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Towards nature-positive engineering: nature-based solutions in attenuating coastal hydrometeorological hazards

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Abstract

Coastal and deltaic regions are highly vulnerable to hydrometeorological hazards such as storms, flooding, and extreme temperatures—risks that are intensifying under climate change. While hard engineering structures (e.g., levees, seawalls) remain widely used, they can be costly, ecologically disruptive, and may exacerbate hazard complexity. Nature-based solutions (NbS), including mangroves, salt marshes, and other coastal ecosystems, offer sustainable and often cost-effective alternatives or complementarities that can mitigate hazards while delivering ecological and societal co-benefits. However, their effectiveness is difficult to assess due to diverse methodological approaches, site-specific coastal dynamics, and inconsistent reporting indicators. This study synthesises the scientific evidence base on the effectiveness of NbS in reducing hydrometeorological hazards in coastal and deltaic environments and evaluates the robustness of methods used to assess their performance. A systematic review and meta-analysis of 383 peer-reviewed English-language articles published between 2008 and 2024 was conducted following Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) protocols and the PICO framework. Using an evaluation approach adapted from the Intergovernmental Panel on Climate Change, each study was assessed for evidence robustness, level of agreement, and overall confidence. The meta-analysis provides quantitative estimates of NbS effectiveness and highlights substantial uncertainties arising from ecological variability, methodological inconsistencies, and heterogeneity in hazard indicators (e.g., wave height, flow velocity, water level, temperature) and measurement units. Findings show that NbS effectiveness is highly context dependent

and influenced by site characteristics, ecological dimensions, system configuration, and hazard intensity. The study emphasises the need for standardised, hazard-specific indicators and greater use of integrated methodological approaches to strengthen the reliability and comparability of future assessments. It also identifies opportunities for advancing hybrid or nature-positive engineering solutions that combine NbS with conventional infrastructure to enhance coastal resilience.

Keywords: Nature-based solutions, performance evaluation, systematic review, level of confidence, nature-positive engineering.

1. Introduction

Nature-positive engineering is an emerging approach that integrates ecological principles into infrastructure design to enhance biodiversity, strengthen ecosystem services, and build climate resilience, while still meeting the functional requirements of traditional engineering (LRF, 2025; Wansbury, 2024). Recent policy developments and regulatory frameworks reflect a paradigm shift toward nature-based solutions (NbS), encouraging their adoption to achieve nature-positive outcomes (Bridges et al., 2024). These outcomes align with the global goal to *"halt and reverse nature loss by 2030 on a 2020 baseline, and achieve full recovery by 2050"* (NPI, 2023). Advancing a nature-positive future offers a wide range of benefits, including the restoration of lost biodiversity and enhanced capacity for climate change mitigation and adaptation (Wansbury, 2024).

Coastal and deltaic regions are characterised by dynamic interactions among river discharge, fluvial sediment input, and marine processes such as waves, tides, and coastal currents (Goodbred Jr and Saito, 2011). These regions support fertile soils, socio-ecologically valuable habitats, and economic activities including agriculture, trade, fisheries, energy production, and manufacturing. Approximately 500 million people—7% of the global population—reside on just 1% of the Earth's land area associated with deltas (Paszkowski et al., 2021). Despite their significance, deltaic and coastal areas are highly vulnerable to hydrometeorological hazards, defined as events triggered by atmospheric, hydrological, or oceanographic processes (UNDRR, 2017). Their vulnerability arises from low-lying topography, shallow riverbeds, subsidence, and direct exposure to oceanic disturbances (Ghosh et al., 2019; Syvitski, 2008; Vörösmarty et al., 2009). Between 1900 and 2023, hydrometeorological hazards—including storms, floods, droughts, and extreme temperatures—accounted for roughly 83% of global hazards, 73% of economic losses, and 76% of fatalities (Guha-Sapir et al., 2023; Lee et al., 2024). Anthropogenic climate change has intensified both the frequency and magnitude of these hazards, a trend projected to continue (Debele et al., 2019; Guerreiro et al., 2018). For example, Guerreiro et al. (2018) identified increasing heatwave days across 571 European cities under the RCP8.5 scenario, alongside expectations of worsening droughts in southern Europe and heightened river flooding in northern Europe.

Historically, hard engineering structures—such as levees, dykes, and seawalls—have been the dominant means of protecting coastal populations and assets (Adnan, 2020), with most global coastlines now incorporating some form of engineered intervention (Mamo et al., 2022). However, the limitations of such measures are well documented (Debele et al., 2019). While these structures reduce certain hazard probabilities (e.g., flood frequency) (Merz et al., 2010), their limitations are widely acknowledged. Hard infrastructure can increase residual risk, disrupt hydrological and geomorphological processes, require substantial capital investment, and contribute to long-term vulnerability. For instance, Di Baldassarre et al. (2017) demonstrated that societal responses to hydrological extremes can alter both the magnitude and spatial distribution of flood events. These interventions often disconnect floodplains from sediment flows, altering geomorphology and reducing ecological functionality (Gergel et al., 2002; Hupp et al., 2009; Morrison et al., 2018; Steinfeld and Kingsford, 2013). The "levee effect," first articulated by White (1942), illustrates how engineered measures may inadvertently increase societal exposure by fostering a false sense of security, ultimately creating infrastructure lock-ins and cycles of escalating investment (Di Baldassarre et al., 2013; Logan et al., 2018).

In recent years, NbS—such as mangroves, saltmarshes, coral reefs, and sand dunes—have emerged as cost-effective, sustainable, and adaptive alternatives or complements to traditional engineering. These nature-based measures can reduce hazard impacts by attenuating waves, stabilising shorelines, promoting sedimentation, or moderating climatic extremes (Cohen-Shacham et al., 2016; Debele et al., 2023; Gain et al., 2022; Kumar et al., 2020; Ou et al., 2022; Shah et al., 2023; Sowińska-Świerkosz and García, 2022). The concept of NbS was first introduced by the World Bank in 2008 (MacKinnon et al., 2008) and has evolved across multiple institutions. The International Union for Conservation of Nature (IUCN) defines NbS as *"…actions to protect, sustainably manage, and restore natural or modified ecosystems, that address societal challenges effectively and adaptively, simultaneously providing human well-being and biodiversity benefits"* (Cohen-Shacham et al., 2016). The European Commission (EC) similarly characterises NbS as *"…solutions that are inspired and supported by nature, which are cost-effective, simultaneously provide environmental, social and economic benefits and help build resilience"* (EC, 2015). NbS are increasingly central to global policy frameworks, including the Sendai Framework for Disaster Risk Reduction, the United Nations Sustainable Development Goals (SDGs), the Paris Climate Agreement, Intergovernmental Panel on Climate Change (IPCC) Sixth Assessment Report, the European Union Nature Restoration Regulation, and the UN Decade on Ecosystem Restoration (EU, 2024; IPCC, 2022; Renaud et al., 2016; UN, 2021), and are now viewed as essential components of climate-resilient infrastructure portfolios (Zuniga et al., 2020).

However, conceptual and operational ambiguities limit the consistency and scalability of NbS implementation. There remains no universal typology for NbS, and existing classification systems vary widely across disciplinary and institutional contexts (Nehren et al., 2023; Sowińska-Świerkosz and García, 2022). For example, the IUCN outlines eight eligibility criteria for identifying NbS interventions (Cohen-Shacham et al., 2016), whereas the EC applies a set of five screening questions to determine whether an intervention qualifies as NbS (EC, 2015). The United Nations Office for Disaster

Risk Reduction (UNDRR) organises NbS into four categories related to climate adaptation, climate mitigation, disaster risk reduction, and environmental management (UNDRR, 2021). Academic reviews also propose varied classification frameworks. Debele et al. (2019) reclassified 24 NbS types into green, blue, and hybrid categories, while Castellar et al. (2021) distinguished between NbS units (stand-alone green technologies) and NbS interventions (actions applied to ecosystems). Martin et al. (2020) introduced a three-tiered typology based on risk, spatial scale, co-benefits, and potential disservices. Nehren et al. (2023) further advanced NbS classification by incorporating five attributes—approach, landscape unit, hazard type, ecosystem functions, and specific measures.

