design, cross-sectoral coordination, and evidence-based prioritization are widely recognized as central to nature-based adaptation[34], our study demonstrates that case-specific understandings of SET risks and NbS feasibility might be an essential first step in designing interventions that are both effective and socially legitimate.

This study presents several limitations. First, the assessment relied on standardized datasets for SETS indicators. While this approach ensures comparability, data availability remains limited, and the set of indicators was necessarily reduced to enable a rigid cross-case comparison within a single study. This simplification risks overlooking locally relevant factors and contextual nuances that could enrich the analysis.

Second, the case study is situated in a Global North context. Although it provides valuable insights, findings may not be directly transferable to rapidly urbanizing regions of the Global South, including parts of Asia, Africa, and Latin America and the Caribbean, where NbS applications, replication, scaling, and monitoring are beginning to emerge in the literature[35]. Expanding research across diverse geographies is essential to capture the heterogeneity of socio-ecological-technical dynamics shaping urban adaptation.

Third, this research focused on flood and heat mitigation, which represent two of the most prominent urban climate hazards. However, future analyses should extend beyond these threats to encompass a broader spectrum of climate- and weather-related risks, including drought, biodiversity loss, and cascading systemic failures[18,36], in combination with other pressing urban challenges, such as lack of recreational space[17].

Fourth, electoral results were used as a spatially available proxy for broader political-environmental receptiveness, enabling comparison across the three cities. While this approach offers insight into the political and institutional context of NbS planning, it captures only an indirect and aggregated dimension of social acceptance. Voting patterns cannot be assumed to represent support for specific NbS interventions. Acceptance of a green roof incentive, a permeable pavement retrofit, a rain garden, or a new urban park may vary substantially depending on perceived costs, land-use trade-offs, maintenance responsibilities, mobility impacts, parking loss, displacement concerns, and trust in local government. Therefore, direct and sustained engagement with local communities and stakeholders remains essential for understanding context-specific values, concerns, and priorities, and for ensuring that NbS interventions respond to local needs. Future applications should treat proxy-based social acceptance as a preliminary indicator and complement it with surveys, interviews, participatory GIS, deliberative workshops, and engagement with local organizations.

Fifth, this study applies an interdisciplinary lens, integrating SETS perspective to advance understanding of urban risks and the feasibility of NbS integration across diverse climatic and planning contexts. Such an approach illustrates the importance of bridging disciplinary boundaries across scientific and sectoral knowledge domains[37]. Yet it also highlights a limitation: interdisciplinary research often remains confined within academic domains and may struggle to address the complexity of societal challenges on its own. Transdisciplinary approaches extend beyond scientific integration by engaging local practitioners, policymakers, NGOs, community groups, and other stakeholders[32]. These collaborations are essential for NbS planning because they enable the co-production of knowledge that is both solution-oriented and transferable.

Conclusions

This cross-city assessment demonstrates how integrating climate risk and feasibility analyses through a SETS lens can strengthen the planning and implementation of urban NbS. Applying the framework across Barcelona, Boston, and Rotterdam revealed both generalizable and city-specific insights into how social, ecological, and technological factors shape NbS potential. Across all three cities, heat hazard was highly correlated with exposure and SETS vulnerability, highlighting densely built urban cores as hotspots for adaptation needs. In these areas, green roofs and permeable pavements emerged as the most feasible interventions, combining strong structural compatibility with high potential for heat mitigation. Flood risk patterns, however, were more spatially heterogeneous, reflecting local topography, drainage infrastructure, and governance approaches. The feasibility of flood-oriented NbS such as rain gardens and urban parks was often limited by space constraints or subsurface conditions, underscoring the importance of multi-scalar coordination across urban catchments. The study also reveals that land use, slope, and administrative suitability are consistently among the strongest drivers of NbS feasibility, suggesting that targeted planning regulations and cross-sectoral cooperation can substantially expand implementation potential. At the same time, the distinct socio-economic profiles of the three cities highlight the need for more equitable NbS design and implementation. In many cases, the areas with the greatest social vulnerability do not coincide with zones of high feasibility, revealing mismatches between need and opportunity that mirror broader patterns of uneven adaptive capacity and institutional neglect. These disparities reinforce calls in the literature for justice-oriented NbS planning that explicitly integrates social vulnerability, redistributive priorities, and procedural inclusion into decision-making.

