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Review

Nature-Based Solutions for Water Management in Europe: What Works, What Does Not, and What's Next?

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Abstract

Nature-based solutions (NbS) are increasingly recognized as strategic alternatives and complements to grey infrastructure for addressing water-related challenges in the context of climate change, urbanization, and biodiversity decline. This article presents a critical, theory-informed review of the state of NbS implementation in European water management, drawing on a structured synthesis of empirical evidence from regional case studies and policy frameworks. The analysis found that while NbS are effective in reducing surface runoff, mitigating floods, and improving water quality under low- to moderate-intensity events, their performance remains uncertain under extreme climate scenarios. Key gaps identified include the lack of long-term monitoring data, limited assessment of NbS under future climate conditions, and weak integration into mainstream planning and financing systems. Existing evaluation frameworks are critiqued for treating NbS as static interventions, overlooking their ecological dynamics and temporal variability. In response, a dynamic, climate-resilient assessment model is proposed—grounded in systems thinking, backcasting, and participatory scenario planning—to evaluate NbS adaptively. Emerging innovations, such as hybrid green–grey infrastructure, adaptive governance models, and novel financing mechanisms, are highlighted as key enablers for scaling NbS. The article contributes to the scientific literature by bridging theoretical and empirical insights, offering region-specific findings and recommendations based on a comparative analysis across diverse European contexts. These findings provide conceptual and methodological tools to better design, evaluate, and scale NbS for transformative, equitable, and climate-resilient water governance.

Keywords: nature-based solutions; water management; climate adaptation

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1. Introduction

Over the past decade, nature-based solutions (NbS) have gained substantial prominence within European environmental policy and academic discourse, particularly in the realm of water management. Defined as interventions that work with and enhance natural processes to address societal challenges while delivering multiple environmental, social, and economic co-benefits [1,2], NbS increasingly complement or offer alternatives to traditional "grey" infrastructure. They provide vital ecosystem services, such as flood attenuation, water purification, groundwater recharge, and improved urban livability [3,4]. This shift reflects broader transitions toward sustainable, integrated, and adaptive governance frameworks designed to confront accelerating climate change, biodiversity loss, and urbanization pressures [5].

The growing interest in NbS across Europe is driven by their capacity to deliver multifunctional benefits and their adaptability across diverse ecological and socio-political contexts. Moreover, NbS align closely with the Sustainable Development Goals and EU strategic priorities [6,7]. Advocates highlight their long-term cost-effectiveness, ability to foster inclusive community engagement, and potential to enhance resilience in both human and natural systems [8,9]. Reflecting this potential, the European Commission has embedded NbS within flagship initiatives, such as the European Green Deal, the EU Biodiversity Strategy for 2030, and the Climate Adaptation Strategy, framing them as instruments for climate resilience, innovation, green job creation, and sustainable competitiveness [1].

Despite strong policy support, the implementation and evaluation of NbS face persistent challenges. Notably, the absence of a unified definition and classification system leads to conceptual ambiguity, hindering policy coherence, comparability, and the transferability of projects [6,10]. Many assessment frameworks treat NbS as static interventions, overlooking their inherent ecological complexity and vulnerability to climate variability and land-use change [11,12]. Furthermore, robust empirical evidence on their long-term effectiveness, cost-efficiency, and scalability—especially under extreme hydrological events—remains limited compared to grey infrastructure [13,14].

This review addresses these gaps by synthesizing interdisciplinary research on NbS applications in European water management. Emphasis is placed on their performance under climate stressors, the suitability of emerging evaluation frameworks, and the enabling governance conditions critical to their success. The analysis is guided by three questions as follows: (1) What evidence supports the effectiveness of NbS in tackling Europe's water-related challenges? (2) What uncertainties and trade-offs remain? (3) What methodological and institutional innovations are required to facilitate their sustained integration into European water governance?

The implementation of NbS across Europe is heterogeneous, shaped by regional variations in climate, governance structures, infrastructure legacies, and socio-economic capacities. Northern European countries often benefit from strong institutions and funding that facilitate innovation in green infrastructure, while Southern and Eastern Europe confront challenges linked to aridity, fragmented governance, and technical constraints [4,15]. This review thus foregrounds these regional disparities to underscore the necessity of context-sensitive approaches that ensure the equitable realization of NbS benefits across Europe.

The contribution of this paper is twofold. First, it offers a critical synthesis of European evidence on the strengths and limitations of NbS, grounded in environmental science, policy analysis, and systems thinking. Second, it proposes a conceptual framework integrating climate resilience, multifunctionality, and socio-institutional dynamics—responding to calls for more adaptive, context-aware, and policy-relevant tools [15]. Together, these insights provide practical guidance for decision-makers, planners, and researchers dedicated to advancing effective, inclusive, and resilient water management strategies.

In sum, this paper delivers a timely, policy-oriented contribution to the European NbS discourse by clarifying potential and constraints, situating NbS within a robust analytical framework, and offering actionable pathways toward climate-resilient water governance.

2. Conceptual Framework

2.1. Defining Nature-Based Solutions

NbS have gained prominence as a unifying concept for ecosystem-based approaches that address societal challenges through the sustainable use, restoration, and enhancement of natural systems. Their appeal lies in their potential to deliver multiple benefits—environmental, social, and economic—while aligning with broader goals such as climate adaptation, biodiversity conservation, and urban resilience. However, despite increasing uptake across science, policy, and practice, the definition and scope of NbS remain contested, leading to persistent conceptual ambiguity and practical implementation challenges.

Two widely cited definitions illustrate this divergence. The International Union for Conservation of Nature (IUCN) defines NbS as "actions to protect, sustainably manage, and restore natural or modified ecosystems that address societal challenges effectively and adaptively, simultaneously providing human well-being and biodiversity benefits" [2]. This formulation emphasizes ecological integrity, adaptive management, and co-benefits for both nature and society. In contrast, the European Commission (EC) provides a broader framing, describing NbS as "solutions that are inspired and supported by nature, which are cost-effective, simultaneously provide environmental, social and economic benefits, and help build resilience" [16]. This perspective foregrounds multifunctionality, cost-effectiveness, and alignment with EU priorities, such as the Green Deal and the EU Strategy on Adaptation to Climate Change.

Although these definitions share common themes, their differing emphases have contributed to blurred conceptual boundaries. Particularly problematic is the lack of clear differentiation between NbS and related ecosystem-based approaches, including Green Infrastructure (GI), Ecosystem-based Adaptation (EbA), Ecosystem-based Disaster Risk Reduction (Eco-DRR), and Ecosystem-based Mitigation (EbM). As Walz et al. [17] observe, these frameworks frequently overlap in terminology and goals, but diverge in institutional anchoring and operational focus. This inconsistency not only risks fragmented governance but also complicates coordination across sectors and limits the coherence of funding mechanisms.

