




ENVIRONMENTAL RESEARCH
LETTERS

TOPICAL REVIEW

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

Mohammed Sarfaraz Gani Adnan^{1,*} , Abiy S Kebede^{1,*} , Kwasi Appeaning Addo², Ashraf Dewan³, Tuhin Ghosh⁴, Christopher J White⁵ and Philip J Ward^{6,7} ¹ Department of Civil and Environmental Engineering, Brunel University of London, Uxbridge UB8 3PH, United Kingdom² Department of Marine and Fisheries Sciences, College of Basic and Applied Science, University of Ghana, PO Box LG 99, Legon, Accra, Ghana³ Spatial Sciences Discipline, School of Earth and Planetary Sciences, Curtin University, Perth 6102, Australia⁴ School of Oceanographic Studies, Jadavpur University, Kolkata 700 032, India⁵ Department of Civil and Environmental Engineering, University of Strathclyde, Glasgow G1 1XJ, United Kingdom⁶ Department of Water and Climate Risk, VU Amsterdam, 1081 HV Amsterdam, The Netherlands⁷ Deltares, Delft, 2629 HV Delft, The Netherlands

* Authors to whom any correspondence should be addressed.

E-mail: sarfaraz.adnan@brunel.ac.uk and Abiy.Kebede@brunel.ac.uk**Keywords:** nature-based solutions, performance evaluation, systematic review, level of confidence, nature-positive engineeringSupplementary material for this article is available [online](#)

OPEN ACCESS

RECEIVED

5 December 2025

ACCEPTED FOR PUBLICATION

26 January 2026

PUBLISHED

6 February 2026

Original content from this work may be used under the terms of the [Creative Commons Attribution 4.0 licence](#).

Any further distribution of this work must maintain attribution to the author(s) and the title of the work, journal citation and DOI.

**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 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.

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 (Wansbury 2024, LRF 2025). 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 (Paszowski *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 (Syvitski 2008, Vörösmarty *et al* 2009, Ghosh *et al* 2019). 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 (Guerreiro *et al* 2018, Debele *et al* 2019). 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, Steinfeld and Kingsford 2013, Morrison *et al* 2018). 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, salt-marshes, 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, Kumar *et al* 2020, Gain *et al* 2022, Ou *et al* 2022, Sowińska-Świerkosz and García 2022, Debele *et al* 2023, Shah *et al* 2023). 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, 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 (Renaud *et al* 2016, UN 2021, IPCC 2022, EU 2024), 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 (Sowińska-Świerkosz and García 2022, Nehren *et al* 2023). 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 (Fairchild *et al* 2021, van Zelst *et al* 2021, Al-Attabi *et al* 2023, De Dominicis *et al* 2023, Toth *et al* 2023, Unguendoli *et al* 2023, Chen *et al* 2024), laboratory experiments (Möller *et al* 2014, Türker *et al* 2019, van Veelen *et al* 2021, Van Dang *et al* 2023), geospatial analytics (Van Coppenolle *et al* 2018, Adnan *et al* 2020, Atmaja *et al* 2024), cost-benefit analyses (Narayan *et al* 2016, Karanja and Saito 2018, Reguero *et al* 2018, Hynes *et al* 2022), multi-criteria decision-making (Lu *et al* 2023, Qin *et al* 2024a), statistical analyses (Costanza *et al* 2008, Das and Vincent 2009, Anderson *et al* 2022), and qualitative approaches (Warner *et al* 2018, Bakhshianlamouki *et al* 2023, Van Hespén *et al* 2023). 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 (Quataert *et al* 2015, Mancheño *et al* 2024), 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 (Debele *et al* 2019, 2023, Chausson *et al* 2020, 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 (Stark *et al* 2016, Du *et al* 2020, Barbour *et al* 2022). 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 (Debele *et al* 2019, Martin *et al* 2020, Castellar *et al* 2021, Gain *et al* 2022, 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 (Möller *et al* 2014, Narayan *et al* 2016, Kumar *et al* 2021, Mudashiru *et al* 2021).

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 (Sudmeier-Rieux *et al* 2021, de Lemos *et al* 2024, Ferrario *et al* 2024). 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.

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 4012 articles from Scopus ($n = 1649$), WoS ($n = 1327$), GeoRef ($n = 961$) and PubMed ($n = 75$).

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	<ul style="list-style-type: none"> • 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. 	<ul style="list-style-type: none"> • 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	<ul style="list-style-type: none"> • Studies evaluating NbS interventions aimed at reducing the impacts of hydrometeorological hazards. 	<ul style="list-style-type: none"> • 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	<ul style="list-style-type: none"> • Studies comparing NbS interventions with baseline scenarios ('as is' or do-nothing approaches) or alternative intervention strategies. 	<ul style="list-style-type: none"> • None
Methodology	<ul style="list-style-type: none"> • Studies employing NbS evaluation methods. 	<ul style="list-style-type: none"> • Studies lacking NbS evaluation methods.
Location	<ul style="list-style-type: none"> • Studies conducted in coastal or deltaic regions. 	<ul style="list-style-type: none"> • Studies not related to coastal or deltaic regions.
Outcomes	<ul style="list-style-type: none"> • Studies measuring the extent of NbS impacts on hydrometeorological hazards. 	<ul style="list-style-type: none"> • Studies that do not assess the impacts of NbS on hydrometeorological hazards.
Study	<ul style="list-style-type: none"> • Peer-reviewed articles published in English between 1 January 2008 and 31 December 2024. 	<ul style="list-style-type: none"> • 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.

After removing 1111 duplicate records, 2901 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, 2500 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 <i>et al</i> 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 ($^{\circ}\text{C}$)).	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

(Continued.)

Table 2. (Continued.)

Variables	Description	Analysis used
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 <i>agreement</i> , <i>inconclusive</i> , and <i>non-agreement</i> , 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 <i>low</i> , <i>medium</i> , or <i>robust</i> 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 IPCC AR5 guidance note on the consistent treatment of uncertainties (Mastrandrea *et al* 2010, 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, mean bias error, absolute Bias, reported R^2 /NSE/kappa statistic/skill, Brier skill score, scatter index, 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, 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 hydro-meteorological hazard indicators. These indicators included percentage reduction (%), absolute changes in physical parameters (e.g. surge height or flood depth in meters), temperature change ($^{\circ}\text{C}$), 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, $^{\circ}\text{C}$, 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 1(a)).

A notable upward trend in research activity was observed over time. As shown in figure 1(b), 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.

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 1(d)). 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 1(e)).