The methods used to evaluate NbS effectiveness are similarly diverse. Case studies employ numerical modelling (Al-Attabi et al., 2023; Chen et al., 2024; De Dominicis et al., 2023; Fairchild et al., 2021; Toth et al., 2023; Unguendoli et al., 2023; van Zelst et al., 2021), laboratory experiments (Möller et al., 2014; Türker et al., 2019; Van Dang et al., 2023; van Veelen et al., 2021), geospatial analytics (Adnan et al., 2020; Atmaja et al., 2024; Van Coppenolle et al., 2018), cost-benefit analyses (Hynes et al., 2022; Karanja and Saito, 2018; Narayan et al., 2016; Reguero et al., 2018), multi-criteria decision-making (Lu et al., 2023; Qin et al., 2024a), statistical analyses (Anderson et al., 2022; Costanza et al., 2008; Das and Vincent, 2009), and qualitative approaches (Bakhshianlamouki et al., 2023; Van Hespen et al., 2023; Warner et al., 2018). Kumar et al. (2021) categorised these methods into empirical, conceptual, and numerical approaches but highlighted the lack of standardisation across studies evaluating NbS for hazards such as flooding, droughts, heatwaves, landslides, and storm surges.

Despite the rapid growth of NbS research, the evidence base remains fragmented. Most case studies examine individual NbS interventions aimed at mitigating a single hazard—for example, the use of mangroves or coral reefs for wave attenuation (Mancheño et al., 2024; Quataert et al., 2015), or urban green–blue infrastructure for reducing heat stress (Augusto et al., 2020; Nardella et al., 2024). These studies employ widely varying metrics and performance indicators (e.g., wave height reduction, temperature decrease, floodwater retention), making cross-comparison challenging (Kumar et al., 2021). Existing review articles (Chausson et al., 2020; Debele et al., 2019; Debele et al., 2023; Kumar et al., 2021; Sudmeier-Rieux et al., 2021) provide systematic qualitative syntheses of NbS performance but rarely offer quantitative assessments of effectiveness. The few reviews that do quantify NbS impacts tend to focus on specific hazards or narrowly defined outcomes. For example, Narayan et al. (2016) performed a cost–benefit assessment of coastal habitats in reducing wave heights, while Ferrario et al. (2024) and Prado et al. (2024) measured NbS effects on flood-related indicators (e.g., runoff, peak flow) and extreme temperature metrics (e.g., urban heat island intensity, surface temperature, thermal comfort). Although these studies provide valuable insights, they capture only a segment of the broad spectrum of hydrometeorological hazard indicators needed to comprehensively assess NbS effectiveness.

As a result, despite their recognised benefits, NbS are not yet widely adopted as primary measures for managing hydrometeorological hazards (Kumar et al., 2020; Vojinovic et al., 2021). Several barriers include limited science-based understanding of NbS effectiveness (Sudmeier-Rieux et al., 2021), lack of standardised hazard-specific classifications (Martin et al., 2020), inconsistent evaluation methodologies (Kumar et al., 2021), and the absence of robust and comparable performance indicators, metrics, and validation frameworks (Kabisch et al., 2016; Kumar et al., 2021). Moreover, the geographic variability of NbS effectiveness—particularly across different climatic and geomorphological contexts—remains poorly understood (Narayan et al., 2016). Although the existing literature demonstrates considerable potential for NbS to mitigate hydrometeorological hazards, few studies explicitly evaluate these solutions within a nature-positive engineering framework or directly compare them with conventional hard structures (Barbour et al., 2022; Du et al., 2020; Stark et al., 2016). Notably, there remains a dearth of studies assessing NbS as complementary or substitute measures capable of achieving equivalent or superior hazard mitigation outcomes relative to traditional engineering. This gap constrains the capacity of planners and engineers to effectively select, integrate, and sequence NbS and hard measures within hybrid or transitional strategies essential for long-term climate resilience (Jordan and Fröhle, 2022).

To address these critical gaps in the scientific evidence on NbS effectiveness for hydrometeorological hazard mitigation in coastal and deltaic regions, this study poses two primary research questions: (1) What is the current state of evidence on the effectiveness of NbS in mitigating hydrometeorological hazards in coastal and deltaic regions? (2) How robust is the existing evidence base, and to what extent does the evidence agree on the effectiveness of NbS in mitigating hydrometeorological hazards? To answer these questions, this study conducts a state-of-the-art systematic review and meta-analysis of peer-reviewed, English-language articles published between 2008 and 2024. The review systematically documents and critically evaluates reported effectiveness across a wide range of NbS measures and indicators, generating new evidence to inform nature-positive engineering, climate resilience planning, and evidence-based policy formulation.

2. Methodology

2.1. Systematic literature review

2.1.1. Review framework and search protocol

This study conducted a systematic literature review following the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) protocol (Liberati et al., 2009) and the PICO framework (Population(s), Intervention(s), Comparator(s) and Outcome(s)) developed by the Collaboration for Environmental Evidence (CEE, 2022). The objective was to identify and analyse research articles related to NbS and their applications in mitigating various hydrometeorological hazards. The literature search was performed across four major scientific databases: Scopus, Web of Science (WoS), GeoRef, and PubMed. Various keyword combinations were applied under four thematic categories: hazards, NbS, methods, and location. The keywords were carefully selected to address two primary research questions of this study. Table S1 (Supplementary Data A) provides different combinations of the keywords used for the literature search.

NbS is a broad and multidisciplinary concept encompassing a wide range of strategies. Various typologies exist for classifying NbS (Nehren et al., 2023). A total of 22 different search terms were considered. The terms selected in this study were based on different NbS measures found in UNDRR (2021). These measures are linked to five ecosystem types. Selected NbS measures include mangroves, salt marsh or other coastal wetlands, restoration of reefs, managed realignment, integrated coastal zone management, sand management, forest conservation, river watershed management, agrobiodiversity, rainwater harvesting, urban green areas, urban wetlands, and sustainable drainage systems. Specific search terms related to these categories were also derived from existing literature (Castellar et al., 2021; Debele et al., 2019; Gain et al., 2022; Martin et al., 2020; Nehren et al., 2023). The search strategy targeted events associated with storms, floods, extreme temperatures, droughts, and extreme precipitation, but each category was operationalized through specific, well-defined search terms rather than broad hazard labels. Table S1 (Supplementary Data A) includes specific terms related to hazards.

The search also included terms related to different methodological approaches used to assess the effectiveness of NbS. These included numerical models, empirical approaches, geospatial approaches, statistical approaches, laboratory experiments, qualitative approaches, cost-benefit analysis, and vulnerability or risk assessment (Kumar et al., 2021; Möller et al., 2014; Mudashiru et al., 2021; Narayan et al., 2016).

All searches were restricted to studies conducted in coastal and deltaic environments, defined as areas located within or directly influenced by the land–sea interface, including coastal cities, peri-urban coastal zones, estuaries, bays, lagoons, deltas, and low-lying coastal plains. The literature search was conducted in September 2025. Boolean operators "AND" and "OR" were utilised to refine the search across different keyword combinations. The full search strings used for each of the three databases are provided in Table S2 (Supplementary Data A).

2.1.2. Eligibility criteria

The selection of articles was primarily guided by the PICO framework (CEE, 2022), which has been widely applied in recent systematic reviews to establish eligibility criteria (de Lemos et al., 2024; Ferrario et al., 2024; Sudmeier-Rieux et al., 2021). Using this framework, the following inclusion criteria were defined:

- **Population:** The study must address exposure to hydrometeorological hazards, including impacts on populations, assets, infrastructure, or coastal areas.
- **Intervention:** The study must focus on NbS as interventions for mitigating hydrometeorological hazards in coastal and deltaic regions.
- **Comparator:** The study must compare NbS interventions with either a baseline scenario (e.g., "as-is" or do-nothing approaches) or other intervention types.
- **Outcome**: The study must assess the effectiveness of NbS in reducing hazard impacts or minimising risk exposure.

