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A bibliometric analysis and overview of the effectiveness of Nature-based Solutions in catchment scale flood mitigation

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ABSTRACT

Riverine flooding is among the most destructive natural hazards globally, leading to economic losses and posing serious threats to lives and infrastructure. Nature-based Solutions (NbS) have emerged as sustainable alternatives to conventional flood management, offering environmental and societal benefits beyond flood protection. However, despite growing interest in NbS, their effectiveness for flood mitigation across different contexts and scales remains inadequately synthesised, hampering their widespread adoption. This systematic review of 141 academic and 7 grey literature documents analysed NbS that operate through three fundamental strategies - detaining floods, reducing flood energy, and diverting floodwater. These NbS interventions are grouped into four categories: managing catchment land cover, storing excess water, reviving alternative routes, and managing the floodplain, where each intervention utilises one or more of the three fundamental strategies for flood mitigation. The analysis reveals that catchment forest cover is the most studied intervention (19.6 %), followed by wetlands (14.3 %) and land use and land cover patterns (13.2 %). Well-designed NbS can significantly reduce flood peaks for frequent smaller events and offer valuable co-benefits. Combined approaches integrating multiple NbS types and conventional infrastructure show enhanced flood mitigation potential. The effectiveness of NbS varies depending upon the catchment's physical characteristics (size, slope, topography, geology), river networks, land use patterns, location of NbS implementation and event magnitude, along with climate condition. These findings advance the current understanding of NbS effectiveness and offer evidence-based guidance for implementing catchment-scale flood mitigation strategies, underscoring the importance of context-specific design.

NbS Impacts and Implications

- **Environmental:** This paper primarily focuses on flood mitigation by Nature-based Solutions (NbS) as a key environmental benefit. NbS deliver substantial environmental co-benefits beyond flood control, including enhanced hydrological processes, ecosystem restoration, and contributions to biodiversity conservation, aligning with global sustainability goals.
- **Economic:** The analysis reveals significant economic advantages through reduced infrastructure costs, enhanced resource provision, and new income generation opportunities. NbS provide cost-effective flood protection while generating additional value through timber production, improved agricultural productivity, and reduced maintenance requirements compared to traditional infrastructure.
- **Social:** This manuscript discusses how NbS enhance community well-being by reducing flood risks and supporting social equity. Their co-benefits include recreational spaces, cultural preservation, and public health improvements, fostering stronger societal ties to natural systems.

Introduction

Riverine flooding ranks among the most destructive natural hazards globally, causing significant economic losses and posing severe threats to human lives and infrastructure [1–3]. In early 2022, catastrophic floods in Australia's Northern Rivers and Southeast Queensland shattered historical records, with total costs reaching USD 4.26 billion, including USD 3.13[1] billion in personal insurance claims [4,5]. Globally,

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[1] Original values in AUD: 6.09 billion in total costs and 4.47 billion in personal insurance claims. Conversion is based on an approximate exchange rate of 0.70 USD per 1 AUD, reflecting the average rate in early 2022.

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floods cause annual damages exceeding USD 40 billion [6,7], with over 1,500 catastrophic incidents documented between 2010 and 2020, inflicting cumulative damages beyond USD 363 billion [8]. In the global context, riverine and flash floods are the most common flood types, with events typically causing up to 1,000 fatalities [1]. Climate change, urbanisation, and anthropogenic land-use changes continue to escalate both the frequency and intensity of floods [9–11], necessitating innovative and sustainable mitigation strategies.

Conventional flood management approaches have historically relied on engineered structural measures such as levees, dams, and channel modifications [12]. While these conventional engineering-centric approaches have provided crucial and effective protection, growing evidence suggests that complementary approaches may help address particular challenges, such as environmental impacts and adaptation to changing conditions [13–15]. This recognition has prompted increasing interest in integrated approaches that combine conventional engineering with Nature-based Solutions (NbS) for flood mitigation [16,17].

Nature-based Solutions are defined as 'actions to protect, sustainably manage and restore natural and modified ecosystems that address societal challenges effectively and adaptively, simultaneously benefiting people and nature' [16]. This represents a paradigm shift in flood management to a sustainable infrastructure approach [18]. NbS involve the sustainable management, protection, restoration and mimicking of natural or semi-natural ecosystems to address societal challenges while simultaneously providing environmental, social, and economic co-benefits [15,16]. In flood management, NbS utilise natural components or nature-mimicking processes to reduce water depths, inundation areas, and flow velocities by replicating how natural systems influence flood dynamics [16]. These outcomes are achieved through mechanisms such as detaining, reducing, and diverting flows, mimicking processes like surface roughness, water storage capacity, soil permeability, and flow diversion, which work together to reduce localised flood impacts [19–21]. By leveraging natural systems' resilience and adaptive capacity, NbS can offer cost-effective, multifunctional solutions for flood mitigation while providing environmental co-benefits [22].

The growing recognition of NbS aligns with IPCC[2] and IPBES[3] findings on addressing climate change and biodiversity loss simultaneously [23]. Unlike conventional infrastructure, NbS have the potential to deliver multiple benefits or co-benefits beyond flood mitigation, contributing to biodiversity conservation, climate change adaptation, and ecosystem service provision [24,25]. This multifaceted approach can be integrated with water resources management (WRM) and ecosystem-based adaptation (EbA), acknowledging the interconnectedness of environmental, social, and economic systems [16]. This resulted in increasing interest from policymakers, practitioners, and communities, positioning NbS as cost-effective, sustainable strategies to enhance resilience against floods and climate hazards [26].

A growing body of literature on NbS encompasses reviews, opinion papers, and case studies addressing their benefits, design, implementation, monitoring, performance, limitations, and stakeholder engagement. While several reviews have explored NbS for flood mitigation, notable limitations persist. Many reviews adopt a narrow focus, addressing only specific interventions, such as forested lands [27] or levee setbacks [28] in flood management. Broader reviews, like Seddon et al. [25], examine NbS within climate mitigation and adaptation but lack depth in assessing their effectiveness specifically for flood mitigation. Existing reviews also tend to have limited geographic scope, such as Dadson et al. [29] and Earl et al. [30], which focus on the UK and tropical islands, respectively. Ruangpan et al. [17] provide a comprehensive NbS review for hydro-meteorological risks but do not critically assess NbS effectiveness specifically for flood mitigation. Furthermore, despite repeated calls in the literature, comprehensive economic assessments and cost-benefit analyses of NbS interventions remain notably scarce, particularly those that quantify both direct flood mitigation benefits and broader ecosystem services, making it difficult for decision-makers to justify NbS investments. Despite growing interest in NbS for flood mitigation, these limitations contribute to a fragmented field with inconsistent terminology and frameworks, hampering effective knowledge transfer across different contexts and disciplines. The lack of systematic evidence synthesis impedes practitioners' ability to identify appropriate interventions and understand their effectiveness across various catchment characteristics and flood scenarios. These gaps collectively indicate the need for a focused, comprehensive investigation that addresses both the technical effectiveness and practical implementation challenges of NbS for flood mitigation.

To address some of these research gaps, a systematic review focused on quantifying the effectiveness of NbS for flood mitigation, with multidimensional analysis and global evidence synthesis, is warranted. This review should also evaluate co-benefits and examine challenges and opportunities for spatial prioritisation and implementation. Consolidating scientific and grey literature can clarify current understanding, identify knowledge gaps, and support NbS applications across diverse geographic and socioeconomic contexts. A critical challenge in advancing NbS implementation is the absence of a comprehensive categorisation framework that organises diverse interventions according to their functional mechanisms and implementation contexts. This review addresses this gap by developing a systematic classification of NbS interventions based on their fundamental flood mitigation strategies, providing practitioners and researchers with a coherent structure to navigate the complex landscape of nature-based flood management approaches.

This systematic review aims to address these gaps by providing a comprehensive assessment of international scientific and grey literature on NbS flood mitigation potential. Specifically, the review: (a) explores state-of-the-art research on NbS as flood mitigation tools with a bibliometric analysis, (b) develops a systematic categorisation framework of NbS functionality in managing floods through detention, reduction, and diversion strategies, (c) examines associated co-benefits across environmental, social, and economic dimensions, and (d) identifies knowledge gaps and future research directions.

This systematic review provides a distinctive perspective by exploring diverse NbS types while exploring their hydrological processes and implementation challenges. The discussion presents high-level findings with an overview of metadata analysis, NbS interventions, categorisation and co-benefits. By employing a rigorous systematic methodology paired with detailed hydrological process analysis (an approach lacking in many existing reviews; e.g., Hewett et al. [31]; Roberts et al. [32]; Thaler et al. [33]), this review establishes a robust evidence base. It offers valuable insights into the effectiveness of various NbS across different catchment scales and contexts, aiding practitioners and policymakers alike.

The structure of this paper follows the objectives outlined above, beginning with a methodological overview, followed by a comprehensive results section that presents the bibliometric analysis and categorisation framework. The discussion then examines in depth the functional mechanisms of different NbS types, assesses their effectiveness across various contexts, evaluates their co-benefits, and identifies key knowledge gaps and future research priorities. This structured approach ensures that all four key objectives—bibliometric analysis, systematic categorisation, assessment of co-benefits, and identification of research gaps—are thoroughly addressed throughout the paper, providing a comprehensive framework to advance NbS implementation for flood management.

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[2] Intergovernmental Panel on Climate Change

[3] Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services

Methods

This systematic review follows the Collaboration for Environmental Evidence [34] guidelines, combining systematic literature search, filtering, and bibliometric analysis. The search strategy encompassed major academic databases: Web of Science, Scopus, PubMed and Google Scholar (search string in Annex 1). The review included literature published between 2013 and 2023, focusing exclusively on publications available in English. Google searches using 32 adapted keywords over two days identify grey literature, supplemented by sources like WorldCat, Dimensions, BASE, Policy Commons and government websites.

The initial search was conducted in September 2023 and yielded 12,831 peer-reviewed academic articles. After removing duplicates, 8,368 articles remained for screening. Following PICO framework criteria and PRISMA guidelines, articles were screened to exclude articles focused on urban areas, coastal regions, purely engineered solutions, and those lacking quantitative flood mitigation data (Fig. 1). Articles focused on urban areas were excluded as several comprehensive reviews already address urban NbS for flood management (e.g., [35–37]), allowing this review to focus specifically on catchment-scale interventions in rural and natural landscapes where significant research gaps remain. This process, supported by the Covidence web application, identified 776 articles for full-text review. Additionally, 200 grey literature results were evaluated from targeted Google searches.

The final full-text screening process applies the same PICO criteria. This screening utilises both Covidence and Elicit AI web applications, selecting 141 academic articles and 7 grey literature documents that met the strict criteria of comparing NbS interventions with conventional practices or baselines. The low number of articles included compared to the initial articles count reflects the scarcity of case studies containing quantitative effectiveness analyses, highlighting a significant gap in the current literature. Data extraction, facilitated by the Elicit and Claude AI tools, captures key variables, including NbS intervention characteristics, flood mitigation strategies, catchment scales and characteristics, targeted benefits, quantification methods, and associated co-benefits. The analysis combined bibliometric and content approaches to evaluate NbS effectiveness for flood mitigation. Additionally, seven documents from grey literature containing 20 case studies were assessed separately, as these cases had not undergone peer review.

Results

Nature-based Solutions have gained global recognition as a complementary or alternative approach to managing flood hazards, encompassing terms such as Natural Flood Management (NFM), Ecosystem-based Adaptation (EbA), Green Infrastructure (GI), and Ecological Engineering. Bibliometric analysis of the selected articles reveals notable geographical patterns and methodological approaches.

Calculations were made by considering each article as one unit, rather than counting individual case studies. Among the 141 peer-reviewed articles, 116 (82.3 %) presented a single case study (defined as a study in one catchment), while 11 articles (7.8 %) presented 2 case studies each, and 4 articles (2.8 %) contained 3 case studies each. The remaining articles contained more cases: five articles presented 4 case studies each, one article included 6 case studies, and one article reported 32 case studies. Additionally, 3 articles mentioned multiple case studies without specifying the exact number.

Geographical distribution

The distribution of 141 articles on NbS exhibits geographical biases (Fig. 2), with the United Kingdom leading at 21.6 % (30.5 articles[4]) of total articles. This disparity suggests high interest, robust environmental policies, and substantial research funding opportunities for NbS initiatives in the UK. Favorable environmental conditions, such as evenly distributed rainfall and suitable climate, make the UK an ideal setting for implementing and studying NbS projects. China (10.6 %) and the USA (10.3 %) follow with significant contributions, reflecting their substantial research capacity and investment in environmental issues.