By combining high-resolution spatial data, statistical validation, and cross-city comparative analysis, this research provides a replicable, data-informed framework for identifying where NbS can most effectively enhance urban resilience. The approach can guide municipalities, planners, and policymakers in embedding NbS within adaptation plans and zoning regulations. Future research should extend this framework to additional hazards, such as drought and wildfire, and explore its application in Global South cities, where data gaps, informal development, and distinct

governance contexts may require further methodological adaptation. Additionally, building on insights from this comparative study, integrating spatial feasibility mapping with participatory planning, monitoring, and evaluation processes offers a pathway to ensure NbS deliver not only risk reduction but also contributes to addressing the systemic drivers of environmental degradation. While some NbS hold transformative potential, many interventions remain incremental, alleviating symptoms without challenging the underlying conditions that perpetuate ecological imbalance and biodiversity loss. Strengthening the transformative capacity of NbS therefore requires institutional commitments to long-term ecological restoration, governance reform, and community co-production.

Methods

General overview

This study applies a SETS framework to identify spatial needs and opportunities for NbS across three coastal cities: Barcelona, Boston, and Rotterdam. The approach builds on an integrated assessment framework[38] and the risk assessment framework[39], both initially implemented in Barcelona, Spain. This work aims to evaluate where NbS are most needed and where they can be most effectively implemented. To better understand the diverse drivers and dynamics shaping the potential for urban NbS, we conducted statistical analyses. This enabled a robust comparison of risk-feasibility relationships and facilitated the identification of both context-specific and generalizable patterns. We developed a workflow to assess urban stormwater risk and the feasibility of NbS across the case study cities (Fig. 6). All statistical and sensitivity analyses were executed in a Python 3.13 environment using PyCharm. Spatial analyses and visualizations were performed using ArcGIS Pro version 3.32 and QGIS version 3.34. The complete codebase will be made openly available via a GitHub repository to support transparency and reproducibility.

Case-studies

This study examines three coastal cities, Barcelona, Boston, and Rotterdam (see Table 6), each situated in distinct climatic and socio-political contexts, offering a diverse basis for analyzing risks and feasibilities. Their urban density profiles vary substantially. Barcelona represents a compact, high-density city, with an average of ~16,000 residents/km². Boston exhibits moderate to high density, averaging around 5000 residents/km², with several pockets of more compact development. Rotterdam, by contrast, presents a more complex spatial structure: while the municipal-level density is roughly 3000 residents/km², this figure is strongly influenced by the extensive port and industrial areas in the western part of the municipality, where population is sparse and urban continuity is limited. The actual urbanized core of Rotterdam has a significantly higher density, around 5500 residents/km², with some neighborhoods exceeding 20,000 residents/km²[40–42]. All three cities have experienced flood events of varying intensities, with projections indicating increasing frequency and severity under future climate scenarios[43,44]. Seasonally, they are also affected by heatwaves of varying intensities, which are similarly expected to worsen[45–47]. Social equity and vulnerability in relation to extreme events, such as flooding and heatwaves, are key concerns in all three cities[39,48,49]. Each of the case study cities is currently developing or implementing greening strategies aimed at climate change adaptation, particularly in response to flood risks and heatwave impacts[50–52].

Analysis of climate risks

This study applies the IPCC risk framework[24], in which risk is conceptualized as a function of hazard, exposure, and vulnerability. Flood and heat hazards were represented by (i) pluvial flood depth (mm) derived from 1-in-100-year (T100) flood-model outputs and (ii) daytime air temperature (°C) during documented historic heatwave events in each case-study city. Exposure was operationalized using population density. The full set of indicators and data sources is provided in Supplementary Table S2. Spatial processing was conducted in ArcGIS Pro 3.32: a 100 × 100 m grid was created, all indicator layers were converted to the grid using the Zonal Statistics tool, and indicators were aggregated within each grid cell. Detailed procedures and formulas are reported in reported in Supplementary Section A.

Analysis of NBS feasibility

NbS have considerable potential to mitigate climate change-induced risks. To quantify this potential, the feasibility of implementing NbS was assessed spatially across the study area. In this study, NbS feasibility is defined as a screening-level measure of spatial suitability and theoretical land-use convertibility for a given NbS type. It does not represent immediate implementation readiness. Rather, the feasibility index identifies areas where the selected SETS indicators suggest comparatively favorable conditions for further planning consideration. Four types of NbS were selected for evaluation, green roofs, rain gardens, porous pavement, and urban parks, based on a comprehensive literature review highlighting their relevance for both stormwater management and urban heat mitigation (see Table 7). These NbS also differ in their transformative potential, understood here as a gradient reflecting the extent to which an intervention alters existing structures, including institutional arrangements, norms, and rules[31,32].

