Rahubadda, R.V.A.D., Ingirige, B. and Kulatunga, U., 2026. Nature-based solutions for flood mitigation: A systematic review of evidence, performance mechanisms, and implementation conditions. In: Waidyasekara, K.G.A.S., Jayasena, H.S., Chandanie, H. and Tennakoon, G.A. (eds). *Proceedings of the 14th World Construction Symposium*, 10-11 July 2026, Sri Lanka. pp. 1208-1222. DOI: https://doi.org/10.31705/WCS.2026.88. Available from: https://ciobwcs.com/papers/

NATURE-BASED SOLUTIONS FOR FLOOD MITIGATION: A SYSTEMATIC REVIEW OF EVIDENCE, PERFORMANCE MECHANISMS, AND IMPLEMENTATION CONDITIONS

R.V.A.D Rahubadda[1], B. Ingirige[2] and U. Kulathunga[3]

ABSTRACT

Flooding is one of the most significant natural hazards worldwide, with risks intensifying due to climate change, rapid urbanisation, and land-use transformation. In response to the limitations of conventional grey infrastructure, Nature-Based Solutions (NBS) have gained increasing attention as sustainable strategies for flood risk management. This study presents a systematic literature review examining how NBS are applied and evaluated in flood mitigation research. Peer-reviewed studies published between 2016 and 2026 were identified through structured searches in Scopus and Web of Science, guided by the PRISMA framework and a SPIDER-based review structure. Following duplicate removal and eligibility screening, 136 studies were retained for analysis. Evidence was synthesised using structured coding, descriptive statistics, and thematic synthesis to examine NBS types, flood hazard contexts, performance indicators, hydrological mechanisms, co-benefits, and governance conditions. The findings show that urban green infrastructure and low-impact development measures dominate the literature, particularly for pluvial flooding, while wetland restoration and river restoration approaches are more commonly applied to riverine flood management. Key hydrological mechanisms include increased infiltration, floodwater storage, hydraulic roughness, and hydrograph desynchronisation. However, the evidence base remains dominated by modelling approaches, with limited long-term empirical monitoring of implemented interventions. This review contributes by linking NBS types, flood hazards, performance evaluation metrics, and implementation conditions. The findings highlight the need for stronger empirical evidence, standardised hydrological indicators, and integrated grey–green infrastructure approaches to support the wider adoption of NBS in sustainable flood risk management.

Keywords: *Flood Risk Management; Green Infrastructure; Nature-Based Solutions; Natural Flood Management; Systematic Literature Review.*

1. INTRODUCTION

Flooding is one of the most frequent and destructive natural hazards worldwide, causing significant economic losses, environmental degradation, and social disruption (Kienzler

[1] Research assistant, Department of Building Economics, University of Moratuwa, Sri Lanka, dilrukshaashen@gmail.com
[2] Professor, School of Science, Engineering & Environment, University of Salford, United Kingdom, M.J.B.Ingirige@salford.ac.uk
[3] Professor, Department of Building Economics, University of Moratuwa, Sri Lanka, ukulatunga@uom.lk

et al., 2016). Climate change, rapid urbanisation, and land-use transformation are intensifying flood risks across riverine, pluvial, and coastal environments (Intergovernmental Panel on Climate Change [IPCC], 2022). Conventional flood management strategies have historically relied on engineered or “grey” infrastructure, including levees, floodwalls, drainage networks, and dams (Devi et al., 2025). Although these structural measures can provide effective protection against flood events, they often involve high construction and maintenance costs and may transfer risks downstream while neglecting broader ecological and social dimensions of resilience (Schubert et al., 2017).

In response to these limitations, NBS have emerged as an increasingly prominent approach in climate adaptation and flood risk management (Griffiths et al., 2024). NBS refer to strategies that utilise natural processes and ecosystem functions to address societal challenges while simultaneously generating environmental, social, and economic co-benefits (Griffiths et al., 2024; Schröder et al., 2025). Examples include wetland restoration, floodplain reconnection, urban green infrastructure, mangrove conservation, and ecosystem-based coastal protection (Sabut et al., 2026; Wu et al., 2022). By enhancing water storage capacity, increasing infiltration, and attenuating flow velocities, these interventions can reduce flood hazards while also improving biodiversity, water quality, and urban liveability (Huang et al., 2026; Watson et al., 2016).

Over the past decade, NBS have gained increasing prominence within global climate adaptation and disaster risk reduction policies. International organisations such as the European Commission, the International Union for Conservation of Nature (IUCN), and the United Nations have actively promoted ecosystem-based approaches as complements to conventional flood defence systems (Devi et al., 2025; Lindenberger et al., 2025). As a result, research on NBS for flood mitigation has expanded rapidly, reflecting a broader paradigm shift in flood management from purely structural protection toward more integrated, adaptive, and ecosystem-based strategies.

Despite this growing body of research, several critical gaps remain in the existing literature. First, studies examining NBS for flood mitigation are often fragmented across different flood contexts, including pluvial, riverine, and coastal flooding, making it difficult to identify how NBS are selected and applied across varying hazard types (Iliadis et al., 2024; Inácio et al., 2023). Second, while many studies report positive outcomes associated with NBS, the evidence base remains heterogeneous in terms of evaluation metrics, reported effectiveness, and the underlying mechanisms through which these interventions influence flood dynamics (Caroppi et al., 2024; Marino et al., 2025). Third, the successful implementation of NBS depends not only on technical performance but also on enabling governance structures, financing mechanisms, and institutional coordination, which remain insufficiently synthesised in the current literature (Inácio et al., 2023; Marino et al., 2025).

Addressing these knowledge gaps is important for supporting the wider integration of NBS into flood risk management and infrastructure planning. Therefore, this study conducts a systematic literature review to examine how NBS are applied and evaluated in flood mitigation research. Specifically, the review synthesises peer-reviewed evidence to identify dominant NBS strategies, analyse their reported mechanisms and effectiveness in reducing flood risks, and examine the governance and implementation conditions that influence their adoption.

Accordingly, this study is guided by three research questions.