The observed geographical distribution is likely influenced by the review's focus on English-language publications, which potentially underrepresents research from non-English speaking regions. This limitation is particularly significant for the Global South, where important work on NbS for flood mitigation might be published in local languages but remains excluded from this analysis. The predominance of countries with strong English-language academic traditions (UK, USA) in Fig. 2 illustrates this potential bias. The combined effect of language restrictions and disparities in research funding, capacity, and policy prioritisation results in minimal representation from many regions worldwide. These biases underscore the need for more globally inclusive research efforts, including multilingual approaches in future studies, to ensure diverse ecological and socio-economic contexts are adequately represented in the NbS literature.

Catchment characteristics

Catchment size classification is essential in flood management studies as it influences the dominant hydrological processes, potential intervention locations, scalability and the cumulative effectiveness of NbS measures [38,39]. Catchments with different sizes exhibit distinct rainfall-runoff relationships and flow patterns, which directly influence both the selection of appropriate NbS interventions and their potential impact on flood mitigation [40,41]. Fig. 3 illustrates the distribution of catchments studied for all NbS interventions according to these size categories. The majority of the case studies (81.6 %) focus on a single catchment, while 17 % examined multiple catchment sites. This review follows the size categorisation for catchments by the Environment Agency (2018), in which catchments are classified as small (up to 10 km^2), medium (up to 100 km^2), and large (up to 1,000 km^2). Among both single-site and multi-site studies, large catchments (100-1000 km^2) are the most frequent (22 % and 4.8 %, respectively). The catchment size is not specified in 2 articles, while three articles that assessed multi-sites do not specify the basin sizes.

Assessment methodologies

Fig. 4 illustrates the methodologies used in the analysed articles, with 116 employing a single assessment method and 28 using multiple methods. The majority (76 of 141) relied on modelling software, with seven studies integrating modelling efforts with additional methods. GIS-based tools such as HEC-RAS, HEC-HMS, MIKE, and SWAT, alongside modelling software like SHETRAN, TOPMODEL, InVEST, PHYSITEL/HYDROTEL, FORTRAN GCC, and WaSiM-ETH, are prominently utilised. Among the modelling studies, only two are validated through field experiments, two through statistical models, and one using aerial imagery. Moreover, Fig. 4 reveals that 31 articles (22 %) rely exclusively on field experiments and measurements with calculations derived from empirical data, while an additional 19 articles use field measurements combined with other methodologies. This significant proportion of field-based research (totalling 50 articles) is noteworthy, as it challenges the common perception that research in this field predominantly relies on modelling and theoretical approaches [24].

Beyond modelling and field experiments, various other methodological approaches were identified in the studies, including aerial imagery, different analytical frameworks, and statistical models—used either individually or in combination. These methodologies were employed both to assess the impact of NbS on flood risk mitigation and to analyse the results. For instance, statistical analysis is often conducted

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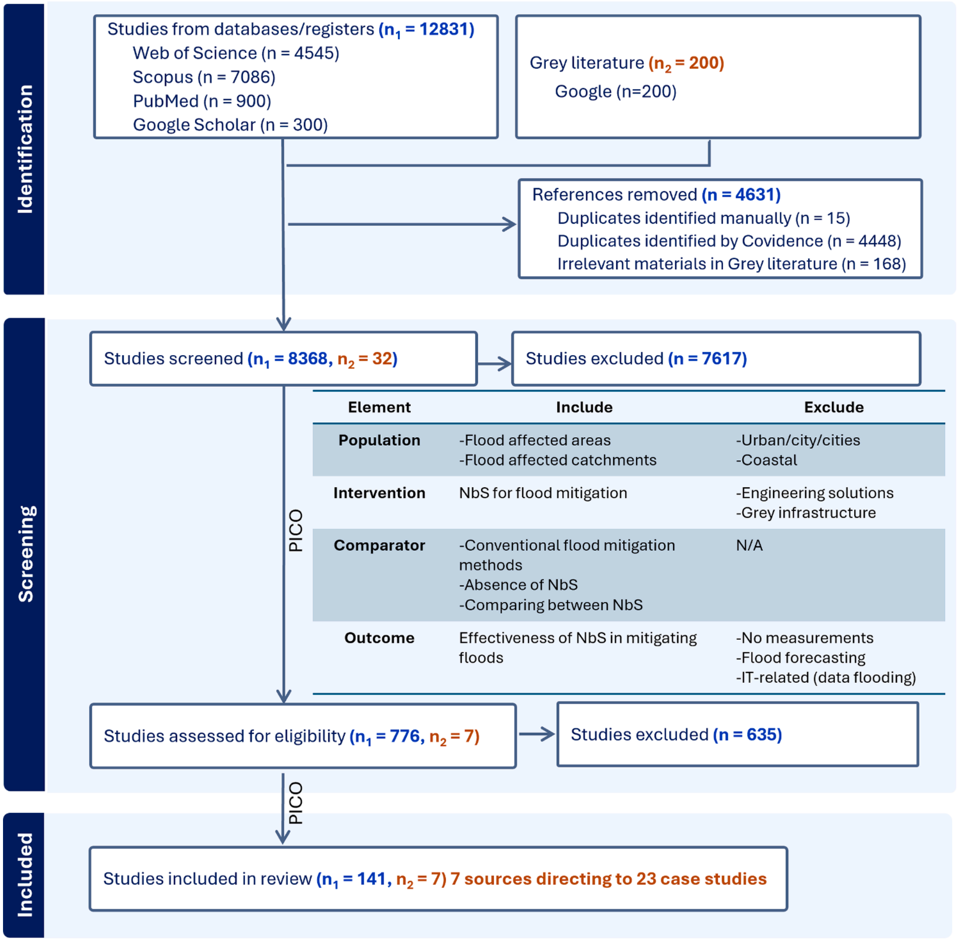
[4] Fractional values represent articles conducted across multiple countries, with each country receiving a proportional attribution.



Element	Include	Exclude
Population	-Flood affected areas -Flood affected catchments	-Urban/city/cities -Coastal
Intervention	NbS for flood mitigation	-Engineering solutions -Grey infrastructure
Comparator	-Conventional flood mitigation methods -Absence of NbS -Comparing between NbS	N/A
Outcome	Effectiveness of NbS in mitigating floods	-No measurements -Flood forecasting -IT-related (data flooding)

Fig. 1. Framework for the systematic review with PICO elements for screening.

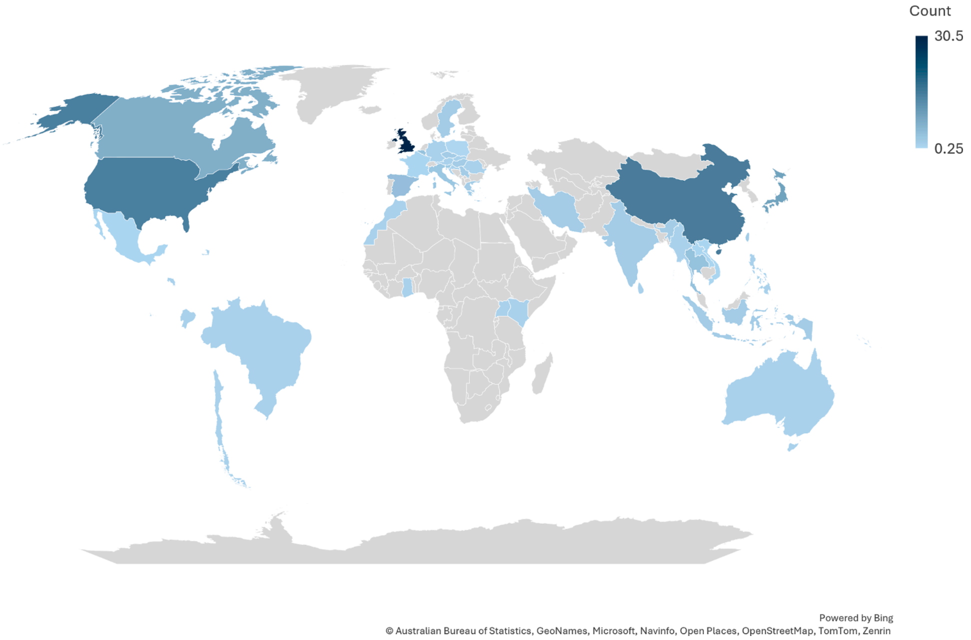


Fig. 2. Global distribution of articles on Nature-based Solutions (NbS) for flood mitigation. Articles involving multiple countries are represented with fractional values.

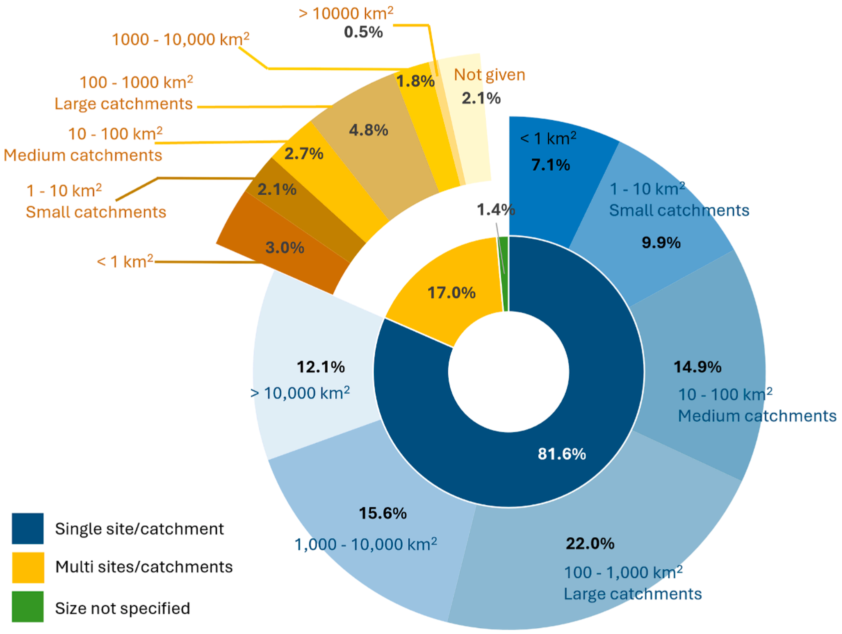


Fig. 3. Catchment size categories for all NbS interventions in the reviewed case studies, based on the size guidelines by the Environment Agency [42].

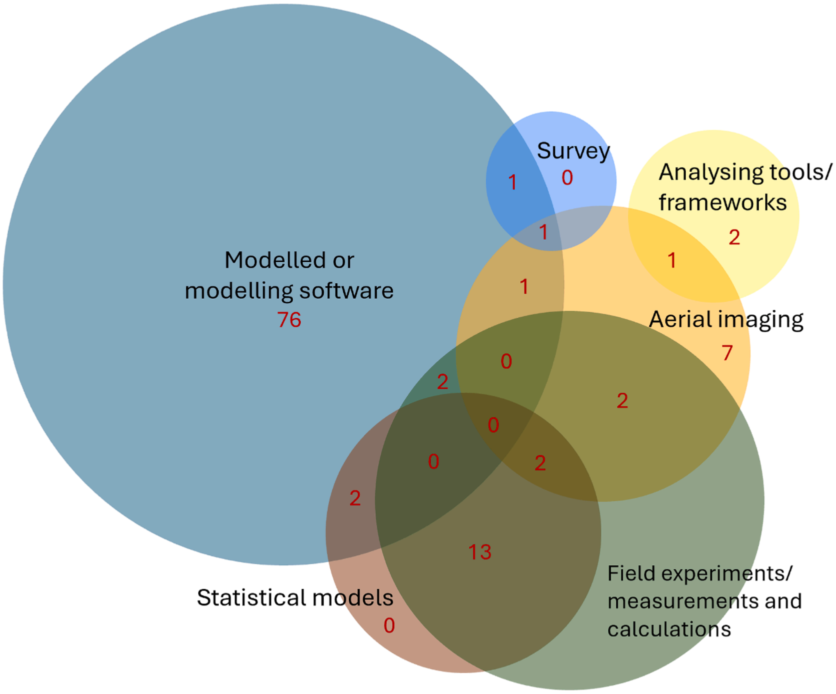


Fig. 4. Study methods used in different articles. Note: This visualisation provides a representative rather than strictly proportional view of article counts, as a linear scaling approach would not accommodate the clear display of all overlap regions.

to interpret the outcomes of hydrological models, ensuring meaningful insights into the effectiveness of NbS interventions [43]. The distribution of methodological approaches indicates opportunities for more diverse data collection strategies, particularly in combining field measurements with advanced remote sensing techniques. This finding aligns with the need for robust empirical evidence to validate the effectiveness of NbS in flood management.