Further ambiguity arises over whether NbS should include technological and biomimetic solutions. While the IUCN's interpretation generally excludes engineered or non-ecological interventions, the EC's more permissive stance allows for hybrid systems that combine natural processes with infrastructure. This divergence reflects a broader debate over whether NbS should mark a paradigmatic shift toward systems thinking and co-benefits—as argued by Faivre et al. [18]—or whether the term is becoming a diluted catch-all that subsumes existing concepts without offering new analytical clarity.

Critics have warned that without clearer definitional boundaries, NbS risk losing their strategic coherence and transformative potential [19,20]. This conceptual vagueness also has practical consequences: it hampers the development of robust monitoring systems, undermines the evaluation of co-benefits, and limits the transferability of successful models across national or regional contexts.

For the purposes of this paper, we adopt NbS as an overarching term that includes both ecological interventions and integrated hybrid systems. Where appropriate, we distinguish green infrastructure as a subset more commonly applied in urban contexts.

Figure 1 illustrates the conceptual overlaps and distinctions between various nature-based and ecosystem-based approaches discussed in the literature. It clarifies this paper's adopted position of considering both ecological and hybrid systems under the umbrella of NbS, while recognizing the operational and definitional tensions noted in policy and practice.

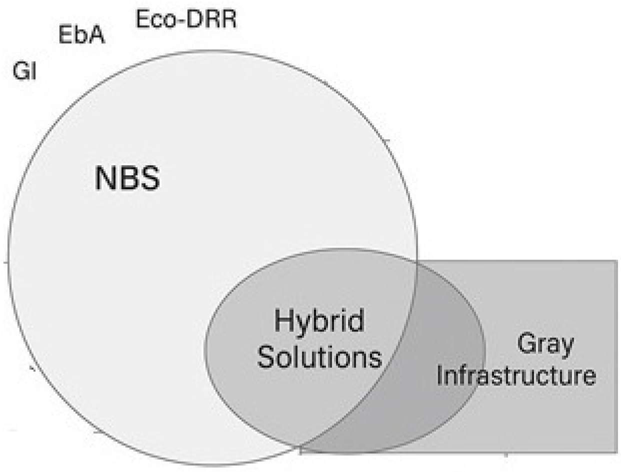


Figure 1. Conceptual relationships among nature-based solutions, green infrastructure, and hybrid approaches (figure created by the author.).

2.2. Key Principles and Features

Despite ongoing debates, the literature and policy guidance converge around several core principles that define the essence of NbS:

Multifunctionality is a defining feature. NbS are designed to deliver simultaneous benefits across environmental, economic, and social domains. A single intervention, such as wetland restoration, may enhance biodiversity, reduce flood risk, improve water quality, and create recreational space [4,21].

Cost-effectiveness is often highlighted, particularly in the long term. Although initial investments in NbS may match or exceed those of grey infrastructure, they tend to require less maintenance over time and deliver multiple co-benefits that improve overall cost–benefit ratios [11,13].

Adaptability and resilience are core attributes. NbS are dynamic interventions that can evolve with environmental and socio-economic changes. Their success depends on design principles that account for ecological resilience and uncertainty [22].

Ecosystem service enhancement is at the heart of NbS. By leveraging provisioning, regulating, cultural, and supporting services, NbS contribute to both biodiversity conservation and human well-being.

Participatory governance is increasingly recognized as critical. The co-design, co-creation, and co-management of NbS ensure that solutions are socially acceptable, locally relevant, and politically legitimate [7,23,24].

Systemic and place-based thinking is essential for the integration of NbS into broader planning and governance processes. A systems approach helps recognize socio-ecological interdependencies and avoid unintended trade-offs [25].

2.3. Implications for Policy and Governance

Conceptual ambiguity surrounding nature-based solutions (NbS) presents significant challenges for public policy and multi-level governance. Divergent frameworks can lead to fragmented policies, weaken accountability, and generate confusion among planners, funders, and decision-makers [17,19]. Without a unified conceptual foundation, policymakers struggle to assess trade-offs, monitor impacts, or justify investments effectively [22].

This fragmentation is particularly acute at the science–policy interface, where institutionalizing NbS risks becoming a technocratic exercise or symbolic gesture unless built on shared understanding and sustained collaboration [19,25]. Successfully integrating NbS into urban and regional planning demands governance frameworks that are simultaneously flexible and robust, able to reconcile competing interests and diverse stakeholder values [24].

3. Applications of NbS in Water Management

NbS for water management encompass a diverse range of interventions that restore, mimic, or enhance natural hydrological functions. These approaches—including constructed and natural wetlands, urban green infrastructure, and watershed restoration—are increasingly recognized for their multifunctional benefits. They effectively reduce flood risk, improve water quality, support biodiversity, and strengthen climate resilience, often delivering greater long-term value compared to traditional grey infrastructure [26–28].

Wetlands, both constructed and natural, serve multiple roles by attenuating peak stormwater flows by 60–80%, filtering pollutants, sequestering carbon, and enhancing habitat diversity [29,30]. Coastal wetlands and mangroves further stabilize shorelines and increase ecosystem resilience against sea-level rise and extreme events [28].

Riparian buffer zones adjacent to waterways reduce sediment and nutrient runoff by 40–90%, especially in agricultural landscapes where they act as critical filters for diffuse pollution [31,32].

In urban areas, green roofs retain 45–60% of annual rainfall and can reduce peak stormwater flows by 20–80%, depending on design and climate conditions [33,34]. Permeable pavements promote infiltration—up to 100% during light rainfall—and lower runoff volumes by 30–70% relative to impervious surfaces [35].

Urban parks and green corridors designed with hydrological principles contribute to delayed runoff and enhanced infiltration, typically reducing neighborhood-scale stormwater volumes by 20–40% [36].

Additional NbS relevant to water management include the following:

- Rain gardens and bioswales, which facilitate localized infiltration and pollutant removal [37–39].
- Reforestation and afforestation within catchments, enhancing soil stability, evapotranspiration, and carbon storage [40–42].
- Floodplain restoration, reconnecting rivers to their natural floodplains to attenuate flood peaks and boost biodiversity [32].
- Agricultural best management practices, such as cover cropping and contour farming, that reduce runoff and improve soil health.

By contrast, conventional grey infrastructure—like culverts, retention basins, and concrete channels—is designed primarily for rapid water conveyance and storage. While grey solutions may manage large peak flows efficiently, their rigid, single-purpose nature limits adaptability, often neglecting co-benefits such as biodiversity enhancement, recreational opportunities, and long-term climate resilience. As Tansar et al. [29] emphasize, grey infrastructure's inflexibility can increase maintenance demands and reduce effectiveness under evolving climate conditions [29].

Among the diverse NbS applied across Europe, three types stand out as particularly effective and widely replicable: constructed wetlands, permeable pavements, and green roofs. Constructed wetlands are among the most multifunctional and cost-effective solutions, providing flood mitigation, water purification, and carbon sequestration across both urban and rural settings. Permeable pavements are highly efficient in reducing runoff and enhancing infiltration in dense urban areas, and their modular design makes them easy to implement retroactively. Green roofs offer valuable stormwater retention and urban cooling, especially in cities with high impervious surface coverage. These three NbS types are consistently cited across case studies as scalable, adaptable, and compatible with hybrid systems, making them strong candidates for broader adoption in European water governance.

