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Review Articles

Nature-based solutions for urban waterfront regeneration: a systematic review of frameworks, strategies and applications

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ABSTRACT

Urban waterfronts, as dynamic interfaces between land and water, face increasing vulnerability due to climate change-induced risks such as sea-level rise, flooding, and extreme weather events, compounded by anthropogenic pressures like urbanisation, pollution, and habitat loss. Traditional hard engineering solutions, while effective in structural resilience, often neglect ecological and social dimensions. Nature-based Solutions have emerged as transformative approaches capable of addressing these multifaceted challenges, offering multifunctional benefits that integrate ecological restoration, climate adaptation and urban liveability. Despite their potential, their application in urbanised waterfronts needs a better understanding, as these techniques have traditionally been adopted in landscapes where land availability allows for larger-scale ecological interventions. This study aims to address this research gap by systematically reviewing academic literature and analysing real-world case studies to examine how NbS are conceptualised, implemented and assessed in urban waterfront regeneration. The findings identified recurring frameworks, analytical dimensions and three strategic orientations: (1) retrofitting waterfront edges with hybrid green-grey solutions to enhance resilience and biodiversity, (2) systemic ecological restoration of degraded waterfront environments and (3) increasing permeability through water-sensitive urban systems. The analysis highlights the multifunctionality of NbS, their capacity to balance ecological, social, and infrastructural objectives, and the prevalence of hybrid approaches in more space-constrained contexts. However, gaps remain in post-implementation monitoring and long-term performance evaluation. This review underscores the need for operational guidelines to scale NbS in urban waterfronts, particularly in underrepresented regions, and emphasises their role as systemic interventions for adaptive urban resilience.

1. Introduction

Urban waterfronts, understood as the zones of interaction between land and water [1], are among the most vulnerable areas within cities. Breen and Rigby (1994) [2] identify three main typologies: riverfronts, lakefronts and seafronts [3], each characterised by distinct hydrological processes and associated risks. Seafronts are shaped by tidal dynamics, wave energy and saline environments, facing coastal hazards such as sea-level rise (SLR), storm surges and shoreline erosion [4]. Riverfronts are governed by freshwater flow and sediment transport, making them particularly susceptible to fluvial flooding, bank erosion and pollution from urban runoff [5]. Lakefronts, in contrast, are defined by still or slow-moving waters and are often affected by eutrophication, stagnation and water-quality deterioration, especially in urbanised settings [6,7].

Globally, this vulnerability is intensifying due to climate change-related threats and non-climatic anthropogenic drivers [4]. Temperatures have increased by 1.1 °C above pre-industrial levels, contributing to a 50 % rise in major flood events between 1980 and 2020 and accelerating SLR to 3.7 mm per year [4,8,9]. Pollution, habitat loss and rapid urbanisation further exacerbate this exposure [10,11].

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Nevertheless, urban waterfronts' ecological fragility contrasts with their historical and cultural importance. For centuries, as cities expanded along waterways, urban waterfronts have been vital to the economic, social and cultural fabric of urban centres, serving as hubs for industry, maritime trade and transportation [1,12,13]. Beyond this functional significance, these spaces shaped urban identity and became an integral part of the urban dynamics [14,10,15].

Industrialisation progressively hardened shorelines and riverbanks through embankments and quay walls, facilitating the urbanisation of waterfronts and the construction of industrial plants, warehouses and factories [16,17]. To meet the growing demands of maritime trade, these spaces were increasingly transformed causing ecological degradation, physical and functional detachment from the urban centres and reduced capacity to buffer ecological shocks [18,5,10,17]. These conditions gave rise to targeted urban waterfront renewal efforts [19,20].

Two interrelated approaches emerged. Urban revitalisation generally refers to the physical and economic renewal of obsolete urban areas, typically through the transformation of former industrial or port zones into mixed-use redevelopments. Urban regeneration denotes a broader and more integrated process encompassing social, economic and environmental objectives, aimed at achieving sustainable and inclusive development [21,22,23]. In this study, urban waterfront regeneration is adopted as the overarching concept and analytical framework for sustainable urban waterfront development, integrating physical renewal with ecological resilience, social inclusion and economic vitality.

Since the Baltimore Inner Harbour project in North America in 1964, cities worldwide, from London's Docklands to Hamburg's HafenCity and Genoa's Expo, have embraced waterfront revitalisation as a catalyst for urban transformation, reconnecting the port-city interface and converting former industrial areas into multifunctional spaces that combine residential, commercial and recreational uses while preserving architectural heritage [24,25,26,27,14].

By the 1990 s, growing awareness of climate change, rapid urbanisation and ecological crisis, under the influence of sustainable development agendas, emphasised the need to integrate sustainable development and resilience [4,8,28,29,11]. This necessity remains urgent today: around 60 % of the world's population resides in coastal cities [30,11] with even higher proportions when riverside and lakeside cities are included, reflecting the historic and ongoing centrality of waterbodies to urban development [30]. Yet, rapid urbanisation, overexploitation of natural resources and unsustainable land-use practices continue to challenge ecological resilience [31].

In response, Nature-based Solutions (NbS) have emerged as innovative strategies that integrate climate change adaptation (NbS-CCA) [32], flood management and urban liveability [33]. In urban waterfronts, NbS address multiple hydrological risks and protection functions: coastal flooding through dunes, tidal wetlands and mangroves that buffer wave energy and storm surges; fluvial flooding through restored floodplains and riparian buffers that regulate flows and provide temporary water storage [34]; and pluvial flooding through distributed green infrastructure such as rain gardens, permeable pavements and green roofs that enhance infiltration and manage runoff [35,36]. Beyond flood defence and hydrological regulation, these interventions generate an array of co-benefits, that enhance ecological integrity, spatial quality and social well-being, while supporting the transition toward sustainable and resilient urban waterfronts [35,37,32,38,39].

Although the concept of NbS has received increasing attention in urban resilience and sustainability, their application to urban waterfront regeneration remains underexplored, particularly beyond coastal environments, where most existing studies are concentrated. While systematic reviews and taxonomies have provided broad insights into the role of NbS in climate adaptation and flood management [35,32,40,41,42,43], they predominantly support the development of natural solutions less constrained or rural settlements [44]. In contrast, urbanised waterfronts, characterised by more spatial and infrastructural limitations, remain comparatively limited [45,46,47].

To address this gap, this research combines a systematic literature review with the analysis of real-world case studies, enabling a comparison between scientific insights and practical implementations. The methodology followed a two-step process. First, a systematic review was conducted using Scopus and Web of Science, complemented by snowballing approaches. This step identified 22 peer-reviewed studies focused on the regeneration of urban waterfronts through NbS. The contributions were then categorised into conceptual/theoretical, real-world case studies, or design/assessment studies, allowing recurring analytical dimensions and guiding approaches to be identified. However, relatively few studies documented real-world implementations in detail.

Second, case studies were collected from specialised NbS databases (OPPLA, Urban Nature Atlas, Climate-ADAPT, GeoIKP) and grey literature, with emphasis on urbanised waterfronts where multifunctionality is shaped by both human, infrastructural and ecological resources. This dual approach made it possible to test the validity of strategies identified in the literature, highlight recurring patterns and best practices and consider how NbS are implemented across different geographic and climatic contexts. A comparative analysis then categorised projects by waterfront type, NbS employed, challenges and objectives.

This review aims to comprehensively examine the application of NbS to activate regenerative practices in urban waterfronts. Specifically, it seeks to answer the following questions: *How are NbS conceptualised, implemented and assessed in the context of urban waterfront regeneration, and what alignments or gaps exist between scholarly frameworks and real-world practices?*

Answering these questions is associated with the following primary objectives of the study:

- Map and synthesise how NbS for urban waterfront regeneration are conceptualised in the academic literature, identifying recurring themes, practices and analytical dimensions.
- Examine real-world case studies to highlight best practices, recurring strategies and regional differences in the implementation of NbS.
- Compare and critically assess the alignments and divergences between scholarly perspectives and practical applications, to inform strategies for guiding sustainable urban waterfront development.

The manuscript is organised into four main sections: (i) a general framework on NbS for climate change adaptation and flood management; (ii) methodology; (iii) results from literature and case study analysis, emphasising the multifaceted application of NbS in urban waterfront contexts; (iv) discussion and (v) conclusion, offering suggestions for future developments. Additionally, the Supplementary Material presents a comprehensive portfolio showcasing an in-depth review of case studies and the NbS adopted for urban waterfront regeneration.

2. Materials and Methods

2.1. Background of the study

NbS have increasingly gained recognition as effective tools for climate change adaptation, disaster risk reduction and flood management. Defined by the IUCN as "actions to protect, sustainably manage and restore natural and modified ecosystems, benefiting people and nature simultaneously" (2020) [33], in urban waterfronts they are designed to enhance flood protection while restoring ecological processes that stabilise hydrological systems and buffer against extreme events [48,49],50]. By attenuating storm surges and wave energy, retaining surface runoff and increasing infiltration, they reduce exposure to coastal, fluvial and pluvial flooding more effectively than conventional grey infrastructure. Beyond their protective capacity, they provide an array of co-benefits, including biodiversity enhancement, regulation of water and carbon cycles, improving microclimatic conditions and supporting public health and well-being [37,50,51].