Beyond the PICO criteria, additional inclusion parameters were established. Only peer-reviewed articles, published in English between 1 January 2008 and 31 December 2024, were considered. This time frame was chosen because the concept of NbS was first introduced by the World Bank in 2008 (MacKinnon et al., 2008). Review papers, conference proceedings, opinion pieces, perspectives, and book chapters were excluded from the selection. A comprehensive list of inclusion and exclusion criteria is provided in Table 1.

Table 1. Inclusion and exclusion criteria used to select studies. The criteria were identified by adopting and modifying the guidelines from the CEE (2022).

Question elements	**Inclusion criteria**	**Exclusion criteria**
Population	▪ Studies addressing elements exposed to hydrometeorological hazards, including populations, infrastructure, assets, and coastal or deltaic areas. ▪ Studies focusing on hydrometeorological hazards such as storms, floods, extreme temperatures, droughts, and extreme precipitation.	▪ Evidence related to NbS interventions that do not address any hydrometeorological hazards. ▪ Evidence concerning hydrometeorological hazards without any connection to NbS interventions. ▪ Studies discussing NbS in relation to animal, bird, plant species, or marine habitats. ▪ Geological studies on hazards such as earthquakes and landslides. ▪ Studies on man-made hazards.
Intervention	▪ Studies evaluating NbS interventions aimed at reducing the impacts of hydrometeorological hazards.	▪ Studies examining the impact of hydrometeorological hazards on NbS interventions (e.g., the effects of storms on mangroves). ▪ Studies that do not assess NbS effectiveness in mitigating hydrometeorological hazards.
Comparator	▪ Studies comparing NbS interventions with baseline scenarios ("as is" or do-nothing approaches) or alternative intervention strategies.	▪ None
Methodology	▪ Studies employing NbS evaluation methods.	▪ Studies lacking NbS evaluation methods.

Location	▪ Studies conducted in coastal or deltaic regions.	▪ Studies not related to coastal or deltaic regions.
Outcomes	▪ Studies measuring the extent of NbS impacts on hydrometeorological hazards.	▪ Studies that do not assess the impacts of NbS on hydrometeorological hazards.
Study	▪ Peer-reviewed articles published in English between 1 January 2008 and 31 December 2024.	▪ Articles published before 1 January 2008 or after 31 December 2024. ▪ Articles in languages other than English. ▪ Review papers, conference proceedings, opinion pieces, perspectives, and book chapters.

2.1.3. Screening process

The screening process of the article was conducted following the PRISMA protocol. Figure S1 (Supplementary Data A) provides an overview of the article screening process, detailing the number of articles reviewed at each stage. The initial search retrieved 4,012 articles from Scopus (*n = 1,649*), WoS (*n = 1,327*), GeoRef (*n = 961*) and PubMed (*n = 75*). After removing 1,111 duplicate records, 2,901 articles proceeded to a two-stage screening process. In the first stage, the titles, abstracts, and keywords of the articles were screened based on the predefined inclusion and exclusion criteria (Table 1). At this stage, 2,500 records were excluded for failing to meet the criteria. The remaining 401 articles and two additional articles identified through snowballing (i.e., references obtained during the initial screening) advanced to full-text evaluation. Following a detailed full-text review, 20 more articles were excluded for three major reasons: (1) review articles, and/or (2) did not evaluate the impact of NbS, and/or (3) unrelated to hydrometeorological hazards. These aspects were not evident in the title, abstract, or keywords, necessitating exclusion at this stage. Using this approach, a total of 383 articles were selected for evaluation and analysis.

2.2. Data extraction and coding

Bibliographic information was recorded for each of the retained studies, and data were extracted on the various aspects as summarised in Table 2. The extracted data facilitated both qualitative and quantitative analyses, allowing for a comprehensive assessment of the effectiveness of NbS measures in mitigating hydrometeorological hazards. After extracting the data, different variables were recoded to facilitate the analysis. For instance, specific NbS terms found in the literature were grouped under 13 NbS measures. Hazard-related terms were grouped under hydrological, meteorological, and hydrometeorological (if both hydrological and meteorological hazards were considered) categories following the EM-DAT classification system (Table 2).

Table 2. Summary of extracted variables and associated coding strategy. Bibliographic information of 383 articles is provided in Supplementary Data B.

Variables	Description	Analysis used
Publication year	Year in which the article was published.	Descriptive statistics
NbS measures	Specific NbS interventions examined in the article. Multiple responses were recorded. Table S3 (Supplementary Data A) provides further details on different NbS measures.	Meta-analysis, descriptive statistics, confidence level analysis
Hazard type	Hydrometeorological hazards examined in the article, including hydrological and meteorological hazards. Table S4 (Supplementary Data A) provides further details on each of these categories.	Descriptive statistics
Role of NbS	NbS interventions were categorised into three roles: alternative, compliment, safeguard. Alternative refers to NbS used in place of traditional structural measures. Complement refers to NbS deployed alongside structural measures to enhance overall system effectiveness. Safeguard denotes NbS implemented for hazard protection without explicit reference to, or integration with, structural measures (Zuniga et al., 2020).	Descriptive statistics
Case study type	Classification of case studies into: (1) real-world studies, and (2) hypothetical studies (e.g., laboratory experiments).	Descriptive statistics
Methods	Methods used in the study. Multiple responses were recorded based on the method categories listed in Table S1 (Supplementary Data A).	Descriptive statistics, confidence level analysis
Country	Country or countries where the case study was conducted. Multiple responses were recorded when applicable. For hypothetical studies, “No country” was recorded.	Descriptive statistics
Effect indicators	Hazard-related indicators used to evaluate NbS effectiveness (e.g., wave height, flow velocity). Studies without measurable hazard indicators (primarily qualitative studies) were recorded as “No indicator.”	Meta-analysis
Effect size	Magnitude of change (reduction or increase) in effect indicators resulting from NbS interventions.	Meta-analysis

Effect unit	Units used to express each effect indicator (e.g., percent reduction, metres, degree Celsius (°C)).	Meta-analysis
Validation	Indicates whether a study validated its results. Recorded as Yes/No.	Descriptive statistics, confidence level analysis
Validation results	Validation metrics reported (e.g., root mean squared error, coefficient of determination (R^2)).	Meta-analysis, confidence level analysis
Agreement	Degree of consistency in the article's findings regarding the effectiveness of NbS in mitigating hydrometeorological hazards in coastal or deltaic regions. Articles were grouped into *agreement*, *inconclusive*, and *non-agreement*, assigned scores of 1, 2, and 3, respectively.	Descriptive statistics, confidence level analysis
Robustness	Robustness refers to the overall quality, reliability, and strength of evidence presented in each study. Articles were categorised as *low*, *medium*, or *robust* based on multiple criteria, including the clarity of mechanistic understanding, strength of theoretical underpinning, availability and quality of data, suitability of modelling approaches, presence of validation, and expert assessment. The detailed procedure for assigning robustness levels is outlined in Section 2.3.1.	Descriptive statistics, confidence level analysis

2.3. Data analyses

2.3.1. Assessing level of confidence

To examine the scientific evidence on the effectiveness of NbS in mitigating hydrometeorological hazards and the assessment methods used, this study used an evaluation framework based on the Intergovernmental Panel on Climate Change (IPCC) AR5 guidance note on the consistent treatment of uncertainties (Mastrandrea et al., 2010; Mastrandrea et al., 2011). As explained by Sudmeier-Rieux et al. (2021), the evaluation framework comprised of three steps:

a) Robustness of evidence

A combination of qualitative and quantitative approaches was applied to score robustness of evidence in each article. First, a multi-metric scoring approach was followed. The data extraction stage extracted various metrics used to validate the results, including root mean square error (RMSE), mean absolute error (MAE), mean bias error (MBE), absolute Bias, reported R^2/NSE/kappa statistic/skill, Brier Skill