3.1. Case Studies and Empirical Evidence from Europe

Table 1 shows how the implementation and outcomes of nature-based solutions (NbS) vary significantly across European regions due to differences in climate, geography, and socio-institutional contexts.

Table 1. Effectiveness of NbS Across European Regions.

Region	City/Country	NbS Types	Objectives/Results	Estimated Impacts	Strengths	Limitations
Northern Europe	Copenhagen, DK	Green roofs, permeable pavements, and rain gardens	↓ surface runoff by 40%		Advanced urban planning	Limited urban space
	Oslo, NO	Green roofs and vegetated slopes	↓ runoff and ↑ biodiversity	↓ runoff by ~35% and ↑ biodiversity by ~30–50%	Institutional support	High cost in cold climates
	Rotterdam, NL	Floating gardens, ecological walls, and resilient green spaces	↑ urban biodiversity and ↑ flood resilience	↑ urban biodiversity by ~25 spp/ha *, ↑ flood resilience by 15–30% *	Innovative solutions in dense areas	Complex integration
	Amsterdam, NL	Permeable pavements and rain gardens	↓ runoff by 30%		Public investment	Vegetation seasonality
	Hamburg, DE	Floating gardens and soft edge engineering	↑ aquatic habitats and ↓ nutrient pollution	↓ nutrient pollution by 15–25% and ↑ aquatic habitats by ~40% area	Adaptation in industrial ports	Logistical constraints
Southern Europe	Lisbon, PT	Green roofs, rain gardens, permeable pavements, and infiltration basins	↓ flood depth; €10 billion in damage avoided	↑ infiltration and ↓ peak flow *	Hydrological efficiency of blue–green solutions	High initial cost
	Barcelona, ES	Green roofs, green corridors, and urban green infrastructure	↓ urban heat and floods	↑ social integration * and ↓ UHI by ~2–3 °C *	Public space integration	High cost and maintenance

Table 1. *Cont.*

Region	City/Country	NbS Types	Objectives/Results	Estimated Impacts	Strengths	Limitations
	Genoa, IT	Coastal ecological restoration and brownfield reconversion	↑ livability and ↑ resilience	↑ coastal resilience by 20–35% *	Community involvement	Development pressures
	Venice, IT	Coastal wetlands and salt marshes	Carbon sequestration and coastal protection	~2–4 $tCO_2eq/ha/yr$ * sequestered and wave damping ↑ 40–60% *	High ecological and cultural value	Vulnerable to subsidence
	Vale do Lobo, PT	Green infrastructure, wetlands, and water reuse	Aquifer regeneration	↑ groundwater table by 0.5–1.2 m *	Ecological integration	Governance barriers
	Albufeira, PT	River restoration with biophilic design	Ecological recovery and cultural valorization	↑ riparian vegetation by 30% and ↓ erosion by 20–35%	Local integration	Low monitoring
	Marseille, FR	Vegetated walls and permeable pavements	↓ urban heat and ↑ vegetation	↑ green cover * and ↓ UHI by 1–2 °C *	High replicability	High urban density
	Verbania, IT	Rain gardens, permeable pavements, and bioswales	Urban stormwater management	42% of city NbS-suitable *	42% of city suitable for NbS	Preliminary data
Western Europe	Antwerp, BE	Green corridors and retention parks	↓ flooding, and sustainable mobility	↑ urban mobility *	Multifunctionality	Urban pressures
	Benidorm, ES	Urban dunes, efficient drainage, and green areas	↓ storm impacts, and efficient drainage use		Effective coastal integration	Limited monitoring
	Rouen, FR	Re-vegetated canals and green roofs	Urban renewal and climate adaptation	↓ UHI by 1.5–2.5 °C * and ↑ infiltration by 20–30% *	Community engagement	Space competition
	Lisbon (riverfront), PT	Hybrid interventions and permeable pavements	Ecological and social regeneration	↑ ecological connectivity by 35–45% and ↓ flood risk by 15–20%	Ecological connectivity	Limited space and lack of assessment

Table 1. *Cont.*

Region	City/Country	NbS Types	Objectives/Results	Estimated Impacts	Strengths	Limitations
	Loire Basin, FR/Portugal	Riparian buffers and kelp forest restoration	↓ sedimentation, and marine ecosystem recovery	↓ sediment load by 20–40% and ↑ marine habitat (~10 km^2)	Large-scale coordination	Agricultural land conflicts
Central Europe	AT, DE, PL, HU, CZ, SK	Afforestation and assisted species migration	Forest adaptation to climate change	↑ climate-resilient forest cover by 10–15% and ↑ genetic diversity by ~20%	Local genetic material valorization	Outdated policy and technical gaps
	Vienna, AT	Danube bank restoration and floodplain parks	Flood and biodiversity management	↓ flood peaks * and ↑ biodiversity *	Large-scale effectiveness	Institutional coordination needed
	Prague, CZ	Urban GI with riverbank zones	Urban ecological regeneration	↓ flood risk by 20–25% and ↑ public space use by 40%	High public acceptance	Insufficient monitoring
Eastern Europe	PL, HU, CZ, RO	SuDS, urban and constructed wetlands, and floodplain restoration	↓ 90–100% pollutants; ROI ~12 years		High restoration potential	Low public uptake and weak monitoring
	Elbe River, DE	Riparian willow forests	↓ water speed, and natural barrier	↓ water speed by 25–40% and ↑ biodiversity by 20–30%	Replicability	Limited scalability

Notes. * Estimated results not explicitly reported in the original case study. Values derived from literature review, and results from European Projects and analogous NbS types. Sources of Literature review: [3,4,10].

In Northern Europe, strong institutional frameworks and advanced urban planning enable cities like Copenhagen and Amsterdam to implement innovative green infrastructure that effectively reduces runoff and enhances urban biodiversity. However, seasonal limitations, such as reduced vegetation effectiveness in colder months, highlight the need for adaptive and integrated solutions that combine green and grey infrastructure.

In Southern Europe, NbS deliver multifunctional benefits by addressing flood control, water quality, urban heat reduction, and biodiversity enhancement. Cities along the Mediterranean coast, including Lisbon and Albufeira, illustrate how ecological restoration can be integrated with local culture and public spaces to increase social acceptance and ecological resilience. Nevertheless, challenges such as summer droughts and fragmented governance often limit the continuity and effectiveness of these interventions, underscoring the importance of drought-resilient designs and improved institutional coordination.

Western Europe demonstrates the value of large-scale ecosystem restoration, particularly in river basins and coastal zones like the Loire Basin and Portugal's Atlantic coast.

These efforts enhance ecological connectivity, reduce sedimentation, and support marine biodiversity. The success in these regions depends on balancing land-use conflicts between agriculture, urban development, and restoration projects. Additionally, hybrid approaches that blend green infrastructure with urban design improve both ecological and social outcomes, offering replicable models for other parts of Europe.

