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# Multiple criteria-based assessment of Nature-based Solutions for flood management: A systematic review

Lorette Gallois<sup>a,b</sup>, Elisabeth Hirtz<sup>a</sup>, Marc van den Homberg<sup>b,c</sup>, Jeewanthi Sirisena<sup>d</sup>, Shreya Mozumdar<sup>a,b</sup>, Marco Cinelli<sup>a,e,\*</sup>

<sup>a</sup> Decision Engineering for Sustainability and Resilience Laboratory, Leiden University College, Faculty Governance and Global Affairs, Leiden University, 2595DG, The Hague, the Netherlands

<sup>b</sup> The Netherlands Red Cross data and digital unit 510, 2593HT, The Hague, the Netherlands

<sup>c</sup> Faculty of Geo-Information Science and Earth Observation/ITC, University of Twente, 7522 NH, Enschede, the Netherlands

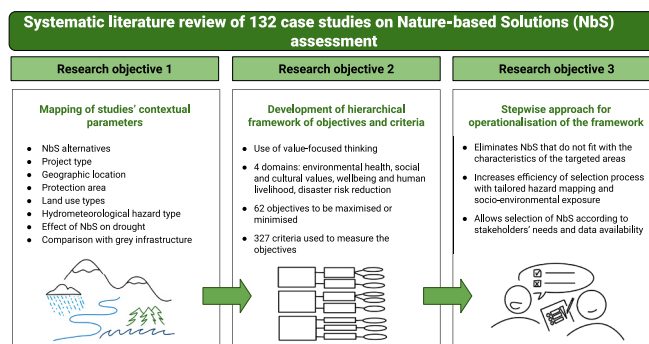
<sup>d</sup> Climate Service Center Germany (GERICS), Helmholtz-Zentrum Hereon, 20095, Hamburg, Germany

<sup>e</sup> Institute of Environmental Sciences (CML), Faculty of Science, Leiden University, 2300 RA, Leiden, the Netherlands

## HIGHLIGHTS

- Lack of comprehensive overview of NbS objectives, assessment criteria, and targeted areas
- Literature review of 92 scientific papers and analysis of 132 case studies
- Hierarchical set of 62 objectives and 327 criteria to evaluate NbS performance
- Stepwise approach for selection of suitable NbS according to area characteristics and NbS benefits
- Decision support tool to combine land suitability and benefits of NbS

## GRAPHICAL ABSTRACT



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## ABSTRACT

Nature-based Solutions (NbS) offer a promising strategy for mitigating flood risks and enhancing resilience to climate change. Despite the recognised benefits of NbS, a comprehensive overview of their targeted areas, objectives, and assessment criteria remains lacking. Our systematic review fills this gap by synthesizing 132 case studies into a structured framework of 62 objectives across four domains: environmental health, social and cultural values, human well-being and livelihoods, and disaster risk reduction. This was achieved via a Multiple Criteria Decision Analysis approach inspired by value-focused thinking. Value-focused thinking allowed mapping what stakeholders aim to achieve, expressed as objectives to be either maximised or minimised. Objectives were clustered, leading to a hierarchy with categories and domains. Each objective has at least one criterion or a few criteria to measure the performance of the NbS. We found limited guidance in recommending relevant criteria according to stakeholders' needs. There are a multitude of case studies for the Global North, but much less for the Global South, though the latter is disproportionately impacted by climate change. We proposed a three-stage

\* Corresponding author at: Decision Engineering for Sustainability and Resilience Laboratory, Leiden University College, Faculty Governance and Global Affairs, Leiden University, 2595DG, The Hague, the Netherlands.

E-mail address: [m.cinelli@luc.leidenuniv.nl](mailto:m.cinelli@luc.leidenuniv.nl) (M. Cinelli).

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approach for selecting NbS alternatives, encompassing land suitability features, socio-environmental risk, and NbS benefits. The proposed hierarchical framework allows stakeholders to tailor their evaluation process to their context and objectives and navigate complex decision-making more effectively. Our findings highlight the importance of stakeholder-driven objectives and traceable assessment criteria. Moving forward, decision support tools integrating context-specific metrics can facilitate decision-making and encourage the widespread adoption of NbS initiatives.

## 1. Introduction

### 1.1. NbS for hydrometeorological disaster risk reduction

Hydrometeorological hazards have globally increased in frequency and intensity, driven primarily by climate change and exacerbated by the interconnected processes of population growth, land use alteration, and urbanisation (IPCC, 2022; Pugliese et al., 2022). Among these hydrometeorological hazards, flooding and drought events have severe impacts on populations and livelihoods. Flood events (whether fluvial, pluvial, or coastal which includes both sea-level rise and storm surge) cause substantial property damage and high numbers of casualties globally (Bae et al., 2021; Rezaie et al., 2020). Furthermore, damages to infrastructure and facilities as well as crop and livestock loss endanger vulnerable populations who depend on these resources (van Coppenolle et al., 2018; Bae et al., 2021). In addition to putting human populations at risk, floods also threaten biodiversity and ecosystem services (Zhang et al., 2021). They cause species death and possible local extinctions, leading to decreases in regulating (e.g., water filtration), supporting (e.g., habitat), provisioning (e.g., food and fuel production), and cultural services (e.g., aesthetic value of nature) (Zhang et al., 2021; TEEB, 2010).

Humanitarian and governmental organisations rely on the Disaster Risk Reduction (DRR) framework to develop and implement strategies aimed at mitigating the adverse effects of flood hazards on populations. This framework is further enriched by the guiding principles outlined in the Sendai Framework for DRR, emphasizing the global imperative for concerted action in DRR efforts (United Nations, 2015). In the last decade, conservation organisations such as the World Wide Fund for Nature (WWF), have also used an ecosystem-based DRR framework (Eco-DRR), integrating it with broader strategies for conservation, nature protection, and ecosystem restoration. These approaches are not only integral to climate change adaptation but also aim to reduce risks for both nature and populations (WWF, 2010). Originally developed to help governments limit the impacts of disasters, the DRR framework aims at helping build communities' resilience to better mitigate and prepare for disasters (Rana et al., 2021). Disaster risk management (the objective of which is DRR), is typically composed of four stages, namely: response, recovery, mitigation, and preparedness (Rana et al., 2021; UNISDR, 2016). While the response and recovery phases are further classified into a post-disaster phase, mitigation and preparedness fall into the pre-disaster phase (Rana et al., 2021). Moreover, it is argued that climate change adaptation measures need to be integrated into the DRR cycle framework, especially relevant in pre-disaster phases, as climate change enhances the frequency and intensity of flood events (Rana et al., 2021). On the one hand, humanitarian organisations act during the response and preparedness phases, with short-term actions, their objectives being to save lives and protect livelihoods (IFRC, 2013). For example, early warning systems provide "timely and meaningful warning information that enables at-risk individuals, communities and organisations to prepare and act appropriately and in sufficient time to reduce harm or loss" (IFRC, 2013). These actions must take place within the (short) timeframe from when the forecast is issued until the occurrence of the event that is forecasted to happen. This means that humanitarian organisations can only initiate short-term actions in the preparedness phase of the DRR framework (IFRC, 2013). On the other hand, conservation organisations' goals typically fit in the mitigation

phase, with more long-term actions aimed at preserving biodiversity and ecosystem services. These long-term actions can, for instance, involve implementing grey infrastructure or nature-based solutions to mitigate the impacts of a disaster (WWF, 2020).

Long-term solutions are essential to sustainably decrease the vulnerability of populations in the face of flood disasters. Traditional water management solutions to mitigate floods and protect communities include the use of grey infrastructure such as dikes, dams, or seawalls (Hewett et al., 2020). However, the use of these engineered solutions is challenged due to their economic and environmental costs (Rojas et al., 2022). For instance, they have been found to disrupt hydrological cycles, prevent sediment accumulation, increase land subsidence, and have had negative impacts on biodiversity (Firth et al., 2020). Furthermore, from a life cycle perspective, the consumption of raw materials during the construction phase of grey infrastructure leads to high environmental impacts and economic costs (Xu et al., 2021). This is why, in recent decades, more focus has been brought on the use of ecosystem-based or Nature-based Solutions (NbS) to reduce the impacts of flooding and other disasters more sustainably (Pineda-Pinto et al., 2022).