NbS interventions

Fig. 5 represents the percentage of each identified NbS intervention type from the 141 articles. During data extraction, we compiled a comprehensive database of NbS interventions and their various terminologies from the reviewed case studies. Given that similar NbS interventions are described using diverse terminology across different journals, disciplines, and countries, establishing a standardised glossary provides a basis for effective knowledge sharing and implementation. Table 1 in Annex 2 presents this database, categorising interventions as natural, nature-based, or nature-mimicking. For easy navigation of those multiple terms, the intervention types are divided into four categories (Fig. 6):

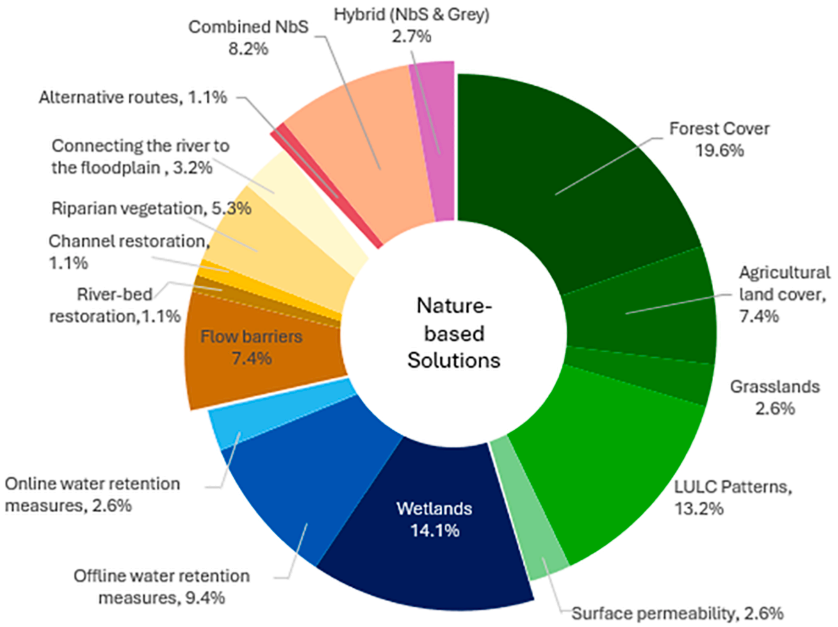


Fig. 5. Types of NbS interventions identified from the case studies. The percentage represents the frequency of discussion of each type.

a) Managing catchment land cover: to manage the vegetative and built environment within the catchment,
b) Storing excess water: to manage water retaining formations to store excess flood water,
c) Managing the floodplain: to manage floodplain connectivity and conveyance.
d) Alternative routes: to revive or construct nature-based diversion channels, including historic river pathways such as paleochannels.

In addition to these four primary categories, two additional approaches emerged from the literature: combined NbS approaches and hybrid interventions. These interventions are defined, and evidence of their effectiveness is presented in the discussion (Sections 4.3 and 4.4). Case studies in these cross-cutting categories were identified during the systematic review process using the same search and screening methodology applied to the primary NbS types.

This categorisation highlights how different parts of the landscape work together and includes interventions that can serve multiple purposes, such as managing water while creating natural spaces that benefit both the environment and communities. This catchment-based management approach provides a comprehensive overview of potential NbS interventions. The following discussion explores these principles, practices and NbS categories in detail.

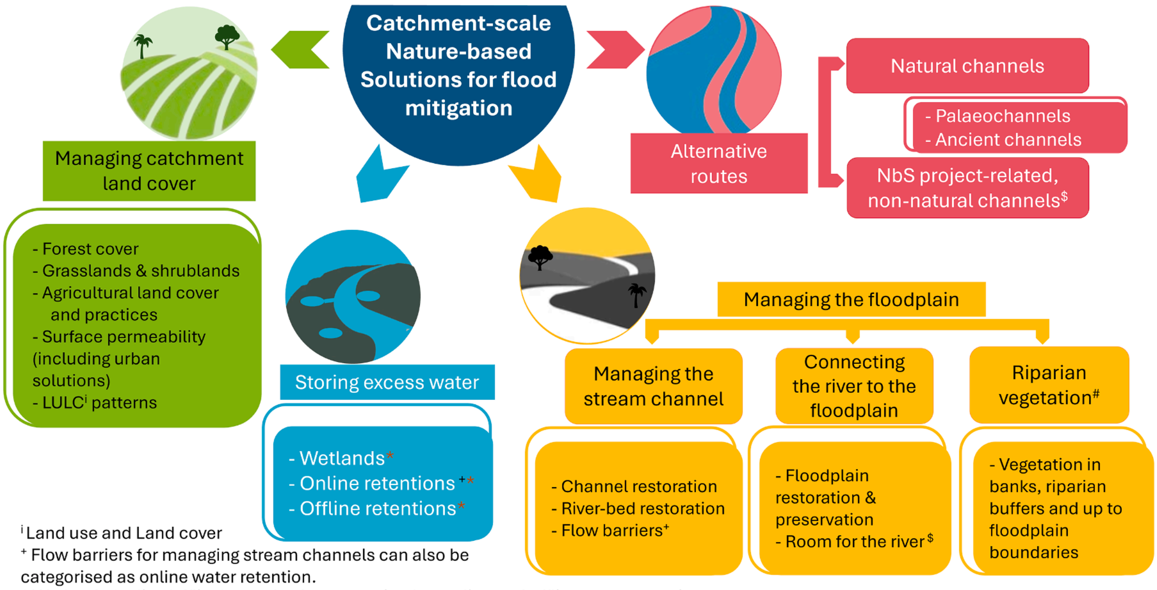
Managing catchment land cover

The analysis of catchment land cover management approaches reveals distinct patterns in research focus and implementation across different NbS. Forest cover emerges as the most extensively studied intervention (Fig. 5), representing 19.6 % of the literature, followed by LULC patterns (13.2 %) and agricultural practices (7.4 %), while grasslands and surface permeability interventions receive considerably less attention (2.6 % each). While acknowledging that all land cover changes inherently affect soil hydraulic properties including permeability (Ks), this classification distinguishes interventions where permeability enhancement is the primary design objective versus those where it is a secondary benefit of broader landscape management. Representation of climate conditions and catchment sizes was depicted in Fig. I in Annex 5. Pie charts numbered 1 in Fig. I display the distribution of case studies across different climate zones based on the Köppen climate classification across the five NbS categories: **a to e**—forest cover, grasslands and shrublands, agricultural land, LULC patterns, and surface permeability. Graphs numbered with a 2 illustrate the catchment sizes examined in each case study, while graphs numbered with a 3 present the mean annual rainfall distribution for the case studies.

Across these interventions, temperate climates, particularly those with dry winters and hot summers (Cfb), dominate the research landscape. Most articles concentrate on small to medium-sized catchments (< 100 km^2), though LULC pattern studies show a notable focus on larger catchments (100-1,000 km^2). The majority of research is conducted in regions receiving moderate mean annual rainfall (500-1,499 mm), with limited cases in high rainfall areas ($> 2{,}000$ mm). This distribution suggests potential research gaps, particularly in tropical climates, very large catchments, and high-rainfall regions, which could be valuable areas for future investigation.

The captured flood-related performance metrics illustrated in Fig. 7, are used in the case studies to assess the flood mitigation potential and reveal different yet complementary aspects of flood dynamics and mitigation effects. Peak flow (maximum discharge) is the most commonly used metric (39.8 %), followed by peak runoff or overland flow (18.4 %), which measures water volume on the surface. Soil water measurements (9.4 %) highlight forests' role in enhancing soil water storage and reducing runoff, influenced by forest type, soil characteristics, and moisture conditions. Factors including forest type, soil characteristics, and antecedent moisture conditions influence the effectiveness of forests in reducing runoff and overland flow.

Direct measurements like flood risk reduction or flood mitigation potential (6.5 %) quantify the overall effectiveness of forest-based interventions in reducing flood impacts. Temporal measurements (4.3 %), which include time to peak flow, flood duration, and lag time, are particularly important as they demonstrate how tree cover can effectively slow down flood progression by delaying peak flow arrival and reducing flood propagation speed through the landscape. Economic and social dimensions are captured through flood damage assessments (2.9 %), which provide tangible evidence of how tree-based flood mitigation strategies can reduce community vulnerability. Several other metrics, though less frequently reported, offer valuable insights into different aspects of flood behaviour. For example, the number of floods tracked event frequency, stream flow measurements provided baseline water movement data, and annual peak flow and runoff measurements



[i] Land use and Land cover

[+] Flow barriers for managing stream channels can also be categorised as online water retention.

[*] Wetlands (online/offline) can also be categorised as online and offline water retention.

[#] Some riparian forest types can be included in forest cover.

[$] High-water channels can be included in both Room for the River and NbS project-related non-natural channels.

Fig. 6. Categorisation of different NbS interventions identified during the literature search.

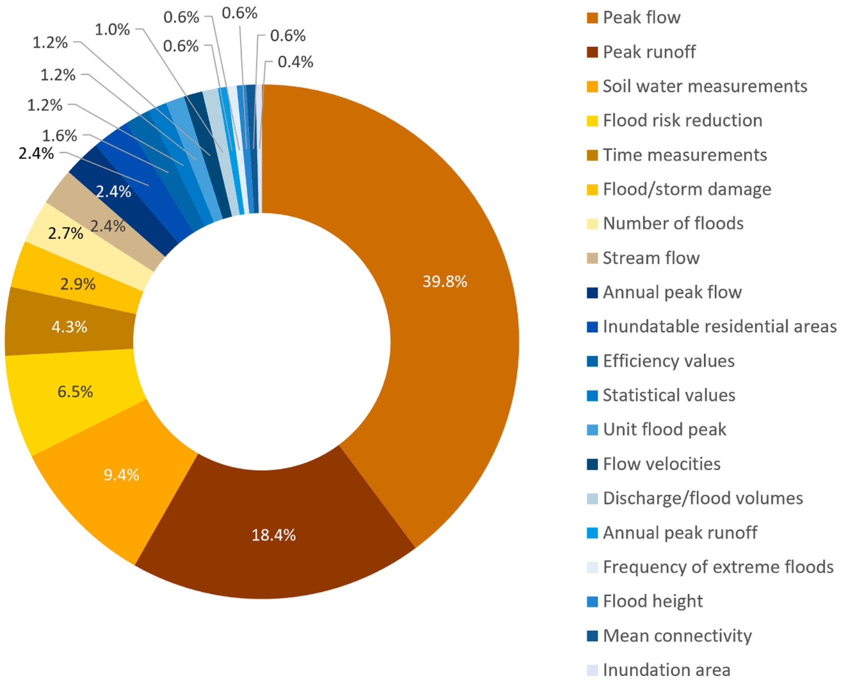


Fig. 7. Measured variables in case studies to quantify the flood mitigation benefit by managing catchment land cover.

captured seasonal and yearly extremes. Flood volumes and heights help quantify the magnitude of flood events, while inundation-related measurements (including inundated residential areas and general inundation areas) map the spatial extent of flooding impacts. Together, these metrics provide a comprehensive framework for evaluating how natural flood management through forest-based solutions affects flood dynamics at multiple scales and timeframes.

Storing excess water

Peak flow reduction (34.4 %) is the predominant metric for evaluating water storage interventions (Fig. 8), followed by flood risk reduction (8.5 %) and flood height (8.2 %). These measurements focus on quantifying direct hydraulic impacts of storage features. Infrequently measured metrics include mean flows (0.5 %) and discharge or flood volumes (0.7 %), suggesting opportunities for more comprehensive evaluation approaches.

Fig. II in Annex 5 illustrates the catchment characteristics associated with interventions for storing excess water, with graphs detailing: a) catchment sizes, b) Köppen climate classifications, and c) mean annual rainfall. Colour palettes represent different interventions: gold for wetland-related NbS, green for offline water retention, and blue for online water retention measures.