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 S2(a) (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

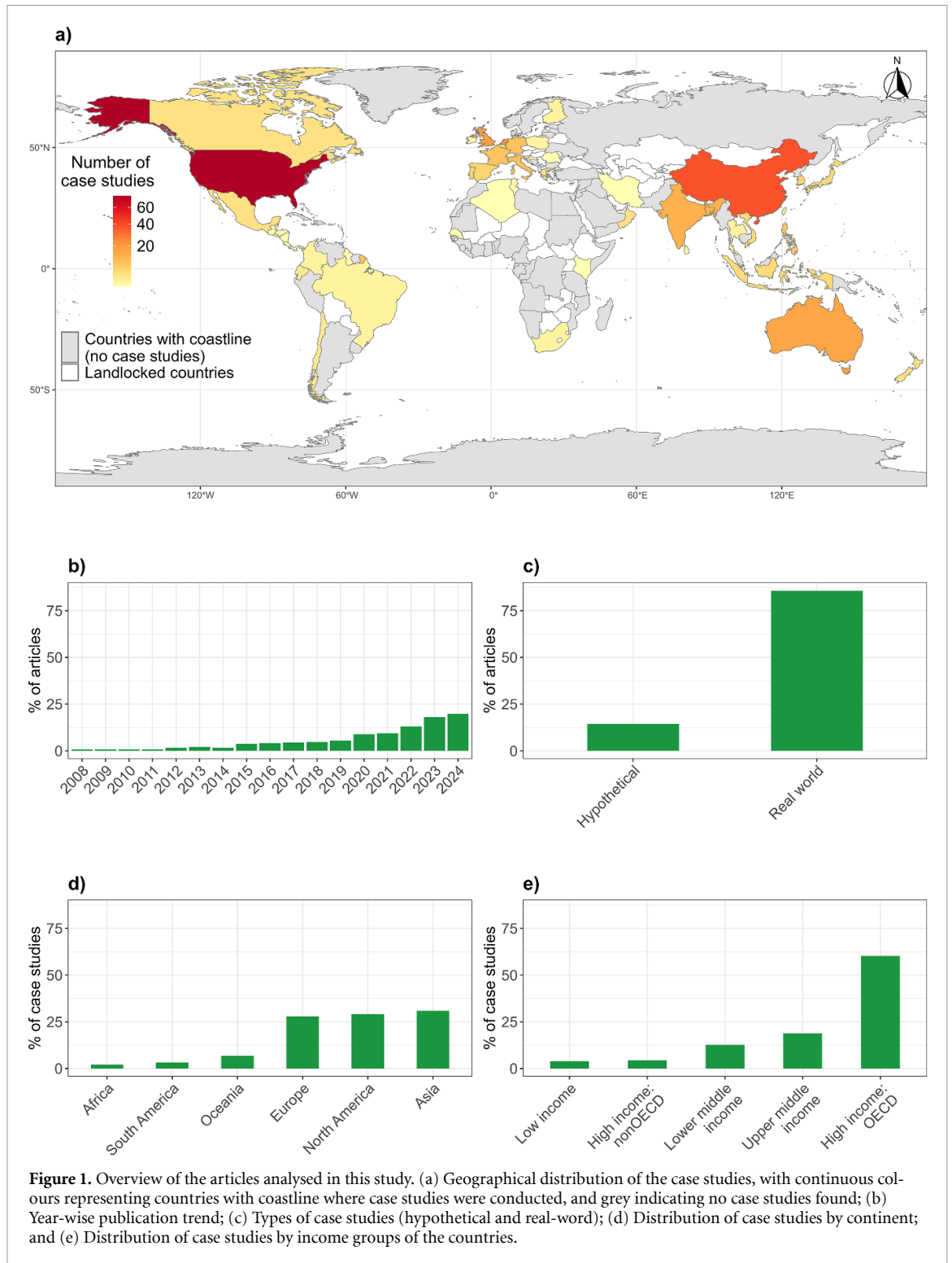


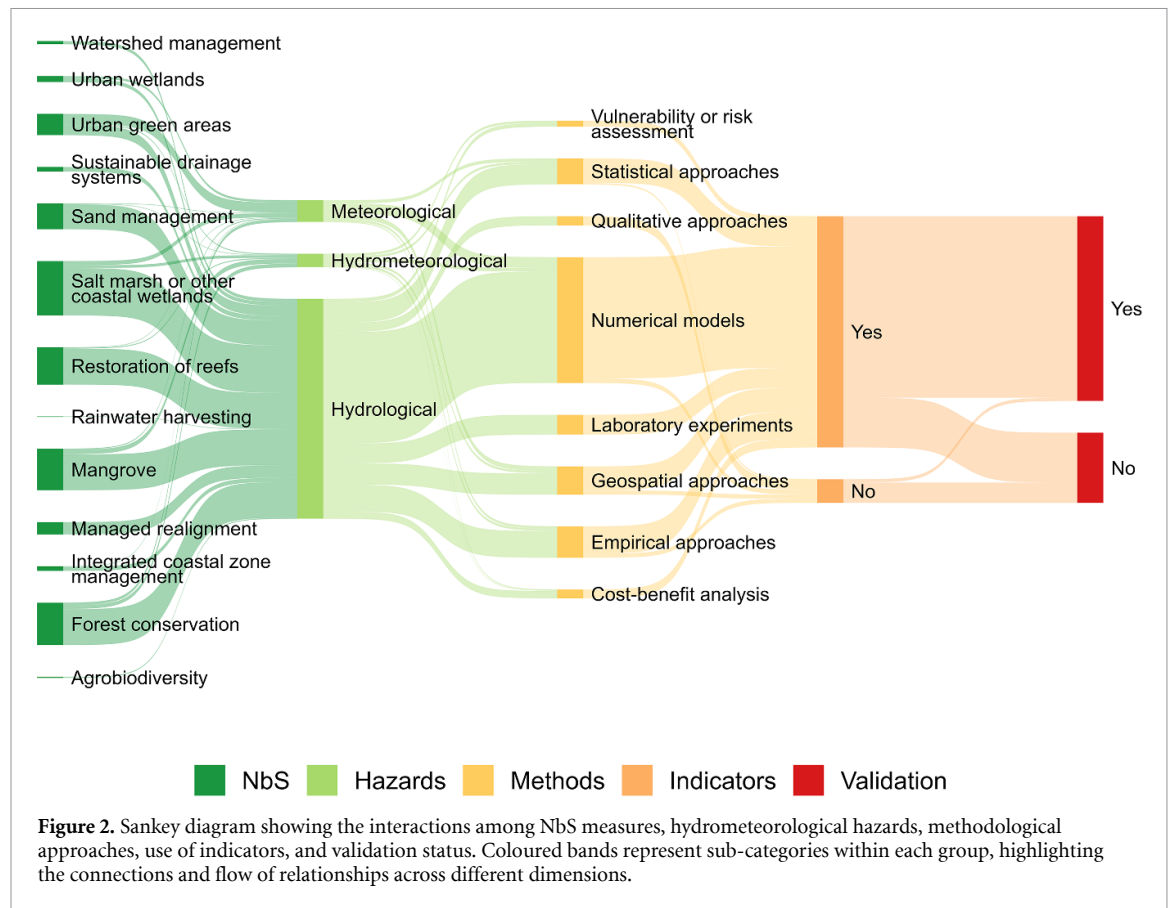
Figure 1. Overview of the articles analysed in this study. (a) Geographical distribution of the case studies, with continuous colours representing countries with coastline where case studies were conducted, and grey indicating no case studies found; (b) Year-wise publication trend; (c) Types of case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

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 S2(b), 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 S2(c), 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).