Score (BSS), Scatter Index (SI/SCI), and *p*-values. Two complementary scoring approaches were applied: (i) a quantile-based approach, in which study-specific metric values were classified into low, medium, or high robustness based on the 33rd and 67th percentiles across all studies, and (ii) an absolute-threshold approach for percentage-based metrics (e.g., RMSE%), assigning scores 1–3 according to predefined cutoffs (e.g., low 30%, medium 10%). For each study, the maximum score across all available metrics was taken as the final robustness value. Studies with missing metrics were assessed individually. For instance, Xu et al. (2023) compared modelled wave heights with measured data, and found good agreement between them. Although no validation metric was reported, the agreement between model and observation was deemed to be robust. However, if no attempt to validate was made, the information was judged to be low in robustness (Mastrandrea et al., 2011; Sudmeier-Rieux et al., 2021).

b) Level of agreement

This step assessed whether the reviewed articles provided consistent evidence regarding the effectiveness of NbS in mitigating hydrometeorological hazards in coastal or deltaic regions. Articles were categorised into three groups: agreement, inconclusive, and non-agreement, with assigned scores of 1, 2, and 3, respectively.

- Agreement indicated strong and consistent evidence supporting NbS effectiveness. For instance, De Dominicis et al. (2023) found that a 600 m patch of mangroves could provide a surge attenuation up to 1.4 m.
- Inconclusive meant that the findings varied, with studies showing mixed results regarding NbS performance. For example, Zhao and Chen (2016) found that the presence of vegetation reduced water level, while increasing flow velocity, on average.
- Non-agreement suggested that the studies did not support the effectiveness of NbS in mitigating coastal hydrometeorological hazards. For instance, French (2008) reported that managed realignment increase peak velocity and discharge by up to 35% and 32%, respectively, concluding that such measure could be questionable in estuarine contexts.

c) Level of confidence

The final step involved evaluating the overall level of confidence in the findings. It provides a qualitative synthesis of the evaluation of evidence and agreement in one metric (Mastrandrea et al., 2010; Mastrandrea et al., 2011). This was determined by combining the robustness and agreement scores for each article. Therefore, the level of evidence scores were plotted against the level of agreement. The outcomes were categorised into nine confidence level. Figure S3 (Supplementary Data A) shows a matrix of the levels of confidence based on combinations of evidence and agreement.

2.3.2. Meta-analyses

A quantitative synthesis was performed for studies reporting continuous effect sizes of NbS on hydrometeorological hazard indicators. These indicators included percentage reduction (%), absolute changes in physical parameters (e.g., surge height or flood depth in meters), temperature change (°C), and in some cases monetary losses (million USD). Because studies reported effects using different units and measurement approaches, separate meta-analyses were conducted for each unit category to ensure conceptual and statistical consistency.

Random-effects models were fitted using the restricted maximum likelihood (REML) estimator to account for variability in true effects across studies (Borenstein et al., 2010). This approach is appropriate given the large, expected heterogeneity arising from differences in ecosystem settings, hazard types, modelling frameworks, and data sources. In several cases, primary studies did not report sampling variances or standard errors. When this occurred, approximate variances were derived from the dispersion of observed effect sizes within the dataset, following a conservative approach that assigns equal variance to studies with missing information. Although this procedure increases uncertainty in heterogeneity estimates, it allows inclusion of a broader evidence base while maintaining transparency.

Influential data points were identified using Cook's distance, and sensitivity analyses were performed by comparing models before and after removing outliers. Observations with Cook's distance greater than 0.5 were treated as influential and removed from subsequent analyses (Cook and Weisberg, 1982). Forest plots were produced to visualize individual study estimates and pooled effects with 95% confidence intervals. Between-study heterogeneity was evaluated using the I^2 statistic and the between-study variance (τ^2), as provided by the metafor R package (Viechtbauer, 2010).

To compare NbS strategies, the meta-analysis results were further examined by grouping effect sizes according to NbS categories and the indicators they influenced. This allowed assessment of how different NbS measures perform across multiple hazard-related metrics and units (e.g., % reduction, meters, °C, monetary units, or % increase), providing a comprehensive evaluation of their protective effectiveness.

3. Results

3.1. Identified case studies and their spatial distributions

Out of the 383 articles, the majority (86%; $n = 328$) focused on real-world case studies, while the remaining were hypothetical or conceptual studies. In total, these articles included 341 real-world case studies (as some articles included multiple case studies) across 60 countries. The United States had the highest number of case studies ($n = 76$), accounting for 22% of the total. This was followed by China ($n = 37$), the Netherlands ($n = 21$), the United Kingdom ($n = 18$), and Australia ($n = 16$), with the remaining countries having 173 case studies (Figure 1a).

336 A notable upward trend in research activity was observed over time. As shown in Figure 1b, studies on the effectiveness of NbS in mitigating hydrometeorological hazards have increased since 2008, following the introduction of the NbS concept by the World Bank (MacKinnon et al., 2008). Notably, approximately 69% (*n = 265*) of the selected articles were published since 2020.

340 There was a clear spatial disparity in the distribution of case studies across continents. Asia accounted for the highest proportion of studies (31%), followed closely by North America (29%) and Europe (28%). In contrast, Africa was the least represented, with only six case studies identified (Figure 1d). Further analysis examined case study distribution based on the income levels of countries. The majority (60%; *n = 205*) were conducted in high-income countries, particularly those classified as members of the Organisation for Economic Co-operation and Development (OECD). Upper middle-income countries accounted for 19% (*n = 64*) of case studies, while low-income countries hosted the fewest (4%; *n = 13*), with the majority of these conducted in Bangladesh (*n = 12*) (Figure 1e).