The analysis of water storage interventions reveals varying research

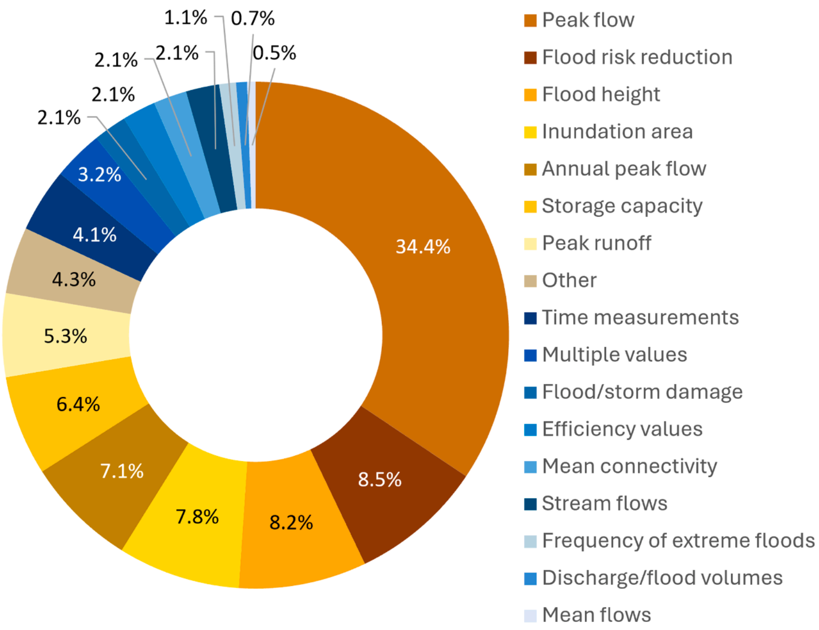


Fig. 8. Measured variables in case studies to quantify the flood mitigation benefit by storing excess water.

emphasis across different approaches, with wetlands receiving the most attention (14.1 %), followed by offline water retention measures (9.4 %) and online water retention measures (2.6 %). Medium to large catchments (100-1,000 km^2) emerge as the primary focus across all intervention types, particularly for offline storage measures and wetlands, while online retention measures show greater application in very large catchments (>1,000 km^2). Considering the climate conditions, these interventions have been studied predominantly in temperate oceanic (Cfb) and warm-summer humid continental (Dfb) regions, with wetlands showing particular prevalence in humid continental climates. Most articles present case studies conducted in areas receiving moderate annual rainfall (500-1,499 mm), with notably fewer investigations in regions experiencing very high (>2,000 mm) or very low (<500 mm) rainfall. This distribution suggests potential opportunities for expanding research into more diverse climatic conditions and rainfall regimes, particularly in extreme precipitation scenarios where water storage interventions might prove especially valuable.

Managing the floodplain

Peak flow (37.3 %) represents the most frequently measured variable for floodplain management interventions (Fig. 9), with time measurements, storage capacity, discharge volumes, and other metrics each accounting for 9 % of measurements. Less frequently assessed metrics include peak runoff (1.5 %), multiple values and annual peak flows (3 % each), indicating a primary focus on immediate hydraulic responses

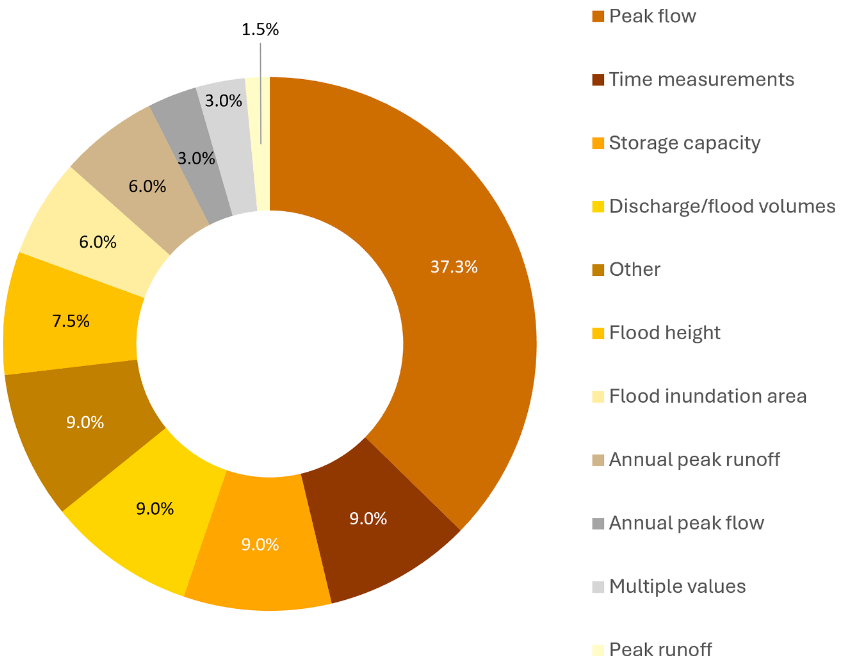


Fig. 9. Measured variables in case studies to quantify the flood mitigation benefit by floodplain management NbS types.

rather than long-term or combined assessment approaches.

Fig. III in Annex 5 presents catchment characteristics associated with managing floodplains for flood mitigation. Graphs depict: a) catchment sizes, b) Köppen climate classifications, and c) mean annual rainfall. Subcategories are color-coded: gold for riparian vegetation, green for floodplain reconnection, and blue for stream channel management.

The analysis of floodplain management approaches demonstrates distinct implementation patterns across different scales and environmental conditions. Managing the stream channel emerges as the predominant intervention strategy, comprising 9.5 % of articles, followed by riparian vegetation (5.3 %) and practices to connect the river to the floodplain (3.2 %). Small to medium catchments (< 100 km^2) serve as the primary testing grounds for stream channel management and riparian vegetation initiatives, while floodplain reconnection shows notable applications in larger catchments (> 100 km^2). The research landscape is predominantly centered in temperate oceanic climates (Cfb), particularly for stream channel management and riparian vegetation studies. However, articles on floodplain reconnection show a more diverse climatic distribution, spanning from warm-summer humid continental to monsoon-influenced subtropical regions. Most interventions have been implemented in areas receiving moderate annual rainfall (500-1,499 mm), suggesting an opportunity to expand research into regions with more extreme precipitation patterns. This distribution of articles indicates potential areas for future investigation, particularly in diverse climatic conditions and catchment scales where certain intervention types remain underexplored.

Alternative routes

The review identifies alternative routes in only two articles (1.1 %), which include both artificial bypass channels and palaeochannels. It is important to note that the limited evidence found in this review may be due to the specific search terms used and the strict selection criteria focusing on flood mitigation. Analysis of catchment characteristics reveals that both case studies were conducted in large catchments: 15,900 km^2 and 2,500 km^2, suggesting the applicability of these interventions at larger spatial scales. Regarding climate conditions, both case studies were conducted in tropical climates - tropical savanna (Aw) and tropical monsoon (Am), representing equal distribution (50 % each). The rainfall distribution shows significant variation between the study sites, with one catchment receiving moderate rainfall (1,092-1,600 mm annually) and the other experiencing very high rainfall (3,010 mm annually).

Discussion

Basic flood management strategies for NbS

Effective flood management practices require mitigation efforts to lower the peak flood levels at sites of interest, thereby reducing the spatial extent of the flood. Analysis of the selected case studies in this review reveals three fundamental strategies through which NbS contribute to flood mitigation: (1) **detaining** the flood upstream of sites of interest (localised storage of flood water), (2) **reducing** the energy of a flood (by diffuse storage solutions to decrease flow generation and manage water movement through the system), and (3) **diverting** the flood water (by altering the route that the flood water takes). These strategies are consistently observed across diverse contexts, highlighting the versatility of NbS in flood risk management. Case studies demonstrated that flood mitigation efforts within a catchment landscape typically employed one or more of these three key 'strategies' (Fig. 10), leveraging natural hydrological processes—such as infiltration, interception, and increased surface roughness—to reduce flood impacts [29]. The following section discusses each strategy in detail, along with the underlying processes and mechanisms.

Detaining floods involves either temporarily retaining excess water or permanently storing it during flood events. By detaining excess water, this strategy primarily reduces the volume of water available in the system, thereby mitigating the risk of flooding. Three key drivers of flood detention, based on storage sources, include: (1) the storage capacity of water-retaining structures, (2) the water-holding capacity of soils, and (3) storage by vegetation through canopy interception. Examples of water-retaining structures include natural retention ponds, wetlands, natural detention basins, ponds, leaky weirs and oxbow lakes. For vegetation-based storage, forests and dense vegetation cover are particularly effective at intercepting and storing rainfall. The extent to which these interventions can reduce larger floods depends upon the volume of storage relative to the floodwater volume.

The water-holding capacity of soils varies significantly with soil characteristics, such as soil type, structure, and organic matter content, and is influenced by processes, such as infiltration and evapotranspiration. Vegetation plays a crucial role in enhancing soil water-holding capacity through multiple mechanisms: plant roots create macropores that improve soil structure and infiltration [60], root systems increase soil organic matter content through decomposition [61], and vegetation cover protects soil from erosion and compaction, maintaining its porosity [61]. Deep-rooted vegetation accesses water from greater depths, effectively increasing the total water storage capacity of the soil profile [62]. Additionally, vegetation mitigates floods through canopy interception, which varies by vegetation type and health, density, maturity, and leaf area index [63]. During intense storms, this process delays and reduces peak runoff, providing crucial time for other flood mitigation systems to respond. By gradually releasing detained water, canopy interception also helps reduce downstream flood water energy and volume [64,65].

Land cover management, conservation practices, and soil management techniques enhance these natural processes, contributing to flood mitigation by improving soil structure and water infiltration. Increased soil water storage capacity helps reduce surface runoff that contributes to peak flows, while also providing long-term benefits through groundwater recharge. However, the effectiveness of these mechanisms becomes limited when soil becomes fully saturated, particularly during high-magnitude rainfall events or in poorly drained soils.

The energy of flood water can be reduced through processes that slow the flow and manage water movement within the catchment landscape, such as runoff reduction, peak flow attenuation, and managing flow capacity. Both runoff reduction and peak flow attenuation can be achieved through similar mechanisms. Surface roughness is an important driver of high flow resistance, which dissipates the kinetic energy of the moving water to slow down the water flow and reduce its erosive power [66]. Interventions such as flow barriers (e.g. leaky weirs, wood debris management), riparian vegetation and catchment afforestation help to increase surface roughness to create flow resistance and effectively slow the flow [65,67]. Infiltration and evapotranspiration also contribute to runoff reduction and peak flow attenuation, but their impact becomes negligible during a major flood event. Reducing the velocity of floodwaters reduces their energy, thereby reducing the discharge at the site of interest, which will increase the time of concentration (the time it takes for runoff from the furthest point in the catchment to reach the outlet) [67,68]. Slowing the flow can increase the volume of water stored upstream, which may, in some cases, lead to upstream flooding [69].

The objective of managing water movement is to mitigate flood risk by managing flow capacities upstream and downstream and regulating water transfer within the landscape and its conveyance through channels, rivers, and other water bodies. Key aspects of managing water movement include improvement of floodplain connectivity (e.g. Room for the River [70]), debris management and riparian vegetation management [68,71–74]. Generally, the effectiveness of such methods is limited to managing small flood events [75,76].

Diverting floodwater is another vital flood management strategy that involves altering its conveyance to redirect it away from vulnerable areas [65]. By modifying the natural or artificial drainage networks,

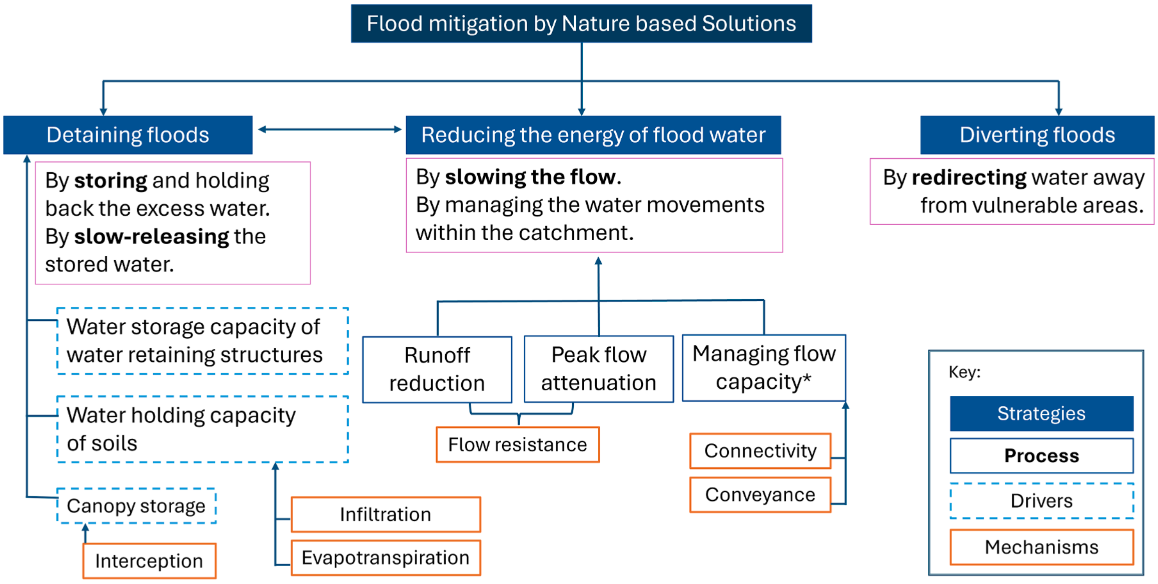


Fig. 10. Strategies, processes, drivers and mechanisms of flood mitigation by Nature-based Solutions.

flood water volume and peak flow reaching critical locations can be reduced, thus minimising the potential for damage [68]. Palaeochannels (palaeochannels / ancient river channels), palaeovalleys and bypasses, or secondary channels are examples of NbS interventions that use diversion strategies.