These multifunctionality and multi-benefit features explain their prominence in policy frameworks for both climate adaptation and disaster risk reduction. The Sendai Framework for Disaster Risk Reduction [52] explicitly recognises ecosystem-based and nature-based approaches as fundamental to reducing disaster risks, particularly those related to floods and extreme weather events. Similarly, the IPCC [4] outlines four key pathways for adaptation to SLR, namely protection, accommodation, advance and retreat, within which Ecosystem-based Adaptation (EbA) and the broader framework of NbS for Climate Change Adaptation (NbS-CCA) have emerged as transformative strategies [32]. Together with the European Green Deal [53], the Nature Restoration Law [54], and the UN Sustainable Development Goals, these frameworks position NbS at the intersection of environmental restoration, climate adaptation and resilient urban planning, promoting approaches that are both cost-effective and ecologically regenerative [48].

A range of frameworks has been developed to categorise NbS. Eggermont et al. [55] proposed a typology based on the degree of human intervention, while Gómez Martín et al. (2020) [41] operationalised this for water-related hazards by including selection criteria such as co-benefits, trade-offs and climate-change impacts. Motta Zanin et al. [40] further refined the framework in Mediterranean coastal contexts, linking intervention types to evidence of effectiveness and governance challenges. The World Bank (2021) [36] advanced an applied portfolio spanning small-scale urban green spaces to large-scale wetlands and coastal buffers, explicitly connecting NbS to water management and resilience. Such frameworks provide useful typological lenses, but targeted reviews are equally critical for completing the framework.

Recent systematic reviews have expanded this need. Johnson et al. [32], in a *meta*-review of over 90 NbS reviews, highlighted how fragmented the field remains despite its rapid growth. Importantly, while their review calls for more integrative perspectives, targeted reviews, such as the present study on urban waterfronts, remain essential to complete this broader picture. Chausson et al. [42], through a systematic mapping of more than 350 studies, confirmed that while NbS are often effective in reducing climate impacts such as floods and erosion, evidence is geographically biased and rarely considers ecological, social and economic outcomes together. Debele et al. [43], analysing 547 NbS case studies for disaster risk reduction, found that most interventions were concentrated in Europe, largely focused on green or hybrid approaches. Complementing this, Aghaloo et al. [35] reviewed 582 urban studies and proposed a taxonomy of 10 approaches and 29 measures, linking intervention type, spatial scale, climate context and co-benefits. Their work emphasises the prominence of Sustainable Urban Drainage Systems (SUDS), Water-Sensitive Urban Design (WSUD) and Blue-Green Infrastructure (BGI) in urban flood resilience, while also pointing to persistent trade-offs in

costs, governance and effectiveness.

To clarify how this study builds upon existing scholarship, Table 1 summarises key systematic reviews and typological studies on NbS, demonstrating both the promise for flood management and climate change adaptation and the need for more context-specific syntheses. While broad frameworks and taxonomies offer valuable guidance, the systematisation and consolidation of knowledge specific to urban waterfront regeneration through NbS, whether coastal, fluvial or lacustrine, remains necessary to capture their distinct vulnerabilities and leverage their unique opportunities for resilient and adaptive urban design.

Table 1
Summary of key scholarly and institutional contributions reviewed in relation to NbS for flood management and climate change adaptation.

Author(s), Year	Type of Contribution	Scope and Aim	Key Findings	Identified Gaps
Aghaloo et al. [35]	Systematic review and taxonomy	Large-scale review of urban NbS literature to classify approaches and measures for urban flood resilience.	Identifies dominant urban NbS (SUDS/WSUD/BGI) and highlights common co-benefits (stormwater regulation, heat mitigation, biodiversity).	Governance, long-term performance monitoring and cost/effectiveness trade-offs remain under-addressed.
Chausson et al. [42]	Systematic review	Systematic mapping of 376 studies evaluating NbS effectiveness for climate and hydro-meteorological hazards.	NbS often reduce climate impacts (floods, erosion); evidence concentrated in natural/semi-natural systems. Most studied: ecosystem creation (34 %) and restoration (29 %), mainly for water scarcity, soil erosion, and flooding.	Geographic bias (mostly Global North and Northern Europe) and weak integration of ecological, social and economic outcomes in many studies. Underexplored hazards ((coastal, wildfire).
Debele et al. [43]	Global case-study analysis	Review of 547 NbS case studies for disaster risk reduction.	Documents wide use of green/hybrid NbS; majority of documented cases cluster in Europe.	Underrepresentation of Global South cases; limited discussion linking governance arrangements to measured outcomes; lack of metrics, and indicators.
Eggermont et al. [55]	Conceptual framing	Early, influential framing of NbS in policy and research (GAIA commentary and syntheses).	Proposed broad typologies and helped shift policy attention to NbS; established links to ecosystem services and societal challenges.	Conceptual and high-level: did not operationalise typologies for specific hydrological or urban contexts.
Gómez Martín et al. [41]	Applied classification	Operationalised NbS classification for water-related hazards, adding selection criteria (co-benefits, trade-offs, climate impacts).	Mapped NbS types to water hazard management and proposed decision criteria for selection in practice.	Limited empirical testing across diverse urban waterfront contexts; need for more evidence on implementation in constrained urban settings.
Johnson et al. [32]	Meta-review of systematic reviews	Synthesised > 90 systematic reviews on NbS for climate adaptation to identify trends and gaps.	Confirms rapid growth of NbS literature but documented fragmentation and inconsistent metrics across reviews.	Calls for more integrative, targeted reviews (e.g., sectoral or context-specific syntheses).
Motta Zanin et al. [40]	Systematic review	Review of 23 documents on NbS in Mediterranean coastal contexts, linking intervention types to evidence and governance challenges.	Highlights effectiveness of coastal NbS (dunes, marshes) and governance/institutional barriers to scaling.	Limited transferability beyond Mediterranean coastal systems; governance and long-term monitoring gaps.
World Bank [36]	Catalogue of solutions	Policy and operational guidance linking NbS to disaster risk reduction and resilience investments.	Provides practical portfolios from small urban installations (green roofs, swales) to large wetlands/coastal buffers and promotes NbS in operational projects. Defines 5 principles: assess benefits/costs; use integrated hybrid systems; follow hierarchy (Protect > Restore > Create); ensure multiscale and stakeholder integration.	Practical guidance often lacks detailed governance pathways, standardized monitoring frameworks and cost-benefit data for mainstreaming.

2.2. Systematic review of academic literature and case studies

This research examines the implementation of NbS in the regeneration of urban waterfronts, focusing on the most widely adopted solutions and analysing their contributions as reflected in both scholarly perspectives and real-world applications. To ensure a transparent and systematic approach, the study employed the PRISMA methodology for the literature review. Searches were performed in Scopus and Web of Science, using the query: ("urban waterfront" OR waterfront OR riverfront OR seafront OR lakefront) AND ("nature-based solution" OR "nature based solution" OR "green infrastructure"), limiting to English language.

Keywords were selected to reflect the study's scope and capture research explicitly addressing urban waterfronts in relation to NbS concepts. The terms "urban waterfront", "riverfront", "seafront" and "lakefront" cover the main water contexts examined, while "nature-based solution" and "green infrastructure" represent the most widely adopted terminology in scientific and policy literature [33,56]. Broader terms such as "regeneration", "flood", "sea level rise" and "climate change" were considered during preliminary testing but excluded from the main query to maintain conceptual precision and avoid retrieving studies outside the NbS focus. Iterative discovery techniques and snowballing approach complemented this research (Fig. 1).

The purpose of this phase was not only to map conceptual framings of NbS in the context of urban waterfront regeneration (e.g., WSUD, BGI, SUDs, living shorelines), but also to identify patterns in terms of the typologies of NbS used and recurring strategies applied. A significant share of publications addressed themes indirectly related to NbS, such as community perception of green–blue infrastructure, waterfront usage and land-use dynamics or the role of governance and environmental justice in planning processes. While valuable, these contributions did not directly inform the research question guiding this review, which focuses on delivering an overview of solutions and strategies through NbS applied in urban waterfront regeneration. A smaller subset of studies (22 papers) provided more targeted insights, explicitly engaging with the scope of the review and highlighting the need for a more focused synthesis.

However, this initial review of academic literature provided a limited overview of how NbS are applied in the context of urbanised waterfronts, both because of the limited number of available studies and evidence of real-world implementations. This research adopts a dual approach, integrating both scholarly literature and real-world case studies.

The case studies were identified from specialised platforms focused on NbS, such as OPPLA, Urban Nature Atlas and Climate-ADAPT, as well as from grey literature, including project reports, government publications and other non-peer-reviewed sources. Additional platforms, such as GeoIKP, focused on coastal resilience and environmental adaptation, were also explored. A snowball sampling approach was employed to further identify relevant case studies.