- **RQ1.** How are Nature-Based Solutions applied and evaluated for flood mitigation across riverine, pluvial, and coastal contexts?
- **RQ2.** What does the literature report regarding the effectiveness, hydrological mechanisms, co-benefits, and potential trade-offs of Nature-Based Solutions in reducing flood risks?
- **RQ3.** What governance, financing, and implementation conditions enable the successful integration and mainstreaming of Nature-Based Solutions in flood risk management?

2. METHODOLOGY

This study employed a systematic literature review (SLR) to identify, screen, and synthesise peer-reviewed research on the application of NBS for flood mitigation. The SLR approach was selected because it provides a transparent, structured, and reproducible method for reviewing a large interdisciplinary body of literature while reducing selection bias through explicit search, screening, and eligibility procedures. The review followed established systematic review guidance (Petticrew & Roberts, 2006) and was reported in accordance with the Preferred Reporting Items for Systematic Reviews and Meta-Analyses 2020.

This study used a SPIDER framework to structure the review and guide the search strategy. The framework was suitable because the review synthesises interdisciplinary evidence on diverse NBS interventions across riverine, pluvial, and coastal flood contexts. The SPIDER elements were defined as follows: Sample: flood-prone urban, riverine, coastal, and catchment systems; Phenomenon of Interest: NBS and related ecosystem-based flood management interventions; Design: empirical studies, modelling studies, evaluation frameworks, and systematic assessments; Evaluation: flood mitigation outcomes, hydrological mechanisms, performance indicators, co-benefits, and governance conditions; and Research type: quantitative, qualitative, and mixed-method studies.

The literature search was conducted in Scopus and Web of Science because these databases provide broad coverage of peer-reviewed research in environmental science, hydrology, climate adaptation, infrastructure, and urban planning. The search strategy was developed around three conceptual domains: flood hazard, NBS, and flood risk reduction outcomes. Search terms were selected to capture both explicit NBS terminology and related concepts, including green infrastructure, blue-green infrastructure, natural flood management, ecosystem-based adaptation, wetland restoration, floodplain restoration, permeable pavements, bioswales, and low-impact development. Boolean operators and wildcard characters were used to improve search sensitivity, and searches were applied to title, abstract, and keyword fields. The final search string was: *TITLE-ABS-KEY (flood* OR flooding OR "river flood*" OR "coastal flood*" OR "pluvial flood*")AND TITLE-ABS-KEY ("nature-based solutions" OR NBS OR "natural flood management" OR "green infrastructure" OR "blue-green infrastructure" OR "ecosystem-based adaptation" OR "ecosystem services" OR "wetland restoration" OR "floodplain restoration" OR "green roof" OR bioswale OR "permeable pavement" OR "stormwater management" OR "low impact development") AND TITLE-ABS-KEY (mitigation OR prevention OR "flood risk reduction" OR "disaster risk reduction")*

The review included peer-reviewed journal articles published in English between 2016 and 2026. Studies were included if they examined the application, performance, modelling, evaluation, or governance of NBS for flood mitigation. Eligible interventions included green infrastructure, wetlands, floodplain reconnection, river restoration, mangroves, coastal ecosystems, and ecosystem-based adaptation. Studies were excluded if they focused on non-flood hazards, discussed ecosystem concepts without direct relevance to flood mitigation, were not peer-reviewed journal articles, were conference abstracts, reports, grey literature, or were not written in English.

The database search identified 924 records from Scopus and Web of Science. After duplicate removal, 548 unique records remained. Title and abstract screening were conducted to assess relevance to NBS and flood mitigation. Records were excluded if they did not focus on flooding, did not examine NBS or related ecosystem-based interventions, or did not address flood mitigation, flood risk reduction, or flood management outcomes. Full-text eligibility assessment was then conducted for potentially relevant studies. At this stage, records were excluded if they were outside the review period, lacked direct relevance to NBS-based flood mitigation, did not provide sufficient methodological or analytical detail, or failed to meet the publication and language criteria. Following all eligibility checks, 136 studies were retained for detailed analysis. The screening process is summarized in the PRISMA flow diagram presented in Figure 1.

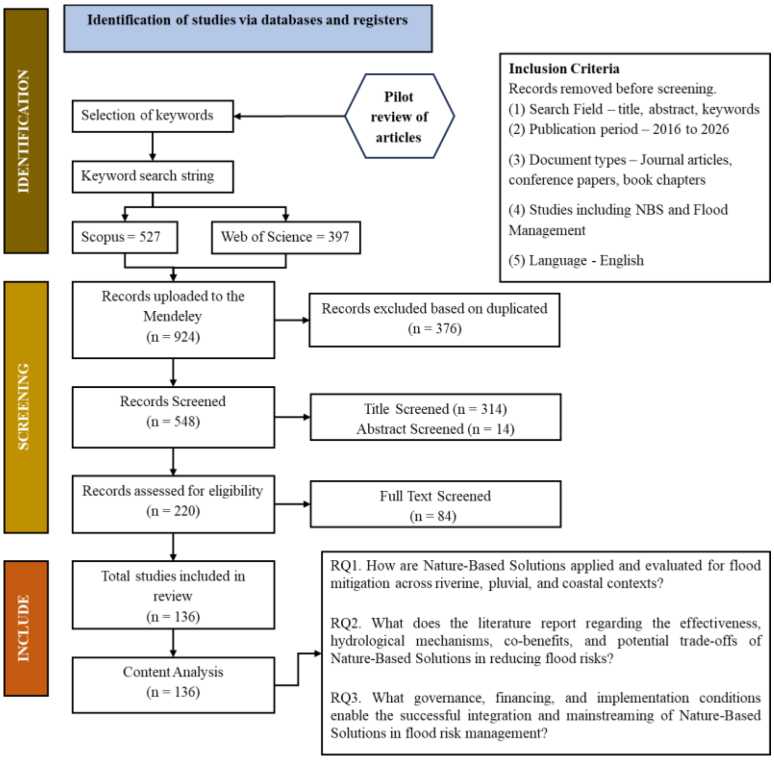

Figure 1: Overview of research methodology.