NbS are defined as "actions to protect, sustainably manage and restore natural and modified ecosystems that address societal challenges effectively and adaptively, simultaneously benefiting people and nature" (IUCN, 2020). By reproducing natural processes, NbS have shown to provide multiple environmental, social, and economic benefits in addition to their technical performance in mitigating the impacts of various hazards such as floods and droughts (Pineda-Pinto et al., 2022; Wójcik-Madej and Sowińska-Świerkosz, 2022; Nassary et al., 2022; van Coppenolle et al., 2018). Furthermore, NbS have been implemented to mitigate flooding impacts in different contexts such as in rural, urban, coastal, or mountainous settings (Dorren and Moos, 2022; Pitman et al., 2015). Wetlands, floodplains, sand dunes, and beaches are some examples of NbS that can mitigate flooding (Watson et al., 2016). It is important to note that NbS refer not to the ecosystems themselves but to these ecosystems' natural processes that provide benefits such as flood management (Sowińska-Świerkosz and García, 2022). Some benefits of ecosystem services provided by NbS include storm surge attenuation, increased species richness, resource provision, increased tourism, and improvements in public health (van Coppenolle et al., 2018; Nassary et al., 2022; Sauer et al., 2022; Pugliese et al., 2022). In the context of this study, NbS are useful solutions that align with the short- and long-term objectives of both humanitarian and conservation organisations in their application of the DRR and Eco-DRR (DeWit et al., 2022).

Due to the multifunctional essence of NbS, their assessment and monitoring should focus on their environmental, social, economic, and risk reduction benefits (Pugliese et al., 2022). In addition, the knowledge and preferences of multiple stakeholders (e.g., technical teams, investors, policymakers, local population) should be included in the development of shared decisions about NbS development (Geukes et al., 2024). A methodology that has been proven as one of the most relevant to tackle multidimensional assessments, while at the same time integrating transparently multiple stakeholders, is Multiple Criteria Decision Analysis (MCDA) (Munda, 2023; Aubert and Lienert, 2024). The contributions of MCDA to NbS decision-making have also been recently discussed in the scientific literature, notably by Ruangpan et al. (2021) and Pugliese et al. (2022). MCDA is a methodology that allows the assessment and comparison of a set of alternatives to assist Decision-Makers (DMs) in making more informed decisions (Cinelli et al., 2020);

Greco et al., 2016). MCDA enables assessing alternatives by accounting for criteria (also called variables or indicators) and preferences of different types that can span across the environmental, social, and economic domains (Wątróbski et al., 2019; Greco et al., 2016). Finally, it provides the DMs with a decision recommendation (e.g., ranking, sorting, choice) by integrating performance ratings for each alternative and preference information on criteria priorities, among others (Lindfors, 2021). The use of MCDA is thus relevant to provide a more holistic assessment of NbS' performances (Pugliese et al., 2022).

### 1.2. Current frameworks to assess NbS

Several studies have employed MCDA frameworks to assess NbS and have shown the applicability of the method to a range of environmental and socio-economic contexts (Ruangpan et al., 2021; Caroppi et al., 2023; Raymond et al., 2017; Pugliese et al., 2022). The studies by Raymond et al. (2017) and Jayasooriya et al. (2019) specifically focus on the assessment of green infrastructure and NbS measures in urban contexts. Raymond et al. (2017) developed a framework for the design and implementation of urban NbS and to assess their performance on ten key societal criteria in urban areas (e.g., climate mitigation and adaptation, participatory planning and governance, coastal resilience). Based on a structured literature review and multi-stakeholder involvement, the framework identifies a set of criteria for each societal challenge that can measure the impacts of NbS implemented in urban areas (Raymond et al., 2017). The framework advanced by Jayasooriya et al. (2019) also builds upon stakeholders' preferences to select performance measures included in a MCDA to select the most appropriate green infrastructure alternative for stormwater management. Although the two frameworks only focus on urban and industrial contexts and are thus limited in their scope, they highlight the necessity of stakeholder elicitation and the relevance of an MCDA approach for effective implementation of NbS (Raymond et al., 2017; Jayasooriya et al., 2019). Caroppi et al. (2023) developed a MCDA-based assessment tool aimed at assessing the hydrometeorological risk reduction and co-benefits (i.e., additional non-intended benefits, beyond the primary objectives initially targeted) of NbS, hybrid and grey infrastructure alternatives in rural and mountainous areas. Their assessment tool is structured around five domains: (1) risk reduction, (2) technical and feasibility aspects, (3) environment and ecosystems, (4) society, and (5) local economy, which are then further divided into categories and objectives (Caroppi et al., 2023). Finally, the framework identifies key performance indicators and indicator information (e.g., metric, direction, and typology) to evaluate the performance of alternatives for each objective (Caroppi et al., 2023). A similar assessment framework was used to compare the performance of a NbS implemented for flood management with a traditional grey infrastructure in a case study on the Isar River in Munich, Germany, as part of the PHUSICOS project (Pugliese et al., 2022; Autuori et al., 2019). Ruangpan et al. (2021) developed a comprehensive MCDA framework to select NbS for different contexts (i.e., urban areas, river basins, coastal areas) and hazards (i.e., fluvial floods, pluvial floods, flash floods, coastal floods, droughts and landslides). In line with the framework by Caroppi et al. (2023) which identified domains and criteria, their MCDA framework is structured around goals and subgoals used to evaluate the selected NbS measures using stakeholders' preferences (Ruangpan et al., 2021). In another project focused on the benefits of floodplain restoration beyond flood risk reduction in the Danube catchment, Perosa et al. (2021) used the concept of ecosystem services as a basis for the identification of criteria to measure the performance of NbS alternatives. Specifically, they employed the Toolkit for Ecosystem Service Site-based Assessment (TESSA) to evaluate floodplain restoration across six ecosystem services groups (Perosa et al., 2021). Finally, Ruangpan et al. (2020) conducted a state-of-the-art review on NbS for hydrometeorological risk reduction, providing an overview of a range of benefits arising from the implementation of small-scale and large-scale NbS. Although the review of Ruangpan et al. (2020) displays several NbS

alternatives as well as their costs, area or volume, and effectiveness, the analysis of the specific environmental, technical, and socio-economic criteria used to measure NbS performance is not included. This overview shows that scientific literature provides frameworks for assessing the performance of NbS, but these focus only on very specific urban and rural contexts. Additionally, these frameworks often rely on a range of criteria that have not followed a harmonised and consistent selection process, as they did not select the criteria through a comprehensive literature review of all potential benefits.

### 1.3. Contributions of this paper

This paper addresses the lack of a systematic analysis of the existing literature on MCDA-based assessment of NbS. The *first objective* of this study is to explore how suitable NbS can be selected according to intrinsic characteristics of the area of interest. The *second objective* of this research is to provide a comprehensive and harmonised framework of environmental, socio-economic, and risk reduction objectives and criteria to assess NbS benefits. Lastly, due to the importance of making conceptual frameworks operational (e.g., see the case of Safe and Sustainable by Design framework of the European Commission (Caldeira et al., 2024)), the *third objective* of this study is to shape an approach to enable the application of our framework to real-world case studies.

The paper is organised as follows. Section 2 introduces the methodology (i.e., a systematic literature review) to develop the framework. Section 3 is divided into four sub-sections and provides results and discussion points. Sub-section 3.1 covers objective (1) and presents an overview of the NbS alternatives analysed in the selected records, as well as the contextual parameters of each case study (e.g., type of project, geographic location, protection area, targeted hazard). Sub-section 3.2 covers objective (2) and presents the framework of benefits identified through the analysis of the case studies. Sub-section 3.3 covers objective (3) and introduces a three-stage approach towards the operationalisation of the framework of objectives. Section 3.4 discusses the study's limitations. Section 4 concludes the study and offers recommendations for further research.

## 2. Methodology

A systematic literature review based on the methodology described by Siddaway et al. (2019) was conducted to screen the available academic literature evaluating large-scale NbS for flood management. This method was chosen as it is a reliable, replicable, and transparent way to provide an overview of the scientific knowledge on NbS and of the gaps in research (Siddaway et al., 2019). The results from the identification, screening, eligibility, and inclusion phases of the SLR were then reported in a Preferred Reporting Items for Systematic reviews and Meta-Analyses (PRISMA) diagram (Page et al., 2021).