Eastern Europe shows vast potential for wetland restoration, sustainable drainage systems (SuDS), and other NbS that improve water retention, pollutant removal, and flood mitigation. While economic benefits and growing policy support encourage adoption, institutional fragmentation, inconsistent monitoring, and low public engagement remain significant barriers. The emergence of research networks and increasing awareness present opportunities to overcome these challenges and expand the application of NbS across this region.

Figure 2 illustrates the distribution of NbS across four European regions—Northern, Western, Eastern, and Southern Europe—highlighting region-specific approaches, such as constructed wetlands, green roofs, and drought-resilient infrastructure.

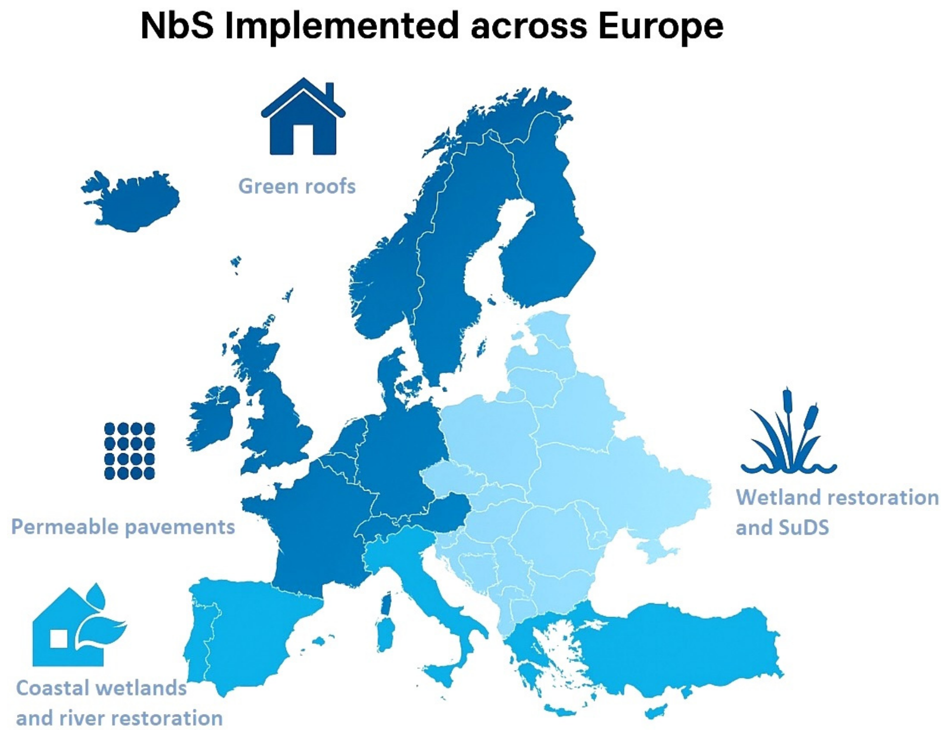


Figure 2. NbS implemented across Europe (figure created by the author). **Dark Blue**—Northern Europe (green roofs and permeable pavements). **Medium Blue**—Southern Europe (coastal wetlands and river restoration). **Light Blue**—Eastern Europe (wetland restoration and SuDS).

Comparative analysis across European regions reveals context-specific preferences and challenges. Northern Europe, with strong institutions and funding, favors technologically integrated green infrastructure. like green roofs and rain gardens, though winter conditions limit year-round effectiveness. Southern Europe often implements coastal wetlands and river restoration, emphasizing resilience to flooding and urban heat, but faces barriers related to drought and governance fragmentation. Western Europe advances hybrid models—such as Lisbon's riverfront revitalization—balancing ecological benefits with dense urban demands. Eastern Europe shows high potential for wetland restoration and SuDS, though institutional gaps hinder scaling. These patterns highlight the need for tailored NbS portfolios that align with each region's bioclimatic, socio-political, and infrastructural conditions.

3.2. Performance Under Current and Future Conditions

According to Table 2, NbS effectively manage frequent, low- to moderate-intensity water events—such as seasonal rainfall and minor floods—by moderating peak flows and enhancing infiltration, especially in small-to-medium catchments. However, NbS face limitations during extreme climate events like severe storms, prolonged droughts, and sea-level rise, primarily due to saturation thresholds and ecosystem degradation. Climate change and land-use pressures are projected to reduce water-related ecosystem service values by 13–26% by 2050, further threatening NbS performance [5]. These challenges highlight the importance of designing adaptive, climate-resilient NbS that incorporate ecological redundancy and diversity. To ensure system resilience and continuity during extreme events, hybrid approaches combining NbS with conventional grey infrastructure are increasingly vital.

Table 2. Effectiveness and Limitations of NbS Under Current and Future Hydrological Scenarios.

Aspect	Findings	Key Sources
Effectiveness under low-to-moderate intensity events	Constructed wetlands reduce peak flows and enhance infiltration in small-to-medium catchments. Green roofs retain rainfall < 30 mm. Urban GI in Munich reduced runoff during 2-year rainfall events.	[12,14,33,43]
Limitations under extreme climate scenarios	NbS may reach saturation during >100 mm/day rainfall. Drought/salinity degrade ecosystems. Coastal NbS face erosion and reduced protection under high-intensity storms.	[11,29]
Climate-induced changes to ecosystem service delivery	Projected 13–26% reduction in water-related ecosystem service value by 2050 due to climate stress and land-use change.	[5]

Notes. Adapted by the author based on data from key sources.

These integrated systems enhance resilience and operational continuity during extreme events, outperforming traditional grey infrastructure alone. Thus, while NbS are vital for improving baseline water management and urban resilience, European water planning must evolve towards dynamic, forward-looking frameworks that explicitly factor in ecological vulnerability, climate variability, and the necessity for adaptable hybrid solutions over time.

4. Evaluation Frameworks: What We Measure and How

4.1. Overview of Existing Assessment Approaches

As NbS gain traction in water management, there is a growing demand for robust, standardized evaluation frameworks capable of assessing their effectiveness across ecological, social, and economic dimensions. Synthesized by the author based on the interpretative analysis of publicly available frameworks, including references: [4,9,14,44], Figure 3 presents a comparative schematic of key evaluation frameworks, assessing their integration across five dimensions, highlighting the proposed framework's comprehensive integration of these elements.

Framework	Climate Integration	Participation	Dynamic Simulation	NbS vs Grey vs Hybrid Comparison	Co-benefit Mapping
Participatory MCDA	⚠	✓	⚠	✓	✓
Co-benefits Typology	⚠	⚠	✗	✗	✓
Structured Project	✗	⚠	✗	✗	⚠
Social/Equity	⚠	✓	⚠	⚠	⚠
Theoretical Simulation	✓	⚠	✓	✓	✓
Proposed Framework	✓	✓	✓	✓	✓

Legend: ✓ = fully integrated; ⚠ = partially integrated; and ✗ = not integrated

Figure 3. Key evaluation frameworks (figure created by the author).