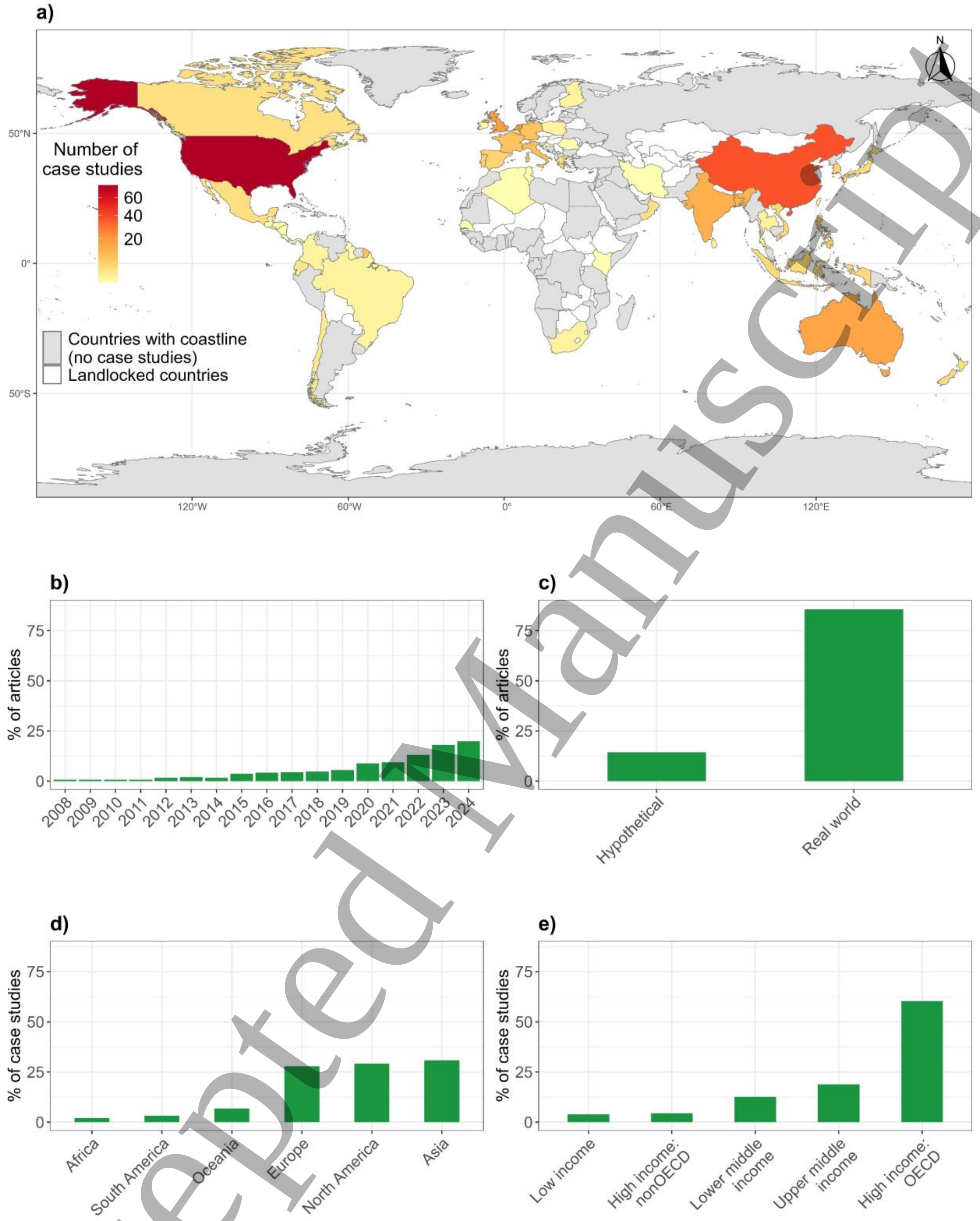

Figure 1. Overview of the articles analysed in this study. a) Geographical distribution of the case studies, with continuous colours representing countries with coastline where case studies were conducted, and grey indicating no case studies found; b) Year-wise publication trend; c) Types of case studies (hypothetical and real-word); d) Distribution of case studies by continent; and e) Distribution of case studies by income groups of the countries.

3.2. NbS interventions in managing hydrometeorological hazards

3.2.1. NbS interventions

Existing studies examined a wide range of NbS measures to assess their effectiveness (Figure 2, Table S3 (Supplementary Data A)). Salt marshes and other coastal wetlands represented the largest share of cases (21%), followed by mangroves (17%) and forest conservation measures (16%), which include vegetation, swamp forests, and natural habitats. In contrast, only a single study evaluated the effectiveness of rainwater harvesting. Figure S2a (Supplementary Data A) shows the distribution of cases across different NbS types.

This study also assessed the functional role of NbS in the reviewed literature. NbS were predominantly implemented as safeguarding measures in coastal and deltaic regions, accounting for 73% of the 383 articles. Additionally, 19% of studies examined NbS as complementary measures alongside hard engineering structures, while 8% considered them as alternative measures (Figure S2b, Supplementary Data A).

3.2.2. Hydrometeorological hazards

Hydrological hazards (e.g., floods, wave action, surge) were the most common, representing 86% ($n = 330$) of all cases. Meteorological hazards, including extreme temperatures, heatwaves, strong winds, and meteorological droughts, accounted for 9%. The remaining 5% of articles assessed both hazard types (Figure S2c, Supplementary Data A). NbS measures such as salt marshes, mangroves, forest conservation, reef restoration, sand management, and managed realignment were primarily applied to hydrological hazards, whereas NbS related to urban ecosystems—particularly urban green areas—were mainly tested for meteorological hazards (Figure 2).

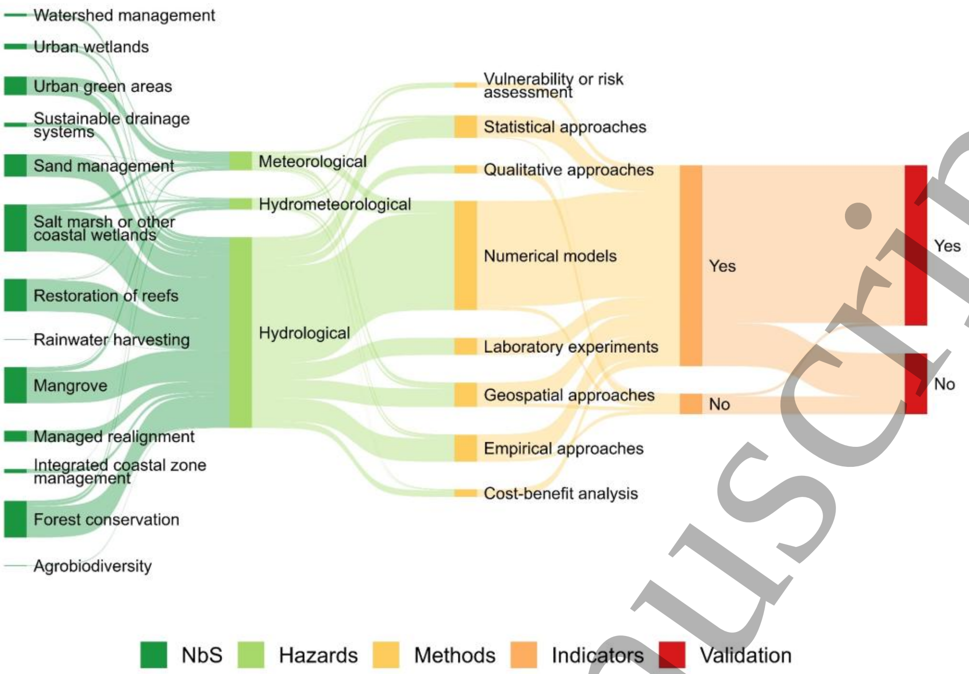

Figure 2. Sankey diagram showing the interactions among NbS measures, hydrometeorological hazards, methodological approaches, use of indicators, and validation status. Coloured bands represent sub-categories within each group, highlighting the connections and flow of relationships across different dimensions.

3.2.3. Methods to evaluate the impacts of NbS

After identifying relevant NbS measures, this study evaluated the strengths and limitations of methodological approaches used to assess their hazard-mitigation performance. Numerical modelling was the most widely applied method, constituting 51% of all approaches. Empirical approaches accounted for 11.5%, followed by geospatial (11%), statistical (9.5%), and laboratory-based methods (9%). Cost–benefit analyses, qualitative methods, and vulnerability or risk assessments were less common (3%, 3%, and 2%, respectively) (Figure 2, Figure S2e (Supplementary Data A)). Hydrological studies predominantly relied on numerical modelling, followed by empirical, geospatial, statistical, and laboratory approaches. Numerical models were also frequently used in meteorological studies. A comprehensive list of modelling approaches identified is provided in Table S8 (Supplementary Data A).

3.2.4. Indicators for assessing NbS interventions

Indicators play a key role in quantifying the effectiveness of NbS interventions. Approximately 91% of the articles used at least one indicator, whereas 9% did not employ any specific metrics (Figure 2, Figure S2d (Supplementary Data A)). In total, 44 unique indicators were identified (Table S5, Supplementary Data A). Wave height was the most frequently used indicator (24.4%), followed by water level (15.7%), economic damage (8%), flood extent (7%), and flow velocity (5.4%). Meteorological studies primarily used temperature as an indicator, which accounted for 5.2% of all cases.

3.3. Level of confidence in NbS interventions and methods used

As outlined in Section 2.3.1, the level of confidence in each article was assessed using robustness and agreement criteria. Validation of methods was a key factor in determining robustness. Overall, 71.5% of the reviewed articles reported some form of validation (Figure 2, Figure S2f (Supplementary Data A)).

With respect to specific NbS interventions, studies on salt marshes or other coastal wetlands exhibited the highest number of cases with robust evidence, followed by those focused on reefs, mangroves, and forest conservation (Figure 3a). Models used in these studies were generally validated against observational data and demonstrated good levels of agreement. In terms of agreement alone, mangrove-related studies showed the highest number of cases, followed by salt marshes, reefs, and forest conservation (Figure 3b). When plotting robustness against agreement, only urban wetlands reached a "very high" confidence level. Agrobiodiversity and sustainable drainage systems demonstrated medium confidence, while the remaining 10 NbS measures showed high confidence (Figure 3c).