Data were extracted using a structured coding sheet developed from the research questions and SPIDER framework. Extracted information included publication year, country or region, flood hazard type, NBS category, research method, performance indicators, hydrological mechanisms, co-benefits, and governance or implementation conditions. Coding combined deductive and inductive approaches. Deductive codes were developed from the review objectives, including flood hazard types, NBS categories, research methods, and evaluation metrics. Inductive coding was used to capture recurring themes emerging from the studies, including institutional barriers, financing constraints, monitoring limitations, and hybrid grey–green infrastructure approaches.

The selected studies were analyzed using descriptive statistics and thematic synthesis. Descriptive analysis identified publication trends, geographic distribution, dominant NBS types, flood contexts, and evaluation metrics. Thematic synthesis was used to interpret how NBS influence flood dynamics and how institutional, financial, and governance conditions affect implementation. A quality appraisal was also conducted based on methodological clarity, relevance to flood mitigation, transparency of data or modelling assumptions, appropriateness of evaluation methods, and clarity of reported outcomes. Studies were not excluded solely on quality; instead, appraisal informed the interpretation of evidence strength.

3. RESULTS AND DISCUSSION

3.1 PUBLISHED ARTICLES, ANNUAL AND WORLDWIDE DISTRIBUTIONS

The systematic review identified a rapidly expanding body of literature on the application of NBS for flood risk reduction between 2016 and 2026. As shown in Figure 2, publication activity remained relatively limited during the early years of the review period, with only one to four studies published annually between 2016 and 2019. This suggests that the application of NBS to flood management was still an emerging research field during this period, despite broader international interest in ecosystem-based adaptation, green infrastructure, and sustainable urban drainage. A clear increase in research activity began in 2020, when the number of publications rose to nine, followed by fourteen in 2021 and sixteen in 2022. Although a slight decline was observed in 2023, with eleven publications, the field expanded substantially thereafter, reaching twenty-six publications in 2024 and peaking at forty-three in 2025. The lower number of publications recorded in 2026 is most likely attributable to the incomplete coverage of the year at the time of data collection rather than a decline in research interest.

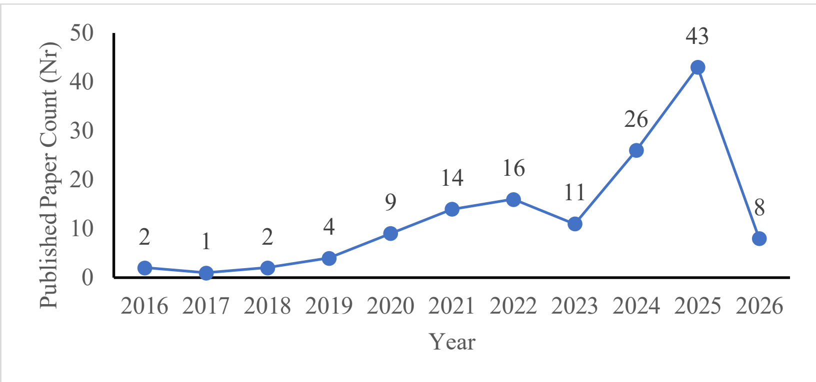

Figure 2: Annual publication trend

This upward trend reflects the increasing recognition of NBS as a complementary approach to conventional flood management. The growing number of studies also corresponds with wider policy interest in climate adaptation, urban resilience, biodiversity restoration, and sustainable infrastructure. Flooding is increasingly understood not only as a hydraulic or engineering problem but also as a socio-ecological challenge shaped by land-use change, catchment degradation, urbanisation, and climate variability. Consequently, the rapid growth of NBS research indicates a broader transition in flood management thinking, moving away from reliance on purely structural defences and towards more adaptive, multifunctional, and ecosystem-based strategies.

However, the geographical distribution of the reviewed studies reveals a pronounced imbalance in the evidence base. As illustrated in Figure 3, the United States accounts for the largest share of publications, with 35 studies. This reflects the country's strong research and policy engagement with sustainable drainage systems, natural flood management, catchment-based planning, and green infrastructure. In comparison, fewer studies were identified from other countries, with China contributing eight publications and Australia contributing seven, while many countries were represented by only one study. Although Europe has played a leading role in climate policy and environmental governance (Oberthür & Kelly, 2008), the number of studies specifically addressing NBS for flood reduction remains unevenly distributed even within Europe and comparatively limited across many flood-prone regions.

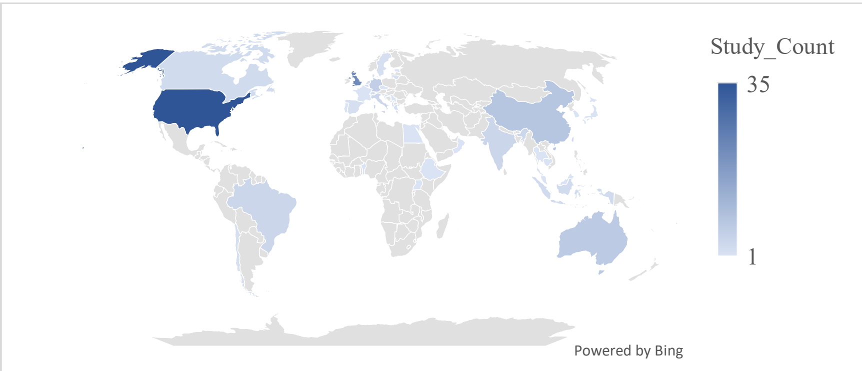

Figure 3: Worldwide distribution map of publications

This geographical imbalance is especially important because many countries in the Global South are highly exposed to flooding due to rapid urbanisation, inadequate drainage infrastructure, informal settlement growth, land-use pressures, and increasing climate-related rainfall extremes. The limited representation of Global South contexts reduces the transferability of current findings, particularly because the performance and feasibility of NBS are strongly shaped by governance capacity, land availability, maintenance systems, hydrological conditions, and socio-economic constraints. This highlights the need for more empirical studies from the Global South that document locally adapted practices, assess hydrological performance, and examine governance and maintenance requirements.