Structured approaches like the World Bank [9] provide practical guidance but are static and assume NbS by default. Liquete et al. [14] offer a participatory multi-criteria framework capable of comparing NbS with grey or "do-nothing" options, though with limited scalability. Raymond et al. [4] contribute a conceptual co-benefits typology valuable for interdisciplinary planning but not suited for intervention comparison. Castelo et al. [44] emphasize social equity through community-based assessments, yet quantification remains challenging. Alshehri et al. [45] introduce simulation-based tools for testing NbS resilience under climate change, though these remain under development. Most existing methods still fall short in addressing climate-adaptive planning, long-term feedbacks, and the dynamic performance of NbS. The proposed framework seeks to fill these gaps by integrating all core dimensions—climate, participation, dynamics, comparisons, and co-benefits—but still requires broader validation.

4.2. Gaps and Limitations in Current Frameworks

Current assessment frameworks have advanced understanding of NbS performance but reveal the following critical gaps:

- Static Assumptions: Many treat NbS as fixed interventions, ignoring ecosystem dynamics, succession, and degradation under climate stress [12,15].
- Lack of Climate-Proofing: Few integrate future climate scenarios (e.g., RCP 4.5 or RCP 8.5) to model NbS robustness against increasing rainfall variability, heat extremes, or sea-level rise [11,13,46].
- Scale Limitations: Most assessments focus on local or pilot scales, neglecting landscape or watershed connectivity crucial for NbS success [47,48].
- Comparative Challenges: Direct comparisons between NbS, grey, and hybrid alternatives remain scarce due to methodological and valuation complexities [14,49].
- Inconsistent Stakeholder Integration: Participatory processes, essential for legitimacy and uptake, are unevenly applied [7,50].

These limitations constrain reliable decision-making and the wider adoption of NbS, especially under uncertain and changing environmental conditions.

4.3. Proposed Dynamic Framework for Climate-Proof NbS

To address these shortcomings, we propose a dynamic, climate-proof evaluation framework that incorporates multifunctionality and participatory engagement, supported by pilot applications or theoretical simulations to test robustness under future scenarios.

This framework synergizes the following:

- Systems Analysis: Structured, problem-solving evaluation of hydrological, ecological, and social dynamics, enabling the assessment of multiple interventions under uncertainty [51,52].
- Backcasting: Normative, future-oriented planning starting from a desired climate-resilient future and working backward to identify pathways and policies [53,54].

Key steps include the following:

- Visioning: Co-creation of a shared future vision with stakeholders, defining baselines, objectives (e.g., flood risk reduction or biodiversity), and sub-goals (e.g., recreation or water quality) [7].
- Identification of Alternatives: Defining nature-based, grey, hybrid, and "do-nothing" options, characterizing mechanisms, scales, expected services, and constraints [55].
- Climate Impact Assessment: Simulating alternatives under future climate scenarios (e.g., RCP 4.5/8.5), incorporating ecosystem changes such as drought impacts or vegetation shifts [56,57].
- Mapping Co-Benefits and Co-Costs: Comprehensive evaluation of direct/indirect impacts across environmental, economic, and social dimensions, including disservices like maintenance burden or vector risks [45,49].
- Evaluation and Selection: Iterative multi-criteria or cost–benefit analyses integrating stakeholder preferences, with feedback loops to refine options [50].
- Pilot projects or theoretical simulations serve as essential tools within this framework, allowing the following:
- Testing of model assumptions and NbS performance under varied and uncertain futures [57].
- Validation of climate resilience and adaptive capacity prior to large-scale implementation [58].
- Stakeholder engagement through scenario visualization and participatory workshops [50].

The innovations of this framework lie in its explicitly dynamic design, which accounts for ecosystem and climate variability over time. It supports evidence-based comparisons between NbS, grey infrastructure, and hybrid approaches, allowing for more informed decision-making. Additionally, the framework fosters transdisciplinary collaboration by integrating scientific, technical, and community knowledge, thus enhancing the relevance, legitimacy, and effectiveness of proposed solutions [7,59]. By embedding pilot testing and simulations, this approach enhances reliability and confidence in NbS as sustainable water management strategies resilient to climate change.

5. Trade-Offs and Disservices in NbS Planning

NbS offer significant co-benefits across ecological, social, and economic dimensions. However, they also generate trade-offs that are often under-recognized in planning and evaluation processes. These trade-offs can limit the effectiveness, equity, and long-term sustainability of NbS interventions. Recognizing and addressing them is crucial to avoid unintended consequences and enhance policy legitimacy.

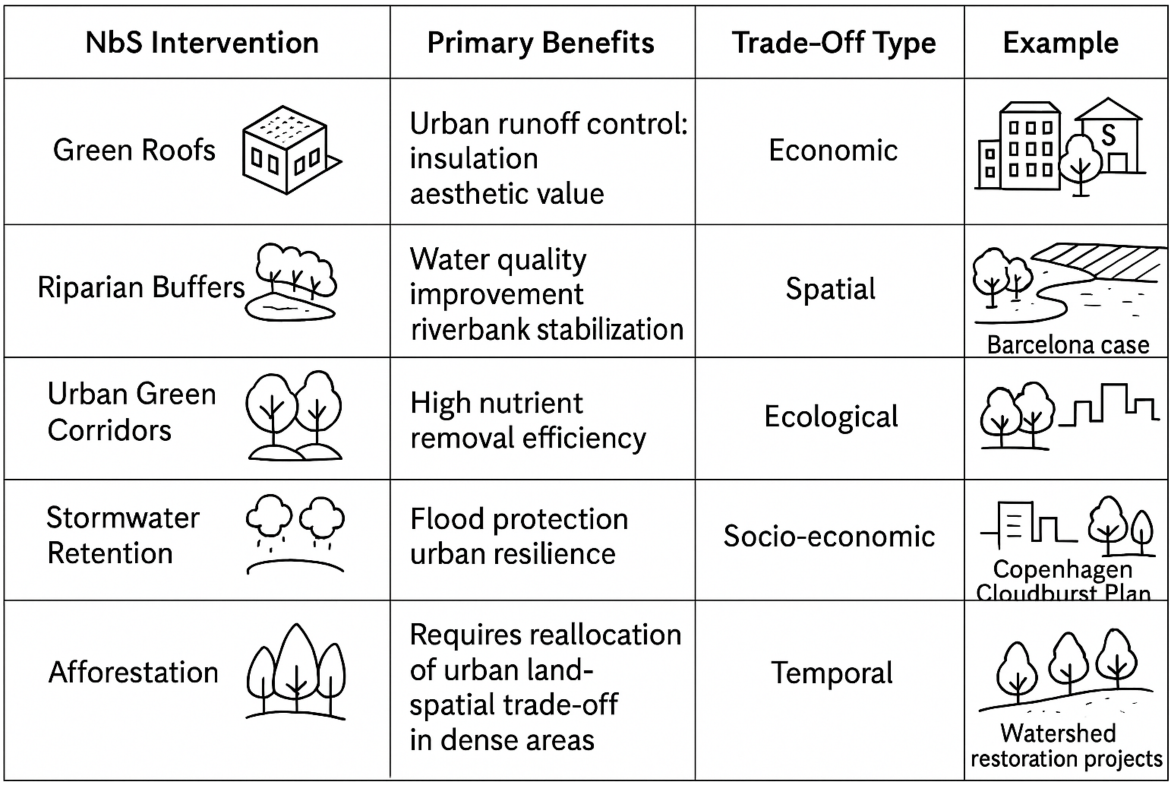
5.1. Typologies of Trade-Offs

Four main categories of trade-offs frequently arise in NbS planning and implementation:

- Spatial trade-offs involve conflicts over land use priorities. Implementing green infrastructure often requires space that might otherwise be allocated to housing, roads, or commercial uses.
- Ecological trade-offs occur when designing for one ecological function undermines another—for instance, creating monoculture wetlands to maximize nutrient retention at the expense of biodiversity.
- Socio-economic trade-offs emerge when NbS investments improve environmental quality but contribute to social exclusion, such as rising property values leading to green gentrification.
- Maintenance and operational trade-offs reflect the tension between the labor- and cost-intensity of maintaining living systems versus their long-term functional benefits and resilience.

5.2. Trade-Offs by NbS Type

Figure 4 categorizes different types of trade-offs associated with NbS interventions by linking their primary environmental and social benefits to the specific challenges they present in implementation, illustrated with real-world examples.



NbS Intervention	Primary Benefits	Trade-Off Type	Example
Green Roofs	Urban runoff control: insulation aesthetic value	Economic	S
Riparian Buffers	Water quality improvement riverbank stabilization	Spatial	Barcelona case
Urban Green Corridors	High nutrient removal efficiency	Ecological	
Stormwater Retention	Flood protection urban resilience	Socio-economic	Copenhagen Cloudburst Plan
Afforestation	Requires reallocation of urban land-spatial trade-off in dense areas	Temporal	Watershed restoration projects

Figure 4. Typologies of Trade-Offs in Nature-Based Solutions (NbS) Interventions (figure created by the author).

For green roofs, the economic trade-off involves more than upfront cost—it includes the long-term challenge of maintenance and the budgetary pressure this places on municipalities, particularly when retrofitting existing urban infrastructure. Riparian buffers, while framed as a spatial issue, carry real tensions in land-use planning as they can displace agricultural activity or limit infrastructure expansion, especially in peri-urban and rural areas. Constructed wetlands present ecological trade-offs that go beyond efficiency; their design often prioritizes monocultures to maximize nutrient removal, which undermines habitat diversity and long-term ecological resilience. Urban green corridors, despite offering benefits like improved air quality and connectivity, can lead to gentrification and the displacement of lower-income populations, raising critical equity and justice concerns.

One trade-off not emphasized in the initial analysis is related to stormwater retention features, which, while essential for flood protection and urban resilience, require the reallocation of scarce urban land. This makes them particularly difficult to implement in dense city environments where space is already at a premium. Similarly, afforestation entails not just delayed benefits, but a long gestation period that demands consistent political and financial support—something that is often difficult to maintain in short-term urban governance cycles. In light of these trade-offs, it becomes clear that integrated planning approaches are essential. Only through explicitly addressing these tensions can cities and stakeholders fully leverage the potential of NbS while minimizing unintended consequences for communities, ecosystems, and local economies.

5.3. Frameworks for Trade-Off Assessment

While Section 4 outlined a dynamic evaluation framework for assessing the robustness of NbS under future climate scenarios, this section focuses specifically on frameworks designed to identify and navigate the socio-ecological trade-offs that often arise during NbS planning and implementation. Identifying and managing trade-offs requires the use of structured, interdisciplinary planning tools. Several frameworks offer guidance, as follows:

- Multi-criteria decision analysis (MCDA) allows for weighing ecological, social, and economic priorities in a transparent and participatory manner.
- Ecosystem service valuation helps quantify benefits and disservices to enable comparison across intervention types.
- Stakeholder mapping and participatory scenario planning can help surface competing priorities, negotiate acceptable trade-offs, and build social legitimacy.
- Adaptive management frameworks, informed by continuous monitoring and feedback, are essential for navigating trade-offs that evolve over time.

While trade-offs are often context-specific and politically sensitive, making them explicit can enhance the robustness and transparency of decision-making. Rather than seeing them as obstacles, planners and policymakers should treat trade-offs as integral features of NbS design, which—if addressed early and inclusively—can lead to more balanced, just, and durable outcomes.

6. Barriers and Enablers for Implementation

The large-scale implementation of NbS in water management remains constrained by a combination of institutional inertia, fragmented policy frameworks, financing gaps, limited spatial integration, and knowledge deficiencies, despite the increased recognition of their value in supporting climate resilience and ecological restoration [7,59]. These barriers are summarized in Table 3, alongside enabling conditions that could support broader adoption.

A core institutional challenge is the fragmented nature of governance, where responsibilities for water, land, and environmental management are split across sectors and administrative levels, leading to poor coordination and inconsistent implementation [46,59]. Regulatory standards further reinforce reliance on grey infrastructure by privileging its predictability and technical familiarity, making it harder for NbS—with their multifunctional and dynamic nature—to gain approval or meet conventional performance benchmarks [4,55]. Without binding mandates, dedicated budgets, or clear performance indicators, NbS continue to be treated as discretionary rather than essential infrastructure components [48,60].

Table 3. Barriers and Enabling Conditions for Scaling Nature-Based Solutions in Water Management.

Barrier Category	Key Barriers	Enabling Conditions
Institutional and Policy	Fragmented governance; outdated regulatory standards favoring grey infrastructure; and lack of mandates, integration, and funding alignment	Integrated policy frameworks; mandated collaboration; updated legal/technical standards; and dedicated funding instruments
Knowledge and Capacity	Absence of long-term monitoring; limited transdisciplinary expertise; and weak stakeholder engagement	Investment in monitoring; transdisciplinary education and networks; and stakeholder co-production
Financial and Spatial	Grey infrastructure biases in funding; undervaluation of long-term NbS benefits; and urban land scarcity	Blended finance; valuation of co-benefits; and spatial planning tools to manage competing land uses

Knowledge and capacity gaps compound these institutional limitations. The lack of long-term monitoring data makes it difficult to evaluate and compare the performance of NbS to grey alternatives in both direct (e.g., flood reduction) and co-benefits (e.g., biodiversity, water quality, and recreational use) [13–15]. Moreover, NbS design requires integrated expertise across disciplines—ecological, hydrological, and social—and processes of co-production with stakeholders to ensure local relevance and legitimacy [4,7,16,59]. In the absence of such transdisciplinary approaches, projects risk being ineffective or poorly aligned with contextual needs [15,61].