Confidence levels also varied across methodological approaches. As shown in Figure 3d, none of the methods achieved very high confidence. Five approaches—numerical modelling, laboratory experiments, vulnerability or risk assessments, empirical approaches, and statistical approaches—fell within the high-confidence category. Studies using cost–benefit analyses or geospatial approaches were classified as medium confidence, while qualitative approaches showed low–medium confidence.

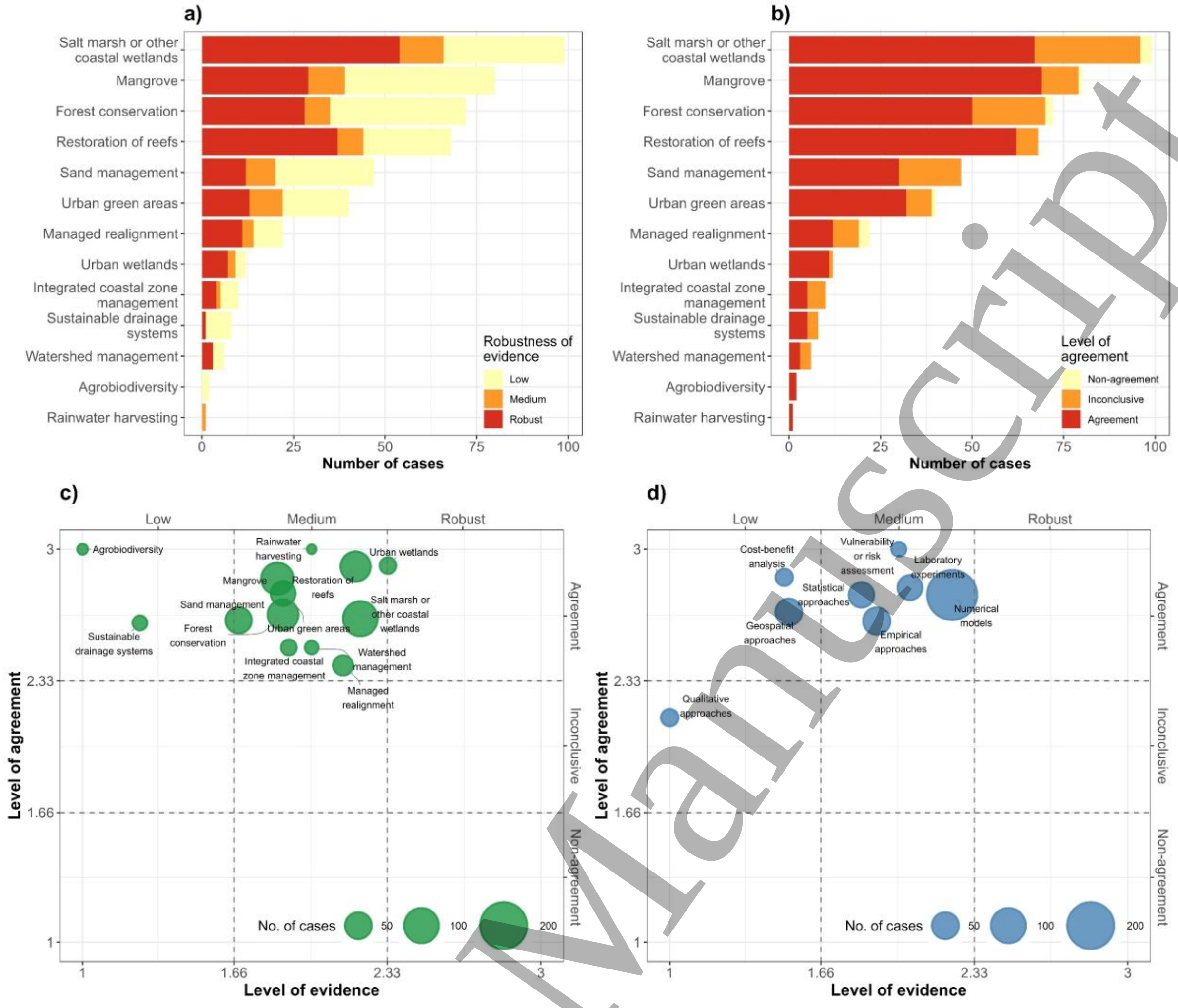

Figure 3. Level of confidence in NbS for attenuating hydrometeorological hazards. a) Number of reviewed articles categorised by the robustness of evidence for each NbS measures; b) Number of reviewed articles categorised by the level of agreement for each NbS measures; c) Average confidence levels across different NbS measures; and d) Average confidence levels across different methodological approaches. To aid interpretation of panels c) and d), a confidence matrix based on combinations of evidence and agreement levels is provided in Figure S3 (Supplementary Data A).

3.4. Effectiveness of NbS measures

3.4.1. Degree of effectiveness

Among the 383 articles, quantitative information on NbS effects was found in 241 articles. Across the 44 indicators identified (see Section 3.2.4), eight different units were used to express effectiveness: percentage reduction, degrees Celsius (°C), metres (m), monetary value (USD), cubic metres (m^3), fatalities, percentage increase, and metres per second (m/s). Percentage reduction was the most common, applied in 73% of cases. Figure 4 presents the mean percentage reduction achieved by different NbS measures across various indicators. Overall, mean effects ranged from a 9% reduction in water levels by implementing managed realignment to an 88.5% reduction in eroded volume from reef restoration. Most reported effects were related to hydrological hazard mitigation. Meteorological studies reported an average 21% reduction in temperature for urban green areas. However, this was based on a single study as most of the meteorological studies used actual temperature reduction (in °C) as an indicator.

Twenty-four studies reported the effects of NbS in reducing surge height, water level, or wave height in metres. Sand management (e.g., dunes) showed the highest mean surge-height reduction of 3.4 m, followed by mangroves at 1.4 m. Reef restoration yielded the highest mean reductions for both water level (1.9 m) and wave height (1.4 m) (Figure S4, Supplementary Data A). Fifteen articles reported temperature reduction outcomes—primarily for urban green areas and forest conservation—with an average reduction of 1.55 °C (Figure S5, Supplementary Data A). Twelve studies used monetary units (USD) to assess coastal protection, economic damage reduction, and related benefits across six NbS measures (Figure S6, Supplementary Data A). Six studies reported percentage increases in benefit–cost (BC) ratio, economic benefits, housing prices, resilience, or tidal prism linked to five NbS measures (Figure S7, Supplementary Data A).