3.2 TYPES OF NATURE-BASED SOLUTION

The reviewed literature demonstrates that NBS for flood management are highly diverse and should not be treated as a single homogeneous category. To improve analytical clarity, this review classified the identified interventions according to three dimensions: intervention type, spatial scale, and dominant flood-mitigation function. This classification enables a clearer distinction between site-level stormwater measures, connected green–blue infrastructure networks, floodplain and wetland storage systems, river restoration and natural flood management, coastal ecosystem-based protection, and catchment-scale interventions.

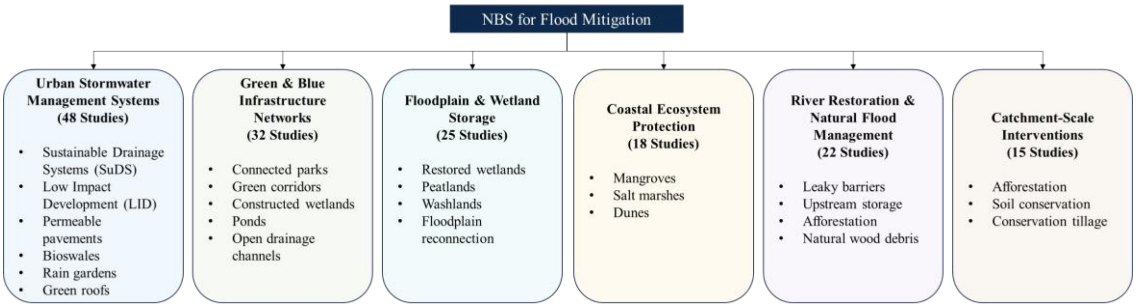

Figure 4: Types of NBS solutions

As shown in Figure 4, urban stormwater management systems represent the most frequently examined category, appearing in 48 studies. This group includes Sustainable Drainage Systems, Low Impact Development measures, permeable pavements, bioswales, rain gardens, green roofs, detention basins, retention systems, and sponge city measures. These interventions are primarily designed to address pluvial flooding by increasing infiltration, reducing runoff volume, enhancing temporary storage, and delaying peak discharge. Their prominence reflects the growing importance of urban flood management under rapid urban expansion and increasing impervious surface cover. However, their effectiveness is usually strongest at the site or neighborhood scale and may be limited during high-intensity or long-duration rainfall events if storage capacity is exceeded or drainage systems are already overloaded.

Green and blue infrastructure networks appeared in 32 studies. These systems include connected parks, green corridors, constructed wetlands, ponds, open drainage channels, and multifunctional urban landscapes. Unlike isolated stormwater measures, green–blue infrastructure networks depend on spatial connectivity and cumulative hydrological effects. Their performance is influenced not only by the capacity of individual components but also by their arrangement within urban drainage networks, catchments, and runoff pathways. Fragmented green spaces may provide local benefits, but their contribution to wider flood mitigation may remain limited unless they are strategically connected to drainage systems, rivers, or receiving water bodies.

Floodplain and wetland storage systems were examined in 25 studies. These include restored wetlands, peatlands, washlands, and floodplain reconnection schemes. Their primary function is to store excess water, attenuate riverine flood peaks, and reduce downstream flood intensity. In contrast to urban stormwater systems, these interventions usually operate at larger spatial scales and are closely linked to river basin hydrology. Their effectiveness depends on available storage volume, floodplain connectivity, vegetation structure, soil conditions, antecedent moisture, and the timing of flood wave propagation. Therefore, their performance can vary considerably between catchments and flood events.

River restoration and natural flood management were identified in 22 studies. These interventions include leaky barriers, upstream storage, afforestation, riparian vegetation restoration, re-meandering, and natural wood debris. They aim to slow runoff, increase channel roughness, enhance temporary storage, and reconnect rivers with floodplains. However, their effectiveness is context-specific and may depend on catchment size, slope, land use, soil permeability, intervention density, and maintenance. Small-scale measures may reduce local flood peaks but may not substantially influence downstream flooding unless implemented at sufficient scale and in hydrologically suitable locations.

Coastal ecosystem-based protection appeared in 18 studies and includes mangroves, salt marshes, dunes, coastal wetlands, and hybrid coastal defense systems. These interventions reduce coastal flood hazards by attenuating wave energy, limiting storm-surge impacts, stabilizing shorelines, and creating buffer zones between the sea and exposed settlements. Their effectiveness depends on ecosystem width, vegetation density, elevation, tidal range, sediment supply, and storm intensity. Catchment-scale interventions, including afforestation, soil conservation, conservation tillage, upland storage, and distributed retention measures, appeared in 15 studies, indicating that watershed-level NBS remain less represented than urban and floodplain-focused approaches.

Therefore, the dominance of urban stormwater systems suggests that NBS research has been strongly shaped by urban flood concerns and the policy visibility of green infrastructure. However, this emphasis may create a narrow understanding of NBS effectiveness if broader and interacting flood mechanisms are underrepresented. Flooding often results from multiple interacting drivers, including intense rainfall, high river levels, storm surge, drainage exceedance, and rising groundwater. Yet groundwater flooding and compound flooding remain insufficiently addressed in the reviewed studies. This is a major limitation because NBS performance under compound conditions may differ from performance under single-source flood events.

3.3 Relationship between the Primary Nature-Based Solution (NBS) Types and the Flood Hazards

Figure 5 illustrates how the primary NBS categories identified in the review are distributed across different flood hazard contexts. The results show that NBS are not applied uniformly across flood types; rather, their use reflects the dominant hydrological and hydraulic processes associated with each hazard. Urban stormwater systems are most strongly associated with pluvial and urban flooding because they address rainfall-runoff generation, surface-water accumulation, and drainage exceedance close to where rainfall occurs. In contrast, floodplain storage, wetland restoration, river restoration, and natural flood management are more commonly linked to riverine flooding, where the main objective is to attenuate flood peaks, increase temporary storage, slow flow conveyance, and reconnect rivers with their floodplains.