Financial and spatial constraints are also significant. Grey infrastructure often benefits from well-established cost–benefit models and short-term planning horizons, while NbS—despite their long-term returns and wider societal value—struggle to secure funding due to limited institutional familiarity and difficulties in monetizing co-benefits [4,16,60]. In urban contexts especially, land availability further complicates implementation, as NbS require space that is often scarce, fragmented, or contested [12,47,55]. Integrated spatial planning and innovative financial mechanisms, such as blended finance and ecosystem service incentives, are needed to unlock the potential of NbS in these settings [15,60,61].

Table 3 highlights the systemic nature of the constraints—how institutional, knowledge-based, and financial–spatial factors intersect—and provides a roadmap for unlocking more scalable and resilient implementation pathways.

An illustrative case outside Europe is the "Agua para Lima y Callao" program in Peru, which integrates nature-based solutions into the water management of the Rimac River basin. Facing challenges similar to those listed in Table 3—such as institutional fragmentation, funding limitations, and lack of data—the initiative established a payment for ecosystem services (PES) mechanism to support upstream watershed restoration. It demonstrates how innovative financial tools, cross-sectoral partnerships, and participatory approaches can enable the scaling of NbS in urban Latin American contexts under water stress and climate risk [62,63]. Comparable advances are also occurring in China, particularly through the "Sponge City" initiative, which implements urban wetlands, green roofs, and permeable pavements to reduce flooding and improve water quality in cities like Wuhan and Shenzhen. These large-scale programs illustrate how NbS can be embedded within national infrastructure planning [64,65]. In Australia, projects such as the revitalization of Melbourne's urban rivers and Brisbane's floodplain reconnection schemes highlight how NbS are integrated into regional climate adaptation strategies, often with strong community engagement and co-benefit evaluation [66,67]. These international cases reinforce that diverse institutional models and socio-ecological contexts can support the mainstreaming of NbS—if paired with adequate financial, regulatory, and participatory mechanisms.

It also reinforces that addressing fragmented governance and regulatory inertia is foundational for systemic change. Grey infrastructure's continued dominance is not merely a technical preference but a reflection of path-dependent policy structures and funding norms [46,59]. Enabling conditions must therefore focus on integrated governance, updated planning standards, and the institutionalization of NbS within funding and procurement systems [55,60].

Moreover, filling knowledge gaps through robust performance monitoring and investing in transdisciplinary and participatory planning approaches will enhance the relevance, legitimacy, and resilience of NbS over time [4,14,61]. Finally, aligning financial mechanisms and spatial planning tools with the multifunctional logic of NbS is critical to shift from pilot-level experimentation toward long-term, integrated deployment [15,49].

In sum, overcoming the barriers identified in Table 3 is key to transitioning from fragmented, project-based applications of NbS to systemic, landscape-scale adoption. Doing so will require coordinated institutional reform, inclusive capacity-building, and innovative funding strategies that recognize and reward the full spectrum of benefits NbS provide under climate and development pressures.

7. Policy Implications and Future Directions

Figure 5 highlights the interlinked policy levers, showing that their combined, coordinated application is essential for scaling NbS systemically—none is effective on its own.

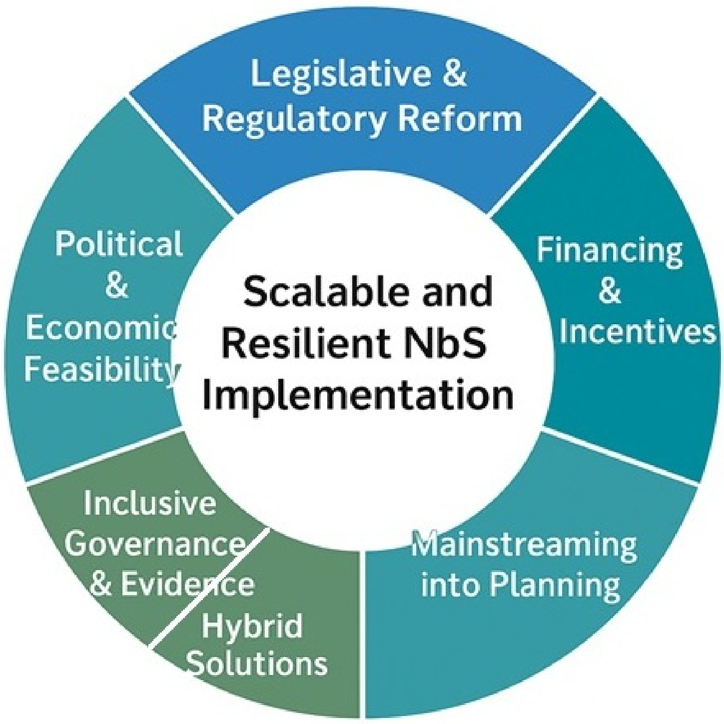


Figure 5. The interlinked policy levers (figure created by the author.).

The policy levers offer a comprehensive strategy to overcome barriers and scale NbS in water management and climate adaptation. These levers operate across regulatory, financial, planning, and governance domains. Legislative and regulatory reform calls for updating laws and planning codes to formally integrate NbS, revising procurement standards, and requiring ecosystem service valuation. Financing and incentives propose the creation of green funds, impact bonds, and blended finance tools, along with tax incentives and subsidies, ensuring transparency and reducing investment risks. Mainstreaming into planning emphasizes embedding NbS into national and local development plans, promoting early integration, cross-sectoral coordination, and municipal capacity-building. Hybrid solutions and innovation encourage the combination of green and grey infrastructure by updating design codes, supporting pilot projects, and enabling adaptive, experimental approaches. Inclusive governance and evidence focus on participatory planning, co-benefit monitoring, and tackling institutional inertia to strengthen legitimacy and stakeholder buy-in. Political and economic feasibility stresses the importance of political leadership, integrated governance, and equitable funding mechanisms to overcome structural and systemic constraints. Together, these levers form a roadmap for embedding NbS into mainstream policy and infrastructure systems, enabling scalable and resilient implementation.

Reforms should prioritize the institutionalization of NbS within existing planning and regulatory codes. This requires amending environmental and urban planning legislation to explicitly include NbS as viable infrastructure. Additionally, procurement and infrastructure evaluation guidelines need revision to allow for adaptive, performance-based designs. It is also essential to mandate the valuation of ecosystem services in cost-benefit analyses in order to internalize the multifunctional value of NbS [4,68,69]. Financial barriers, especially at the local government level, continue to pose a persistent challenge for NbS implementation. To address this, tailored financing instruments and incentive structures are necessary to unlock capital and reduce investment risks. Establishing green climate funds, adaptation grants, and public–private partnerships specifically dedicated to NbS projects can create more reliable funding streams. Furthermore, the utilization of green and environmental impact bonds can help mobilize long-term private and institutional finance. Offering tax incentives, subsidies, and blended finance mechanisms will reduce upfront costs and improve the bankability of NbS projects. It is equally important to ensure transparency and accountability in fund allocation so that investments maximize climate resilience and promote social equity [9,70].