The case studies were selected according to criteria that prioritised urban waterfronts, such as riverbanks, coastal zones, harbours, and lakeshores, where spatial constraints and infrastructural boundaries are more pronounced than in rural settings. Only projects that involved NbS, defined as interventions utilising natural processes to address urban challenges, were considered, while projects relying solely on hard engineering solutions (e.g., seawalls or concrete embankments) were excluded. Additionally, the projects had to integrate a multidisciplinary approach, balancing ecological, social and cultural objectives and had to have been implemented within the last 15 years or to include historic cases that remained relevant to the research's focus on contemporary urban regeneration practices.

Through this comprehensive selection process, 74 case studies were identified (see in the Supplementary Materials): 23 from OPPLA, 7 from Climate-ADAPT, 27 from Urban Nature Atlas and 5 from GeoIKP. In addition, 8 academic papers reporting real-world cases and 4 contributions from grey literature were included (Fig. 2). Collectively, this portfolio provided a rich source of insights into the patterns of NbS adoption in urban waterfront regeneration.

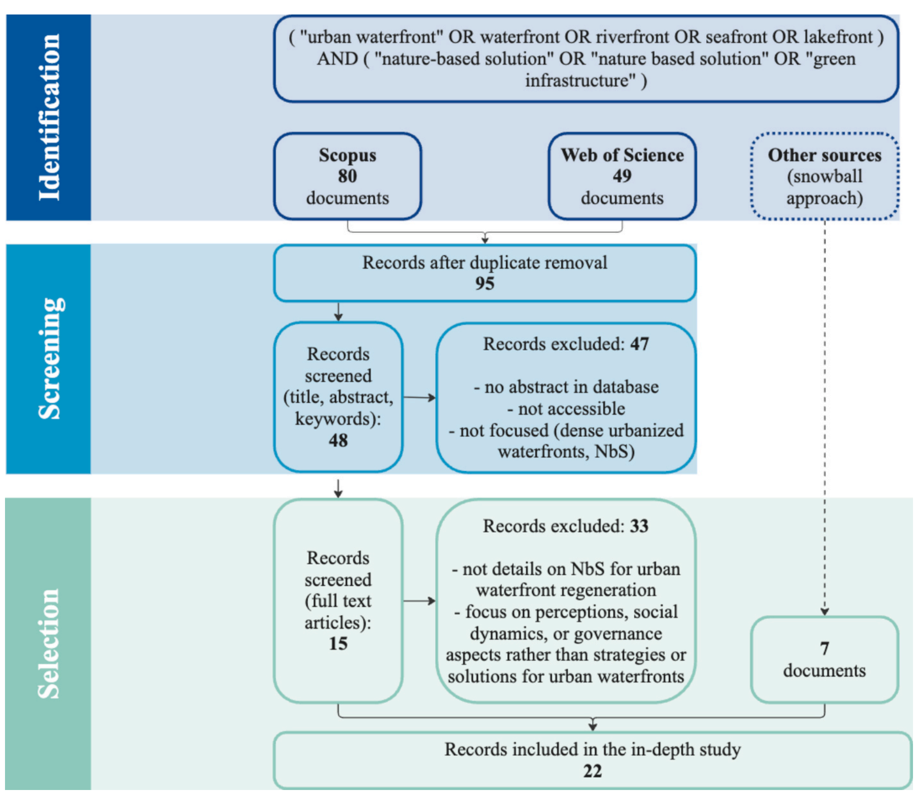

Fig. 1. PRISMA flow diagram illustrating the selection process of peer-reviewed articles.

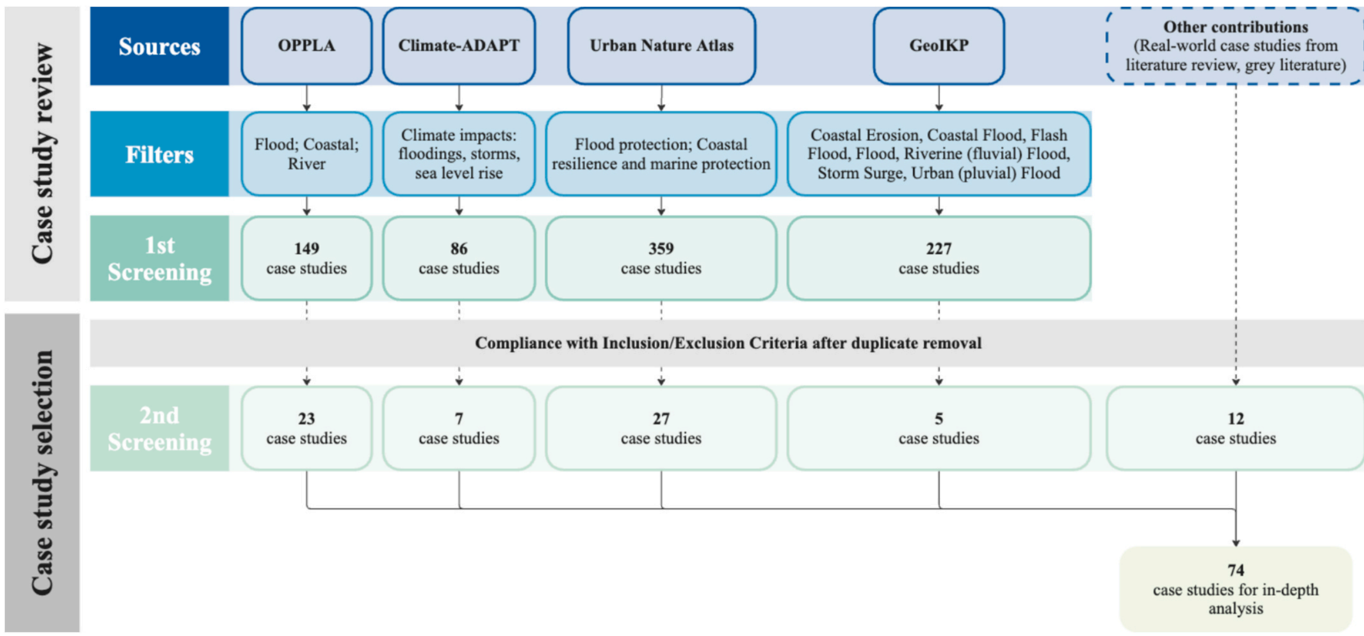

Fig. 2. Flow diagram illustrating the systematic approach used for the selection of case studies.

3. Results

3.1. NbS in urban waterfront regeneration in academic literature

Starting from a general overview, the 22 selected papers were divided into categories based on their contribution to the topic, as shown in Table 2. These works can be grouped into three main categories: conceptual or theoretical contributions (10 papers); real-world case studies, which document implemented interventions in urban waterfronts (11 papers); and design projects and assessment studies, evaluating or modelling the effectiveness of NbS (7 papers).

Table 2
Contribution to the knowledge from the academic literature.

Source: Author(s), Year	Conceptual/ theoretical	Real-world case study	Design/ assessment
Akhnoukh & Campbell [57]			✓
Bansal & Haridasan [58]		✓	
Baptist et al. [59]		✓	✓
Bin Zaman et al. [60]	✓	✓	
Blau et al. [61]	✓		
Bredes et al. [45]		✓	
Curran & Hamilton [62]		✓	
Durán Vian et al. [17]	✓		✓
Dyson & Yocom [47]	✓		
Ficzkowski & Krantzberg [63]	✓		
Gorzka, Burda & Nyka [64]		✓	✓
Karamouz & Heydari [65]			✓
Matos et al. [66]	✓	✓	
Mayer-Pinto et al. [67]	✓		
Mell [68]		✓	
Mosaad et al. [69]	✓		
Niehuns Antunes et al. [70]			✓
Ramírez-Agudelo et al. [71]		✓	
Ryu [72]	✓		
Starzyk et al. [73]			✓
Van Der Spek et al. [74]		✓	
Wu & Liu [75]	✓	✓	

Conceptual and theoretical works (e.g., [47,63,67,72] mainly provide frameworks, principles, or general guidelines for implementing NbS in waterfronts. These contributions often highlight the multifunctionality of NbS and propose it as an alternative or complement to grey infrastructure. They also tend to explore broader ideas such as ecosystem service enhancement, habitat restoration and socio-cultural benefits. However, these papers are less concerned with site-specific interventions and more with advancing theoretical and strategic models, such as living shorelines or WSUD.

Real-world case studies (e.g., [58,59,68,71] focus on documented NbS implementations in urban waterfronts. They present direct evidence of how NbS function in practice, providing valuable insights into strategies, limitations and contextual conditions. These studies tend to emphasise flood risk reduction, stormwater management or habitat restoration through specific solutions adopted. These case-based contributions were then integrated into the case study analysis after further investigation into other specialised sources.

Design and assessment studies (e.g., [45,62,70,73]) evaluate or model the performance of NbS interventions through a scenario analysis or by comparing them with grey alternatives. These works provide quantitative or qualitative assessments of NbS efficiency in achieving the predetermined objectives. Several contributions overlap in contributions, for example, by providing a conceptual framework while also presenting case-based applications (e.g., [66,75,60]).

Despite differences in their methodological contributions to the knowledge, the academic literature consistently revolves around four analytical dimensions as recurring topics that form a framework for interpreting NbS in urban waterfront regeneration: (i) waterbody typology, (ii) climate-related and human-induced challenges, (iii) resilience and adaptation objectives and (iv) NbS typologies. This framework is particularly relevant for the subsequent analysis of real-world case studies (Table 3).