The above three flood management strategies have been implemented through a variety of NbS interventions. While each flood management strategy offers distinct benefits, the most effective NbS interventions often integrate multiple strategies simultaneously to enhance overall flood mitigation. Understanding this interconnected relationship between mechanisms and NbS interventions highlights how natural systems can comprehensively address flood management challenges through various complementary processes. NbS can restore, conserve, and manage natural ecosystems to mitigate flood risks while providing other co-benefits [16]. For example, instead of constructing a concrete retention pond, an NbS approach might involve restoring a wetland that can store and slowly release floodwaters [15]. Similarly, rather than building a levee or dam, an NbS approach could focus on reconnecting a river to its floodplain, allowing the natural capacity of the floodplain to store and convey water [71]. Techniques such as riparian buffer zones, channel re-meandering, and wetland restoration play a role as NbS for managing connectivity and conveyance, as they utilise natural processes to slow down and store water. Hydrological connectivity refers to the physical linkages that facilitate water transfer between different landscape elements (such as hillslopes, channels, and floodplains), while conveyance describes how efficiently water is transported through these connected pathways [77]. By leveraging the inherent ability of natural systems to detain floods, reduce the energy of floods and divert floodwater, NbS can provide a more sustainable and resilient approach to flood management while delivering multiple ecological and societal benefits [78].

How does each NbS intervention contribute to flood management?

Managing catchment land cover

Managing catchment land cover is a fundamental approach to flood mitigation that addresses both natural and human-modified landscapes across the catchment. Catchment land cover encompasses natural areas (forests, woodlands, grasslands), agricultural lands, and urban, suburban, and rural residential areas, including both floodplain zones and the broader landscape. Land use and land cover change (LULCC) is one of the most important drivers of the natural runoff regime [79], with human activities significantly impacting hydrological processes, particularly through the replacement of natural vegetative cover with impermeable surfaces. These modifications affect runoff generation, infiltration, interception, evapotranspiration, and groundwater recharge, influencing hydrodynamic processes within the catchment at various spatial and temporal scales [80–82]. The impacts are especially critical in floodplain areas, which have historically attracted human settlement and continue to face development pressure [83]. Furthermore, growing population and food demand create additional pressure on natural land cover through agricultural expansion. Given these challenges, strategic land use management, including risk-based land use planning that limits development in flood-prone areas, serves as an essential tool for catchment-level flood mitigation.

Forest cover. According to Fig.5, Forest cover emerges as the most extensively studied intervention. This category considered the potential of forest-related land cover to improve catchment hydrological processes with different terminologies, such as forests, tree planting, afforestation, reforestation, woodlands, and vegetation (see Annex 2 for the list of terminologies). Forests play a dual role in flood mitigation by detaining floods and reducing their energy through multiple complementary mechanisms. The detention of floods is primarily achieved through the forests' complex root systems that enhance soil water-holding capacity [60,61] while their canopy structure promotes rainfall interception and evapotranspiration to create additional water storage capacity [63]. The reduction of flood energy occurs through increased surface roughness [66], where the combination of different vegetation layers creates an effective natural system for slowing water movement across the landscape- shrubs provide ground-level resistance while tree canopies offer additional flow barriers.

The flood mitigation benefits of forests also include significant long-term hydrological regulation. Enhanced infiltration in forested areas promotes subsurface water movement through interflow, rather than rapid surface runoff, helping to attenuate peak flows within the catchment [84]. This process not only reduces peak flow heights but also delays their timing, providing crucial additional preparation time for downstream areas during flood events. Furthermore, forests' higher transpiration rates compared to shorter vegetation types, help reduce annual runoff volumes and support overall catchment water balance.

Grasslands and shrublands. Grasslands and shrublands are discussed less frequently than other vegetative interventions (Fig. 5), using a range of terms, such as grass, shrublands, pastures, moorlands, and peatlands/peat grasslands. They, particularly those with diverse plant species, can detain floods by improving soil structure and increasing organic matter content, enhancing the water-holding capacity of soil to store excess water [85]. Grass cover increases surface roughness, which slows overland flow and enhances the likelihood of water infiltration. By regulating the flow and promoting a more gradual release of water from the soil, grasslands extend the time it takes for water to reach streams and rivers. For example, Bond et al. [86] found that rank grassland[5] delayed the total flow peak by 30 minutes compared to the baseline land cover during 6-hour storms, and by 45 minutes during 24-hour storms in the Swindale catchment, UK. This delay was observed when converting grazed grasslands and hay meadows to rank grassland.

Agricultural land cover and practices. Conventional agricultural practices like heavy grazing, rotational burning, and over-irrigation modify natural soil conditions through compaction and reduced permeability, while soil erosion from poor farming methods leads to sedimentation in waterways. Such practices accelerate water runoff and increase flood risk by reducing the land's natural water absorption capacity and channel flow capacity [87]. When managed sustainably, agricultural lands can contribute to flood mitigation through two primary strategies: enhancing water storage capacity (detaining floodwater) and improving flow regulation (reducing the energy of floods), both of which work in tandem. These mechanisms operate through various processes, such as improved soil-water interactions, enhanced infiltration, and strategic water flow management.

Sustainable agricultural practices, which are discussed in different terms such as croplands, cover crops, paddy fields, and various management practices such as agroecosystems, crop rotation, terracing, soil and crop management, and grazing management, enhance flood mitigation through multiple pathways. Mature vegetation with extensive root systems creates channels for water infiltration [88], while cover crops, crop rotation, and reduced tillage practices increase soil organic matter content and reduce compaction [89,90]. Specific agricultural systems have demonstrated notable effectiveness - agroforestry systems can improve soil infiltration capacity, while providing additional canopy interception benefits [89,90]. Similarly, paddy fields serve as natural retention basins, with their conversion to other land uses potentially increasing flood frequency at the watershed scale [91,92]. Terracing in hilly areas has shown peak discharge reductions for various return period events [93], while strategic vegetation barriers and buffer zones contribute to slowing water movement across the landscape [94]. While these practices offer significant flood mitigation benefits as part of integrated catchment management strategies, caution is needed when implementing monoculture-based agricultural practices as NbS, as low-biodiversity systems can lead to maladaptation [25].

Land use and land cover (LULC) patterns. Land use and land cover patterns, representing 13.2 % of the reviewed interventions (Fig. 5), provide valuable insights into how landscape-scale approaches can significantly influence flood dynamics through multiple hydrological pathways. This category considered the terms including land use change, LULC changes/modifications, land use regulation, land use management, and avoiding fragmentation. Different land use and land cover patterns within catchments significantly influence flood mitigation by driving natural runoff regimes [79]. The existing LULC patterns of catchments, including natural and managed landscapes, work primarily through manipulating water movement across the catchment landscape, reducing runoff, and attenuating peak flows to provide flood protection [95]. The effectiveness of these interventions is particularly evident in the spatial arrangement of land uses within the catchment, where modifications to natural drainage networks and flow connectivity can significantly impact flood behaviour.

Large-scale changes in catchment surfaces through deforestation, urbanisation, residential development, and agricultural practices alter roughness coefficients and permeability, affecting the natural storage potential of catchments and floodplains [95]. Natural land covers - forests, grasslands, and woodlands - generally manage floods more effectively compared to croplands, despite both representing vegetation cover. This difference arises because agricultural soils are altered to maximise production rather than conservation [96,97], leading to different impacts on flood regulation. Modifications to natural drainage networks and flow connectivity through practices such as channelisation or removing natural barriers can significantly impact flood behaviour. Studies have demonstrated the importance of spatial arrangement - for instance, Buisan et al. [98] showed that sound spatial land use planning increased lag time by 400 % compared to baseline conditions. The conservation of natural conditions, including vegetation and soil, particularly in upstream areas, plays a crucial role in downstream flood behaviour [99,100]. The effectiveness of LULC patterns varies with catchment characteristics - small, steep catchments with quick-saturating soils may require different approaches, such as dense vegetation combined with strategically placed retention areas, compared to larger, flatter catchments. Urban land covers are not the focus of this review, while the large-scale permeability-related LUC are discussed in the next section.

Surface permeability. Surface permeability interventions, though representing only 2.6 % of the analysed studies (Fig. 5), demonstrate significant potential for flood mitigation despite their limited representation in the literature. Interventions focused on large-scale surface permeability are covered with terms like permeable concrete, permeable pavement/pavers, porous pavement, and changing catchment permeability, including urban interventions such as sponge cities. Surface permeability plays a crucial role in flood mitigation, particularly in urban and peri-urban catchments where development activities often replace natural land cover with impermeable surfaces. Higher imperviousness ratios in developed and urbanised catchment areas substantially hinder infiltration, leading to increased runoff volumes and flood-prone areas [101,102], thereby weakening natural flood protection mechanisms. The relationship between imperviousness and flood risk is notably non-linear, as demonstrated in various catchment studies. For instance, in the Upper Woluwe catchment (31 km^2) in Chormanski et al. [103], both the amount and spatial concentration of impervious surfaces strongly influenced peak runoff, while Su & Duan [101] showed catchments with over 70 % impervious cover experienced more severe flooding.

The effectiveness of permeable interventions is evidenced through multiple studies. Research from Italy and Belgium demonstrates that even minor changes in surface permeability can significantly impact flood behaviour - sealing just 1.5 % of basin surface increased peak flow and runoff by 6.2-6.3 % [104,105]. More dramatically, studies across multiple catchments show that converting 4-8 % of impervious areas to permeable surfaces can reduce peak flows by 20-80 %, depending on storm intensity and local conditions [104,106]. In one notable case in Guangzhou, an 80 % peak flow reduction was achieved with just 8 % porous pavement coverage, though this exceptional result was attributed to specific local conditions [107]. Despite challenges in scaling hypothetical scenarios, strategically placed permeable surfaces demonstrate significant impact, underscoring their practical integration into construction, disaster risk reduction, and policy planning. These studies collectively highlight the importance of considering both the quantity and spatial distribution of impervious surfaces in urban planning and flood management. They also underscore the increased vulnerability of smaller, impervious urban catchments to climate change impacts,

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[5] Rank grasslands: Grassland that has grown abundantly without being cut or grazed for some time, and as a result has become tall, tussocky, and dominated by coarse species of grass.

emphasising the need for targeted adaptation strategies in these areas.

Storing excess water

Storing excess water is a critical approach to flood mitigation that harnesses both natural and engineered storage systems within catchments. Natural storage systems, such as wetlands, a focus of this review, provide multiple hydrological functions, including water retention, groundwater recharge, and flow regulation. In contrast, engineered retention measures offer controlled storage solutions in strategic locations. This approach encompasses natural wetlands, which serve as nature's water regulators, alongside purposely designed offline and online water retention measures. These storage mechanisms play a vital role in catchment hydrology by temporarily detaining floodwater, reducing peak flows, and regulating water release patterns.

Wetlands. Wetlands represent the second largest type of nature-based solution, accounting for 14.1 % of all interventions identified (Fig. 5). Wetlands, recognised as one of the most productive ecosystems globally [108], play a crucial role in flood mitigation, primarily through flood detention, while also contributing to energy reduction and occasional floodwater diversion. As natural retention basins, wetlands detain floods by temporarily storing excess surface water during flood events, supported by their organic-rich soils with high water-holding capacity and vegetation that intercepts rainfall [109–113]. Dense wetland vegetation reduces the energy of floodwater by increasing the surface roughness and creating flow resistance. The combination of extensive root systems and permeable soils enhance water infiltration, ultimately reducing surface runoff [114–116]. Additionally, wetlands can divert floodwater, with riparian wetlands serving as natural floodways that disperse water across the floodplain [117].

The effectiveness of wetlands exhibits complex dependencies on their characteristics and location. Online wetlands—those directly connected to river systems—generally demonstrate superior flood reduction capabilities compared to offline systems, primarily due to their direct hydrological connectivity [44,116,118,119]. Larger wetland areas are typically associated with greater flood mitigation effectiveness; however, this relationship is non-linear, with diminishing returns observed beyond certain thresholds [45,120].