### 2.1. Search terms identification

To study the use of NbS as a means for disaster risk reduction and environmental protection relating to flood impacts, search terms were divided into three categories: (1) terms linked to alternatives for environmental safeguarding, (2) terms linked to disaster risk reduction, and development, and (3) terms linked to the types of natural hazard studied. The search string used consisted of the following:

("nature-based solutions" OR "green infrastructure" OR "landscape restoration" OR "community-based land and water management" OR "ecosystem conservation" OR "climate resilience" OR "ecosystem restoration" OR "ecosystem protection" OR "ecosystem management" OR "environmental protection" OR "eco\* disaster" OR "ecosystem creation") AND ("disaster risk reduction" OR "humanitarian aid" OR "humanitarian development" OR "resilience" OR "vulnerability" OR "risk" OR "climate change adaptation" OR "anticipatory action") AND ("flood\*" OR "storm surge").

2.2. Screening and eligibility of case studies

The search was conducted on the search engine Web of Science ([www.webofscience.com](http://www.webofscience.com)), which is one of the most authoritative scientific databases, and the resulting papers were extracted from the website on the 19th of February 2023. The aim was to include case studies focusing on the implementation of NbS for flood management and the monitoring of their performance on risk reduction and co-benefits they also provide. These case studies had to include specific NbS alternatives implemented in a clearly defined geographical context. This enabled us to relate the area-specific socio-cultural characteristics with the benefits brought by the NbS. Once the search results were obtained, the resulting paper titles and abstracts were screened, and

studies were excluded if they met any of the exclusion criteria. The exclusion criteria for the titles, abstracts, and articles were:

- 1) Unavailable in English
- 2) Paper is a literature review
- 3) Duplicate papers
- 4) Not about NbS or no specific NbS alternative studied
- 5) No focus on flood mitigation performance of NbS
- 6) NbS are urban interventions
- 7) Focus is on developing or testing the accuracy of a model
- 8) Study does not assess NbS and only provides governance and policy recommendations
- 9) Studies about best location for implementation of NbS

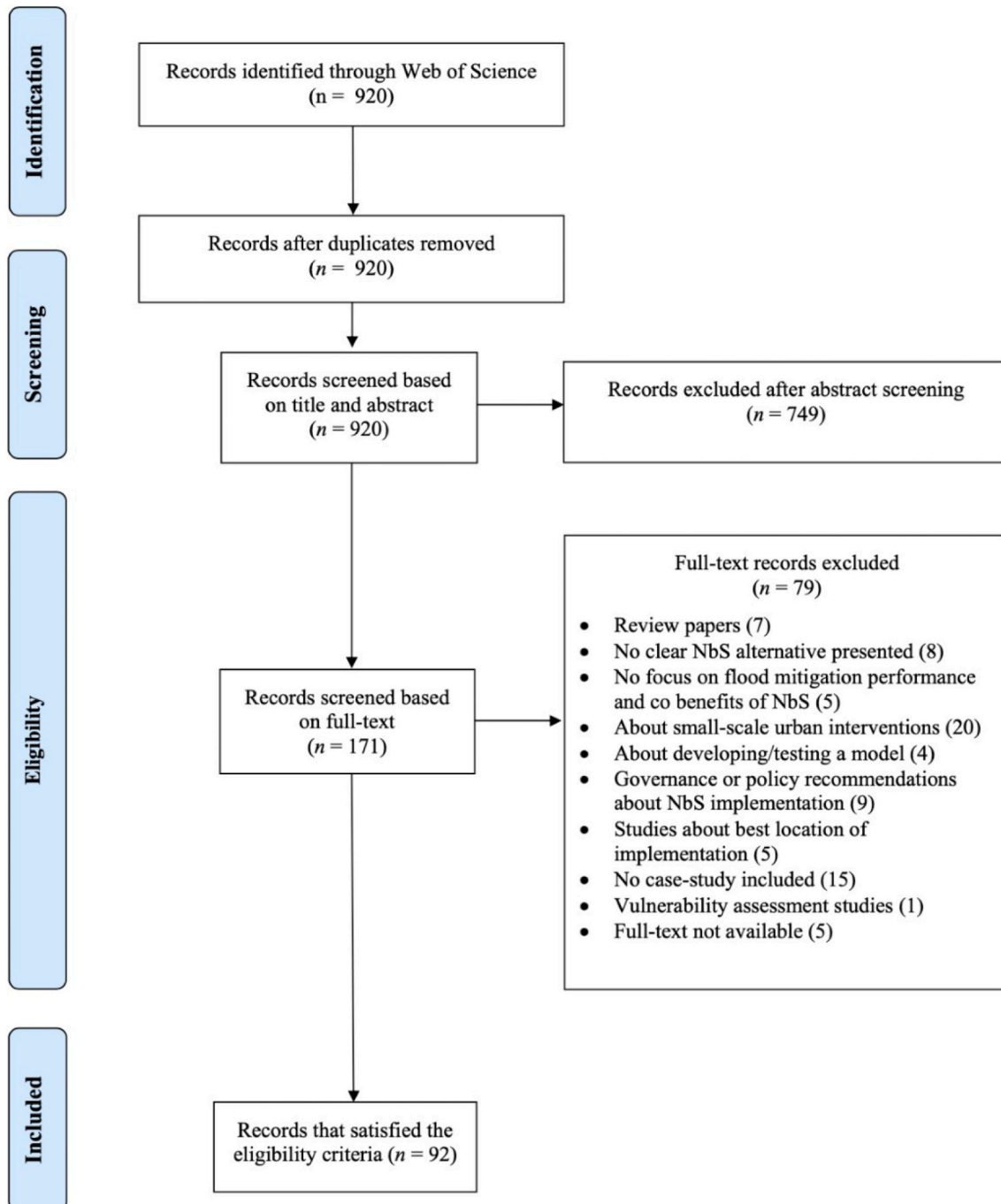


Fig. 1. Overview of the systematic literature review selection process based on the PRISMA guidelines from Page et al. (2021), with ‘n’ the number of papers remaining after each step of the selection.

- 10) No case study included
- 11) Flooding impact assessments
- 12) Full text is unavailable

A similar process was then applied for the screening of full texts.

The application of search terms in the Web of Science database resulted in 920 records, which were screened for duplicates (Fig. 1). There were no duplicates, and 920 articles were thus screened based on title and abstract. During this selection step, 749 articles were excluded, which led to 171 records included for full-text screening. Out of these 171 records, 79 were excluded, mainly because the articles did not include a case study (19 %), or the focus was on small-scale urban NbS implementations (25 %), which did not meet the inclusion criteria of large-scale measures. Finally, 92 records were included in the literature review. From these 92 records, a total of 132 case studies were analysed.

In addition, we constructed a keyword map to visually identify patterns of co-occurrence and relationships among the selected terms, and to highlight dominant themes and their interconnections within the literature, which emphasises research focus areas in the selected articles (Figure A in the ESM) (van Eck and Waltman, 2023).

### 2.3. Analysis of the peer-reviewed literature

The selected papers were analysed after screening (Table A: Table used to record land features, NbS measure characteristics, and objectives

and criteria from studies; in the ESM). To explore how suitable NbS can be selected based on the intrinsic characteristics of specific areas (*objective 1*), the first component of the analysis involved recording the contextual land features and hazard types associated with the NbS alternatives, drawing on those identified by Ruangpan et al. (2021). The analysis began by documenting NbS alternatives and project types (whether the studied NbS was a new measure or the improvement of an existing measure). It was followed by categorizing the land features of their implementation, including geographic location, type of targeted protection area (i.e., the affected area, which is categorised as coastal, mountainous, river basin, and urban, non-urban or both), and prevalent land use types (agricultural land, forested land, artificial surfaces, wetlands, water bodies). Following these land features, the hydrometeorological hazard types (fluvial flood, flash flood, pluvial flood, sea-level rise or storm surge) were also analysed. The results from the above-mentioned analysed features are visualised in Table 1. The table includes relative frequencies of NbS alternatives analysed in relation to each land features and hydro-meteorological hazards. These frequencies provide an overview of the type and quantity of NbS alternatives documented in the case studies and indicate how these alternatives were analysed concerning specific land features and hazards. The frequencies were calculated and then used to fill in the cells of the table linking rows (NbS alternatives) with columns (land features and hazard types) according to Eq. (1):

$$Relative\ frequency_{land\ feature\ or\ hazard} = \frac{number\ of\ case\ studies\ assessing\ the\ NbS\ alternative\ with\ a\ land\ feature\ or\ hazard}{total\ number\ of\ case\ studies\ assessing\ that\ NbS\ alternative} \quad (1)$$