Studies predominantly examine riverine and deltaic settings (e.g., [58,61,68,60]) or coastal and estuarine contexts (e.g., [57,59,45,72]), with a smaller literature on lakefronts (e.g., [63,69]). Across all contexts, climate-related challenges vary by waterbody: SLR, storm surges and coastal erosion in coastal and estuarine studies [59,73,74]; river flooding, pluvial flooding and heat stress in riverine and deltaic settings

Table 3
Summary of reviewed studies, clustered by waterbody type, highlighting the dominant climate-related and anthropogenic drivers, corresponding objectives, and the relevant NbS applied to address them. The table illustrates how NbS functions and typologies vary across coastal and estuarine, river and delta, and lakefront contexts, reflecting differences in hydrological challenges, spatial conditions, and adaptive priorities in urban waterfront regeneration.

Waterbody type	Author(s), Year	Climate challenges	Non-climatic anthropogenic drivers	Objectives	Relevant NbS for the challenges addressed
Coastal and Estuary	Akhnoukh & Campbell [57], Baptist et al. [59] Bredes et al. [45] Gorzka, Burda & Nyka [64] Karamouz & Heydari [65] Matos et al. [66] Mayer-Pinto et al. [67] Ramírez-Agudelo et al. [71] Ryu [72] Van Der Spek et al. [74]	• Sea-level rise • Storm surge • Coastal erosion • Wave surge • Salinity intrusion • Heat stress	• Hard armouring • urbanisation • habitat degradation • Subsidence • Poor land-use planning • Ownership fragmentation	• Accessibility and recreation • Biodiversity enhancement • Ecosystem service enhancement • Erosion control • Flood risk reduction • Habitat restoration • Heat mitigation • Heritage conservation • Resilient infrastructure • Stormwater management • Urban regeneration • Wave attenuation	• **For coastal erosion, SLR and storm surge**: dune restoration, sand nourishment, salt marshes, tidal pools, vegetated dunes, hybrid edge solutions and living shorelines. • **For wave attenuation and salinity intrusion:** seagrass restoration, sand-based breakwaters, breakwaters stone reef, sediment reuse and vegetated/bioengineered gabions. • **For heat stress, hard armouring and habitat degradation:** Seagrass restoration, vegetated buffer, biodiversity support devices, habitat nest and living shorelines.
River and Delta	Bansal & Haridasan [58] Bin Zaman et al. [60] Blau et al. [61] Curran & Hamilton [62] Durán Vian et al. [17] Dyson & Yocom [47] Gorzka, Burda & Nyka [64] Karamouz & Heydari [65] Mell [68] Niehuns Antunes et al. [70] Ramírez-Agudelo et al. [71] Starzyk et al. [73] Wu & Liu [75]	• Fluvial flooding • Pluvial flooding • Heat stress • Stormwater runoff • Drought • Bank erosion	• Urbanisation • Water pollution • Impermeable surfaces • Poor drainage	• Accessibility and recreation • Biodiversity enhancement • Ecosystem service enhancement • Erosion control • Flood risk reduction • Habitat restoration • Heat mitigation • Heritage conservation • Resilient infrastructure • Stormwater management • Urban regeneration • Water quality improvement	• **For fluvial and pluvial flooding:** riparian buffers and greenways, river and stream renaturation, floodable green areas and green levee. • **For stormwater runoff and poor drainage**: bioswales, rain gardens, bioretention areas, retention basin and ponds, permeable pavements and parking, green roofs and green walls. • **For bank erosion and channelisation:** green embankments, vegetated/ bioengineered gabions, hybrid edge solutions and terraces • **For heat stress and drought:** urban parks, urban groves and street trees, depaving asphalt/concrete. • **For water pollution and ecological degradation:** constructed wetlands, constructed floating green islands, wetland restoration, habitat nest and biodiversity support devices.
Lakes	Dyson & Yocom [47] Ficzkowski & Krantzberg [63] Gorzka, Burda & Nyka [64] Mosaad et al. [69]	• Fluctuating water levels • Eutrophication • Bank erosion • Stormwater runoff • Pluvial flooding	• Urbanisation • Water pollution • Impermeable surfaces • Poor drainage	• Accessibility and recreation • Biodiversity enhancement • Ecosystem service enhancement • Erosion control • Flood risk reduction • Habitat restoration • Heat mitigation • Resilient infrastructure • Stormwater management • Urban regeneration • Water quality improvement	• **For fluctuating water levels and pluvial flooding:** retention basins, floodable green areas and constructed wetlands. • **For eutrophication and water pollution:** wetland restoration and vegetated buffers. • **For bank erosion and habitat degradation:** vegetated/ bioengineered gabions, riparian buffers and hybrid edge solutions. • **For stormwater runoff and poor drainage:** bioswales, rain gardens and permeable pavements

[58,17,75]; fluctuating water levels and eutrophication for lakes [63, 69]. These hydrological threats, compounded by urbanisation, habitat loss, shoreline armouring and pollution, drive similar objectives: flood and erosion control, habitat restoration, water-quality improvement and public-space enhancement.

Finally, a wide spectrum of NbS is deployed, reflecting the variety of environmental challenges, spatial constraints, and socio-ecological objectives associated with these areas. To organise the typologies of interventions, NbS were identified through their recurrence in the systematic literature review and then were subsequently cross-referenced with existing classifications and taxonomies, including those proposed by Aghaloo et al. [35] and the World Bank [36], to ensure conceptual rigour and comparability. From this synthesis, three contexts particularly relevant to urban waterfronts were derived, capturing both the ecological processes targeted, such as erosion control, water retention, habitat restoration, and the urban constraints shaping their implementation, like the degree of urbanisation and land availability. These categories are not rigidly separated; rather, they often overlap and interact, reflecting the multifunctional and adaptive nature of NbS.

– **Urban ecological restoration measures**, including wetland, mangroves and dunes restoration, as well as riparian buffers and greenways, are often deployed to control erosion, habitat degradation and biodiversity loss, providing protective and regenerative resilience by re-establishing natural processes and buffer zones (e.g., [59,67,63]. In urbanised waterfronts, however, their large spatial requirements and reliance on relatively more rural settings limit their direct application. As a result, restoration efforts in such contexts tend to occur at smaller scales or as partial ecological insertions, underscoring the tension between ecological goals and spatial feasibility [76].

– **Hybrid and adaptive edge solutions**, like living shorelines, ecological seawalls and hybrid edge solutions, which address shoreline hardening, flood exposure and infrastructural vulnerability, offering adaptive resilience that reconciles ecological functionality with engineered stability in urbanised waterfront edges (e.g., [47,57,45]. These solutions are widely adopted in the literature as effective responses to shoreline and bank hardening. While their ecological impacts, such as habitat provision at the waterfront's edge, may be less systemic than full restoration, they allow natural processes to operate within built environments, enhancing a flexible approach in space-constrained areas.

– **Water-sensitive urban systems**, such as bioswales, permeable pavements, rain gardens and retention ponds, respond mainly to pluvial and stormwater management pressures, enhancing absorptive resilience and urban permeability while mitigating heat stress and runoff accumulation (e.g., [58,68,70]). They also encompass urban greening strategies, including green roofs, walls and parks, which extend ecological functionality into dense urban areas while delivering co-benefits for liveability (e.g., [62,75]). Beyond the waterfront boundary, these interventions work efficiently in combination with the regulation and retention of water upstream to reduce the pressure on waterfronts, particularly during overflowing water and extreme weather events.

Collectively, urban ecological restoration, hybrid and adaptive edge solutions and water-sensitive urban systems directly respond to the combined ecological, hydrological and urban pressures of these sites. Yet, while effective resilience in urban waterfronts often depends on the integration of different NbS interventions, certain typologies are inherently tied to specific hydrological contexts and challenges (e.g., dunes to coastal protection, riparian buffers to fluvial resilience or bioswales and