The design and capacity of wetlands are critical determinants of their performance. Wetlands often provide effective temporary flood protection during the initial stages of a storm and for short-duration events [113]. However, once their storage capacity is exceeded, discharge levels can revert to baseline conditions, reducing their effectiveness [49]. Wetland depth also plays a significant role, with deeper wetlands offering greater storage capacity and enhanced flood protection [120, 52].

Catchment characteristics further moderate the relationship between wetland size and effectiveness. The impacts are typically more pronounced in smaller catchments [116]. Spatial distribution within the catchment is another crucial factor. Upstream wetlands often provide the most substantial flood mitigation benefits, midstream wetlands show moderate effectiveness, and downstream wetlands can, under certain conditions, exacerbate flood risks if they become overloaded [44,45]. However, these spatial relationships are not universal and depend on specific catchment characteristics and wetland types [118].

Offline water retention measures. Offline water storage measures create dedicated areas for temporary floodwater storage disconnected from the main river or stream. For flood mitigation, the purpose of offline water retention is mainly targeted at detaining flood water; and can also target reducing energy and diverting flood water. The detention mechanism operates by temporarily storing excess floodwaters in designated areas, effectively reducing peak flows in downstream reaches. Flow regulation is achieved through controlled outflow mechanisms that extend high-flow durations while reducing their intensity, allowing for more manageable discharge patterns [121]. Additionally, these structures can promote groundwater recharge through infiltration, contributing to the catchment's overall water balance [122].

Common interventions include detention ponds, retention areas, natural pools, oxbow lakes, and seasonal lakes, each adapted to local conditions and requirements. The effectiveness of offline storage systems is highly dependent on their design characteristics, spatial placement, and integration with existing catchment features. Detention ponds and retention areas must be strategically positioned to intercept significant flow paths while maintaining safe distances from critical infrastructure [123]. The storage capacity needs to be carefully calculated based on expected flood volumes and return periods, with consideration for both frequent events and extreme scenarios [124]. Studies have shown that distributed networks of smaller storage areas can often provide more effective flood protection than single large facilities, particularly in complex catchment geometries [125]. Detention ponds are typically designed to empty completely between storm events, providing maximum storage capacity for subsequent rainfall [126]. Retention ponds maintain a permanent pool of water, offering additional environmental benefits while still providing flood storage capacity [127]. Natural pools and oxbow lakes can be enhanced or restored to serve dual purposes of flood management and habitat creation, aligning with broader ecosystem restoration goals [71]. The effectiveness of offline storage measures appears to be most pronounced in temperate regions with moderate rainfall, where storage capacities can be optimized for typical storm events while maintaining reasonable construction and maintenance requirements.

Online water retention measures. Online water storage measures involve modifications within river channels or floodplains to temporarily store excess water, reduce peak flows, and mitigate downstream flood risks. These measures mainly operate through flood detention through temporary storage and additionally rely on other strategies: flow regulation through controlled release and, in some cases, flood diversion. By creating additional capacity within the river system to temporarily hold excess water, such interventions detain and regulate floodwater through managed outflows. Further, some online storage interventions can alter the path of floodwaters, potentially diverting them away from critical areas.

Various online storage structures are identified in the literature, including inline storage ponds, basins, lakes, and flow attenuation ponds. Leaky weirs, discussed in Section 4.3.3 on flow barriers, are also considered online water storage interventions. The effectiveness of these measures depends on catchment-specific factors such as area, slope, hydrology, and storage capacity. For instance, in the steep Upper Guadalquivir Basin (6.9 km^2, mean slope 19 %), wetlands with limited storage (0.097 hm^3) offer only temporary flood protection, while a larger reservoir pond (0.39 hm^3) sustains flood peak reductions during extreme storms due to its greater capacity [49]. This underscores the need for storage solutions tailored to catchment characteristics.

In medium-sized catchments (10–100 km^2), Bokhove et al. [50] compared the effectiveness of leaky dams and reservoirs during 100-year floods. While 2,400 leaky dams achieved only 4.24–8.48 % flood excess volume (FEV) reduction due to limited capacity and coordination challenges, reservoirs achieved 27–53 % FEV reduction due to larger storage volumes, controlled releases, and strategic placement. Similarly, in larger catchments (>100 km^2), properly sized storage can reduce flood peaks by up to 40 % and delay flood progression [51]. Vojinovic et al. [128] that storage effectiveness depends more on the ratio of storage capacity to flood volume than catchment size alone, highlighting the importance of aligning storage design with expected flood volumes.

Online storage measures demonstrate their viability across all catchment scales when appropriately designed and positioned. Upstream and midstream placements generally offer superior benefits compared to downstream locations [53,125,129]. In medium-sized catchments, distributed storage networks arranged in series along stream channels enhance flood attenuation compared to parallel configurations, particularly when reservoirs are spaced at least 800 m apart to prevent flow regulation inefficiencies [125]. Larger catchments require proportionally larger storage volumes, but their performance depends on event magnitude, as systems are typically more effective during frequent events than extreme ones [52,53]. These findings emphasise the importance of realistic design parameters and appropriate sizing when incorporating online water retention measures into integrated flood management strategies.

Managing the floodplain

Floodplain management refers to a systematic approach aimed at reducing flood risks while preserving the natural functions of floodplains. Moving away from conventional methods that constrain river flow and disconnect floodplains, modern approaches increasingly emphasise the value of NbS that work with and support natural processes [130]. Floodplains contribute to flood mitigation through all above three strategies: flood detention by temporarily storing excess water in natural depressions and soil, energy reduction through increased surface roughness and flow resistance, and flood diversion by providing natural pathways for water movement. NbS practices in floodplains focus on restoring and enhancing their natural flood mitigation capabilities, while also delivering additional ecological and societal benefits.

Managing the stream channel. Stream channel management represents a shift from historical practices that viewed natural elements as obstacles to water flow, now recognising them as integral components of natural flood mitigation systems. These interventions function by detaining floods with temporary storage, reducing energy through increased channel roughness, and regulating flow with controlled water movement. Three main intervention types were identified in this review: channel restoration (1.1 % of total interventions: Fig.5), riverbed restoration (1.1 %), and flow barriers (7.4 %).

Channel restoration enhances hydrological functions through re-meandering, sediment management, and channel re-profiling. These interventions primarily function by increasing channel roughness and enhancing floodplain connectivity. Studies demonstrate significant benefits, with restored channels reducing peak flows [131], and the effectiveness increases when combined with floodplain reforestation [132]. Riverbed restoration focuses on modifying physical characteristics, to enhance flow resistance and improve infiltration. Fully vegetated channels improve Manning’s n values to slow the flow, though this requires careful management to prevent excessive upstream flooding [133].

Flow barriers, including leaky barriers and woody debris dams, emerged as the most studied approach. These structures operate mainly by detaining flood water and reducing flow energy. The effectiveness of these structures stems from their ability to form a "leaky" system, which permits water to flow gradually through them instead of rapidly flowing over or bypassing them. Their effectiveness is particularly evident in smaller catchments, with networks of leaky barriers achieving flood excess volume reductions during extreme events [50]. Peak flow reductions are more pronounced during smaller, frequent floods and gradually diminish for larger, less frequent events, highlighting their optimal performance under shorter recurrence intervals [134].

The effectiveness of these interventions depends heavily on strategic implementation: coordination of barrier heights, storage volumes, and network position. Flow barriers show greater effectiveness in channels with gradients less than 4 % [135], while channel restoration benefits are maximised in the middle reaches [136]. Performance was better when barriers were distributed across tributaries rather than concentrated on the main stem of the river [137]. Individual barriers (leaky weirs) showed measurable impact for smaller events, however, networks of multiple barriers were needed for meaningful impact during larger events [137]. Success requires careful balancing of flood management objectives with other floodplain functions [138,139], thorough stakeholder engagement, and consideration of local socio-economic contexts while incorporating adaptive capacity for future climate scenarios [140].

Riparian vegetation. Riparian vegetation management involves maintaining and enhancing vegetation along streambanks and floodplain boundaries, including riverine vegetation, riparian forests, and buffer strips, to mitigate flooding. This approach operates through several strategies: enhanced surface roughness and improved soil structure. Vegetation increases friction and flow resistance along riverbanks and floodplains, dissipating flood energy, reducing flow velocities, and promoting more uniform flow distribution [66,141]. Complex root systems enhance soil infiltration and water storage capacity by creating macropores, strengthening flood resilience [20,142].

The effectiveness of riparian vegetation depends on several factors, including vegetation type, maturity, structure, buffer width, and placement. For instance, vegetation type determines the surface roughness, as woody perennials typically show greater effectiveness than grass buffers [54]. Mature riparian buffers consistently mitigate peak flows better than younger vegetation, with peak flow reductions of 1 % across different maturities and a 3 % delay in time to peak during 10-year events. However, during 100-year events, only mature vegetated buffers achieve such delays [54]. The width of riparian buffers affects their effectiveness, though the relationship is non-linear and reaches a practical limit. For example, 30 m forested buffers reduced flow by 2.8 % compared to 1.3 % for 15 m buffers during 2-year floods in highly developed areas [75]. Strategic placement of the buffer affects the effectiveness.

The placement and continuity of riparian vegetation prove critical for flood management outcomes [48,54,87]. Riparian vegetation or buffer strips adjacent to main channels provides more consistent flood mitigation benefits than disconnected buffers, as it effectively attenuates flood flows and enhances soil infiltration through increased hydraulic roughness [48,54,87]. Flood management impacts vary between upstream and downstream reaches. Extensive upstream vegetation can locally increase flood impacts but often reduces downstream floods, where flooding poses greater risks [143]. Cumulative benefits depend on storm intensity, antecedent conditions, and the spatial arrangement of interventions. Combining multiple natural flood management approaches does not necessarily yield additive benefits, underscoring the importance of strategic placement over buffer width alone [54]. Properly designed riparian vegetation measures, tailored to local catchment characteristics, maximise their potential to mitigate flood risks effectively.

Connecting the river to the floodplain. Floodplain reconnection represents a fundamental shift from conventional flood control approaches, which historically relied on levees and channelisation to confine rivers. This category encompasses various NbS interventions, from preservation and restoration of natural floodplains to engineered approaches like the Room for the River programme [70,144], representing 3.2 % of all identified interventions (Fig. 5). Common implementations include removing or lowering dams and levees, adjusting adjacent flood banks, constructing setback levees, and relocating structures from floodplains where feasible. These interventions aim to restore natural flood mitigation functions while delivering additional ecosystem benefits. The flood mitigation strategies of floodplain reconnection operate through three primary pathways. First, restored floodplain connectivity increases water detention capacity by creating additional space for temporary flood storage. Second, reconnected floodplains help reduce flood energy by allowing water to spread across wider areas, reducing flow velocities. Third, strategic floodplain reconnection can facilitate the diversion of flood flows away from critical areas through natural overflow pathways.

Evidence demonstrates varying effectiveness across different implementations. The Room for the River programme in the Netherlands achieved water level reductions of 6-12 cm through lowering groynes[6] along a 75 km river stretch, while dyke relocation reduced water levels by 35 cm [145]. Studies show that increasing floodplain width by 50 % and 150 % led to water level reductions of 3-47 cm [146]. Effectiveness varies with flood magnitude - floodplain reconnection reduced inundation areas by 84.7 % for 5-year events but only 44.3 % for 100-year events [147], indicating diminishing returns for extreme floods. Strategic placement of all these interventions within the catchment proves crucial, with midstream interventions often demonstrating optimal effectiveness by providing both upstream storage and downstream protection [46]. However, interventions must be carefully tailored to local conditions, particularly in water-scarce regions requiring enhanced water retention.

Alternative routes

Alternative routes - bypass channels and palaeochannels as the two main approaches- encompass both natural and artificial bypass channels that divert floodwater away from vulnerable areas, through flood diversion and flow regulation. The diversion mechanism works by redirecting excess water through alternative pathways, while flow regulation is achieved through controlled water distribution across multiple channels, effectively reducing pressure on main waterways.

Bypass or high-water channels[7] can be designed to mimic natural systems, providing additional flow capacity during flood events. In Chao Phraya River basin, Thailand (Aw, 1,092-1,600 mm annual rainfall [128]) demonstrated that large-scale bypass channels, when integrated with other solutions, reduced runoff volume and peak discharge during high-frequency events, though effectiveness decreased during low-frequency events [128].