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) (figures 2 and S2(e) (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

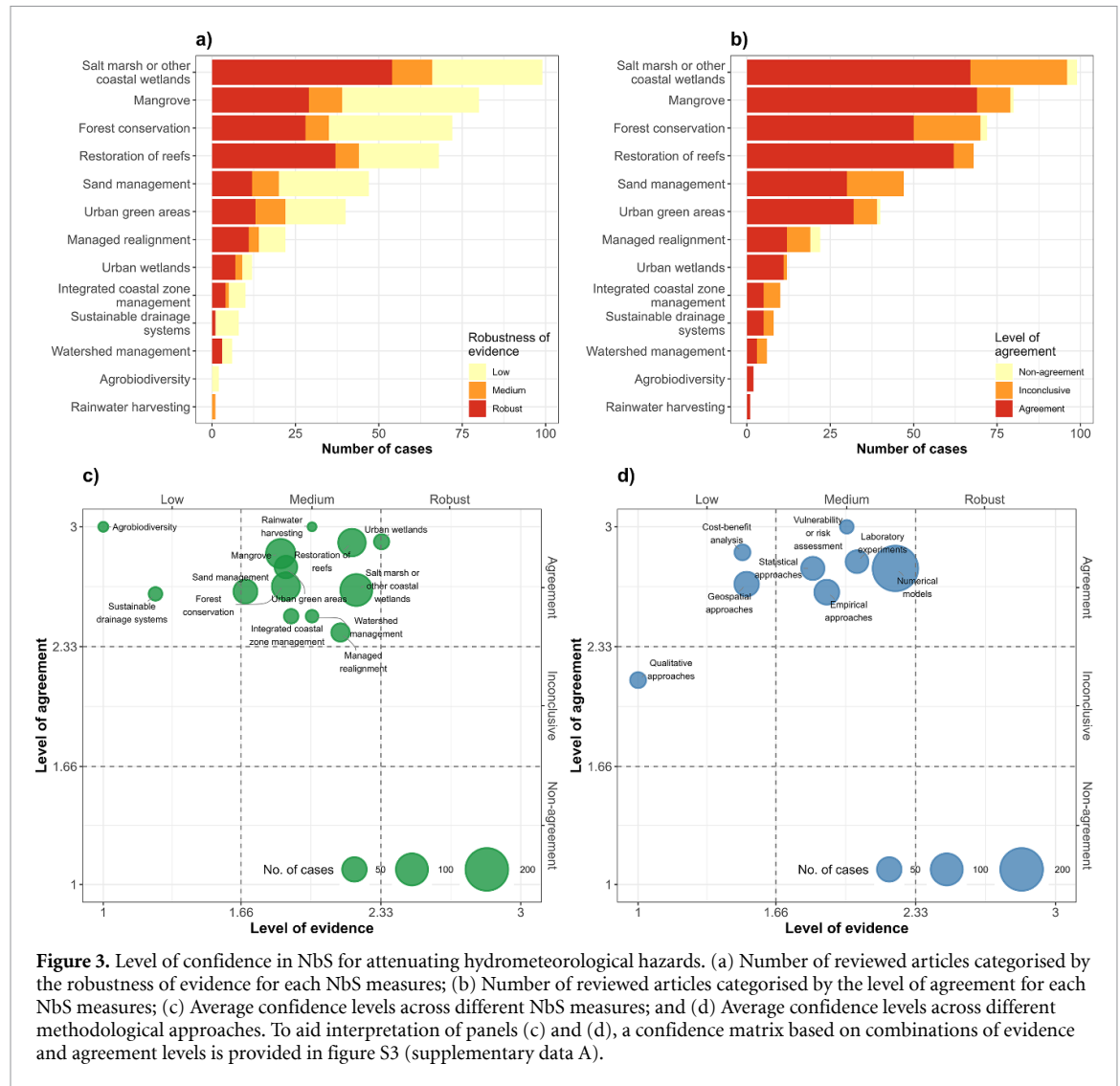
Indicators play a key role in quantifying the effectiveness of NbS interventions. Approximately 91% of the articles used at least one indicator, whereas 9% did not employ any specific metrics (figures 2 and S2(d) (supplementary data A)). In total, 44 unique indicators were identified (table S5, Supplementary 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 (figures 2 and S2(f) (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 3(a)). 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 3(b)). 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 3(c)).

Confidence levels also varied across methodological approaches. As shown in figure 3(d), 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.

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 ($^{\circ}\text{C}$), metres (m), monetary value (USD), cubic metres (m^3), fatalities, percentage increase, and metres per second (m s^{-1}). 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 $^{\circ}\text{C}$) 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 $^{\circ}\text{C}$ (figure S5, supplementary