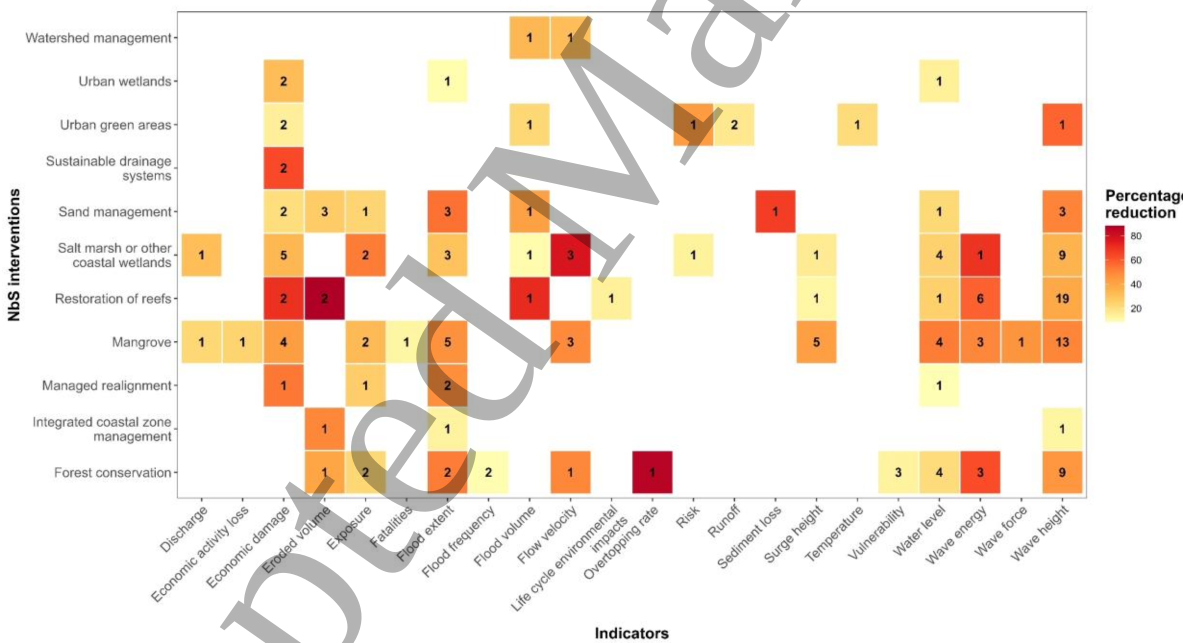

Figure 4. Mean percentage reduction in hydrometeorological hazard indicators achieved by different NbS interventions. Each cell reports the number of studies evaluating a given NbS–indicator combination.

3.4.2. Uncertainties in the estimates

The meta-analyses revealed substantial uncertainty in the estimated protective effects of different NbS measures against hydrological hazards. Figure 5 summarises the mean percentage reduction achieved by salt marshes or other coastal wetlands and by mangroves. In both cases, the random-effects models indicated varying levels of heterogeneity (I^2) and between-study variance (τ^2), depending on the indicator (Tables S6–S7, Supplementary Data A). For salt marshes and other coastal wetlands, I^2 ranged from moderate (36.2% for flow velocity) to substantial (73.8% for exposure). Mangrove-related estimates showed considerably higher heterogeneity, with I^2 values ranging from 70.4% (wave height) to 91.4% (water level). These levels of dispersion suggest that observed variation largely reflects real differences in study conditions rather than random sampling error.

Such variability likely arises from ecological and geomorphological differences among sites, variation in vegetation structure and maturity, hydrodynamic contrasts, differences in physical attributes such as mangrove-belt width, and inconsistencies in indicator measurement and reporting. Consequently, pooled effect sizes should be interpreted as broad central estimates across highly diverse systems rather than precise or universally transferable values. While the REML estimator effectively accommodates this variability, the wide confidence intervals and elevated τ^2 values underscore the persistent uncertainty surrounding the magnitude of the risk-reduction benefits provided by these NbS. Additional forest plots for other NbS types are presented in Figures S8–S13 (Supplementary Data A). Studies assessing urban green areas for meteorological hazard mitigation (e.g., temperature reduction) also showed high uncertainty, with an I^2 value of 76.7% (Figure S14, Supplementary Data A).

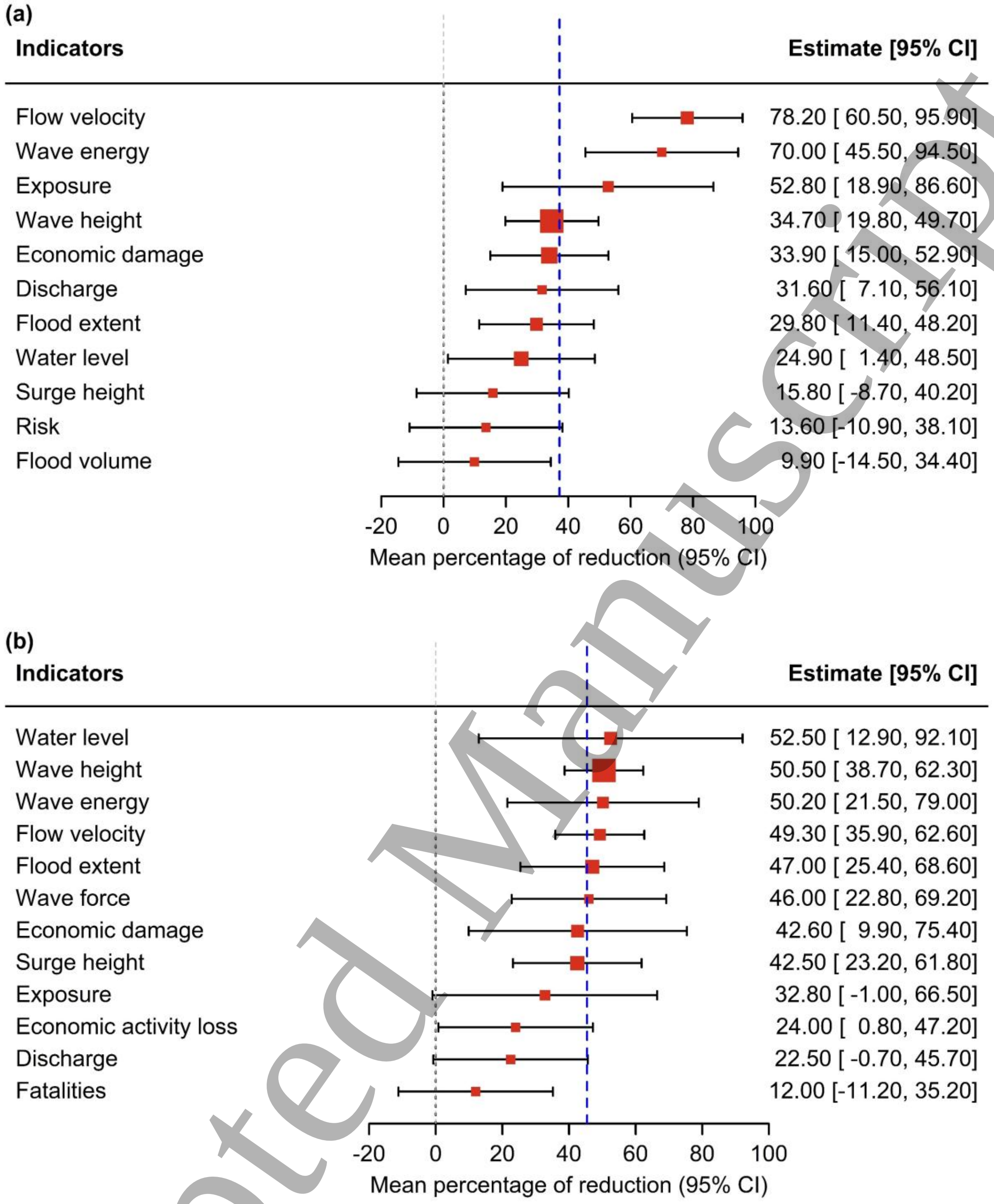

Figure 5. Forest plots showing the mean percentage reduction achieved by (a) salt marshes or other coastal wetlands and (b) mangroves across different hydrological hazard indicators. Red dots represent the pooled mean effect for each indicator, with dot size proportional to the number of contributing studies. Horizontal lines indicate the 95% confidence intervals associated with each estimate.

4. Discussion

This study provides a systematic review and meta-analysis aimed at establishing a scientific evidence base on the effectiveness of NbS in mitigating hydrometeorological hazards in coastal and deltaic regions. A total of 383 peer-reviewed English-language articles published since 2008 were analysed. The distribution of case studies was uneven, with most research concentrated in high-income OECD and upper-middle-income countries across Europe, Asia, and North America. Representation from low-income and lower-middle-income countries—particularly in the global south, where hydrometeorological hazard exposure is high—remains limited (Chausson et al., 2020). Although the absence of studies in landlocked countries is expected due to the coastal focus of the review, many coastal nations exposed to severe hazards lack published evidence on the efficacy of NbS. Despite 179 countries having coastlines (https://worldpopulationreview.com/), case studies were found in only 60, indicating a substantial geographic gap. While interpreting these results, care should be given as this study relied solely on peer-reviewed English literature; therefore, relevant grey literature and non-English studies may not be captured.