Green and blue-green infrastructure networks occupy an intermediate position because they can contribute to both pluvial and riverine flood management. Their effectiveness depends on how well individual green and blue spaces are connected to runoff pathways, drainage systems, river corridors, and receiving water bodies. Similarly, catchment-scale interventions, such as afforestation, upland storage, soil conservation, and distributed retention, operate across broader hydrological systems by influencing runoff generation, flow pathways, and downstream flood peaks. These interventions are therefore less tied to a single flood type and more relevant to multi-scale flood management.

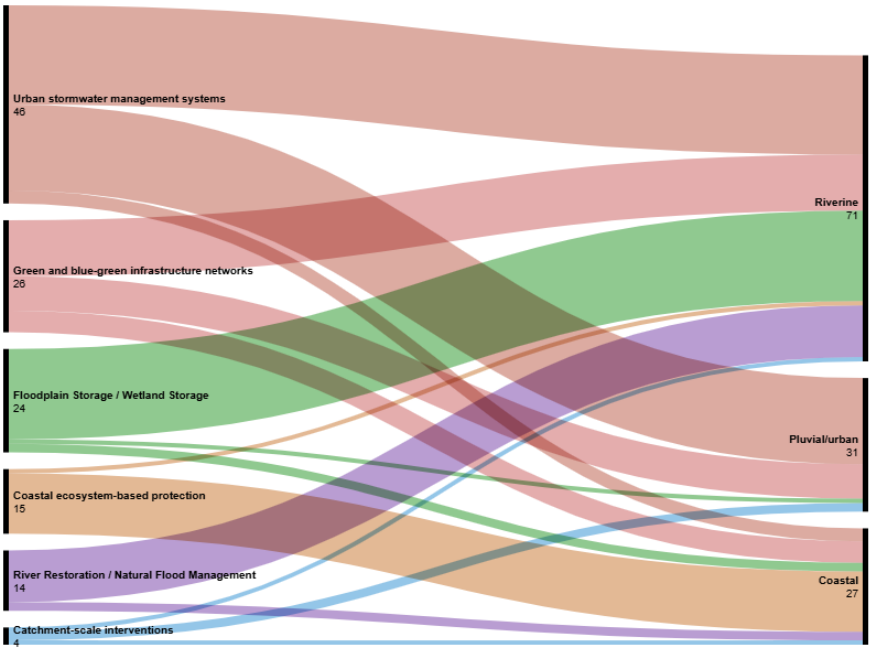

Figure 5: Relationship between the primary NBS types and the flood hazards addressed in the selected studies

Coastal ecosystem-based protection is primarily associated with coastal flooding, where mangroves, salt marshes, dunes, reefs, and coastal wetlands reduce hazards by dissipating wave energy, moderating storm-surge impacts, trapping sediment, and stabilising shorelines. However, the limited number of studies addressing groundwater and compound flooding indicates an important gap in the evidence base. Many real flood events involve interacting drivers, such as intense rainfall, high river levels, storm surge, drainage exceedance, and rising groundwater. Therefore, Figure 5 highlights not only the dominant pairing between NBS types and flood hazards, but also the need for future studies to assess how NBS perform under overlapping and multi-source flood conditions.

3.4 OUTCOME METRICS USED TO EVALUATE NBS EFFECTIVENESS

Figure 6 summarises the outcome metrics used to evaluate the effectiveness of NBS in the reviewed literature. The findings show that most studies rely on broad flood risk or flood hazard indices, reported in 73.5% of the reviewed studies. These indices commonly combine hazard intensity, exposure, and vulnerability to estimate overall flood risk reduction. Although useful for communicating wider risk implications, such composite indicators can obscure the specific hydrological processes through which NBS influence flood behaviour. This is important because different NBS types operate through different mechanisms and are therefore expected to affect different flood variables.

Urban stormwater interventions, such as green roofs, permeable pavements, rain gardens, bioswales, and detention systems, are mainly assessed in relation to pluvial flooding. Their effectiveness is commonly measured using runoff reduction, drainage performance, flood depth, surface water accumulation, and stormwater load indicators (Hankin et al., 2021). In contrast, floodplain restoration, wetland rehabilitation, river re-meandering, and riparian buffer interventions are more frequently evaluated in fluvial flood contexts using peak discharge, inundation extent, flood storage, flow attenuation, and water-level indicators (Schröder et al., 2025). Coastal ecosystem-based protection, including mangroves, salt marshes, dunes, and coastal wetlands, is usually assessed through wave attenuation, storm-surge reduction, shoreline stability, erosion control, and avoided damage (Inácio et al., 2023). These patterns indicate that performance assessment is shaped by both the NBS intervention type and the dominant flood mechanism being addressed.