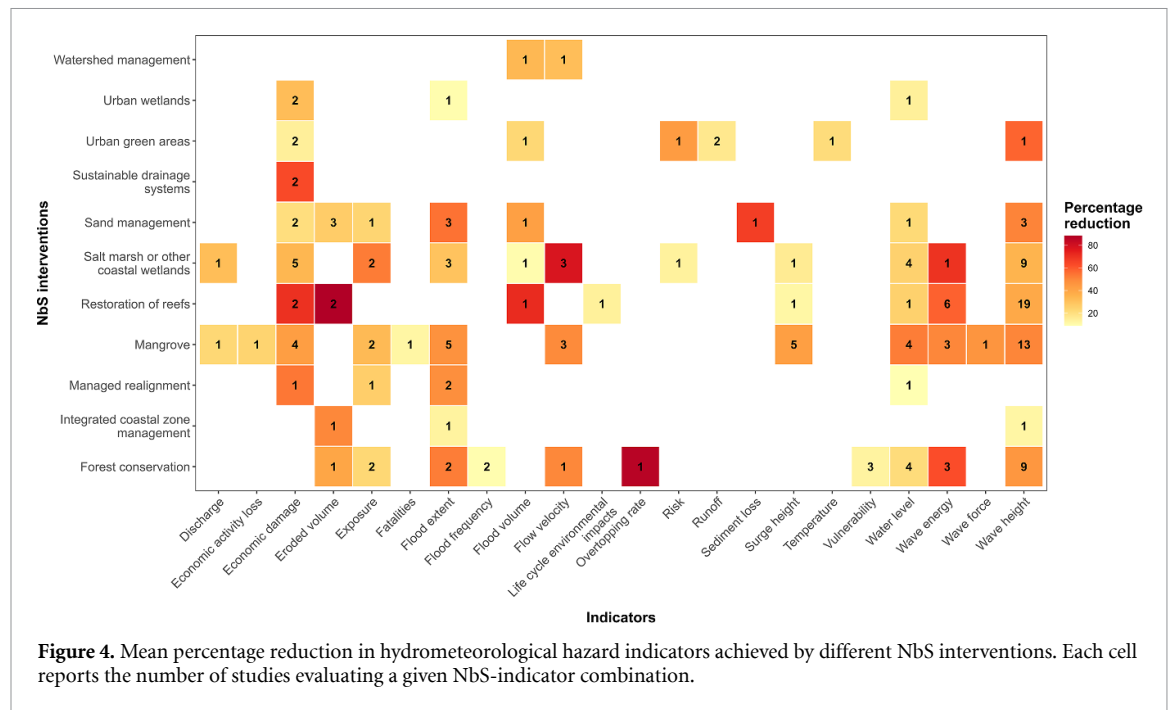


Figure 4. Mean percentage reduction in hydrometeorological hazard indicators achieved by different NbS interventions. Each cell reports the number of studies evaluating a given NbS-indicator combination.

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 ratio, economic benefits, housing prices, resilience, or tidal prism linked to five NbS measures (figure S7, supplementary data A).

3.4.2. Uncertainties in the estimates

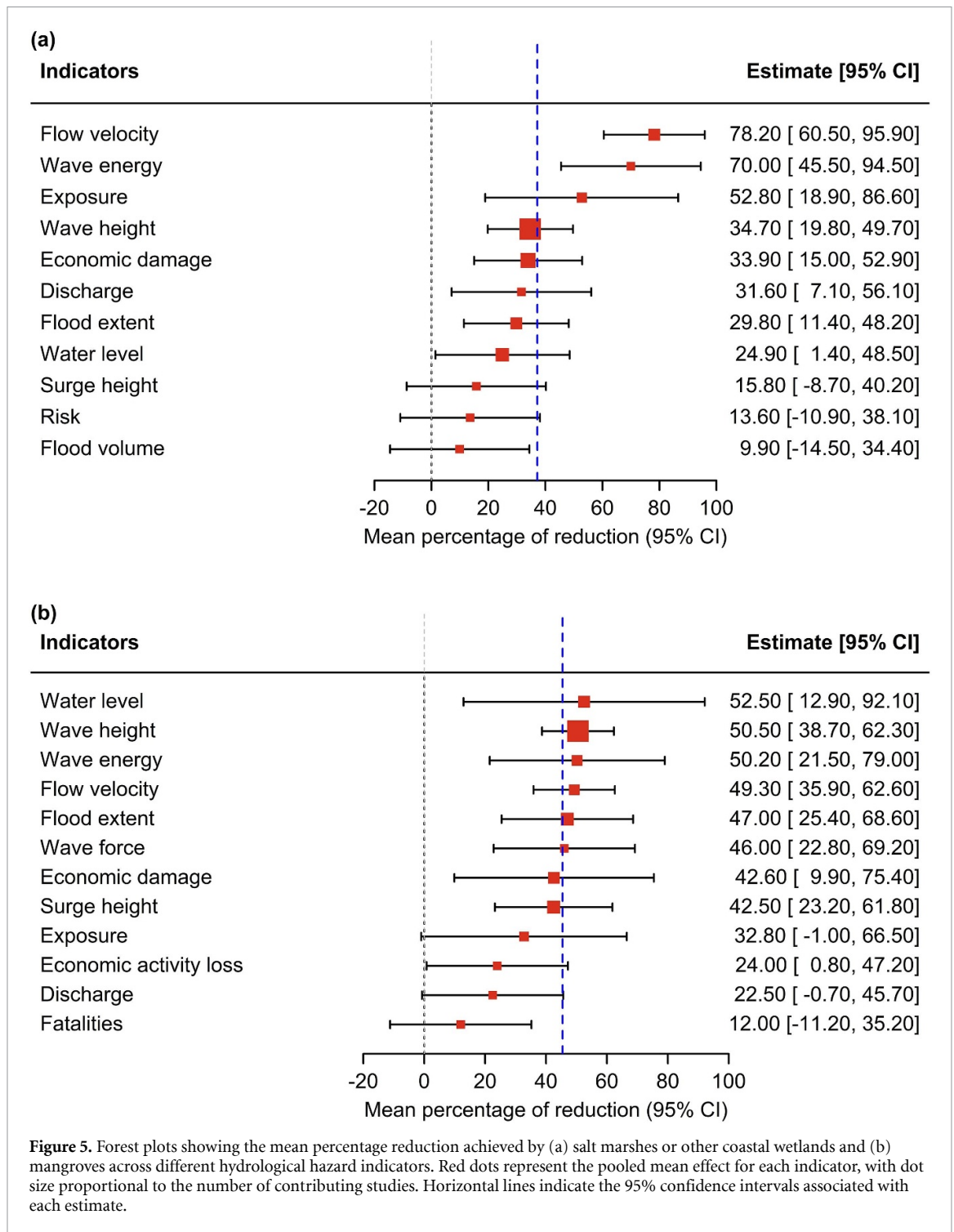
The meta-analyses revealed substantial uncertainty in the estimated protective effects of different NbS measures against hydrological hazards. Figure 5 summarises the mean percentage reduction achieved by salt marshes or other coastal wetlands and by mangroves. In both cases, the random-effects models indicated varying levels of heterogeneity (I^2) and between-study variance (τ^2), depending on the indicator (tables S6 and 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).

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 (Costanza et al 2008, Das and Vincent 2009, Zhang et al 2012, Barbier et al 2013, Ferrario et al 2014, Stark et al 2015, Del Valle et al 2020, Sheng et al 2022, Mancheño et al 2024). 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, Zhang et al 2012, Liu et al 2019, Du et al 2020, Menéndez et al 2020, Sheng et al 2022, Seujip et al 2024). 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 Karunaratna (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 (Sohn *et al* 2020, Dang *et al* 2021). 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 (Liu *et al* 2019, Du *et al* 2020, Barbour *et al* 2022). 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 (Liu *et al* 2019, Adnan *et al* 2020, Du *et al* 2020, Barbour *et al* 2022). Due to these challenges, most of the studies have evaluated NbS in isolation as safeguard

measures (Barbier *et al* 2013, Beck *et al* 2018, Al-Attabi *et al* 2023) 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 (Möller *et al* 2014, Castagno *et al* 2022, Mancheño *et al* 2024), flood depth, and flood extent (Karamouz *et al* 2022, Montgomery *et al* 2022), measured in different units (e.g. metres, m s^{-1} , percentage reduction), while meteorological studies use temperature ($^{\circ}\text{C}$) (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 (Rahman *et al* 2017, Lu *et al* 2023). 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 (Debele *et al* 2019, Kumar *et al* 2021, Banerjee *et al* 2023).