Most studies evaluated the effectiveness of NbS in mitigating hydrological hazards—including floods, storm surges, and wave action. This aligns with the long-standing focus on coastal protection in NbS research (Barbier et al., 2013; Costanza et al., 2008; Das and Vincent, 2009; Del Valle et al., 2020; Ferrario et al., 2014; Mancheño et al., 2024; Sheng et al., 2022; Stark et al., 2015; Zhang et al., 2012). Salt marshes and mangroves, in particular, have been widely studied and are well established as effective natural barriers in both global north and south (Das and Vincent, 2009; Du et al., 2020; Liu et al., 2019; Menéndez et al., 2020; Seujip et al., 2024; Sheng et al., 2022; Zhang et al., 2012). By contrast, the role of NbS in mitigating meteorological hazards—such as extreme temperatures and droughts—remains underexplored, despite their increasing sensitivity to climate change and their implications for water security (Debele et al., 2019), critical infrastructure (Leal Filho et al., 2024), and human health (Lüthi et al., 2023; Matthews et al., 2025).

This study assessed whether the reviewed literature agreed on the hazard-mitigating potential of various NbS measures. While most studies supported their effectiveness, some reported mixed or negative outcomes—particularly for managed realignment. For example, French (2008) documented increased peak velocity and discharge in an estuarine system following managed realignment, and Bennett and Karunarathna (2020) found negligible effects on flood levels in Wales. Pontee (2015) similarly reported increased water levels in parts of the Steart Estuary due to altered tidal propagation following embankment breaching. These examples underscore the need for scientific understanding of site-specific hydrodynamics when designing and implementing large-scale interventions such as managed realignment.

Assessing the level of agreement alone provides an incomplete picture of NbS performance. Therefore, this study evaluated the robustness of evidence using combined qualitative and quantitative criteria. Most NbS categories demonstrated high confidence levels, reflecting medium robustness and high agreement. However, significant variability in robustness scores was observed for agrobiodiversity and sustainable drainage systems. Some studies presented highly robust evidence (Barbour et al., 2022; Qin et al., 2024b), whereas others provided limited support due to methodological or data constraints (Dang et al., 2021; Sohn et al., 2020). Limited ground observations for model validation, combined with inherent uncertainties in numerical modelling (Hall and Solomatine, 2008), likely contribute to overall medium or low robustness scores.

Effectiveness of NbS is highly context dependent and influenced by numerous factors, including site characteristics, ecological dimensions (e.g., mangrove belt width), system configuration (e.g., dune–canal combinations), and hazard intensity. As a result, several studies reported mixed or inconclusive findings. For example, Marsooli et al. (2016) found that salt marshes can reduce peak water velocity but may slightly increase water levels under certain vegetation conditions. Evidence also indicates that hybrid approaches combining NbS with engineered structures can enhance effectiveness (Barbour et al., 2022; Du et al., 2020; Liu et al., 2019). Yet, only a limited number of studies have explored NbS as complementary measures, partly because the lack of standardised criteria prior to the IUCN NbS standards (introduced in 2020) hindered their classification and assessment (Sowińska-Świerkosz and García, 2022). Quantifying the performance of complementary solutions—such as tidal river management integrated with embankments—remains challenging and typically requires multi-method approaches (Adnan et al., 2020; Barbour et al., 2022; Du et al., 2020; Liu et al., 2019). Due to these challenges, most of the studies have evaluated NbS in isolation as safeguard measures (Al-Attabi et al., 2023; Barbier et al., 2013; Beck et al., 2018) rather than as integrated components of broader risk management strategies.

A major challenge in evaluating and communicating NbS effectiveness is the lack of standardised indicators and the considerable uncertainty surrounding results. Hydrological studies frequently rely on indicators such as wave height, current velocity (Castagno et al., 2022; Mancheño et al., 2024; Möller et al., 2014), flood depth, and flood extent (Karamouz et al., 2022; Montgomery et al., 2022), measured in different units (e.g., metres, m/s, percentage reduction), while meteorological studies use temperature (°C) (Arrar et al., 2024; Lin and Zhang, 2024; Spyrou et al., 2024). The indicators used are closely linked to the methodological approach; numerical hydrological modelling often prioritises hazard intensity metrics (Kumar et al., 2021). However, inconsistent or non–hazard-specific indicators make cross-study comparisons difficult. As shown in the meta-analysis, considerable heterogeneity persists across NbS measures, arising from ecological variability, geomorphological differences, and inconsistent reporting practices. This highlights the need for consistent, transparent, and hazard-specific indicators to strengthen the evidence base and facilitate comparability (Kabisch et al., 2016; Kumar et al., 2021).

Finally, combining multiple methodological approaches generally yielded higher confidence levels. Integrating numerical models with geospatial approaches improved understanding of tidal river management (Adnan et al., 2020) and mangrove systems (Azeez et al., 2022). When cost–benefit analysis was combined with numerical models, the robustness of evidence increased (Du et al., 2020; Karamouz and Heydari, 2020). Similarly, numerical models paired with empirical observations strengthened reliability (Lu et al., 2023; Rahman et al., 2017). Despite these advantages, relatively few studies employ such integrated frameworks, suggesting a need for methodological diversification to improve accuracy and spatial resolution in NbS assessments.

5. Limitations and future research directions

There is growing recognition of the value of NbS in attenuating hydrometeorological hazards. Yet, significant knowledge gaps remain regarding their effectiveness across different hazard indicators. This study synthesised the scientific evidence base through a systematic review and meta-analysis of peer-reviewed literature, assessing both performance and methodological robustness of NbS interventions.

The following limitations should be considered when interpreting the findings. First, the review used four major databases. Relevant studies indexed elsewhere—such as Compendex—were not included. Second, the analysis was restricted to peer-reviewed English-language publications, excluding potentially relevant grey literature and non-English studies. Inclusion of these sources might alter the geographic distribution of studies and diversify the evidence base. Third, the reported effectiveness of NbS may be subject to uncertainties. Although the meta-analysis produced average values (e.g., percentage reductions in hazard indicators), effectiveness is highly dependent on local conditions, proximity to hazard sources, event characteristics (regular vs. extreme), and dimensions of the NbS measures. Despite these limitations, this study provides the first comprehensive synthesis of NbS effectiveness across a wide range of hydrometeorological hazard indicators.

Future research should further investigate the potential of NbS as complementary measures alongside conventional engineered structures. Evaluating hybrid or nature-positive engineering solutions—including their cost-effectiveness, long-term resilience, and ecological co-benefits—would enhance understanding of their role in strengthening coastal resilience (Cohen-Shacham et al., 2016). More effective communication frameworks are also needed to translate scientific evidence into actionable guidance for policymakers and stakeholders, promoting the integration of NbS into climate adaptation and disaster risk reduction strategies (Banerjee et al., 2023; Debele et al., 2019; Kumar et al., 2021).

Coastal and deltaic regions often experience multiple or compound hazards, such as tidal surges coinciding with high river flows, with cascading impacts (Lee et al., 2024). Yet, few studies evaluate

NbS through a multi-hazard lens (Debele et al., 2019; Debele et al., 2023). Integrating NbS into multi-hazard risk assessment frameworks would capture the interconnected nature of hydrometeorological hazards and provide more realistic estimates of their effectiveness. Developing standardised, transparent, and hazard-specific indicators is essential for improving comparability and stakeholder understanding. These indicators should be easily interpretable and facilitate engagement across governance levels.

Overall, future research can help advance more resilient, adaptive, and sustainable coastal and deltaic communities, solidifying the role of NbS in global climate adaptation, disaster risk reduction, and sustainable development. By identifying key trends, methodological gaps, and challenges, the findings of this review offer valuable insights for researchers, practitioners, and policymakers.

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