The feasibility assessment examines the urban landscape from a multidisciplinary perspective, integrating social, ecological, and technological dimensions. The selected indicators for assessment are presented in Table 8 while detailed classification criteria and the rationale for indicator selection are provided in Supplementary Section B.

In the case of Boston, spatially resolved empirical data at the city scale was mostly unavailable for green roofs, limiting the ability to assess the feasibility. Moreover, current stormwater management practices in the city typically channel rooftop runoff to adjacent lawns or vegetated areas, enhancing natural infiltration and reducing stormwater volumes, while heat mitigation strategies often rely on cool or reflective roofs[53,54]. Consequently, green roofs were not included in the feasibility assessment for Boston.

ArcGIS Pro 3.32 was used to convert spatially explicit indicator data into raster format, classifying areas into three feasibility categories for NbS implementation, ranging from low to high feasibility (0, 0.5, 1), with thresholds detailed in Supplementary Section B. Final feasibility maps were produced using geometric mean aggregation, normalized to a 0–1 scale, divided into five quantiles, and standardized on a 100 × 100 m grid using Zonal Statistics to calculate mean values per cell, with detailed methodologies and formulas provided in Supplementary Sections A, B.

Complementary data analysis

Spatial autocorrelation was then assessed using Moran's I[55] tool in ArcGIS Pro to detect clustering patterns of both risk and feasibility indexes. This analysis enabled the identification of spatial dependencies and localized hotspots, which are critical for understanding the spatial dynamics of urban risks and NbS feasibilities.

To explore the relationship between climate-related needs and opportunities for NbS implementation, we conducted a statistical analysis. We applied bivariate correlation analysis using Pearson's correlation coefficient within each case study to quantify the linear associations among aggregated risk indices, SETS vulnerability, feasibility scores, and their individual components. This provided a general measure of alignment between areas of elevated climate risk and the potential for effective NbS deployment. This analysis was performed in Python 3.13 within a PyCharm development environment to automate index computation, apply perturbations, and generate city-specific and aggregated sensitivity outputs.

To validate the robustness of the indices and assess model sensitivity, a one-at-a-time (OAT) sensitivity analysis[56] was conducted. Each risk and feasibility indicator was independently perturbed by ±10%, and the resulting changes in composite indices were recorded. This approach quantified the relative influence of individual indicators on overall index scores and helped identify the most sensitive components of the framework. This analysis was performed in Python 3.13 within a PyCharm development environment, using standard scientific libraries (pandas, numpy, and pathlib) to automate