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, 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.

Data availability statement

All data that support the findings of this study are included within the article (and any supplementary files).

Supplementary Data A available at <http://doi.org/10.1088/1748-9326/ae3d4d/data1>.

Supplementary Data B available at <http://doi.org/10.1088/1748-9326/ae3d4d/data2>.

Acknowledgments

This study was funded by the Leverhulme Trust through an Early Career Fellowship awarded to MSGA [Grant Reference ECF-2023-074]. ASK acknowledges support from the IUCN Global EbA Fund through the project ‘Upscaling Mangrove Restoration for Coastal Hazard Reduction in a Deltaic Environment: Prioritizing Restoration Efforts for Nature-based Solutions in the Volta Delta’. CJW acknowledges funding from the European Union’s Horizon Europe programme under the project ‘Multi-hazard and risk informed system for enhanced local and regional disaster risk management (MEDiate)’ project [Grant Agreement No. 101074075].

Author contributions

Mohammed Sarfaraz Gani Adnan  0000-0002-7276-1891

Conceptualization (equal), Data curation (lead), Formal analysis (lead), Funding acquisition (lead), Methodology (lead), Project administration (equal), Software (lead), Visualization (lead), Writing – original draft (lead), Writing – review & editing (equal)

Abiy S Kebede  0000-0002-7844-1151

Conceptualization (equal), Funding acquisition (supporting), Investigation (equal), Methodology (supporting), Project administration (equal), Resources (equal), Supervision (lead), Validation (equal), Writing – original draft (supporting), Writing – review & editing (equal)

Kwasi Appeaning Addo

Conceptualization (equal), Investigation (equal), Resources (equal), Validation (equal), Writing – review & editing (equal)

Ashraf Dewan


Conceptualization (equal), Investigation (equal), Resources (equal), Validation (equal), Writing – review & editing (equal)

Tuhin Ghosh

Conceptualization (equal), Investigation (equal), Resources (equal), Validation (equal), Writing – review & editing (equal)

Christopher J White

Conceptualization (equal), Investigation (equal), Resources (equal), Validation (equal), Writing – review & editing (equal)

Philip J Ward  0000-0001-7702-7859
 Conceptualization (equal), Investigation (equal),
 Resources (equal), Validation (equal), Writing –
 review & editing (equal)

References

- Adnan M S G, Talchabhadel R, Nakagawa H and Hall J W 2020 The potential of tidal river management for flood alleviation in south western Bangladesh *Sci. Total Environ.* **731** 138747
- Adnan M 2020 The legacy of polders: diagnosing complex flooding processes and adaptation options in the coastal region of Bangladesh *School of Geography and the Environment, Vol. Doctor of Philosophy (Dphil)* (University of Oxford)
- Al-Attabi Z, Xu Y, Tso G and Narayan S 2023 The impacts of tidal wetland loss and coastal development on storm surge damages to people and property: a Hurricane Ike case-study *Sci. Rep.* **13** 4620
- Anderson C C, Renaud F G, Hanscomb S and Gonzalez-Ollauri A 2022 Green, hybrid, or grey disaster risk reduction measures: what shapes public preferences for nature-based solutions? *J. Environ. Manage.* **310** 114727
- Arrar H F, Kaoula D, Santamouris M, Foufa-Abdessemed A, Emmanuel R, Matallah M E, Ahriz A and Attia S 2024 Coupling of different nature base solutions for pedestrian thermal comfort in a Mediterranean climate *Buuld. Environ.* **256** 111480
- Atmaja T, Setiawati M D, Kurisu K and Fukushi K 2024 Advancing coastal flood risk prediction utilizing a GeoAI Approach by considering mangroves as an Eco-DRR strategy *Hydrology* **11** 198
- Augusto B, Roebeling P, Rafael S, Ferreira J, Ascenso A and Bodilis C 2020 Short and medium-to long-term impacts of nature-based solutions on urban heat *Sustain. Cities Soc.* **57** 102122
- Azeez A, Gnanappazham L, Kr M, Revichandran C, John S, Seena G and Thomas J 2022 Multi-decadal changes of mangrove forest and its response to the tidal dynamics of thane creek, Mumbai *J. Sea Res.* **180** 102162
- Bakhshianlamouki E, Augustijn E-W, Brugnach M, Voinov A and Wijnberg K 2023 A participatory modelling approach to cognitive mapping of the socio-environmental system of sandy anthropogenic shores in the Netherlands *Ocean Coast. Manage.* **243** 106739
- Banerjee S, Ladd C J T, Chanda A, Shil S, Ghosh T, Large A and Balke T 2023 Securing the sustainable future of tropical deltas through mangrove restoration: lessons from the Indian Sundarban *One Earth* **6** 190–4
- Barbier E B, Georgiou I Y, Enchelmeier B and Reed D J 2013 The value of wetlands in protecting southeast Louisiana from hurricane storm surges *PLoS One* **8** e58715