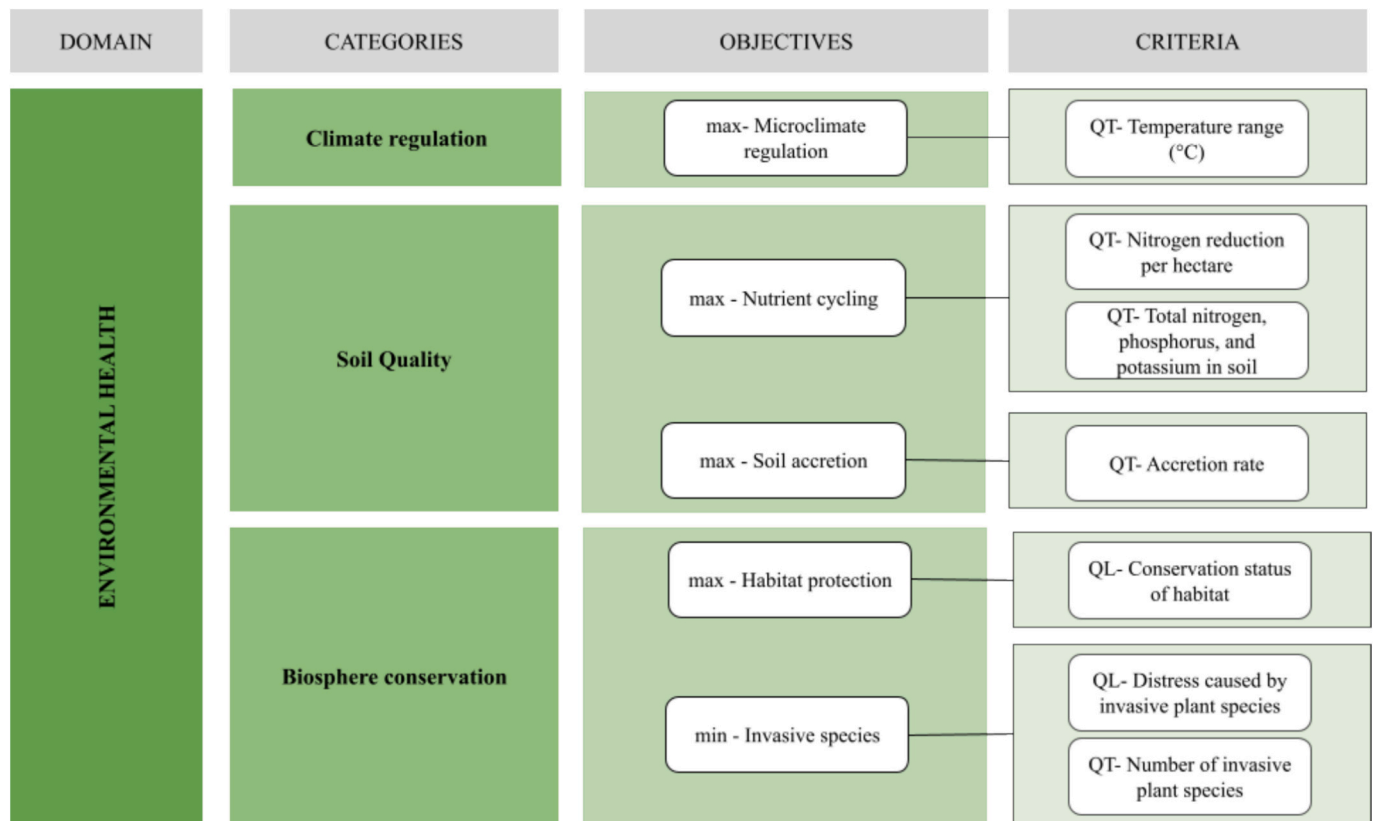


Fig. 2. Example of visualisation of an objectives' hierarchy for the environmental health domain. QT = quantitative, QL = qualitative.

In addition to geographic location, type of protection area, prevalent land use types, and hydrometeorological hazard type, we recorded whether the study mentioned effects of the NbS on drought events. Droughts relate to periods of below average precipitation which lead to impacts on ecosystems, agriculture, and thus population livelihoods (Juana et al., 2014). Given that some NbS alternatives affect technical aspects such as infiltration capacity, it is highly relevant to study the impact of flooding management NbS on droughts and ensure that their implementation will not worsen the effects of droughts and water scarcity events on both nature and populations (Penning et al., 2023). In addition, most of the current literature focuses on NbS measures' potential for targeting a single hazard, whereas research points to the need to study the combination of hazards (Penning et al., 2023). Finally, our analysis mentioned whether the case studies analysed the performance of NbS in comparison with other grey measures.

To address *objective 2*, the second component of the literature analysis was based on a conceptualisation of how to assess benefits of the NbS. This was achieved via an MCDA approach inspired by value-focused thinking (VFT) (Keeney and Parnell, 2007; Keeney, 1992). VFT is a way of approaching complex decision-making that emphasises the need to identify the values that stakeholders have to solve a decision problem (Keeney, 2004). These values are directly related to what the stakeholders aim to achieve, which can be expressed as objectives to be either maximised or minimised (Keeney, 2007). For example, assuming noise pollution and air quality as two objectives, the first should be minimised, while the latter should be maximised. Objectives can then be clustered in groups of relevance, leading to hierarchies. These hierarchies can have multiple levels, starting from the highest possible level, called domain, followed by more granular levels, which we label as categories. In our case, the framework was constructed inductively: we first identified 62 specific objectives across the case studies, then organised these into 12 distinct categories based on thematic similarities and finally grouped these categories into four main domains (*environmental health, social and cultural values, human well-being and livelihood, and disaster risk reduction*). The last step of the VFT approach we used involves the operationalisation of the objectives, meaning the definition of how each objective can be measured using criteria (Keeney and Gregory, 2005). Two types of criteria were chosen for this purpose, either qualitative or quantitative. Quantitative criteria are those that relate to objectives that can be verified using measurements and experiments (Cinelli et al., 2022). Qualitative criteria are those that relate to objectives that cannot be measured quantitatively – instead, subjective judgements are used to characterise the performance on a preference-oriented scale (e.g., good, medium, bad performance

(Keeney and Parnell, 2007)). Fig. 2 displays an example of an objectives' hierarchy, with four levels: domain, categories, objectives, and criteria, as described above. This visualisation exemplifies the fact that a category can contain multiple objectives, and that a single objective can also be measured using different criteria, qualitative or quantitative.

### 3. Results and discussion

#### 3.1. NbS alternatives and their contextual land features

##### 3.1.1. NbS alternatives

A total of 28 alternatives has been identified through the analysis of 132 case studies. The most frequently analysed NbS alternatives were wetlands, an umbrella term also encompassing marshes, swamps, or fens, studied in 18.9 % ( $n = 25$ ) of case studies (Rojas et al., 2022; Andrikopoulou et al., 2021; Dang et al., 2021). River restoration was the second most studied NbS alternative, at 18.2 % ( $n = 24$ ) (Spyrou et al., 2022; Dubo et al., 2023; Mukherjee et al., 2022). Floodplain restoration was analysed in 14.4 % of records ( $n = 19$ ) (Fonner et al., 2022; Worley et al., 2022). Multiple NbS alternatives could be recorded in a single study, either because the study focused on the implementation of a combination of NbS, or because it assessed more than one alternative.

##### 3.1.2. Project type

For the 132 analysed case studies, 68.9 % included NbS alternatives that are improvements to existing measures. This mostly included measures such as reforestation, which refers to forest restoration (i.e., efforts aimed at rehabilitating degraded forest areas to their original state of biodiversity and ecological function (Lavers et al., 2022; Gunnell et al., 2019)). This alternative differs from afforestation, which refers to the planting of trees in an area that was not previously forested land and is thus considered a new measure. Additionally, restoration projects such as wetland, mangrove, or coral reef restoration, involve the rehabilitation of degraded ecosystems to enhance their ecological integrity and functionality and thus fall into the category of improvements to existing measures (Mukherjee et al., 2022; Ourloglou et al., 2020; Daigneault et al., 2016). New measures were studied in 30.3 % of the studies while the remaining 0.8 % of studies did not specify whether the NbS was an existing or a new measure.