Palaeochannels, ('prior streams', 'ancestral streams', or ancient channels) are remnant fluvial channels, filled with younger sediments over time [148], and formed through various climatological, geological, or anthropogenic processes [149]. They support flood mitigation through reconnection with current fluvial systems, natural water storage, and groundwater-surface water interactions [150]. Studies in Spain documented activation of palaeochannels at specific flow thresholds (300-360 m^3/s), while Indian research showed significant flood recession capabilities, with palaeochannels emptying 87.39 % of floodwater while surrounding areas retained 50 % after 44 days [128,151]. A study documented 115 palaeochannels across Indian river basins, showing varied hydrology from dry channels that activate only during heavy rainfall to permanent water bodies [152].

Implementation challenges include hydrological uncertainties, maintenance requirements, land-use conflicts, and governance complexity. The limited evidence in this review may stem from our search methodology, as palaeochannel research typically appears in geological rather than flood management literature. For successful implementation, alternative routes should be integrated within comprehensive flood management approaches following thorough assessment of local conditions and stakeholder engagement, balancing flood protection with ecosystem preservation.

Combined NbS interventions for flood mitigation

This approach involves the strategic integration of multiple NbS interventions from different categories to achieve synergistic flood mitigation effects across the catchment. These approaches leverage complementary mechanisms to enhance overall effectiveness. The review identified 15 articles (8 %) demonstrating how these combined approaches achieve synergistic effects beyond what individual measures can accomplish alone. Unlike single-intervention approaches, combined strategies simultaneously leverage multiple flood mitigation mechanisms—enhancing water storage capacity, reducing floodwater energy, and modifying flow pathways—creating complementary interactions that amplify overall effectiveness.

The effectiveness of combined approaches demonstrates complex dependencies on strategic spatial distribution across catchment zones. Evidence supports a hierarchical spatial approach: upstream interventions focus on water retention and runoff reduction through afforestation and soil conservation [132,153], midstream measures emphasise flow attenuation through wetlands and leaky barriers [47], and downstream interventions prioritise efficient flow conveyance [46]. This distribution enables complementary mechanisms to work synergistically, creating multiple lines of defense while maximising water retention throughout the catchment [48].

Scale considerations significantly influence intervention selection and design. Smaller catchments benefit from intensive land use changes combined with in-channel measures [19], while larger catchments require more distributed approaches [47]. Combined approaches demonstrate particular effectiveness in addressing varying flood magnitudes - with widespread infiltration and small-scale storage managing frequent events, while larger-scale solutions handle less frequent floods [50]. These interventions also offer temporal adaptability through evolving components like reforestation and wetland restoration, increasing effectiveness over time [58].

However, implementation of these integrated approaches faces unique challenges. The interactions between multiple NbS interventions create complex, nonlinear relationships that require sophisticated modeling and monitoring capabilities [47]. Scale dependency poses particular challenges, as benefits observed in small experimental catchments may not translate directly to larger basins [54]. Additional challenges include coordination across multiple stakeholders, vegetation establishment periods, and diminishing effectiveness during extreme events [137]. Future developments should focus on advancing modelling tools, integrating smart technologies, maximising ecosystem service co-benefits, and developing supportive policy frameworks to realise the full potential of combined NbS approaches [15,25,59,128].

Combining NbS with Grey infrastructural solutions as hybrid interventions

Integrating NbS with conventional grey/engineering infrastructure emerged as an approach to mitigate catchment-level floods in 5 documents (2.7 % of reviewed literature). Hybrid interventions leverage the complementary strengths of both approaches while addressing their individual limitations. Rather than viewing green and grey solutions as mutually exclusive, this strategy acknowledges their complementary roles across diverse watershed conditions and flood scenarios [56]. Although green interventions offer environmental sustainability, they may not provide adequate flood protection during extreme events—a critical consideration in light of climate change. Treating green and grey solutions as complementary, rather than mutually exclusive, may be advantageous where their unique strengths and limitations can be employed to address flooding in different watershed types and local conditions. By combining natural and infrastructural components, hybrid approaches may reduce the variability in effectiveness observed with standalone interventions, allowing for adaptations suited to specific catchment characteristics.

The strategic implementation of hybrid solutions demonstrates

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[6] A shore protection structure built perpendicular to the shoreline of the coast (or river), over the beach and into the shoreface (the area between the nearshore region and the inner continental shelf), to reduce longshore drift and trap sediments.

[7] The creation of secondary channels by digging them in the floodplain area allows for more water to pass through the area, without lowering the whole floodplain.

several key advantages. Spatial optimisation enables grey infrastructure placement at critical protection points while distributing NbS across the catchment for enhanced water retention [57]. The complementarity extends to temporal aspects - grey infrastructure provides immediate protection based on current design standards, while NbS components can adapt and potentially increase in effectiveness over time [128]. Together, they create multiple lines of defense against flood risk while offering multifunctional benefits, combining dedicated flood protection with broader ecosystem services.

However, implementation faces several challenges. Integration complexity requires sophisticated modelling and planning, while maintenance needs may increase due to system diversity. The evolving nature of NbS elements introduces uncertainty compared to grey infrastructure's predictable performance [59]. Public acceptance presents another challenge, particularly regarding environmental impact concerns [143]. Balancing environmental costs poses substantial challenges, especially concerning carbon emissions from grey infrastructure construction and potential ecosystem disruption [154,155].

Future research priorities should focus on developing integrated modelling tools for complex system interactions and establishing standardised performance metrics that consider both flood mitigation capabilities and broader ecosystem services. Practices such as protected watersheds, spongy catchments and integrated water resource management can combine both NbS and hybrid approaches. While hybrid interventions offer promising solutions that potentially outperform individual strategies, their successful implementation requires innovative design, careful planning, and adaptive management approaches.

Co-benefits

Nature-based Solutions delivers multiple benefits beyond their primary flood mitigation function. During the review, information on co-benefits mentioned in each study were specifically. This involved recording all benefits explicitly mentioned in each paper beyond flood mitigation, categorising these benefits into environmental, social/cultural, and economic dimensions based on established ecosystem services frameworks (e.g., [156]), and quantifying both the frequency of mentions and the depth of analysis (mentioned versus quantitatively assessed). Analysis of the reviewed literature reveals that while all case studies focused on flood mitigation effectiveness, 84 articles also discussed additional benefits, with only 5 articles providing quantitative assessments of these co-benefits (Fig. 11a). The co-benefits span environmental, social/cultural, and economic dimensions, with environmental benefits dominating the discourse, accounting for 65 % of all mentioned co-benefits (Fig. 11b).

Environmental co-benefits demonstrate the most diverse and frequently cited category, encompassing biodiversity conservation (15 %), hydrological benefits (24 %), air purification (9 %), and soil conservation (12 %). Biodiversity benefits primarily manifest through habitat creation and support for wildlife [46,110], restoration of ecosystem processes [157], and enhancement of species diversity [46,158]. Hydrological co-benefits extend beyond flood control to include water purification, sediment trapping, and groundwater recharge [92,114,159]. Soil conservation benefits are particularly notable in catchment-scale interventions, with improved soil moisture, enhanced infiltration, and erosion control frequently cited [20]. Climate change mitigation and adaptation emerge as cross-cutting benefits, with interventions contributing to carbon sequestration, local climate regulation, and enhanced resilience to extreme events [48,160,161].

Social and cultural benefits, accounting for 16 % of identified co-benefits, demonstrate the broad societal value of NbS flood mitigation approaches. Recreational opportunities emerge as the dominant social benefit (8 %), encompassing enhanced public spaces, tourism development, and improved amenity provision [20,128]. Public health benefits (3 %) extend beyond flood mitigation to include improved quality of life and enhanced community wellbeing through increased access to natural

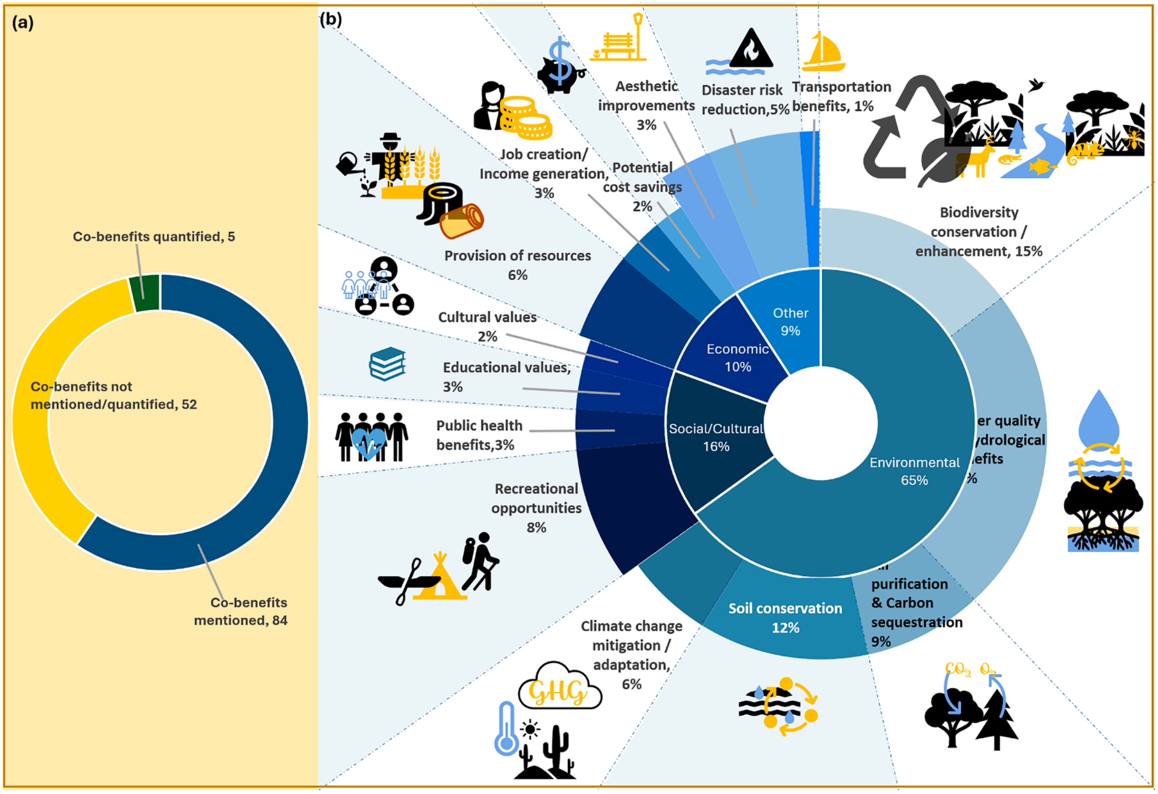

Fig. 11. Co-benefits identified in case studies in addition to the primary flood mitigation benefit. (a) Number of articles that mentioned, quantified, or did not mention co-benefits; (b) Graphical representation of the specific co-benefits reported.

spaces [15]. Several articles prominently featured educational values, offering opportunities for environmental education and enhanced understanding of ecological processes [106,48]. Cultural benefits, while less frequently quantified, include strengthened social cohesion and preservation of cultural services, particularly in areas where conventional flood management practices hold cultural significance [162,163].

Economic co-benefits, representing 10 % of documented benefits, demonstrate the potential for NbS to generate tangible economic value alongside flood protection. Resource provision (6 %) emerges as the primary economic benefit, encompassing timber production, enhanced agricultural productivity, and improved irrigation capabilities [110,164,165]. Job creation and income generation (3 %) occur through both implementation and maintenance phases, particularly benefiting local communities through new employment opportunities and enhanced economic resilience [163,166]. Cost savings (2 %) manifest through reduced infrastructure maintenance requirements and enhanced longevity of existing flood protection systems. Some articles also highlight the potential for innovative funding mechanisms and economic efficiencies through reduced reliance on conventional grey infrastructure, though these benefits often require longer timeframes to realise [48]. These economic advantages, while sometimes challenging to quantify, contribute significantly to the overall value proposition of NbS approaches.

The wide range of identified co-benefits underscores the holistic value proposition of NbS approaches to flood mitigation. However, the limited quantification of these benefits—evident in the fact that only five articles provide quantitative assessments [142,167–170]—highlights the need for more robust evaluation frameworks to fully capture and communicate the comprehensive value of NbS implementations. Future research should prioritise developing standardised metrics for assessing and quantifying these diverse co-benefits, enabling more complete cost-benefit analyses and supporting evidence-based decision-making in flood management strategies. However, all planning steps should account for potential maladaptation and disservices, such as safety risks, crime, and health concerns in poorly managed green spaces [24,171,172].