- Barbour E J, Adnan M S G, Borgomeo E, Paprocki K, Khan M S A, Salehin M and Hall J W 2022 The unequal distribution of water risks and adaptation benefits in coastal Bangladesh *Nat. Sustain.* **5** 294–302
- Beck M W, Losada I J, Menéndez P, Reguero B G, Díaz-Simal P and Fernández F 2018 The global flood protection savings provided by coral reefs *Nat. Commun.* **9** 2186
- Bennett W G and Karunarathna H 2020 Coastal flood alleviation through management interventions under changing climate conditions *Int. J. Disaster Resil. Built Environ.* **11** 187–203
- Borenstein M, Hedges L V, Higgins J P T and Rothstein H R 2010 A basic introduction to fixed-effect and random-effects models for meta-analysis *Res. Synth. Methods* **1** 97–111
- Bridges T et al 2024 Innovating through nature-positive engineering: how can we move forward? *Int. J. Mar. Coast. Law* **39** 541–50
- Castagno K A, Ganju N K, Beck M W, Bowden A A and Scyphers S B 2022 How much marsh restoration is enough to deliver wave attenuation coastal protection benefits? *Front. Mar. Sci.* **8** 756670
- Castellar J A, Popartan L A, Pueyo-Ros J, Atanasova N, Langergraber G, Säumel I, Corominas L, Comas J and Acuña V 2021 Nature-based solutions in the urban context: terminology, classification and scoring for urban challenges and ecosystem services *Sci. Total Environ.* **779** 146237
- CEE 2022 Guidelines and standards for evidence synthesis in environmental management Version 5.1 ed A S Pullin, et al (Collaboration for Environmental Evidence (CEE))
- Chausson A et al 2020 Mapping the effectiveness of nature-based solutions for climate change adaptation *Glob. Change Biol.* **26** 6134–55
- Chen W, Staneva J, Jacob B, Sánchez-Artús X and Wurpts A 2024 What-if nature-based storm buffers on mitigating coastal erosion *Sci. Total Environ.* **928** 172247
- Cohen-Shacham E et al 2016 *Nature-based Solutions to Address Global Societal Challenges* (IUCN International Union for Conservation of Nature)
- Cook R D and Weisberg S 1982 Criticism and influence analysis in regression *Sociol. Methodol.* **13** 313–61
- Costanza R, Pérez-Maqueo O, Martínez M L, Sutton P, Anderson S J and Mulder K 2008 The value of coastal wetlands for hurricane protection *Ambio* **37** 241–8
- Dang N A, Benavidez R, Tomscha S A, Nguyen H, Tran D D, Nguyen D T H, Loc H H and Jackson B M 2021 Ecosystem service modelling to support nature-based flood water management in the Vietnamese Mekong River Delta *Sustainability* **13** 13549
- Das S and Vincent J R 2009 Mangroves protected villages and reduced death toll during Indian super cyclone *Proc. Natl Acad. Sci.* **106** 7357–60
- De Dominicis M, Wolf J, van Hespren R, Zheng P and Hu Z 2023 Mangrove forests can be an effective coastal defence in the Pearl River Delta, China *Commun. Earth Environ.* **4** 13
- de Lemos G L et al 2024 *Nature-based Solutions Experiences: A Systematic Literature Review for Public Policies* (Nature-Based Solutions) pp 100121
- Debele S E et al 2019 Nature-based solutions for hydro-meteorological hazards: revised concepts, classification schemes and databases *Environ. Res.* **179** 108799
- Debele S E et al 2023 Nature-based solutions can help reduce the impact of natural hazards: a global analysis of NBS case studies *Sci. Total Environ.* **902** 165824
- Del Valle A, Eriksson M, Ishizawa O A and Miranda J J 2020 Mangroves protect coastal economic activity from hurricanes *Proc. Natl Acad. Sci.* **117** 265–70
- Di Baldassarre G, Martinez F, Kalantari Z and Viglione A 2017 Drought and flood in the Anthropocene: feedback mechanisms in reservoir operation *Earth Syst. Dyn.* **8** 225–33
- Di Baldassarre G, Viglione A, Carr G, Kuil L, Salinas J L and Blöschl G 2013 Socio-hydrology: conceptualising human-flood interactions *Hydrol. Earth Syst. Sci.* **17** 3295–303
- Du S et al 2020 Hard or soft flood adaptation? Advantages of a hybrid strategy for Shanghai *Glob. Environ. Change* **61** 102037
- EC 2015 Towards an EU research and innovation policy agenda for nature-based solutions & re-naturing cities: final report of the horizon 2020 expert group on 'nature-based solutions and re-naturing cities' (European Commission(EC): Directorate-General for Research and Innovation)
- EU 2024 Regulation (EU) 2024/1991 of the European Parliament and of the Council of 24 June 2024 on nature restoration and amending Regulation (EU) 2022/869 ed E. U. (EU) Document 32024R1991
- Fairchild T P, Bennett W G, Smith G, Day B, Skov M W, Möller I, Beaumont N, Karunarathna H and Griffin J N 2021 Coastal wetlands mitigate storm flooding and associated costs in estuaries *Environ. Res. Lett.* **16** 074034