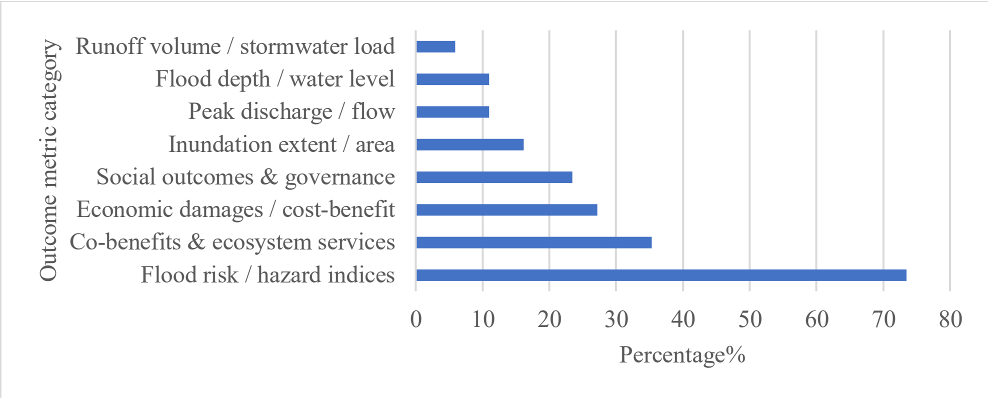

Figure 6: Outcome metrics reported in the reviewed studies

However, direct hydrological performance indicators are reported less consistently than broader risk-reduction and co-benefit outcomes. Co-benefits and ecosystem services are reported in 35.3% of studies, including biodiversity enhancement, water quality improvement, urban cooling, carbon storage, recreation, and landscape amenity. Economic damage reduction and cost–benefit assessments appear in 27.2% of studies, while social and governance outcomes are reported in 23.5%. By comparison, inundation extent appears in only 16.2% of studies, while peak discharge and flood depth or water level is each reported in 11.0%. Runoff volume or stormwater load is reported in only 5.9% of studies. This imbalance suggests that the literature gives greater attention to broad risk-reduction narratives and ecosystem-service benefits than to measurable hydrological performance. As a result, it remains difficult to compare NBS effectiveness across studies, flood types, spatial scales, and intervention designs.

A further limitation concerns temporal performance and uncertainty. Approximately 61% of the reviewed studies rely on hydrological or hydraulic modelling frameworks, including SWMM, HEC-RAS, and MIKE FLOOD, to estimate NBS performance under different rainfall, climate, land-use, and urbanisation scenarios(Ahiablame et al., 2012; Eckart et al., 2017). These approaches are valuable for testing design alternatives and future conditions, and previous studies have shown that NBS performance can vary with rainfall intensity, spatial configuration, and intervention scale (Ruangpan et al., 2024; Schubert et al., 2017). However, modelled results remain sensitive to assumptions, parameterisation, rainfall inputs, spatial resolution, and the representation of vegetation and soil processes. Moreover, relatively few studies evaluate how NBS performance changes over time as vegetation matures, soils become compacted, sediment accumulates, maintenance regimes vary, and flood extremes intensify. The limited availability of long-term empirical monitoring therefore remains a major weakness, as also highlighted by Chausson et al. (2020) and Elmqvist et al. (2013).This creates a trade-off in performance assessment: while co-benefits are widely reported, they are not always evaluated alongside direct hydrological indicators.

3.5 Mechanisms through which NBS Influence Flood Risk

The reviewed studies consistently identify several hydrological and ecological mechanisms through which NBS influence flood hazards. One of the most widely documented mechanisms is increased infiltration and soil water storage. Urban green infrastructure interventions such as permeable pavements, bioswales, rain gardens, and vegetated surfaces enhance infiltration rates and reduce surface runoff volumes during rainfall events (Ahiablame et al., 2012; Bush et al., 2021). These processes delay runoff generation, reduce peak discharge, and lower pressure on conventional drainage systems.

Wetlands and floodplain restoration provide floodwater storage and attenuation benefits

(Lindenberger et al., 2025; Watson et al., 2016). By reconnecting rivers with floodplains or restoring wetland storage capacity, these systems can temporarily retain high flows and reduce downstream flood peaks. Vegetation-based systems also increase hydraulic roughness, slowing water movement across landscapes. Riparian vegetation, floodplain forests, and mangroves can reduce flow velocity and modify the propagation of flood waves (Dadson et al., 2017). In coastal settings, dense vegetation and complex root structures can attenuate wave energy and reduce storm-surge impacts, supporting findings from coastal wetland studies (Inácio et al., 2023).

Another important mechanism is hydrograph desynchronisation through distributed interventions. When NBS measures are implemented across multiple locations in a catchment, they can delay runoff generation from different sub-catchments and reduce the synchronisation of peak flows. This distributed effect can lower downstream flood peaks, particularly in urban drainage networks where runoff convergence is rapid (Dadson et al., 2017). This finding reinforces the importance of evaluating NBS not only as isolated interventions but also as components of wider catchment and infrastructure systems. Nevertheless, the effectiveness of NBS is highly context specific. Performance varies according to rainfall intensity, catchment size, soil permeability, antecedent moisture conditions, land availability, vegetation maturity, maintenance quality, storage capacity, and integration with grey infrastructure (Giordano et al., 2020). NBS may perform well during frequent low-to-moderate events but become less effective when storage capacity is exceeded or systems become saturated. Therefore, NBS should not be presented as universal replacements for conventional flood defences. Instead, they should be understood as adaptive components within multi-layered flood risk management systems.

Governance and institutional conditions also strongly influence NBS implementation. Fragmented responsibilities remain a major barrier, operating both horizontally and vertically (Griffiths et al., 2024). Horizontally, weak coordination between water management authorities, planning departments, environmental agencies, infrastructure providers, and landowners can make responsibilities for planning, funding, maintenance, and monitoring unclear (Schröder et al., 2025). Vertically, misalignment between national adaptation policies, regional catchment strategies, local planning controls, and site-level delivery capacity can limit the translation of broad NBS commitments into implemented projects. Land availability is another constraint, especially in dense urban areas where space for green infrastructure or floodplain reconnection is limited (Hankin et al., 2021). Financial barriers further reinforce these challenges because conventional funding mechanisms often favour grey infrastructure with easily defined costs and outputs, whereas NBS benefits are distributed across multiple sectors, beneficiaries, and timeframes. This can undervalue ecosystem-service benefits in cost–benefit assessment and weaken provision for long-term maintenance, despite evidence that NBS can generate resilience and wider environmental benefits (Ruangpan et al., 2024; Seddon et al., 2020).

A central implication of the reviewed evidence is that hybrid grey–green infrastructure systems may offer a practical pathway for integrating NBS into flood management, particularly where ecological measures alone are unlikely to provide sufficient protection during extreme events (Kim, 2024). Hybrid systems combine engineered structures with ecological processes, allowing NBS to manage frequent or moderate flood events while conventional infrastructure provides additional protection during larger or more hazardous events. However, this should be interpreted cautiously, as much of the evidence remains conceptual, model-based, or derived from case-specific applications. Differing perspectives exist regarding the scalability, reliability, cost-effectiveness, and maintenance requirements of hybrid systems. While some studies present grey–green integration as a means of improving flexibility, redundancy, and multifunctionality, others highlight trade-offs related to land availability, institutional coordination, long-term maintenance, uncertain performance under extreme or compound flooding, and the difficulty of balancing hydrological objectives with co-benefits such as biodiversity, recreation, and urban amenity. Therefore, hybrid systems should not be presented as universally superior solutions, but as context-dependent strategies whose effectiveness depends on design, scale, governance capacity, and local hydrological conditions.