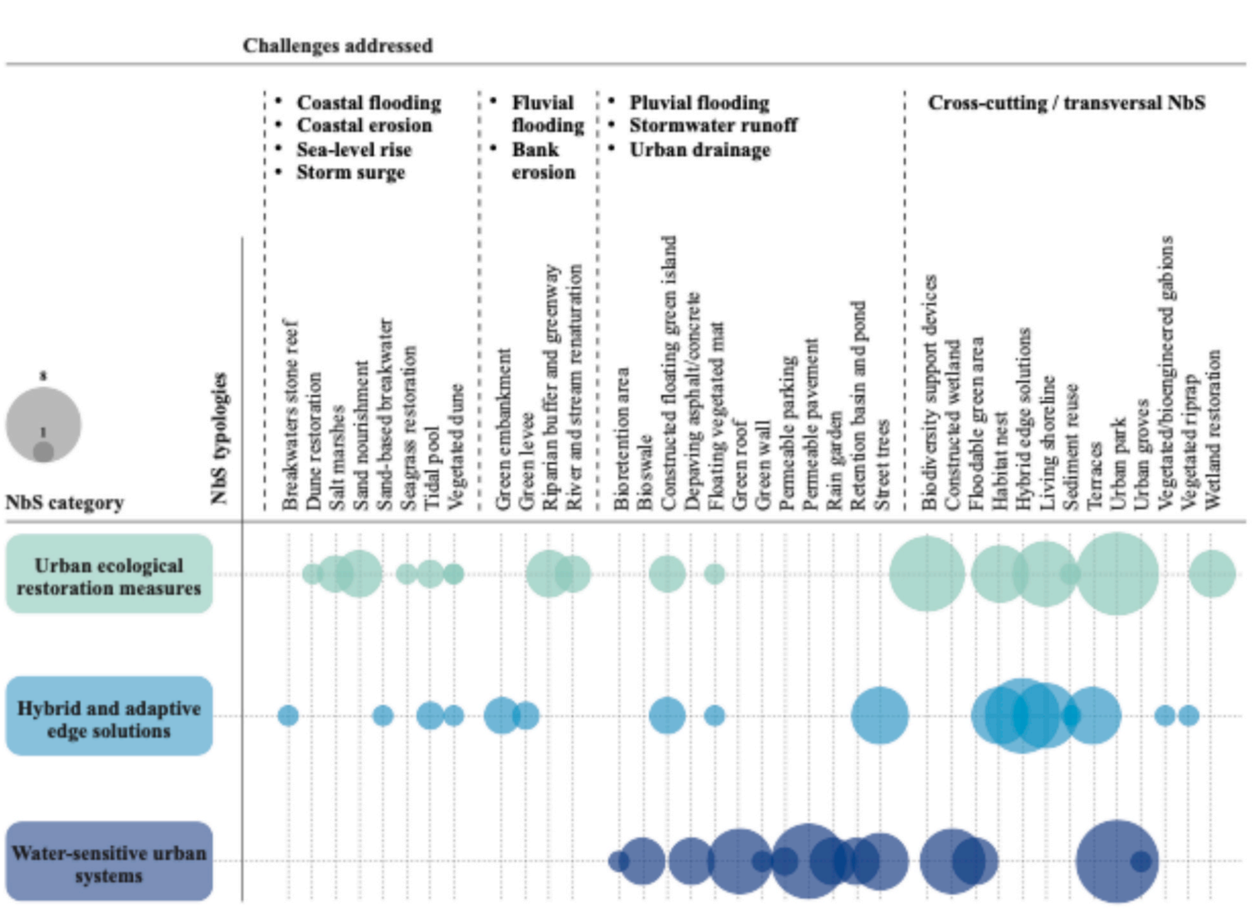

Fig. 3. Recurring NbS contexts for urban waterfronts (ecological restoration, hybrid and adaptive edges and water-sensitive urban systems) with representative intervention typologies and their relative frequency in the reviewed literature.

permeable pavements to pluvial management of urban spaces). Fig. 3 organises these NbS typologies according to the primary challenges they address, grouped under coastal hazards (coastal flooding, erosion, SLR, storm and wave surge), fluvial hazards (fluvial flooding and bank erosion), and pluvial or urban drainage issues (stormwater runoff, pluvial flooding, and urban drainage), alongside a set of cross-cutting interventions that operate across multiple contexts. Taken together, the figure illustrates how NbS adoption in the urban waterfront context is shaped less by the availability of techniques than by the degree of urbanisation, land pressures and the need to balance systemic restoration goals with context-specific adaptability.

Building on these patterns, the clustering of interventions along the three mentioned contexts informed broader orientations that could capture not only what types of NbS are applied, but also how and where they tend to be implemented. Accordingly, the application of NbS can be summarised as: (i) interventions focused on retrofitting the waterfront edge, including solutions that integrate ecological functions and biodiversity enhancement into built structures along more constrained shorelines; (ii) systemic ecological restoration of waterfront environments, covering the restoration of larger natural habitats and degraded waterfront spaces and aiming to re-establish ecological processes, improve resilience, and recover habitat; (iii) measures enhancing permeability within adjacent waterfront urban areas, extending the impact of NbS beyond the immediate waterfront and using green and water-sensitive infrastructure to improve hydrological regulation, connectivity and multifunctional resilience across the urban fabric. To further examine how these orientations are operationalised and implemented, the next section focuses on the analysis of 74 real-world case studies.

3.2. Case study analysis

To complement the conceptual orientations identified in the literature, a comparative analysis of 74 international case studies was conducted. These cases, mapped across diverse climatic and geographic contexts (Fig. 4), offer a perspective on how NbS are implemented in practice for urban waterfront regeneration. The analysis not only serves to ground three guiding orientations emerging from the review, but also expands them by highlighting the challenges, objectives and NbS typologies implemented.

The portfolio spans a wide range of interventions, depending on the waterfront context and the dominant risks addressed. In coastal and estuarine environments, where exposure to SLR, storm surge and erosion prevails, NbS combine large-scale protective and restorative measures, such as dunes, sand nourishment and salt marshes, with hybrid edge solutions like living shorelines and vegetated gabions that stabilise the waterfront and create intertidal habitats. In riverine and deltaic settings, characterised by fluvial and pluvial flooding, runoff and bank erosion, the prevalent NbS focus on systemic ecological restoration and permeability enhancement. Riparian buffers, floodable parks and terraced embankments reconnect floodplains and regulate flows, while bioswales, permeable pavements and retention ponds mitigate stormwater accumulation and improve infiltration. These measures address both hydraulic regulation and urban resilience, illustrating how restoration and water-sensitive design intersect in complex urban systems. In lacustrine contexts, where challenges include fluctuating water levels, eutrophication and water-quality degradation, NbS prioritise ecological restoration and water purification. Constructed wetlands and vegetated buffers improve nutrient uptake, stabilise banks and enhance aquatic biodiversity, while complementary urban-scale measures reduce polluted runoff from adjacent areas.

3.2.1. Interventions focused on retrofitting the waterfront edge

The waterfront edge is a critical zone where urban infrastructure meets the aquatic ecosystem; thus, its design has direct implications for both biodiversity and resilience. Enhancing this interface could involve the use of hybrid solutions that simultaneously strengthen soil stability, support climate adaptation and foster ecological functions.

Firstly, physical or structural modifications of riverbanks and lakefronts illustrate how NbS can ensure flood protection and accommodate river overflow while creating a gradient transition between land and water. In the Isar-Plan in Munich, naturally developing banks combined with gravel stone and stone rock steps in a honeycomb design, reintroduced natural dynamics and habitats. Similarly, Bath Quays Waterside Park demonstrates how green embankments can both act as seawalls when water levels are high and water retention barrier.

In the coastal and estuarine contexts, focus shifts to erosion, wave energy dissipation and SLR. Dune restoration and sand nourishment

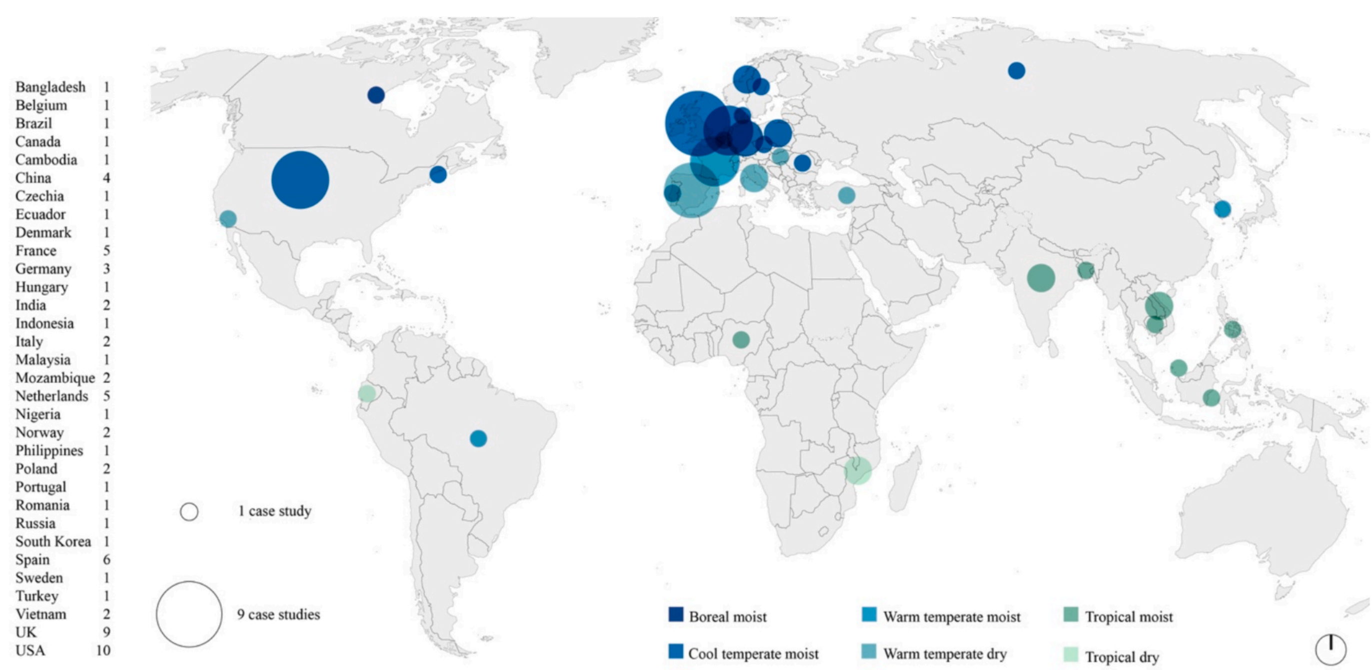

Fig. 4. Map of the 74 case studies and their climatic regions.

projects, such as Barcelona's hybrid dunes and Cape May Point in New Jersey, demonstrate how sand-based interventions can stabilise shorelines, whether through semi-fixed dunes or the advancement of the shoreline, enhance biodiversity, and provide protection even in dense or space-constrained contexts. Innovative models, such as the Sandbar Breakwater in West Africa, push this concept even further by replacing rock-intensive breakwaters with sand-based structures that rely on natural sediment accretion, significantly reducing the ecological footprint of coastal defences [74].