To prevent NbS from remaining peripheral or reactive, they must be institutionalized across national and municipal planning regimes from the outset. This involves mainstreaming NbS into national adaptation strategies, local development plans, and zoning policies. Integrating NbS early in project design is crucial to avoid costly retrofits later. Facilitating cross-sector collaboration among departments of planning, environment, water, and finance is also key to coordinated action. Building capacity within local governments for the design, evaluation, and management of NbS will further support effective implementation [44,71,72].

In complex urban environments, combining green and grey infrastructure through hybrid systems offers practical and scalable solutions. To enable this, infrastructure design standards should be revised to accommodate hybrid and innovative approaches. Supporting pilot and demonstration projects that integrate NbS with engineered systems can build a strong evidence base. Encouraging adaptive management frameworks that promote iterative learning and long-term monitoring will accelerate improvement and broader adoption. Additionally, creating regulatory space and funding incentives that foster experimentation is vital for innovation [68,71,73].

Sustainable and equitable NbS implementation requires governance models that emphasize participation, legitimacy, and the incorporation of robust local knowledge. This involves fostering participatory planning processes that actively engage communities, private sector actors, and marginalized groups. Developing localized evidence on the co-benefits of NbS—such as improvements in public health, biodiversity, and social cohesion—

strengthens the case for their adoption. Addressing institutional inertia and building political will by aligning NbS with broader development goals are necessary to overcome resistance. Using evidence-based advocacy to shift public and political narratives in favor of NbS can increase support and funding [4,70,72].

The viability of scaling NbS also hinges on political leadership and the ability to navigate complex policy landscapes and power structures. Cultivating political champions and coalitions that support NbS innovation and investment is critical. Promoting integrated governance structures that align mandates across sectors and levels of government will help overcome fragmentation. Furthermore, it is imperative that NbS planning and funding address equity concerns, especially for vulnerable communities. Recognizing and addressing structural constraints, such as short-term political cycles, budget rigidity, and institutional fragmentation, are necessary steps toward long-term sustainability [68,69,71]. While these policy levers provide a universal framework, their application must be context-specific. For instance, in rapidly urbanizing regions of Southeast Asia, hybrid infrastructure solutions combining NbS with flood-control engineering have shown promise (e.g., sponge city projects in China and community-based mangrove restoration in the Philippines). In contrast, Latin American contexts such as Peru's upper Rimac watershed have demonstrated how watershed payments and public utility-led financing mechanisms can embed NbS within municipal water security strategies. In high-income countries with rigid infrastructure standards, regulatory reform and procurement innovation are often the critical enablers. Tailoring interventions to the socio-political, economic, and ecological conditions of each region is essential to maximize effectiveness and legitimacy.

In conclusion, the operationalization of NbS at scale requires more than technical solutions; it demands a comprehensive rethinking of policy, finance, and governance systems. Advancing NbS calls for legislative change, financial innovation, cross-sector planning, inclusive governance, and strong political commitment. Without coordinated action across these domains, the transformative potential of NbS will remain untapped. However, with the right policies and institutional alignment, NbS can become a cornerstone of resilient, equitable, and sustainable water and climate strategies.

8. Conclusions

NbS are gaining momentum across Europe as viable, multifunctional alternatives and complements to traditional grey infrastructure in water management. Their capacity to integrate ecological performance with social and economic benefits positions them as essential tools in climate adaptation and sustainable development. However, realizing their full potential requires confronting persistent uncertainties, embracing emerging innovations, and reconfiguring institutional, financial, and governance systems.

What We Know

- NbS are effective in managing frequent, low- to moderate-intensity hydrological events, such as urban runoff and seasonal flooding.
- Among the most widely applied and evidence-backed NbS in European water management are constructed wetlands, riparian buffer zones, urban green corridors, green roofs, bioswales, and floodplain restoration. These have demonstrated consistent effectiveness in reducing runoff, enhancing ecological connectivity, and improving water quality, particularly in urban and peri-urban settings.
- Empirical evidence across Europe shows NbS interventions reduce surface runoff, attenuate peak flows, improve water quality, and enhance biodiversity and public space.
- NbS provide significant co-benefits, including urban cooling, carbon sequestration, recreational opportunities, and increased social cohesion.

- ○ While upfront costs can be comparable to grey infrastructure, NbS tend to be more cost-effective in the long term due to lower maintenance needs and their delivery of multiple ecosystem services.
- ○ Their flexibility across spatial scales—from site-specific rain gardens to catchment-scale wetland restoration—makes them suitable for both urban and rural contexts.
- ○ EU policies such as the Green Deal, Biodiversity Strategy for 2030, and Climate Adaptation Strategy actively promote NbS, contributing to increased institutional support.

What Remains Uncertain

- ○ There is a lack of long-term, high-resolution monitoring data on NbS performance, especially under conditions of extreme weather and climate variability.
- ○ Few rigorous comparative studies assess the relative effectiveness and cost-efficiency of NbS versus grey or hybrid infrastructure, limiting evidence-based decision-making.
- ○ Many successful NbS applications are highly context-specific, making it difficult to generalize or scale them across different ecological, regulatory, and socio-economic settings.
- ○ Trade-offs and disservices—such as increased maintenance, spatial conflicts, or social inequalities like green gentrification—are often underreported or poorly managed in planning processes.
- ○ Existing institutional and regulatory frameworks often favor grey infrastructure, presenting structural barriers to NbS mainstreaming.
- ○ Governance fragmentation and uneven stakeholder engagement limit coordinated action and reduce the legitimacy and uptake of NbS initiatives.

Moreover, future research should expand beyond European case studies to include underrepresented regions, such as Latin America, Southeast Asia, and Sub-Saharan Africa, where distinct climatic, institutional, and socio-political conditions may influence NbS design, performance, and scalability.

What Is Emerging and Future Directions

- ○ Hybrid infrastructure approaches that integrate NbS with grey systems are being explored to enhance resilience, flexibility, and performance during extreme events.
- ○ New evaluation frameworks—such as systems thinking, backcasting, and scenario simulation—are emerging to assess NbS under dynamic and uncertain future conditions.
- ○ Transdisciplinary collaboration and participatory co-design processes are increasingly recognized as essential to tailoring NbS to local contexts and securing long-term community stewardship.
- ○ Digital innovations, including simulation platforms, geospatial planning tools, and AI-assisted monitoring, are improving the precision and adaptability of NbS planning.
- ○ Innovative financing mechanisms, such as green bonds, blended finance, and performance-based procurement, are being tested to overcome budgetary and valuation challenges.
- ○ Integrated governance models—linking water, land use, biodiversity, and climate policy—are slowly replacing fragmented approaches, supported by EU-level coordination and funding instruments.

In conclusion, NbS must be understood not as isolated interventions, but as components of broader systemic transformations in water governance. Their successful implementation will depend on dynamic planning, institutional alignment, and inclusive, equitable approaches that recognize the co-evolving relationships between ecosystems and societies. When these conditions are met, NbS can serve as foundational elements in building climate-resilient, socially just, and ecologically sound water systems across Europe.

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