3.6 POLICY IMPLICATIONS FOR MAINSTREAMING NBS IN FLOOD RISK MANAGEMENT

The synthesis of evidence indicates several policy-relevant implications for mainstreaming NBS in flood risk management. These should be interpreted as evidence-informed directions rather than universal prescriptions, as the strength of evidence varies across intervention types and flood contexts. First, relatively strong evidence suggests that NBS should be considered early in spatial planning, since land availability, landscape connectivity, and hydrological pathways strongly influence their feasibility and performance. Second, the literature provides moderate support for using broader appraisal methods, including ecosystem service valuation and multi-criteria decision analysis, because conventional cost–benefit approaches may overlook co-benefits such as biodiversity, carbon sequestration, water quality, and recreation. Third, strong evidence highlights the need for long-term monitoring to validate modelled outcomes and reduce uncertainty regarding real-world performance and maintenance. Finally, cross-sector governance coordination emerges as an important but more context-dependent implication, requiring further evidence across different institutional settings.

4. CONCLUSIONS

This systematic literature review examined the role of NBS in flood mitigation, focusing on their application across pluvial, riverine, and coastal flood contexts, their underlying hydrological mechanisms, and the governance conditions influencing implementation. Based on 136 peer-reviewed studies, the findings confirm a rapidly growing interest in NBS as sustainable and multifunctional approaches to flood risk management. The review shows that urban green infrastructure and low-impact development measures dominate the literature, particularly for pluvial flooding in urban areas. Wetland restoration, floodplain reconnection, and river restoration are more commonly associated with riverine flood management, while mangroves and other coastal ecosystems are frequently examined for coastal flood protection. Across these contexts, NBS reduce flood hazards through enhanced infiltration, increased water storage, vegetation-induced hydraulic roughness, and delayed runoff at catchment scale. However, the evidence base remains uneven. Current research is geographically biased, with limited representation from the Global South, despite these regions facing increasing flood exposure. The literature also relies heavily on modelling, composite indices, and pilot-scale assessments, while long-term empirical monitoring and direct hydrological validation remain limited. These gaps constrain confidence in the transferability and real-world performance of NBS. Thus, this review demonstrates that NBS can play a significant role in future flood mitigation when integrated into spatial planning, supported by multi-criteria evaluation, and coordinated through cross-sector governance. Advancing hybrid gray–green infrastructure and strengthening empirical evidence will be essential for mainstreaming NBS as credible, scalable, and context-sensitive flood mitigation strategies.

5. REFERENCES

Ahiablame, L. M., Engel, B. A., & Chaubey, I. (2012). Effectiveness of low impact development practices: literature review and suggestions for future research. *Water, Air, & Soil Pollution*, *223*(7), 4253–4273. https://doi.org/10.1007/s11270-012-1189-2

Bush, J., Ashley, G., Foster, B., & Hall, G. (2021). Integrating green infrastructure into urban planning: Developing Melbourne's green factor tool. *Urban Planning*, *6*(1), 20–31. https://doi.org/10.17645/up.v6i1.3515

Caroppi, G., Pugliese, F., Gerundo, C., De Paola, F., Stanganelli, M., Urciuoli, G., Nadim, F., Oen, A., Andrés, P., & Giugni, M. (2024). A comprehensive framework tool for performance assessment of NBS for hydro-meteorological risk management. *Journal of Environmental Planning and Management*, *67*(6), 1231–1257. https://doi.org/10.1080/09640568.2023.2166818

Chausson, A., Turner, B., Seddon, D., Chabaneix, N., Girardin, C. A. J., Kapos, V., Key, I., Roe, D., Smith, A., Woroniecki, S., & Seddon, N. (2020). Mapping the effectiveness of nature-based solutions for climate change adaptation. *Global Change Biology*, *26*(11), 6134–6155. https://doi.org/10.1111/gcb.15310

Dadson, S. J., Hall, J. W., Murgatroyd, A., Acreman, M., Bates, P., Beven, K., Heathwaite, L., Holden, J., Holman, I. P., Lane, S. N., O'Connell, E., Penning-Rowsell, E., Reynard, N., Sear, D., Thorne, C., & Wilby, R. (2017). A restatement of the natural science evidence concerning catchment-based 'natural' flood management in the UK. *Proceedings of the Royal Society A: Mathematical, Physical and Engineering Sciences*, *473*(2199), 20160706. https://doi.org/10.1098/rspa.2016.0706

Devi, N., Ganapathy, A., Silva, A. F. R., Vorogushyn, S., Apel, H., Kreibich, H., Oostwegel, L. J. N., Kuiry, S. N., & Sairam, N. (2025). Lost water bodies and a flooded city – Counterfactual scenarios of the extreme Chennai flood highlight the potential of nature-based solutions. *Urban Climate*, *61*, 102454. https://doi.org/10.1016/j.uclim.2025.102454

Eckart, K., McPhee, Z., & Bolisetti, T. (2017). Performance and implementation of low impact development – A review. *Science of The Total Environment*, *607–608*, 413–432. https://doi.org/10.1016/j.scitotenv.2017.06.254

Elmqvist, T., Goodness, J., Marcotullio, P. J., Parnell, S., Sendstad, M., Wilkinson, C., Fragkias, M., Güneralp, B., McDonald, R. I., Schewenius, M., & Seto, K. C. (2013). Urbanization, biodiversity and ecosystem services: Challenges and opportunities: A global assessment. In *Urbanization, Biodiversity and Ecosystem Services: Challenges and Opportunities: A Global Assessment*. Springer Netherlands. https://doi.org/10.1007/978-94-007-7088-1