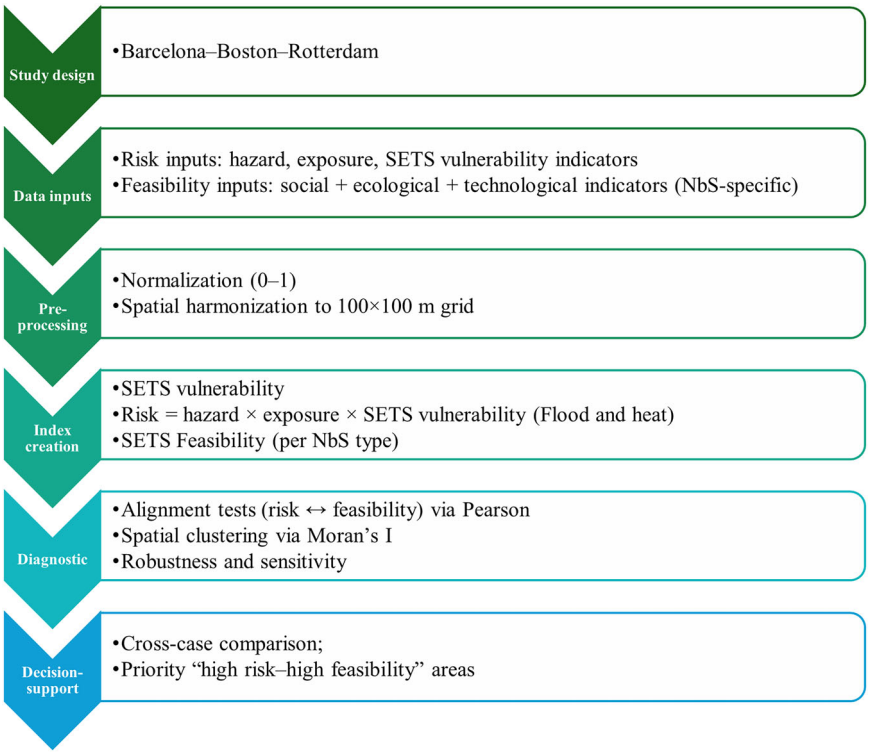


Fig. 6 | Six-stage workflow used to assess flood and heat risk and the feasibility of nature-based solutions (NbS) using Social-Ecological-Technological Systems (SETS) perspective.

Table 6 | Basic information about three case studies

	Barcelona	Boston	Rotterdam
Mean annual precipitation	600 mm/year[57]	1100 mm/year[52]	835 mm/year[51]
Population	1.7 million people[40]	652 thousand people[41]	611 thousand people[42]
Total area	101.35 km^2[40,]	125 km^2[41,]	319 km^2[42,]
Population density	16,905 residents/km^2 [40]	5212 residents /km^2[41,]	3000 residents /km^2[42,]
Urban greening plans	Pla Natura[50]	2030 Climate Action Plan developed by Boston city administration[52]	Programmakader Weerwoord 2030[51]

Table 7 | NBS types and functionalities

Green roofs
Green roofs are vegetated layers installed on top of building rooftops that capture and retain rainfall, slowing runoff while promoting evapotranspiration (Bosch et al., 2023). They can also reduce building surface and near-surface air temperatures through a combination of shading, possible increased albedo of the vegetation layer, substrate thermal buffering, and evapotranspiration[58].
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[59]. Vegetation and wet soils in rain gardens also cool their immediate surroundings via shading and evapotranspiration, reducing surface and near-surface air temperatures compared with adjacent impervious surfaces, especially overnight and following irrigation/rain events[60].
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. Permeable pavements also mitigate surface heat by enabling evaporative cooling when moisture is present and by utilizing high-albedo materials that reflect more solar radiation, thereby reducing surface temperatures[59].
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 great role in stormwater management through floodable designs that store, capture, and channel runoff, serving as multifunctional elements that enhance and complement existing infrastructure[61]. Parks are among the most effective NbS for reducing ambient air temperatures at neighborhood scales due to combined effects of tree shading, high vegetation cover and evapotranspiration, and eventual water bodies[62].

index computation, apply perturbations, and generate city-specific and aggregated sensitivity outputs.

To assess the robustness of the composite indices to the choice of aggregation rule, each index was recalculated using a set of alternative equal-weight operators after min–max normalization (1) of all constituent indicators to a common 0 to 1 scale within each case study and index. The sensitivity analysis included the arithmetic, geometric, harmonic, and quadratic means, together with the median, while minimum, maximum, and selected power means were used as additional boundary-case operators to test more extreme compensability assumptions. Missing data were

Table 8 | Relevance of indicators for different NbS (✓ -suitable, ×- not suitable)

	Indicators	Green roofs	Rain garden	Porous pavement	Urban parks
Social	Current land use	✓	✓	✓	✓
	Social acceptance	✓	✓	✓	✓
	Administrative suitability	✓	×	×	×
Ecological	Ground slope	×	✓	✓	×
Technological	Distance buildings	×	✓	×	✓
	Underground structures	×	✓	×	×
	Rooftop slope	✓	×	×	×

handled using an index-specific complete-case approach, whereby observations with missing constituent indicators were excluded only from the corresponding index calculation. Robustness was then evaluated by comparing the dispersion of aggregated scores and the variation in rank positions across aggregation methods. This analysis was performed in Python 3.13 within a PyCharm development environment, using standard scientific libraries (pandas, numpy, math, typing and pathlib) to automate index computation, apply perturbations, and generate city-specific and aggregated sensitivity outputs.

Data availability

The raw input datasets used in this study are derived from publicly available sources, which listed in Supplementary Tables S2–S6, together with the corresponding source information. The processed datasets generated and analyzed during the current study are available from the corresponding author request.

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