Grey literature; European examples

By assessing selected grey literature documents, significant insights emerge regarding NbS implementation in European contexts. The document collection encompassed multiple sources with case studies published between 2013 and 2024, primarily from the UK government's Working with Natural Processes (WWNP) scheme, offering empirical evidence on various NbS interventions. The geographical concentration of case studies in the UK, with a single case from the Netherlands, reflects a significant regional bias in the available grey literature. This specific regional focus, while valuable for understanding local implementations, influenced the decision to analyse these sources separately from the academic literature pool.

Beyond the poor geographical representation that limited the applicability of findings across diverse environmental contexts, several other factors influenced this decision, such as;

a) Methodological consistency: The grey literature sources often lacked standardised methodologies for measuring and reporting outcomes, making direct comparisons between studies challenging.
b) Variable reporting depth: The level of detail and technical information provided varied considerably across documents, with some offering limited quantitative data or methodology descriptions.
c) Limited temporal scope: Many studies focused on short-term outcomes, with few providing long-term monitoring data necessary for understanding the evolution of NbS effectiveness over time.
d) Context specificity: The studies predominantly reflected conditions specific to Western European climates, topography, and governance structures, limiting their relevance to other global contexts.
e) Documentation format: The grey literature was often designed for general audiences or policymakers rather than academic scrutiny, sometimes lacking the rigorous analytical framework typical of peer-reviewed research.
f) Language accessibility: Grey literature is often written in local languages. Since the search was limited to English-language sources, this may have further constrained the geographical diversity and comprehensiveness of the reviewed documents.
g) Verification challenges: Unlike peer-reviewed academic literature, these documents did not undergo the same level of independent scientific scrutiny, potentially affecting the reliability and validity of their findings.

These limitations, coupled with reduced independent scientific scrutiny, influenced the decision to maintain methodological rigour by treating grey literature insights separately.

The reviewed documents revealed several predominant NbS types, with flow barriers, afforestation, and peatlands/grasslands restoration emerging as frequently implemented interventions. Flow barriers demonstrated effectiveness in flood mitigation through enhanced peak flow attenuation and velocity reduction [173,174]. Afforestation showed notable long-term benefits for flood control, particularly evident in cases in the UK, where strategic tree planting enhanced flood mitigation capacity [173,175]. Combined NbS approaches demonstrated synergistic effects, exemplified by the Nant Barrog catchment's integration of natural dams, land use management, and farm storage systems [176].

These case studies highlighted substantial co-benefits extending beyond flood mitigation, including improved water quality, enhanced biodiversity, carbon sequestration, and sediment retention. However, several limitations warrant consideration - particularly the geographical bias towards the UK, variability in quantification methods, and limited long-term effectiveness data. Future research priorities should include expanding geographical scope, developing standardised assessment methods, conducting longitudinal studies, and investigating scalability across catchment sizes. While these limitations necessitate careful interpretation, the grey literature provides valuable insights into practical NbS implementation and effectiveness in European contexts.

Nature-based Solutions – effectiveness for flood mitigation

By following the above discussion, distinct patterns and driving factors that influence the effectiveness of NbS across various implementation contexts were identified. Table 1 synthesises these key effectiveness factors, providing a framework for evaluating and selecting appropriate NbS interventions based on specific catchment conditions.

The performance of NbS interventions is fundamentally governed by catchment characteristics, including size, slope, topography, geology, river networks, and land use patterns. The extent of NbS coverage within the catchment emerged as another crucial factor, with larger implementations generally showing greater impact, though this relationship often proves non-linear and reaches diminishing returns beyond certain thresholds.

Spatial distribution particularly demonstrates critical importance: upstream interventions typically focus on water retention and flow reduction, midstream measures emphasise flow attenuation, while downstream management prioritises maintaining clear floodways for efficient water conveyance. Event magnitude consistently emerges as a critical determinant of effectiveness across all NbS types. While strategically implemented interventions demonstrate substantial flood peak reductions during frequent, smaller events, their performance generally diminishes during extreme events. This pattern highlights the importance of realistic expectations when implementing NbS, particularly in regions experiencing increasing frequency of high-magnitude events due to climate change. The timing of effectiveness represents another important consideration. Unlike conventional infrastructure, which

Table 1
Key effectiveness factors and evidence for NbS in catchment scale flood mitigation.

Category	Effectiveness factor	Example citations
Spatial considerations	Upstream locations are most effective for storage/detention.	[44,45]
	Midstream locations are optimal for flow attenuation.	[46,47]
	Downstream should focus on conveyance.	[46]
	Strategic distribution improves overall effectiveness.	[48]
Scale dependencies	Small catchments (<10km^2): significant impact from modest interventions.	[49]
	Medium catchments (10-100km^2): networked approaches are most effective.	[50]
	Large catchments (>100km^2): require proportionally larger interventions.	[51]
Event magnitude	Most effective during frequent flood events.	[52,53]
	Enhanced protection for events with high intensities when multiple NbS types are combined.	[50,47]
	Effectiveness often diminishes during extreme events.	[54,55]
Implementation approach	Combined approaches are often more effective than single measures.	[19,48]
	Integration with existing infrastructure enhances outcomes.	[56,57]
	Strategic placement is crucial for optimal performance.	[47]
Time considerations	Vegetation-based interventions require a maturation period before achieving full flood mitigation benefits.	[25,48,58,59]

provides immediate protection upon completion, many NbS interventions—particularly vegetation-based approaches—require maturation periods before achieving full flood mitigation benefits. This temporal dimension necessitates forward-looking planning and interim measures during establishment phases. These findings advance the current understanding of NbS effectiveness and offer evidence-based guidance for implementing catchment-scale flood mitigation strategies.

Limitations and considerations

While NbS demonstrate significant potential for flood mitigation, several limitations and considerations in their effectiveness warrant attention when implementing these approaches at the catchment scale. These constraints span technical, environmental, social, and economic dimensions that can affect both the feasibility and effectiveness of NbS interventions (Table 2).

The effectiveness of NbS exhibits strong dependencies on both spatial and temporal factors. Almost all interventions show diminishing returns during extreme events. In majority of cases reviewed, the effectiveness decreases as flood magnitude increases [54,55,177]. The relationship between intervention scale and effectiveness often proves non-linear - benefits observed in small experimental catchments may not translate proportionally to larger basins [54]. This variability depends heavily on factors such as catchment size, spatial arrangement, and storm intensity [54,55,177]. While most NbS interventions show reduced effectiveness during extreme events, strategies that improve surface permeability combined with strategically planned LULC can offer relatively better protection against extreme floods. Additionally, time lags between implementation and full effectiveness can be substantial, particularly for vegetation-based interventions that require maturation periods [48].

Environmental constraints significantly limit NbS application. Soil characteristics and groundwater conditions can restrict the effectiveness of infiltration-based measures, particularly in areas with clay soils or high groundwater tables [152,156]. Local climate patterns influence the performance of vegetation-based interventions [108–110]. Climate change adds another layer of complexity, potentially altering the long-term effectiveness of interventions through changing precipitation patterns and increased frequency of extreme events [59]. The carbon footprint of implementation, particularly for hybrid approaches involving grey infrastructure, requires careful consideration [154,155].

Implementation faces substantial socio-economic barriers. Land availability and competing demands often create conflicts, particularly in areas with high agricultural or urban development pressure [138,139]. The cost implications can be substantial - while NbS may offer long-term cost benefits, they often require significant initial investment and ongoing maintenance [117]. For instance, permeable surfaces need regular maintenance to remain effective, as clogged pores can reduce infiltration capacity. Public acceptance can vary, with resistance sometimes stemming from aesthetic concerns or preferences for conventional infrastructure [180]. Additionally, socio-economic and political constraints must be considered when planning large-scale land use changes, requiring substantial financial resources, political will, and public support.

Governance and institutional challenges present additional hurdles. Complex stakeholder landscapes require careful coordination across multiple jurisdictions and interest groups [140]. Existing regulations and funding mechanisms may not adequately support NbS approaches, while standardized frameworks for measuring and validating effectiveness remain limited [59]. The need for long-term monitoring and maintenance can strain institutional capacities and resources [137], necessitating adaptive management approaches to address changing environmental conditions and intervention performance over time.

Summary

This systematic review analysed scientific literature on Nature-based Solutions (NbS) for flood mitigation through three fundamental strategies: flood detention through temporary storage, flood energy reduction

Table 2
Common limitations and considerations affecting the effectiveness of NbS for flood mitigation.

Category	Limitation/Consideration	Example Citations
Technical	Diminishing effectiveness during extreme events.	[55,177]
	Scale dependency and non-linear benefits.	[54]
	Time lag between implementation and effectiveness.	[48]
Environmental	Soil and groundwater constraints.	[165,178]
	Climate change impacts on long-term effectiveness.	[179]
	Carbon footprint of implementation.	[154,155]
Socio-Economic	Land availability and competing demands.	[138,139]
	Cost implications and funding requirements (depending on the cost-benefit analysis).	[117]
	Public acceptance and resistance.	[180]
Governance	Complex stakeholder coordination.	[140]
	Regulatory and institutional barriers.	[59]
	Maintenance and monitoring requirements.	[137]

by slowing water movement, and floodwater diversion through alternative pathways. Analysis of 141 academic articles and 7 grey literature documents revealed four distinct functional groups of NbS interventions: managing catchment land cover (45.4 %), storing excess water (26.1 %), managing floodplain (18.1 %), and reviving alternative routes (1.1 %), with combined NbS and hybrid interventions accounting for 8.2 % and 2.7 %, respectively.

Despite the growing body of evidence supporting NbS for flood mitigation, this review identifies critical knowledge gaps for future research attention. These include the necessity for more quantitative assessments, a better understanding of implementation challenges in different environments and contexts, and methodological requirements. First, additional quantitative assessments are required, particularly regarding long-term performance in a range of environments, performance changes with climate change impacts and cost-benefit analyses. For long-term performance evaluation, it may be helpful if physics-based flood models are coupled with separate vegetation growth models (for trees, bushland, pastures, etc.) to capture the biophysical dynamics that influence NbS effectiveness over time. While flood models excel at their primary purpose of simulating hydraulic processes, the complex biological dynamics of vegetation require dedicated growth models, necessitating an integrated modelling approach. Regarding climate change impacts, while 61 % of articles referenced this factor, only 12.8 % quantitatively assessed its effect on NbS flood mitigation potential, highlighting a limited understanding of NbS performance under changing climate conditions. Cost-benefit analyses across different scales remain limited, making it difficult for decision-makers to justify NbS investments compared to conventional infrastructure, particularly when considering both direct flood mitigation benefits and broader ecosystem services. Second, for implementation, challenges persist in understanding how to integrate multiple NbS interventions across landscapes, particularly optimal spatial configurations, and long-term maintenance requirements. Third, methodological gaps indicate the need for standardised assessment frameworks, improved large-scale modelling capabilities, and better integration of field measurements with predictive models.

Successful NbS implementation requires strategic integration across catchment landscapes. Managing catchment land cover serves as an important measure through detention and energy reduction, while water storage measures demonstrate effectiveness across all scales when properly positioned. Floodplain management enhances both detention and energy reduction through features such as leaky barriers and riparian vegetation, with distributed networks typically offering greater flood attenuation during larger events. Placing leaky barriers strategically rather than randomly could achieve similar effectiveness with around half the number of barriers. Maximum effectiveness is achieved through integrated approaches combining multiple NbS types strategically across catchments. Design considerations must incorporate local hydrological, topographical, and climate conditions, with interventions proportionally sized to catchment characteristics and expected flood volumes. While NbS may have limitations for flood mitigation during extreme events, when strategically designed and implemented at the catchment scale, they offer viable and sustainable approaches to flood mitigation. Future success depends on continued research, policy development, and practical experience across diverse contexts, supported by long-term monitoring programs and standardised assessment approaches.

This comprehensive review demonstrates that NbS, when properly designed and implemented, represent effective strategies for flood mitigation, working with rather than against natural processes. The evidence supports their expanded use in comprehensive flood management approaches when adapted to local contexts, and in some cases when integrated with existing infrastructure.

CRediT authorship contribution statement

Prabhasri Herath: Writing – review & editing, Writing – original draft, Visualization, Methodology, Formal analysis, Conceptualization. **Roslyn Prinsley:** Writing – review & editing, Supervision, Methodology, Conceptualization. **Barry Croke:** Writing – review & editing, Supervision, Methodology, Conceptualization. **Jai Vaze:** Writing – review & editing, Supervision, Methodology, Conceptualization. **Carmel Pollino:** Supervision, Conceptualization.

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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Supplementary materials

Supplementary material associated with this article can be found, in the online version, at doi:10.1016/j.nbsj.2025.100235.

Data availability

I have shared the data I used in Annexes.

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