Terracing also offers effective edge retrofits. For example, in Shanghai's Soochow Creek [75], terraces were combined with stepped wetlands to increase the resilience of both banks and soil permeability, while in Cambodia and Turkey, vegetated or bioengineered gabions, porous cages filled with natural materials such as stones, plants or even oyster reefs, capture debris and sediment and allow species to colonise, which in turn reinforces the structure [36]. These approaches connect closely with the broader concept of living shorelines, which combine structural reinforcement with habitat creation. Some key examples of these interventions are the Harlem River Park in New York [45], with the use of gabion baskets filled with rocks and oyster shells and habitat benches, in the Palangrers Beach in Girona, with the living crib wall or in the Port of San Diego [45], where shaped ecological concrete has been used to simulate the slope on a vertical shoreline and increase the tidal pool development in intertidal and subtidal zones.

Such biodiverse edges serve not only as protective barriers but also as nurseries for fish, feeding grounds for birds and habitats for invertebrates. In more urbanised contexts with pontoons or docks, strategies such as increasing light penetration beneath structures, as in the Seattle Seawall, or adding 'piling habitat' for shelter, further enhance ecological functionality. While such retrofits focus on reconfiguring the edge itself, their effectiveness is amplified when combined with broader ecological restoration strategies across urban waterfront environments.

3.2.2. Systemic ecological restoration of urban waterfront environments

The second guiding orientation involves the restoration of degraded natural areas on urban waterfront environments. These places are often located in zones where natural ecosystems have been significantly altered or degraded due to industrial activities, urban sprawl and pollution. Restorative efforts aim to reverse the ecological damage by rehabilitating habitats, reintroducing biodiversity and enhancing the natural function of these spaces.

A key strategy is daylighting rivers and streams, which involves depaving and removing potential obstructions, to restore waterways to their natural state [77,78]. Urban development often tends to redirect or bury these waterways in order to meet the demand for usable land. However, throughout the years, this has resulted not only in nutrient pollution and habitat loss, but also, given the exacerbating impacts of climate change, in an increase in downstream flooding [78]. A notable and well-known example of a successful daylighting is the Cheonggyecheon Restoration Project in Seoul, South Korea, where dismantling an elevated freeway restored a 5.8 km section of the historic Cheonggyecheon Stream. The project enhanced the natural landscape by restoring the ecosystem and revitalising the area, while catalysing socio-economic growth and urban renewal.

Other restoration strategies include revitalising green corridors. Linear parks, greenways and mangrove buffers, such as along the Philippines or Recreio corridor in Brazil, combine vegetation, wetlands and coastal ecosystem restoration to enhance biodiversity, store carbon, and mitigate flooding or erosion. Post-industrial sites can also be repurposed into ecological hubs. Lardner's Point Park in Philadelphia and Aygalades Park in Marseille transformed brownfields into floodable and permeable green spaces with restored wetlands and tidal marshes.

Finally, an interesting approach in the use of NbS for urban waterfront regeneration combines re-naturalisation processes on former industrial sites with the creation of new habitats to support biodiversity. In some cases, like in Bergen, disused infrastructure, such as old pontoons, docks or vessels, has been repurposed for habitat nesting and microalgae allotment. In others, such as Olympic Village development, entirely new habitat islands have been designed to accommodate biodiversity and counterbalance the environmental impacts of post-industrial sites.

These projects demonstrate how NbS can transform neglected urban waterfronts into vibrant ecological hubs, addressing diverse challenges, to support a more sustainable coexistence between urban functions and natural ecosystems.

3.2.3. Measures enhancing permeability within adjacent waterfront urban areas

The last approach focuses on enhancing permeability around waterfront areas, which addresses stormwater management and flood risks by allowing water to infiltrate into soils rather than run off impermeable surfaces. Examples include green roofs, bioswales and, in general, SUDs, which mimic natural hydrological processes by detaining, filtering and slowly releasing water. These examples range from city-scale approaches, with acupuncture solutions along the waterline, to neighbourhood-scale redesigns and the creation of specific, localised systems tailored to place-based challenges.

At the city scale, Rotterdam's "Waterproof City" project demonstrates an adaptive approach to flood resilience, combining permeable paving, vegetation, rain gardens, bioswales, along floodable squares to capture stormwater effectively. Similarly, in Sheffield, UK, a radial park system based on a network of "riverside parkways" has been proposed. These linear parks are designed to follow the city's major watercourses, integrating solutions such as river renaturation, pocket parks and urban tree planting.

At the neighbourhood scale, the Climate Innovation District in Leeds, along the river Aire, integrates climate-resilient public spaces with SUDs. In Rouen, France, the former industrial area of Luciline, located along the Seine River, has been transformed into an eco-district that integrates climate change adaptation and mitigation solutions. The redevelopment includes a network of small canals connected to the Seine to drain water from the built environment, as well as vegetation-covered ditches, green roofs and tree corridors. Green roofs have been incorporated into heritage buildings along the riverfront for water storage.

The analysis of case studies highlights the need for a combined approach, rather than a singular focus on the waterfront edge as the main driver of climate adaptation. While edge-focused strategies provide critical protection and ecological enhancement, their effectiveness is more when complemented by permeability-oriented designs and restoration actions within adjacent urban areas. Such integration ensures that NbS function not only as technical tools but as part of a holistic, multi-scalar framework for resilience.

4. Discussion

To build on these insights, the present systematic review aims to provide a more integrated understanding of NbS in the context of urban waterfront regeneration, clarifying both theoretical approaches and practical implementations. While previous reviews have predominantly addressed urban or coastal settings for NbS development [32], this study positions them within the specific spatial context of urban waterfronts, encompassing a diverse range of waterbody typologies and considering the distinctive ecological, social and infrastructural interactions that emerge at the interface between urban and aquatic systems. This perspective offers a more targeted and nuanced understanding of the potential of NbS to enhance resilience, support ecosystem services and improve urban liveability in urbanised waterfronts. At the same time, the review highlighted a number of challenges and limitations that must be taken into account when interpreting the results.

One of the main challenges concerns the complexity of defining what constitutes an 'urban' environment. Since urbanisation is a dynamic process rather than a fixed or uniform condition, the concept of 'urban' remains fluid and often ambiguous. A similar issue arises with the term 'waterfront', which is described in multiple, often conflicting ways and lacks a standard use. Scholars frequently utilise expressions such as city-port, harbourfront, riverside, river edge, water edge or shoreline interchangeably to describe comparable contexts [79,80,17]. The interpretation of these terms varies between authors and has evolved over time, reflecting disciplinary and regional differences in how waterfronts are conceptualised. When these two issues intersect, namely the difficulty of defining what is'urban' and the inconsistent terminology of the 'waterfront', they contribute to a fragmentation of knowledge, making it challenging to analyse urbanised waterfront regeneration systematically. This fragmentation is further exacerbated by the scarcity of literature focusing specifically on urban waterfronts, which constrains both the availability of documented case studies and the number of peer-reviewed contributions.