The percentage of studies focusing on new NbS measures was lower than the percentage of studies focusing on existing NbS measures (respectively 31.1 % and 68.9 %). Improving an existing NbS through restoration might be more cost-efficient than implementing a new measure. Restoration can be more easily accepted by communities and might reach effectiveness for flood reduction faster (Seddon et al.,

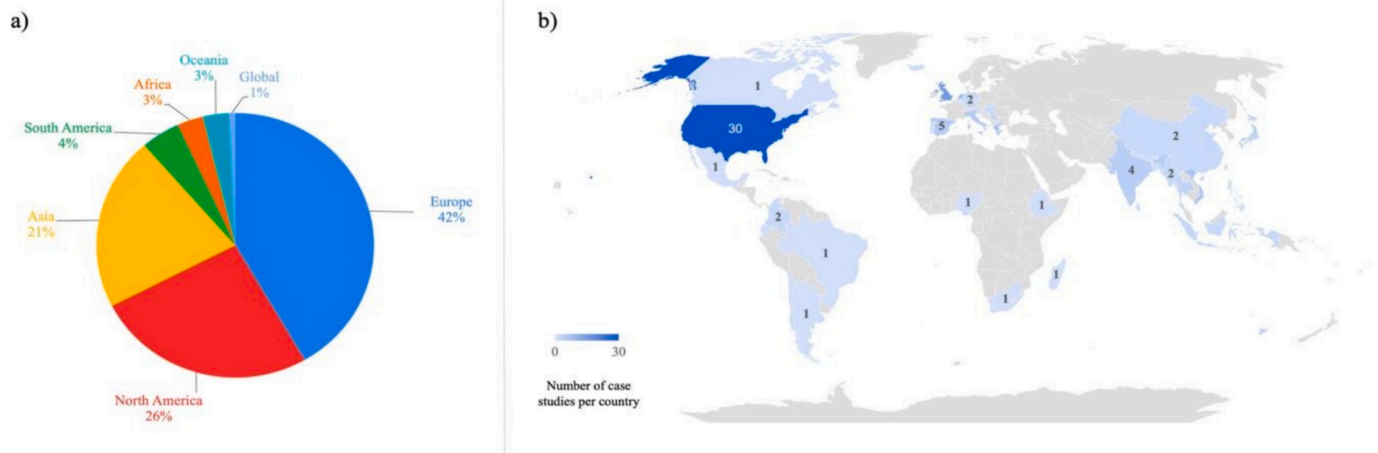


Fig. 3. (a) Relative frequency of case study geographic location per continent; (b) Geographic distribution of case studies of NbS worldwide, with a total of 132 case studies.

2020). In addition, there are several governance barriers to the implementation of new NbS measures, pertaining to the approval and issuance of land-use rights and permits, and to trade-offs between using land for agricultural purposes or for ecosystem restoration (Seddon et al., 2020).

### 3.1.3. Geographic location

Fig. 3 presents the relative frequencies of case studies' geographic locations, with part (a) categorizing them by continent and part (b) showing the frequencies in specific countries. There are 42 % ( $n = 55$ ) of case studies situated in more than ten countries in Europe. The country with the most case studies in Europe was the United Kingdom (U.K.), representing 26.8 % ( $n = 15$ ) of European case studies. In North America, 26 % ( $n = 34$ ) of case studies were situated, in which 88.2 % ( $n = 30$ ) were in the United States (U.S.). Case studies in Asia represented 21 % ( $n = 28$ ) of total case studies, with the majority in Vietnam (21.4 %,  $n = 6$ ). The South American countries have less focus on NbS (4 %,  $n = 6$  of studies), with 33.3 % ( $n = 2$ ) in Colombia. Furthermore, 3 % ( $n = 4$ ) of case studies targeted Africa, with an equal share of 25 % between Nigeria, Ethiopia, South Africa, and Madagascar. Case studies in Oceania represented 3 % ( $n = 4$ ) of the total case studies, with 75 % ( $n = 3$ ) in Australia and 25 % ( $n = 1$ ) in Fiji. Finally, the 1 % ( $n = 1$ ) of case studies in the 'Global' category focused on the use of NbS for coastal protection globally (Tiggeloven et al., 2022).

Most case studies (67.4 %,  $n = 89$ ) focused on NbS in Western countries, encompassing case studies in Europe, North America, and Australia. These results are in line with the findings of Chausson et al. (2020) who conducted the first systematic mapping of NbS globally and highlighted the imbalance in geographic distribution of NbS, with 79 % interventions in the Global North.

The analysis of the geographic location of NbS measures revealed that most studies focused on measures implemented in Global North countries. However, the Global South regions are already, and will continue to be, disproportionately impacted by climate change (Chausson et al., 2020). Regions especially vulnerable to these impacts are Small Islands Developing States, lower-income nations whose geographic locations make them particularly exposed to both tropical storms and sea-level rise (Akiwumi, 2022; Chausson et al., 2020). To tackle those impacts, which encompass extreme hydrometeorological events such as floods and droughts, NbS measures are essential climate change adaptation and DRR interventions in urban and rural settings of the Global South (Woroniecki et al., 2022; Torres et al., 2023).

### 3.1.4. NbS land features and targeted hydrometeorological hazards

**3.1.4.1. Protection areas and prevalent land use types.** The protection areas of NbS were characterised as either urban, non-urban, or both (e.g., if the study focused on a catchment or national scale, which encompassed both types of areas) and then as coastal, mountainous, or river basins. The most frequent protection areas studied in the analysed literature were coastal areas encompassing urban and non-urban areas (30.3 %), followed by non-urban river basins (22.7 %), and river basin areas encompassing both urban and non-urban areas (15.9 %). Seeing as this study focuses on large-scale NbS spanning over large areas, most of the projects have been or are planned to be implemented in areas with a combination of land use types. Therefore, several land use types, namely agricultural land, forested land, artificial surfaces, wetlands, and water bodies, could be recorded for each case study. The most prevalent land use types where NbS were implemented were artificial surfaces (47.8 %), wetland (41.0 %), and water bodies (39.6 %).

**3.1.4.2. Hydrometeorological hazard type.** The analysis included five types of floods: fluvial floods (river floods which occur when water from lakes or rivers overflow), flash flooding (which occurs as a consequence of extreme precipitation events over a short amount of time), pluvial floods (surface water floods which occur when rain leads to a flood,

independent of any water body), sea-level rise, and storm surges (Zurich, 2019). Fluvial flooding is the most targeted hazard, studied by 51.5 % of papers. The studies focused on NbS targeting storm surges, flash flooding, sea-level-rise for 41.7 %, 4.0 %, and 5.3 %, respectively.

**3.1.4.3. Connecting NbS alternatives, land features, and targeted hydrometeorological hazards.** A visual map of the frequency of NbS alternatives mentioned across the 132 case studies according to the land features and the type of hazard they targeted is shown in Table 1.

Each row is a NbS alternative, and for each NbS, one can see how frequently they have been studied per se (in the "Case study frequency" column), as well as in relation to a particular land feature and hazard type. On the one hand, by examining the table row by row, one can quickly determine whether an NbS is suitable for various land features and/or hydrometeorological hazards. For instance, based on this analysis, coral reefs primarily target coastal areas, water bodies, and storm surges. Climate-smart agriculture is designed for river basins and fluvial floods but can be applied to various protection areas and land-use types. Conversely, rock-detention structures/gabions are more versatile, suitable for all protection areas, and land use types, and can address all hazards except sea-level rise. In each of the table's categories, the frequencies do not total 100 %, as several features could be present simultaneously in a case study area. Focusing on the 'floodplain restoration' alternative, it is shown that in 100 % of the case studies with floodplain restoration as the NbS of focus, the alternative was targeting fluvial flooding. However, 15.8 % of the case studies also studied floodplain restoration as a solution for pluvial flooding.

On the other hand, examining the columns allows researchers to identify which land features and hazards have received the most and least attention. For instance, when focusing on protection areas, it is evident that NbS for mountainous regions are significantly fewer in number compared to those for coastal areas and river basins. Specifically, many NbS (12 out of 28) are tailored to river basins, with some also suitable for coastal areas, whereas the reverse is less common. When focusing on hazards, fluvial floods have the most available NbS (21 alternatives), with a similar trend observed for storm surges (17 alternatives). However, flash floods have only three identified NbS, and sea-level rise has only seven. For pluvial floods, there is a moderate variety of NbS available (11 out of 28).