Giordano, R., Pluchinotta, I., Pagano, A., Scrieciu, A., & Nanu, F. (2020). Enhancing nature-based solutions acceptance through stakeholders' engagement in co-benefits identification and trade-offs analysis. *Science of The Total Environment*, *713*, 136552. https://doi.org/10.1016/j.scitotenv.2020.136552

Griffiths, J., Borne, K. E., Semadeni-Davies, A., & Tanner, C. C. (2024). Selection, Planning, and Modelling of Nature-Based Solutions for Flood Mitigation. *Water*, *16*(19), 2802. https://doi.org/10.3390/w16192802

Hankin, B., Page, T., McShane, G., Chappell, N., Spray, C., Black, A., & Comins, L. (2021). How can we plan resilient systems of nature-based mitigation measures in larger catchments for flood risk reduction now and in the future? *Water Security*, *13*, 100091. https://doi.org/10.1016/j.wasec.2021.100091

Huang, R., Tian, Z., Fan, D., Ye, Q., Liu, Q., Kong, M., Wang, Y., Lyu, J., & Sun, L. (2026). Nature's double defense: How mangroves and intertidal topography shape coastal flood mitigation. *Ocean & Coastal Management*, *272*, 108004. https://doi.org/10.1016/j.ocecoaman.2025.108004

Iliadis, C., Glenis, V., & Kilsby, C. (2024). A cost-benefit 'source-receptor' framework for implementation of Blue-Green flood risk management. *Journal of Hydrology*, *634*, 131113. https://doi.org/10.1016/j.jhydrol.2024.131113

Inácio, M., Barboza, F. R., & Villoslada, M. (2023). The protection of coastal lagoons as a nature-based solution to mitigate coastal floods. *Current Opinion in Environmental Science & Health*, *34*, 100491. https://doi.org/10.1016/j.coesh.2023.100491

Intergovernmental Panel on Climate Change [IPCC]. (2022). *Climate Change 2022: Impacts, Adaptation and Vulnerability. Contribution of Working Group II to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change*. https://www.ipcc.ch/report/ar6/wg2/downloads/report/IPCC_AR6_WGII_FullReport.pdf

Kienzler, S., Kreibich, H., Müller, M., Pech, I., & Thieken, A. H. (2016). Assessment of flood loss model transferability considering changes in precaution of flood-affected residents in Germany . *3rd European Conference on Flood Risk Management (FLOODRISK 2016)*, 1–11. https://doi.org/10.1051/e3sconf/20160713002

Kim, K.-G. (2024). *Overview and Exploration of Nature-Based Flooding Solutions: The Green Transition* (pp. 59–75). https://doi.org/10.1007/978-3-031-50365-8_6

Lindenberger, A., Rauch, H. P., Kasak, K., Stelzhammer, M., & von der Thannen, M. (2025). Impact of various flood conditions on the CO2 ecosystem exchange as a component of floodplain grassland restoration. *Ecological Engineering*, *212*, 107489. https://doi.org/10.1016/j.ecoleng.2024.107489

Marino, M., Baptist, M. J., Alkharoubi, A. I. K., Nasca, S., Cavallaro, L., Foti, E., & Musumeci, R. E. (2025). Nature-based Solutions as Building Blocks for coastal flood risk reduction: a model-based ecosystem service assessment. *Scientific Reports*, *15*(1), 12070. https://doi.org/10.1038/s41598-025-95230-4

Oberthür, S., & Kelly, C. (2008). EU leadership in international climate policy: Achievements and challenges. *The International Spectator*, *43*(3), 35–50. https://doi.org/10.1080/03932720802280594

Petticrew, M., & Roberts, H. (2006). *Systematic Reviews in the Social Sciences*. Wiley. https://doi.org/10.1002/9780470754887

Ruangpan, L., Vojinovic, Z., Plavšić, J., Curran, A., Rosic, N., Pudar, R., Savic, D., & Brdjanovic, D. (2024). Economic assessment of nature-based solutions to reduce flood risk and enhance co-benefits. *Journal of Environmental Management*, *352*, 119985. https://doi.org/10.1016/j.jenvman.2023.119985

Sabut, A., Bhat, A. M., Tripathi, I. M., & Mohapatra, P. K. (2026). Optimizing Green Infrastructure for Urban Flood Mitigation Using the SWMM: A Case Study in Kozhikode, India. *Journal of Hydrologic Engineering*, *31*(2). https://doi.org/10.1061/JHYEFF.HEENG-6677

Schröder, P. T., Wübbelmann, T., & Kabisch, N. (2025). A scenario-based modelling approach to implementing nature-based solutions for flood risk mitigation in Hannover. *NPJ Urban Sustainability*, *6*(1), 21. https://doi.org/10.1038/s42949-025-00326-5

Schubert, J. E., Burns, M. J., Fletcher, T. D., & Sanders, B. F. (2017). A framework for the case-specific assessment of Green Infrastructure in mitigating urban flood hazards. *Advances in Water Resources*, *108*, 55–68. https://doi.org/10.1016/j.advwatres.2017.07.009

Seddon, N., Chausson, A., Berry, P., Girardin, C. A. J., Smith, A., & Turner, B. (2020). Understanding the value and limits of nature-based solutions to climate change and other global challenges. *Philosophical Transactions of the Royal Society B: Biological Sciences*, *375*(1794), 20190120. https://doi.org/10.1098/rstb.2019.0120

Watson, K. B., Ricketts, T., Galford, G., Polasky, S., & O'Niel-Dunne, J. (2016). Quantifying flood mitigation services: The economic value of Otter Creek wetlands and floodplains to Middlebury, VT. *Ecological Economics*, *130*, 16–24. https://doi.org/10.1016/j.ecolecon.2016.05.015

Wu, Y., Sun, J., Jun Xu, Y., Zhang, G., & Liu, T. (2022). Projection of future hydrometeorological extremes and wetland flood mitigation services with different global warming levels: A case study in the Nenjiang river basin. *Ecological Indicators*, *140*, 108987. https://doi.org/10.1016/j.ecolind.2022.108987