- FAO 2021 Food and agriculture organization of the United Nations
- Ferrario F, Beck M W, Storlazzi C D, Micheli F, Shepard C C and Airoldi L 2014 The effectiveness of coral reefs for coastal hazard risk reduction and adaptation *Nat. Commun.* **5** 1–9
- Ferrario F, Mourato J M, Rodrigues M S and Dias L F 2024 Evaluating Nature-based Solutions as urban resilience and climate adaptation tools: a meta-analysis of their benefits on heatwaves and floods *Sci. Total Environ.* **950** 175179
- French J 2008 Hydrodynamic modelling of estuarine flood defence realignment as an adaptive management response to sea-level rise *J. Coast. Res.* **2** 1–12
- Gain A K et al 2022 Overcoming challenges for implementing nature-based solutions in deltaic environments: insights from the Ganges-Brahmaputra delta in Bangladesh *Environ. Res. Lett.* **17** 064052
- Gergel S E, Dixon M D and Turner M G 2002 Consequences of human-altered floods: levees, floods, and floodplain forests along the Wisconsin River *Ecol. Appl.* **12** 1755–70
- Ghosh A, Das S, Ghosh T and Hazra S 2019 Risk of extreme events in delta environment: a case study of the Mahanadi delta *Sci. Total Environ.* **664** 713–23
- Goodbred S L Jr and Saito Y 2011 *Tide-dominated Deltas. Principles of Tidal Sedimentology* (Springer) pp 129–49
- Guerreiro S B, Dawson R J, Kilsby C, Lewis E and Ford A 2018 Future heat-waves, droughts and floods in 571 European cities *Environ. Res. Lett.* **13** 034009
- Guha-Sapir D et al 2023 EM-DAT: The CRED/OFDA international disaster database UCLouvain (available at: www.emdat.be)
- Hall J and Solomatine D 2008 A framework for uncertainty analysis in flood risk management decisions *Int. J. River Basin Manage.* **6** 85–98
- Hupp C R et al 2009 Floodplain geomorphic processes and environmental impacts of human alteration along coastal plain rivers, USA *Wetlands* **29** 413–29
- Hynes S et al 2022 Estimating the costs and benefits of protecting a coastal amenity from climate change-related hazards: nature based solutions via oyster reef restoration versus grey infrastructure *Ecol. Econ.* **194** 107349
- IPCC 2022 Climate change 2022: impacts, adaptation and vulnerability *IPCC Sixth Assessment Report*
- Jordan P and Fröhle P 2022 Bridging the gap between coastal engineering and nature conservation? A review of coastal ecosystems as nature-based solutions for coastal protection *J. Coast. Conserv.* **26** 4
- Kabisch N et al 2016 Nature-based solutions to climate change mitigation and adaptation in urban areas: perspectives on indicators, knowledge gaps, barriers, and opportunities for action *Ecol. Soc.* **21** 15
- Karamouz M and Heydari Z 2020 Conceptual design framework for coastal flood best management practices *J. Water Resour. Plann. Manage.* **146** 04020041
- Karamouz M, Zoghi A and Mahmoudi S 2022 Flood modeling in coastal cities and flow through vegetated BMPs: conceptual design *J. Hydrol. Eng.* **27** 04022022
- Karanja J M and Saito O 2018 Cost–benefit analysis of mangrove ecosystems in flood risk reduction: a case study of the Tana Delta, Kenya *Sustain. Sci.* **13** 503–16
- Kumar P et al 2020 Towards an operationalisation of nature-based solutions for natural hazards *Sci. Total Environ.* **731** 138855
- Kumar P et al 2021 Nature-based solutions efficiency evaluation against natural hazards: modelling methods, advantages and limitations *Sci. Total Environ.* **784** 147058
- Leal Filho W, Abeldaño Zuñiga R A, Sierra J, Dinis M A P, Corazza L, Nagy G J and Aina Y A 2024 An assessment of priorities in handling climate change impacts on infrastructures *Sci. Rep.* **14** 14147
- Lee R et al 2024 Reclassifying historical disasters: from single to multi-hazards *Sci. Total Environ.* **912** 169120
- Liberati A, Altman D G, Tetzlaff J, Mulrow C, Götzsche P C, Ioannidis J P A, Clarke M, Devereaux P J, Kleijnen J and Moher D 2009 The PRISMA statement for reporting systematic reviews and meta-analyses of studies that evaluate health care interventions: explanation and elaboration *Ann. Intern. Med.* **151** W–65–W–94
- Lin C and Zhang S 2024 Impact of green roofs and walls on the thermal environment of pedestrian heights in urban villages *Buildings* **14** 4063
- Liu X, Wang Y, Costanza R, Kubiszewski I, Xu N, Gao Z, Liu M, Geng R and Yuan M 2019 Is China's coastal engineered defences valuable for storm protection? *Sci. Total Environ.* **657** 103–7
- Logan T, Guikema S D and Bricker J D 2018 Hard-adaptive measures can increase vulnerability to storm surge and tsunami hazards over time *Nat. Sustain.* **1** 526–30
- LRF 2025 *Nature-positive Engineering* (Lloyd's Register Foundation (LRF))
- Lu P, Sun Y and Steffen N 2023 Scenario-based performance assessment of green-grey-blue infrastructure for flood-resilient spatial solution: a case study of Pazhou, Guangzhou, greater Bay area *Landsc. Urban Plan.* **238** 104804
- Lüthi S et al 2023 Rapid increase in the risk of heat-related mortality *Nat. Commun.* **14** 4894
- MacKinnon K et al 2008 Biodiversity, climate change, and adaptation: nature-based solutions from the World Bank portfolio (World Bank)
- Mamo L T, Dwyer P G, Coleman M A, Dengate C and Kelaher B P 2022 Beyond coastal protection: a robust approach to enhance environmental and social outcomes of coastal adaptation *Ocean Coast. Manage.* **217** 106007
- Mancheño G A, Vuik V, van Wesenbeeck B K, Jonkman S N, van Hespren R, Moll J R, Kazi S, Urrutia I and van Ledden M 2024 Integrating mangrove growth and failure in coastal flood protection designs *Sci. Rep.* **14** 7951
- Marsooli R, Orton P M, Georgas N and Blumberg A F 2016 Three-dimensional hydrodynamic modeling of coastal flood mitigation by wetlands *Coast. Eng.* **111** 83–94
- Martin E G, Máñez Costa M and Schwerdtner Máñez K 2020 An operationalized classification of nature based solutions for water-related hazards: from theory to practice *Ecol. Econ.* **167** 106460
- Mastrandrea M D et al 2010 Guidance note for lead authors of the IPCC fifth assessment report on consistent treatment of uncertainties
- Mastrandrea M D, Mach K J, Plattner G-K, Edenhofer O, Stocker T F, Field C B, Ebi K L and Matschoss P R 2011 The IPCC AR5 guidance note on consistent treatment of uncertainties: a common approach across the working groups *Clim. Change* **108** 675–91
- Matthews T et al 2025 Mortality impacts of the most extreme heat events *Nat. Rev. Earth Environ* **6** 1–18
- Menéndez P, Losada I J, Torres-Ortega S, Narayan S and Beck M W 2020 The global flood protection benefits of mangroves *Sci. Rep.* **10** 4404
- Merz B, Hall J, Disse M and Schumann A 2010 Fluvial flood risk management in a changing world *Nat. Hazards Earth Syst. Sci.* **10** 509–27
- Möller I et al 2014 Wave attenuation over coastal salt marshes under storm surge conditions *Nat. Geosci.* **7** 727–31
- Montgomery J, Bryan K R and Coco G 2022 The role of mangroves in coastal flood protection: the importance of channelization *Cont. Shelf Res.* **243** 104762
- Morrison R R, Bray E, Nardi F, Annis A and Dong Q 2018 Spatial relationships of levees and wetland systems within floodplains of the Wabash Basin, USA *JAWRA J. Am. Water Resour. Assoc.* **54** 934–48
- Mudashiru R B, Sabtu N, Abustan I and Balogun W 2021 Flood hazard mapping methods: a review *J. Hydrol.* **603** 126846
- Narayan S, Beck M W, Reguero B G, Losada I J, van Wesenbeeck B, Pontee N, Sanchirico J N, Ingram J C, Lange G-M and Burks-Copes K A 2016 The effectiveness, costs and coastal protection benefits of natural and nature-based defences *PLoS One* **11** e0154735