Results suggest that some NbS are inherently more adaptable (e.g., wetlands), while others are highly specialised (e.g., coral reefs in coastal contexts). In addition, it also highlights some gaps in research concerning the studied land features. For example, mountainous regions and flash floods have received less attention, with fewer NbS alternatives available. Overall, the table provides a resource for DMs by mapping out which NbS are best suited for specific contexts. The ability to quickly identify the most studied and likely effective NbS for a particular land feature or hazard can streamline the decision-making process.

### 3.1.5. Impact on and adaptability of NbS to drought events

Most of the case studies (90.9 %) did not mention any impact of the studied NbS alternatives on lowering or increasing drought risk. Among the rest of the studies (9.1 %), one mentioned that the vegetation in the area where a rock detention structure was implemented was seen to be more resilient to drought, due to an increase in water availability in the region (Gooden and Pritzlaff, 2021). Another study highlighted that water storage ponds were beneficial for both floods and droughts as they allowed for groundwater replenishment, which contributed to the availability of water in shallow wells even during droughts (Woldearegay et al., 2019).

In terms of risk analysis, droughts and floods are generally studied separately (Matanó et al., 2022; Brunner et al., 2021). This is explained by the fact that the two hazards 'operate' in different ways: whereas droughts can span over long periods of time and affect large areas, floods have a more sudden onset, and their impacts are limited to smaller areas

**Table 1**

Relative frequencies of NbS alternatives mentioned in the 132 case studies as calculated using Eq. (1) as well as in relation to land features and hazard types.

	CASE STUDY FREQUENCY	LAND FEATURES											HAZARD				
		Protection area						Area's land-use types					Hydrometeorological				
		Coastal	Mountainous	River basin	Urban	Non-urban	Both	Forested land	Agricultural land	Wetland	Water bodies	Artificial surfaces	Not specified	Fluvial flood	Flash flood	Pluvial flood	Sea-level rise
Afforestation	4.5	31.6		100	16.7	50	33.3	50	83.3		50	66.7	100				
Barrier island	2.3	66.7	33.3	66.7	66.7		33.3	33.3	33.3	33.3	66.7	100	66.7			33.3	66.7
Beach restoration	12.1	100			31.3	12.5	56.3	25	12.5	50	43.8	43.8			81.3	25	
Climate-smart agriculture	6.8			100	22.2	33.3	44.4	33.3	88.9	22.2	44.4	66.7	100				
Coral reef	2.3	100			33.3	33.3	33.3	33.3			100						100
Climate-smart agriculture	0.8			100	22.2	33.3	44.4	33.3	88.9	22.2	44.4	66.7	100				
Drainage basin (NRWM)	2.3			100		100		33.3	100			100	100				
Dunes	5.3	100			37.5	37.5	25	37.5	12.5	25	75	50				62.5	62.5
Earth bunds	0.8			100			100	100	100	100	100		100		100		
Floating vegetated mats	0.8	100			100						100	100					100
Floodplain restoration	12.4	21.1	5.3	100	36.8	31.6	31.6	52.6	36.8	15.8	73.7	63.2	5.3	100		15.8	
Furrows	0.8			100		100			100	100	100			100		100	
Mangrove	12.1	100				12.5	87.5	18.8	6.3	10	25	6.3				6.3	100
Marsh	11.4	100		6.7	33.3	13.3	53.3	13.3	6.7	80	26.7	46.7	20			13.3	80
Natural canal restoration	0.8	100		100	100						100	100	100				
Natural dams	4.5		50	83.3	16.7	66.7	16.7	33.3	50	16.7	100	50		83.3	33.3		16.7
Natural features dikes	0.8	100				100				100	100					100	100
Open grassland	2.3	33.3		66.7	66.7		33.3	66.7	33.3		33.3	66.7	66.7	66.7	33.3		33.3
Oyster reef	2.3	100			66.7		33.3	33.3	33.3	66.7	66.7	100					100
Polders	0.8			100			100	100	100	100	100			100		100	
Ponds/defention basin	9.1	22.2	22.2	75	50	41.7	8.3	41.7	50	16.7	83.3	58		75		41.7	8.3
Reforestation	13.6	27.8	5.6	83.3	33.3	38.9	27.8	77.8	66.7	5.6	55.6	72.2		83.3	5.6		16.7
Re-vegetation	3	75		25	25	25	50	50	50	100		75		25			75
River re-meandering	4.5		16.7	100	33.3	66.7		16.7	33.3	16.7	66.7	50		100			
River restoration	18.2	8.3	20.8	100	41.7	37.5	20.8	37.5	37.5	29.2	62.5	62.5	8.3	95.8	8.3	20.8	4.2
Rock-detention structures/gabions	6.8	33.3	55.6	88.9	11.1	55.6	33.3	55.6	55.6	33.3	22.2	33.3		66.7	11.1	11.1	33.3
Soil conservation	4.5	50		100	50	83.3		100	16.7	16.7	83.3	83.3		100			
Submerged natural breakwater	1.5	100			50		50	25	25	50	75	50				25	100
Wetlands	18.9	52	4	68	40	20	40	48	44	36	56	72	8	64		4	36

0-19%	20-39%	40-59%	60-79%	80-100%

encompassing one or two catchments (Matanó et al., 2022). However, the two hazards are linked by the same hydrological cycle, and a drought event can increase flood risk (Matanó et al., 2022; Brunner et al., 2021). For instance, an area affected by a two-year drought in Kenya became more vulnerable to pluvial floods and landslides because of its dried and cracked soil (Matanó et al., 2022). Therefore, the integrated management of flood and drought risks is necessary to better mitigate the impacts of both hazards (Ward et al., 2020). The effect of NbS on droughts and, inversely, the effects of droughts on NbS for flood management should thus be integrated in future studies. For instance, on the one hand, a re-vegetation measure could mitigate flood impacts through high storage capacity, thus reducing the future impacts of droughts. On the other hand, droughts can impact vegetation cover and thus increase flood risks (Matanó et al., 2022).

### 3.1.6. Comparison with grey infrastructure

Only 19.7 % of studies compared the implementation of an NbS with grey or hybrid infrastructure and the rest of 80.3 % of studies did not compare the performance and co-benefits of NbS with grey infrastructure. Arkema et al. (2017) compared the flood protection value of salt marshes to levees. They concluded that, while marshes alone did not significantly reduce the need of a levee, over 30 years, the marsh-based approach provided substantial additional benefits, including \$113 million in ecosystem service co-benefits (mainly from recreation) and \$4 million in extra flood protection for residents. This led them to opt for a hybrid measure for flood management. Their analysis demonstrates the importance of comparing NbS with traditional grey infrastructure, highlighting how the integration of NbS alongside conventional approaches can yield significant additional socio-economic benefits and enhance overall resilience to coastal hazards if an NbS measure does not provide high enough risk reduction, or if a grey measure is already in place.

Although there is a growing interest in NbS for flood management, the available literature lacks a repository of quantitative and qualitative data on the benefits of NbS to upscale their implementation. Once the benefits of NbS have been identified and recorded, one can compare them with those of grey infrastructure measures. Until this data is available and supported by publications, stakeholders might prefer the traditional 'hard' infrastructure measures over NbS, which are still widely seen as 'soft' in comparison (Anderson et al., 2022). It must also be noted that hard infrastructure is often already implemented for risk reduction. In the Global North, large parts of stream basins are under intensive land use, whereby the landscape is 'engineered' to optimise drainage efficiency (Kelly et al., 2017). However, this has undesirable effects on economy, ecology, and health (Buisje et al., 2002). In these cases, studies should also investigate if the existing grey infrastructure will be future-proof under different climate change scenarios and how it then compares to restoring the landscape and implementing NbS.

## 3.2. The framework of objectives and criteria to measure the co-benefits of NbS

### 3.2.1. Objectives used to assess the performance of NbS

The application of VFT to the analysis of the 132 case studies resulted in the development of a hierarchical framework with four overarching domains, 12 categories, and 62 objectives (Fig. 4).

The three most frequently analysed categories across case studies were 'water management' from the *disaster risk reduction* domain, 'economic viability' from the *human well-being and livelihood* domain, and 'biosphere conservation' from the *environmental health* domain. As for the *social and cultural values* domain, its most mentioned category was 'recreation and tourism' (Fig. 5).

Through the analysis of 132 case studies, 16 objectives were identified and grouped into four categories in the *environmental health* domain. The most analysed objectives throughout categories in this domain were 'habitat protection' (31.1 %) from the 'biosphere

conservation' category, 'surface water quality' (25.8 %) from the 'water quality' category, and 'carbon sequestration' (22.7 %) from the 'climate mitigation' category (Figure B in the ESM).