Despite the limitations of the systematic review, a clear difference emerges when comparing literature and case studies in how NbS are identified and represented. In the academic literature, NbS are often presented as discrete typologies, making them relatively easy to classify and analyse. Solutions such as living shorelines (e.g. [45,63]), targeted bioengineering techniques that enhance edge hybridity and adaptability (e.g. [57,72]) or SUDs (e.g. [70,60]) are explicitly discussed and assessed for the delivery of resilience and adaptation goals. In contrast, case studies tend to embed NbS within broader spatial or urban design interventions, where multiple strategies are implemented simultaneously. For instance, a real-world urban waterfront regeneration may combine flood protection structures, habitat restoration and public space redesign, making it difficult to isolate and evaluate individual NbS types. While this is to be expected in practice, as real-world projects are inherently multi-dimensional, bringing together insights from both literature and case studies allows for a more comprehensive understanding and enables more quantifiable assessments than relying solely

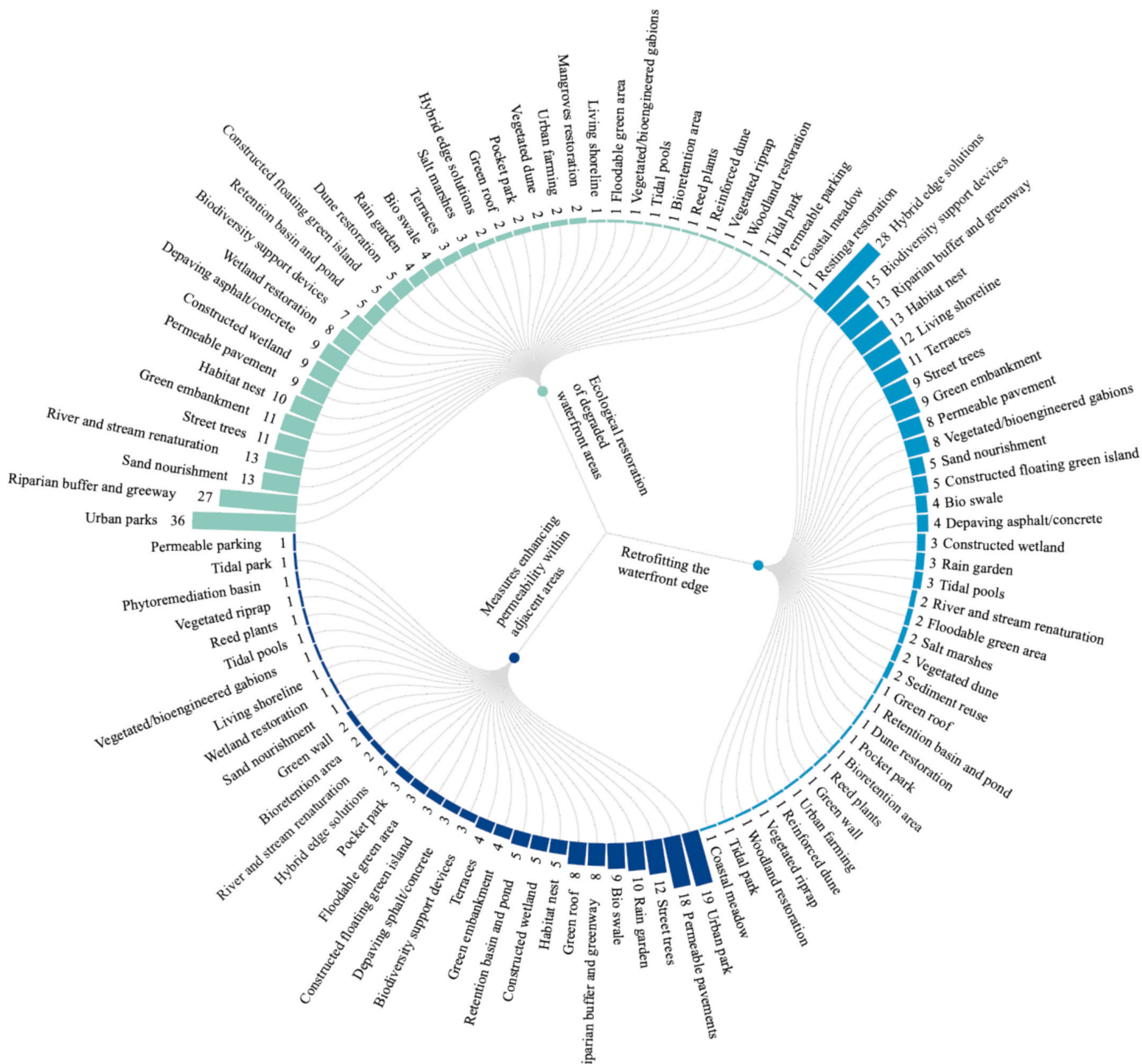

Fig. 5. Radial diagram showing the distribution of NbS typologies across the three orientations: waterfront edge retrofitting, systemic ecological restoration and permeability enhancement.

on descriptive analyses.

This contrast highlights a theory–practice gap: while academic research categorises NbS as discrete typologies, practice emphasises their integration into complex socio-ecological and spatial systems. To reconcile these perspectives, the analysis translated typological classifications into three orientations that reflect how and where NbS are operationalised in urban waterfront contexts: (i) interventions focused on retrofitting the waterfront edge, (ii) systemic ecological restoration of degraded waterfront environments and (iii) measures enhancing permeability within adjacent waterfront urban areas.

The distribution of NbS across the three identified strategies highlights distinct patterns of practice and research focus (Fig. 5)

– For waterfront edge retrofitting, the most cited NbS are hybrid edge solutions, vegetated or bioengineered gabions and living shorelines. These approaches dominate both scholarship and practice due to their direct response to critical climate-driven stressors such as SLR,

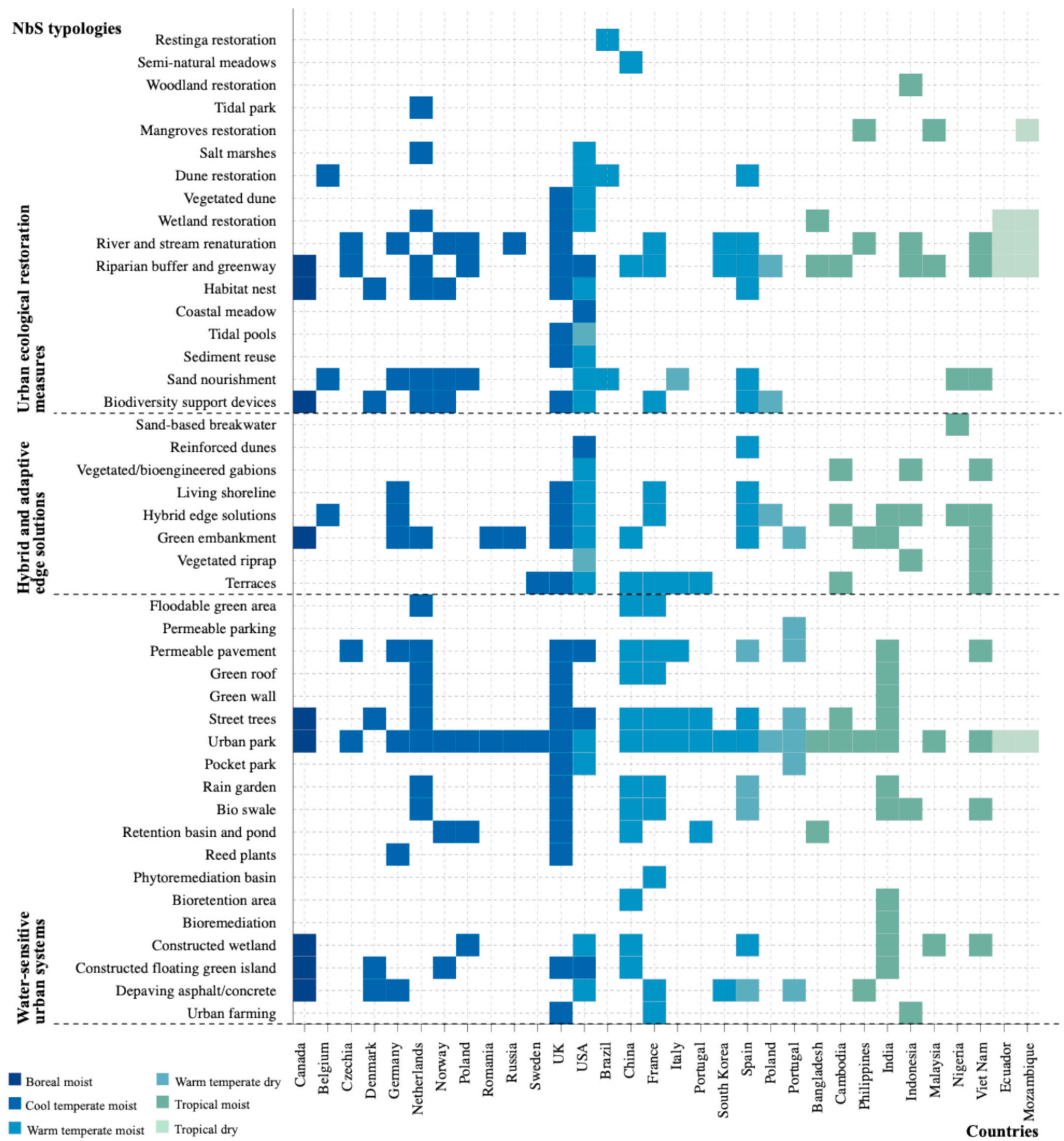

Fig. 6. Heatmap showing the distribution of NbS across countries and climatic regions. The grid highlights a denser clustering of NbS in cool and warm temperate moist regions, largely reflecting the concentration of highly urbanised, high-income countries (e.g., Europe, North America, East Asia) that invest in urban-oriented NbS.

erosion, and storm surge events. Their prominence also illustrates the growing preference for hybrid NbS [41,40,41,43], which integrate structural reinforcement with ecological enhancement, thereby offering multifunctional performance advantages over conventional engineering solutions in denser waterfront contexts. – Within the systemic ecological restoration, frequently recurring approaches include river and stream renaturation, wetland and dune restoration. These solutions are valued not only for their role in recovering degraded ecosystems but also for their capacity to deliver multiple co-benefits: deliver biodiversity gains, water-quality improvements and important social co-benefits such as recreational amenity and cultural reconnection to water landscapes [42,75,40].