- Nardella L, Sebastiani A, Stafoggia M, Buonocore E, Paolo Franzese P and Manes F 2024 Modeling regulating ecosystem services along the urban–rural gradient: a comprehensive analysis in seven Italian coastal cities *Ecol. Indic.* **165** 112161
- Nehren U et al 2023 Towards a typology of nature-based solutions for disaster risk reduction *Nat. Based Sol.* **3** 100057
- NPI 2023 The definition of nature positive (Nature Positive Initiative (NPI))
- Ou X, Lyu Y, Liu Y, Zheng X and Li F 2022 Integrated multi-hazard risk to social-ecological systems with green infrastructure prioritization: a case study of the Yangtze River Delta, China *Ecol. Indic.* **136** 108639
- Paszkowski A, Goodbred S, Borgomeo E, Khan M S A and Hall J W 2021 Geomorphic change in the Ganges–Brahmaputra–Meghna delta *Nat. Rev. Earth Environ.* **2** 763–80
- Pontee N I 2015 Impact of managed realignment design on estuarine water levels *Proc. Inst. Civ. Eng. Marit. Eng.* **168** 48–61
- Prado H A, Rodrigues T, Manes S, Kasecker T, Vale M M, Scarano F R and Pires A P F 2024 Designing nature to be a solution for climate change in cities: a meta-analysis *Sci. Total Environ.* **954** 176735
- Qin P, Jiang Y and Cheng C 2024a How do structural safety, ecological functions and social development influence construction of ecological seawalls for coastal protection and sustainability? *Water Resour. Manage.* **38** 1807–24
- Qin X, Wang S and Meng M 2024b SEA for better climate adaptation in the face of the flood risk: multi-scenario, strategic forecasting, nature-based solutions *Environ. Impact Assess. Rev.* **106** 107495
- Quataert E, Storlazzi C, van Rooijen A, Cheriton O and van Dongeren A 2015 The influence of coral reefs and climate change on wave-driven flooding of tropical coastlines *Geophys. Res. Lett.* **42** 6407–15
- Rahman M M, Schaab C and Nakaza E 2017 Experimental and numerical modeling of tsunami mitigation by canals *J. Waterw. Port Coast. Ocean Eng.* **143** 04016012
- Reguero B G, Beck M W, Bresch D N, Calil J and Meliane I 2018 Comparing the cost effectiveness of nature-based and coastal adaptation: a case study from the Gulf Coast of the United States *PLoS One* **13** e0192132
- Renaud F G et al 2016 *Ecosystem-based Disaster Risk Reduction and Adaptation in Practice* (Springer)
- Seujip M S, Bertin X, Sakho I and Diouf M B 2024 Impact of mangrove on tidal propagation in a tropical coastal lagoon *Environ. Earth Sci.* **83** 52
- Shah M A R et al 2023 Quantifying the effects of nature-based solutions in reducing risks from hydrometeorological hazards: examples from Europe *Int. J. Disaster Risk Reduct.* **93** 103771
- Sheng P Y, Paramygin V A, Rivera-Nieves A A, Zou R, Fernald S, Hall T and Jacob K 2022 Coastal marshes provide valuable protection for coastal communities from storm-induced wave, flood, and structural loss in a changing climate *Sci. Rep.* **12** 3051
- Sohn W, Brody S D, Kim J-H and Li M-H 2020 How effective are drainage systems in mitigating flood losses? *Cities* **107** 102917
- Sowińska-Świerkosz B and García J 2022 What are Nature-based solutions (NBS)? Setting core ideas for concept clarification *Nat. Based Sol.* **2** 100009
- Spyrou C, Koukoulou M, Saviolakis P-M, Zerefos C, Loupis M, Masouras C, Pappa A and Katsafados P 2024 Green roofs as a nature-based solution to mitigate urban heating during a heatwave event in the City of Athens, Greece *Sustainability* **16** 9729
- Stark J, Plancke Y, Ides S, Meire P and Temmerman S 2016 Coastal flood protection by a combined nature-based and engineering approach: modeling the effects of marsh geometry and surrounding dikes *Estuarine Coastal Shelf Sci.* **175** 34–45
- Stark J, Van Oyen T, Meire P and Temmerman S 2015 Observations of tidal and storm surge attenuation in a large tidal marsh *Limnol. Oceanogr.* **60** 1371–81
- Steinfeld C and Kingsford R T 2013 Disconnecting the floodplain: earthworks and their ecological effect on a dryland floodplain in the Murray–Darling Basin, Australia *River Res. Appl.* **29** 206–18
- Sudmeier-Rieux K et al 2021 Scientific evidence for ecosystem-based disaster risk reduction *Nat. Sustain.* **4** 803–10
- Syvitski J P 2008 Deltas at risk *Sustain. Sci.* **3** 23–32
- Toth L T et al 2023 The potential for coral reef restoration to mitigate coastal flooding as sea levels rise *Nat. Commun.* **14** 2313
- Türker U, Yagci O and Kabdasli M S 2019 Impact of nearshore vegetation on coastal dune erosion: assessment through laboratory experiments *Environ. Earth Sci.* **78** 1–14
- UN 2021 *United Nations Decade on Ecosystem Restoration 2021–2030* (United Nations (UN) Environment Programme)
- UNDRR 2017 *Sendai Framework Terminology on Disaster Risk Reduction* (United Nations Office for Disaster Risk Reduction (UNDRR))
- UNDRR 2021 *Words into Action: Nature-based Solutions for Disaster Risk Reduction* (United Nations Office for Disaster Risk Reduction (UNDRR))
- Unguendoli S, Biolchi L G, Aguzzi M, Pillai U P A, Alessandri J and Valentini A 2023 A modeling application of integrated nature based solutions (NBS) for coastal erosion and flooding mitigation in the Emilia-Romagna coastline (Northeast Italy) *Sci. Total Environ.* **867** 161357
- Van Coppenolle R, Schwarz C and Temmerman S 2018 Contribution of mangroves and salt marshes to nature-based mitigation of coastal flood risks in major deltas of the world *Estuar. Coasts* **41** 1699–711
- Van Dang H, Park H, Shin S, Tomiczek T, Cox D T, Lee E, Lee D and Lomonaco P 2023 Physical model comparison of gray and green mitigation alternatives for flooding and wave force reduction in an idealized urban coastal environment *Coastal Eng.* **184** 104339
- Van Hesperen R et al 2023 Mangrove forests as a nature-based solution for coastal flood protection: biophysical and ecological considerations *Water Sci. Eng.* **16** 1–13
- van Veelen T J, Karunarathna H and Reeve D E 2021 Modelling wave attenuation by quasi-flexible coastal vegetation *Coastal Eng.* **164** 103820
- van Zelst V T, Dijkstra J T, van Wesenbeeck B K, Eilander D, Morris E P, Winsemius H C, Ward P J and de Vries M B 2021 Cutting the costs of coastal protection by integrating vegetation in flood defences *Nat. Commun.* **12** 6533
- Viechtbauer W 2010 Conducting meta-analyses in R with the metafor package *J. Stat. Softw.* **36** 1–48
- Vojinovic Z, Alves A, Gómez J P, Weesakul S, Keerakamolchai W, Meesuk V and Sanchez A 2021 Effectiveness of small-and large-scale nature-based solutions for flood mitigation: the case of Ayutthaya, Thailand *Sci. Total Environ.* **789** 147725
- Vörösmarty C J, Syvitski J, Day J, de Sherbinin A, Giosan L and Paola C 2009 Battling to save the world's river deltas *Bull. At. Sci.* **65** 31–43
- Wansbury C 2024 Briefing: time for transformation—the opportunity for civil engineering to contribute to a nature-positive future *Proc. Inst. Civ. Eng. Civ. Eng.* **177** 150–3
- Warner J F, van Staveren M F and van Tatenhove J 2018 Cutting dikes, cutting ties? Reintroducing flood dynamics in coastal

- polders in Bangladesh and the netherlands *Int. J. Disaster Risk Reduct.* **32** 106–12
- White G F 1942 *Human Adjustment to Floods: A Geographical Approach to the Flood Problem in the United States* (The University of Chicago)
- Xu D-S, Yan Y-L, Wang X and Qin Y 2023 Numerical modelling of the physical response of coral reef Sandy island to sea level rise by considering seasonal patterns *Ocean Coast. Manage.* **245** 106860
- Zhang K, Liu H, Li Y, Xu H, Shen J, Rhome J and Smith T J 2012 The role of mangroves in attenuating storm surges *Estuarine Coastal Shelf Sci.* **102** 11–23
- Zhao H and Chen Q 2016 Modeling attenuation of storm surge over deformable vegetation: parametric study *J. Eng. Mech.* **142** 06016006
- Zuniga M C S *et al* 2020 Increasing infrastructure resilience with nature-based solutions (NbS)