The case study analysis yielded ten objectives categorised in the *social and cultural values domain*. For this domain, 20.5 % of case studies mentioned the objective 'recreational value' from the 'recreation and tourism' category, 16.7 % mentioned the objective 'education raising and awareness' from the 'cultural services' category, and 13.6 % mentioned the objective 'tourism', also from the 'recreation and tourism' category (Figure C in the ESM).

For the *human well-being and livelihood* domain, 22 objectives were identified. The most mentioned objectives were 'maintenance costs' (22.7 %) from the 'economic viability' category, 'value of storm protection' (22 %) from the 'economic viability' category, and 'human casualties' (20.5 %) from the 'public health' category (Figure D in the ESM).

Finally, 16 objectives were identified and clustered in the *disaster risk reduction* domain. Notably, 27.3 % of case studies mentioned the objective 'erosion control' from the 'stability management' category, 22 % mentioned the objective 'wave energy' from the category 'water management', and 'peak flow' from the same category was mentioned in 21.2 % of case studies (Figure E in the ESM).

### 3.2.2. Criteria used to measure objectives

In addition to providing a structured connection between domains, categories and objectives, the VFT approach enables the identification of strategies to operationalise each objective via the use of criteria. In total, 327 different criteria were recorded to measure the achievement of the 62 objectives in the framework (Table B in the ESM). For most objectives, more than one criterion was identified or used to measure the achievement of a single objective. For instance, 16 criteria were recorded from the case studies to measure the single objective 'habitat protection', 12 criteria were identified to measure the 'value of storm protection', and eight criteria were used to measure the objective 'education and awareness raising', demonstrating a wide spectrum of criteria used for the assessment of NbS. The wide spectrum of criteria allows stakeholders to choose those that fit the objectives of interest for their specific project, a characteristic which is further emphasised in Section 3.3, detailing a three-stage approach to select NbS.

For each domain, the relative frequency of criteria used to measure the NbS achievement on a certain objective was recorded for each case study. A few examples are presented in Fig. 6. The first main outcome of this analysis is that most studies did not report criteria to measure the objectives. This can be seen for the four examples provided in Fig. 6. Secondly, all objectives were associated to several criteria to measure their achievement. For instance, 16 different criteria were recorded for the objective 'habitat protection' from the 'biosphere conservation' category and *environmental health* domain.

Our analysis revealed that while most studies identified objectives achieved by NbS, they often lacked specific criteria for measuring these objectives, making it difficult to operationalise the assessment of NbS. This, in turn, hinders the ability to evaluate their performance (or complementarity) relative to grey infrastructure. Furthermore, the lack of standardised metrics poses a challenge in the comparison of different NbS alternatives or evaluation of their effectiveness in specific contexts. This gap underlines the need for more detailed and context-specific criteria to enable better assessment and comparison of NbS.

However, the analysis also highlighted a wide range of criteria that can be used to achieve a single objective. Two factors could explain this finding. First, the objectives gathered from the literature might be too broad conceptually and could potentially be divided into more specific, lower-level objectives, each measurable by a single criterion or a reduced set of criteria. For instance, 'implementation costs' and 'maintenance costs' are quantitatively measurable and encompass various cost components. 'Implementation costs' could be further divided into more granular elements, such as 'implementation labour costs' and

'monitoring NbS performance labour costs,' to enhance specificity. Second, the variety of criteria may be due to the specificity of the implementation context, which is also linked to the land features recorded in the analysis. Therefore, each context, with its unique combination of land features, and each NbS alternative might sometimes require tailored criteria to accurately measure the achievement of the target objective.

### 3.3. Three-stage approach for selection of NbS

Based on the study's findings, a three-stage approach for the application of the framework to assess and select NbS for flood mitigation is proposed. This approach is inspired by the research introduced in [Higuera Roa et al. \(2023\)](#), as well as in [Ruangpan et al. \(2021\)](#) with their MCDA-based work, and in [Brill et al. \(2021\)](#) with their NbS Benefits Explorer tool. It is structured in three stages ([Fig. 7](#)), which allows progressively filtering NbS alternatives first according to their land suitability, followed by the socio-environmental risk of the area, and finally based on their benefits. The current framework should be considered in combination with frameworks or guidelines focusing more specifically on stakeholder engagement for a just implementation of NbS. For instance, [Ibrahim et al. \(2025\)](#) developed a framework that expands the IUCN NbS Standard which highlights stakeholder engagement in only one of their eight criteria for NbS implementation and management. They provide guidance on "why, who, when and how" to engage stakeholders for landscape-based NbS projects, based also on the European Union's "Guidelines for Co-creation and Co-governance of Nature-based Solutions" ([European Commission, 2023](#)). Importantly, they highlight the need for situational engagement of stakeholders based on these stakeholders' interests and expertise ([Ibrahim et al., 2025](#)).

#### 3.3.1. Stage 1: selection based on land suitability features

The *first stage* evaluates the suitability of NbS alternatives in conjunction with the area's land features. As demonstrated in [Table 1](#), some NbS alternatives can only be implemented in certain areas, pertaining to its land features, and would not be appropriate in every context. For instance, an oyster reef alternative would not be suited to a river basin context targeting fluvial flooding. As a result, the starting pool of NbS can firstly be restricted by selecting only those that match the type of geographic location, targeted protection area, and land use type of the case study of interest ([Ruangpan et al., 2021](#)). [Table 1](#) provides an overarching mapping of the NbS to the different land suitability features. It can thus serve as a first screening tool to filter out those NbS that do not match the land features of interest. This stage can also be achieved using GIS-MCDA approaches such as the one developed by [Ozkiper et al. \(2024\)](#) for the mapping of environmental suitability of NbS.

#### 3.3.2. Stage 2: selection based on area's socio-environmental risk

The *second stage* builds on the first one by assessing the selected alternatives from the previous stage according to socio-environmental risk features, including local characteristics and hazard specificities. In terms of environmental features, in addition to the type of hazard of interest, this may include metrics such as soil pH, soil texture, slopes, altitude, ecosystem types, rainfall, humidity, elevation, or frequency of extreme events ([Higuera Roa et al., 2023](#)). In terms of social features, this may for instance include considerations of access to infrastructure and available workforce. [Table 1](#) can also serve here as a screening tool to discard those NbS that do not match the targeted hazard. For the other environmental and social features of interest, the assessment can be based on literature reviews (both grey and scientific) and expert elicitation. Only the NbS that will match the socio-environmental risk features of interest will then be included in the last stage.

#### 3.3.3. Stage 3: selection based on NbS benefits across comprehensive set of objectives

Once the smaller set of NbS that matches the target land suitability and socio-environmental risk features is obtained, they should be assessed according to their performance on a set of objectives chosen by the project's stakeholders from the framework of objectives identified in the present study. Similarly, criteria to operationalise the objectives should also be selected according to the projects' needs and resources. For this purpose, [Table B](#) in the [ESM](#) includes all the different criteria of our framework that can be discussed by the stakeholders. As far as the selection of the objectives and the criteria, the analysts in charge of the application of the framework can proceed as follows. If the project is limited in terms of time and resources, the recommendation is to start by selecting the objectives and respective criteria that are more time- and resource-efficient to apply. These can be used to further reduce the NbS to a smaller set. Only when this set of NbS is identified, criteria that is more time- and cost-intensive for data collection could be applied to evaluate the remaining NbS. If the project is not limited in terms of resources and time, the objectives and criteria with the highest priority for the stakeholders could be used first to reduce the NbS of interest. After this, second and third priority objectives and criteria can be used to further reduce the pool of candidate NbS, until the most suitable one(s) are found. Due to the lack of dominating NbS (i.e., best performance on all the chosen criteria), as well as the different preferences of the stakeholders, the analysts can also employ MCDA methods to aggregate the performances and stakeholders' preferences to find the NbS that fits best with the requirements of the project, or select a subset that shows promising potentials.

### 3.4. A SWOT analysis of the proposed research strategy

The research strategy we proposed is based on the use of VFT to support the assessment process of NbS based on objectives that stakeholders care about and their measurement solutions, which we call criteria. A SWOT analysis of this strategy allows the community to reflect on its methodological and practical implications for future extensions and revisions.