– In the category of urban permeability enhancement, the most common NbS are bioswales, permeable pavements, and rain gardens. These measures function by retaining and infiltrating stormwater, thereby improving hydrological performance and mitigating pluvial flood risk. Concurrently, they contribute to urban climate regulation through localised heat reduction and support improvements in urban livability, ecological connectivity, and public space quality [35,32].

Another key finding is the acknowledgement of alternative solutions that may not be traditionally classified as NbS but still contribute significantly to biodiversity and ecosystem health. Two relevant examples are the application of ecological concrete and the beneficial reuse of dredged sediments. As demonstrated in the case of the Port of San Diego, biomaterials and specifically ecological concrete, not only contribute to lowering the overall carbon dioxide emissions related to concrete production, but also, since it's shaped with a peculiar circular form, it creates tidal habitats for biodiversity nesting. This dual role, structural stabilisation combined with habitat provision, illustrates the capacity of engineered substrates to function as eco-engineered tidal habitats.

Similarly, the beneficial reuse of dredged sediments constitutes an emerging adaptive strategy in sediment-based systems. When applied in controlled deposition schemes, dredged material can be allocated to the formation of artificial habitat islands, accelerating sediment accretion and vegetation colonisation. Alternatively, targeted placement along mudflats, sandy foreshores and eroding riverbanks enhances shoreline resilience by dissipating wave energy and mitigating saline intrusion. In both cases, sediments conventionally treated as waste streams are revalorised as functional ecological infrastructure, contributing simultaneously to biodiversity enhancement, climate adaptation, and sediment stabilisation in urban waterfront contexts.

The comparative analysis of NbS distribution across climatic regions and countries underscores a series of notable patterns in both adoption and functional emphasis (Fig. 6). Certain interventions, such as riparian buffers, bioswales, permeable pavements and urban parks, emerge as'baseline' strategies due to their multi-benefit capacity and transferability across a broad spectrum of climatic conditions. Their recurrence is primarily associated with the prevalence of pluvial flooding and stormwater runoff, which constitute generic urban challenges independent of specific hydroclimatic or geomorphological contexts. These solutions typically address water management through retention and infiltration, functioning at the local scale rather than as formal defence systems. In contrast, NbS targeting coastal and fluvial flooding operate with more site-dependent hydrodynamic conditions, such as wave energy or river discharge, and context-specific design. Examples include dunes and hybrid edge solutions, green embankments or floodable terraces, which simultaneously serve as protective infrastructure and ecological transition zones between land and water.

Conversely, other NbS display strong biogeographic specificity. Their implementation depends not only on hydraulic function but also on ecological feasibility. Mangrove restoration and woodland regeneration are predominantly implemented in tropical zones, where they align with coastal protection and carbon sequestration goals. Such solutions cannot be transposed to temperate or arid contexts because of their reliance on native species and local sedimentary and climatic conditions. In contrast, dune reinforcement or engineered nature-based features are most prevalent in temperate regions, where they contribute to shoreline stabilisation, habitat diversification and nutrient cycling. These distinctions underline that while some NbS provide broadly transferable solutions for pluvial resilience, others must be tailored to the specific hydrological and ecological regimes of their setting.

A further divergence is evident in the scale and typology of NbS across regions. In temperate moist regions, the predominance of engineered, small-scale interventions, particularly those oriented to stormwater management and urban retrofitting, contrasts with the dominance of ecosystem-based approaches in tropical and dry regions, where larger-scale ecological processes remain the principal focus. Such differences are shaped not only by biophysical conditions but also by socioeconomic determinants, such as financial capacity to invest in retrofitting, governance priorities and the degree of urban spatial constraints. The comparatively limited representation of ecosystem-based solutions in this review is also attributable to its scope: urbanised waterfronts and areas inherently restrict the feasibility of large-scale ecological restoration. This spatial limitation drives a stronger emphasis on hybridised and infrastructural NbS typologies, which integrate ecological principles within engineered frameworks to optimise performance under constrained conditions.

Additionally, post-implementation monitoring and adaptive management must be prioritised to evaluate long-term ecological and socioeconomic outcomes. In the academic literature, as evident in the typologies of contributions, scholars directly engage with the design, modelling scenarios, or quantifying effectiveness [65,70]. Others adopt a dual approach, combining conceptual frameworks with the assessment of real-world interventions, thereby offering insights into both theoretical and practical outcomes [59,74]. However, the case study analysis indicates a gap in post-implementation assessments. Many projects lack sufficient data to measure their long-term ecological and infrastructural performance, also due to their historical significance. Other projects are not actively monitored after a restoration project is complete [81,82]. Uncertainties related to climate change represent a significant challenge for the implementation of NbS [76]. The unpredictability of future climate, combined with the high upfront investments of nature-based features, complicates the evaluation of the long-term performance and resilience of these solutions.

This limitation is often linked to the governance and policy contexts in which projects are embedded. Across projects, governance modalities, from multi-level governance arrangements to top-down approaches, do not form a single, uniform pattern: projects vary in design, oversight and reporting. In this review, the level of available documentation depended in part on the platforms consulted (e.g., Urban Nature Atlas tended to offer more detailed project backgrounds), which means that informational visibility is uneven across cases. Regionally, Global North and more specifically Northern European cases more often coincide with multi-level governance and EU funding streams that provide more structured policy frameworks and reporting channels (e.g., Flanders, Belgium; Utrecht, Netherlands; Munich, Germany; Sheffield, UK). By contrast, Mediterranean and many Global South cases tend to be single project-based or top-down, with less evidence of long-term strategic planning or continuous monitoring (e.g., Bari, Italy; Lisbon, Portugal; Cheonggyecheon, South Korea; Lekki, Nigeria).

Taken together, these findings demonstrate that NbS implementation in regenerating urban waterfronts is site-specific, shaped by hydrological and ecological conditions, governance structures and socioeconomic capacities. Recognising the context dependency is critical for translating NbS from conceptual models into effective, place-based strategies for sustainable and resilient waterfront regeneration.

5. Conclusion

This review reaffirms the critical role of NbS in advancing climate change adaptation and fostering the ecological regeneration of urban waterfronts. The academic literature proved instrumental in identifying key NbS categories, recurrent analytical dimensions and providing conceptual frameworks that enabled a systematic classification of interventions. These insights facilitated a structured comparative analysis of 74 international case studies, illustrating how NbS are translated from conceptual models into practical applications.

Findings demonstrate that NbS in waterfront contexts extend far beyond technical devices for stormwater management or shoreline stabilisation. Rather, they function as systemic strategies capable of reshaping ecological processes, reconfiguring urban morphologies and redefining social uses of waterfront spaces. Therefore, three recurring orientations were identified: (i) retrofitting of waterfront edges, (ii) ecological restoration of degraded environments and (iii) enhancement of permeability within adjacent urban fabrics. Together, these constitute complementary layers of intervention that operate across spatial and functional scales.

The analysis also underlined several challenges. Spatial limitations, fragmented ownership and competing land uses complicate NbS adaptation in dense urban fabrics. Governance and policy integration remain critical for ensuring equitable access and community engagement. Moreover, the lack of systematic monitoring in real-world case studies limit the ability to assess ecological and socio-economic outcomes over time, a gap made more pressing by the accelerating uncertainties of climate change.

Despite these constraints, NbS represent a transformative tool for achieving global sustainability agendas, including the SDGs. Even under space-limited conditions, adaptive and hybrid strategies, such as terraced riverbanks integrating engineered floodwalls with biodiversity niches or eco-corridors supported by SUDs, illustrate that multifunctional ecological and social benefits can be achieved without requiring extensive land availability.

The review also revealed pronounced geographic disparities in NbS adoption and research. At the global scale, representation from the Global South remains limited, with most empirical evidence and implementation projects concentrated in the Global North. Within the European context, a further asymmetry emerges: Northern European countries lead in adoption, supported by strong governance frameworks and financing tools and policy instruments. By contrast, Mediterranean countries, despite being recognised as climate "hotspots" [83], continue to face persistent barriers, including insufficient funding, fragmented governance and limited institutional capacity. Addressing these disparities requires not only greater international cooperation to strengthen Global South participation, but also targeted capacity-building and innovative financing to advance NbS implementation in vulnerable Mediterranean regions.

Future research should prioritise the development of adaptable NbS frameworks tailored specifically to urbanised waterfronts, particularly in underrepresented contexts such as the Mediterranean. Establishing operational guidelines that integrate ecological, social and infrastructural objectives would provide decision-makers with robust tools to embed NbS within systemic resilience strategies. Advancing this agenda is essential to bridging the persistent theory–practice divide and positioning NbS as a cornerstone of adaptive, climate-resilient urban waterfront planning.

CRediT authorship contribution statement

Sara Marzio: Writing – review & editing, Writing – original draft, Visualization, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Jacopo Tosi:** Writing – original draft, Methodology, Conceptualization. **Francesca Poggi:** Writing – review & editing, Validation, Supervision, Methodology, Conceptualization. **Miguel Amado:** Writing – original draft, Validation, Supervision, Project administration, Methodology, Funding acquisition.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.cacint.2025.100281.

Data availability

No data was used for the research described in the article.

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