*Strengths* - This study's approach allows transparently and consistently mapping what stakeholders care about (categories and objectives) with how they can measure (criteria) the achievement or not of what they care about. VFT allows introducing tools from operational research in the domain of NbS assessment resulting in a consistent terminology that experts and stakeholders of different backgrounds can relate to.

*Weaknesses* - The application of VFT to shape the hierarchical structure of objectives and criteria is a time-consuming process, especially because authors use different terminology in their own papers. As a result, this requires the researchers to relate the concepts of categories, objectives, and criteria to the different terminology used in the papers. Currently, the framework does not involve expert input on the proposed hierarchical structure. As suggested in [Section 4](#), future research could explore the systematic involvement of stakeholders at each stage of the approach.

*Opportunities* - The proposed three-stage approach and framework of objectives provide a platform to shape decision support systems that can be comprehensive as well as tailored to the type of NbS and stakeholders involved. It offers the possibility of cross-domain collaborations among institutions of different types using consistent terminology.

*Threats* - The application of the criteria is grounded on data availability. Even if the best stakeholders are included in the selection of the relevant criteria, their implementation is dependent on data availability and/or experts' commitment. Their implementation thus requires time and funding.

### 3.5. Ongoing research and initiatives

To illustrate current directions in NbS research linked to the present

DOMAINS	CATEGORIES	OBJECTIVES			
ENVIRONMENTAL HEALTH	Climate regulation	max - Microclimate regulation	max - Carbon sequestration		
	Soil Quality	max - Soil moisture	max - Soil accretion	max - Soil fertility	max - Nutrient cycling
		max - Soil organic matter	max - Soil stability		
	Biosphere conservation	max - Species diversity	max - Species richness	max - Species survival	max - Habitat protection
		min - Invasive species			
Air Quality	min - Air pollution				
Water Quality	max - Surface water quality	max - Groundwater quality			
SOCIAL AND CULTURAL VALUES	Cultural Services	max - Spiritual value	max - Education and awareness raising	max - Cultural heritage	max - Aesthetic value
	Social cohesion	max - Community engagement	max - Community empowerment	max - Stakeholder involvement	min - Population emergency displacement
	Recreation and tourism	max - Recreational value	max - Accessibility	max - Tourism	
HUMAN WELL-BEING AND LIVELIHOOD	Public Health	max - Mental well-being	min - Health impacts	max - Access to water	min - Human casualties
	Economic Viability	max - Employment	max - Income for local communities	max - Value of forest production	max - Value of seafood production
max - Value of fishery		min - Business interruption	max - Number of livelihood opportunities	max - Agricultural productivity	
max - Implementation costs		max - Availability and use of local materials	min - Maintenance costs	min - Damage to infrastructure and property	
max - Property and land value		max - Value of storm protection	min - Agricultural damage		
DISASTER RISK REDUCTION	Stability Management	max - Coastal stability	max - Erosion control	max - Sediment trapping	
	Water Management	max - Aquifer recharge	min - Peak flow	min - Wave energy	max - River discharge regulation
max - Storage capacity		min - Duration of flooding	min - Spatial spread of flooding	min - Frequency of flood occurrences	
min - Runoff		max - Infiltration capacity	min - Time for measure to reach effectiveness	max - Effectiveness of measure over time	

Fig. 4. Framework to assess NbS benefits structured hierarchically in domains, categories, and individual objectives.

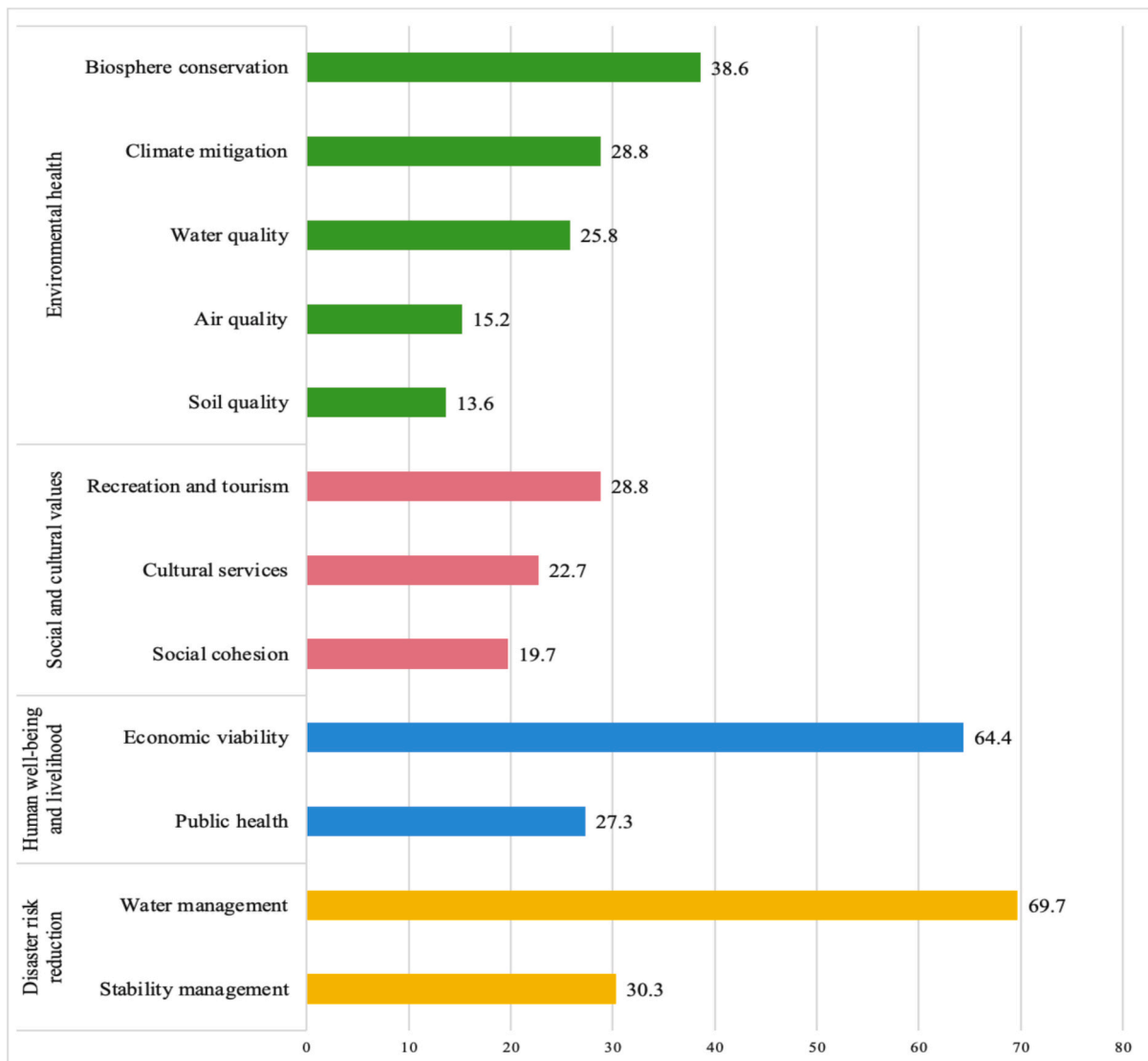


Fig. 5. Relative frequency distribution of objectives per category and domain assessed in the case studies ( $n = 132$ ). More than one objective per category and across domains could be recorded for each case study.

study, the authors conducted targeted desk research about ongoing and recently completed NbS projects. The full list of projects identified from the desk research is included in Table C in the ESM. The projects that emerged were largely NbS case studies, many of which also developed an NbS decision-support tool. They include a variety of NbS ranging from small-scale urban NbS to large-scale NbS like wetland restoration or river storage reactivation. Nearly all the projects provided some guidance on relevant criteria for assessing NbS and their benefits. The projects largely support with the planning of NbS, helping NbS implementers gaining a proper understanding of what they are, what benefits they can provide, and what alternatives exist to address specific climate challenges. For example, Urban Nature Labs was a European Union funded project that ran from 2017 to 2022, with 28 partners from ten European cities (UNALAB, 2024). The implementation and monitoring of NbS were meant to gain knowledge and expertise on both their impacts on ecosystems and on the inclusion of and impacts on local stakeholders. Some tools and NbS projects that emerged also support the assessment of NbS by providing guidance on relevant criteria for assessing the benefits and services that they provide. For example, the RECONNECT project, based on various real-world NbS projects, includes the tools HydroNET and Argos, which allow for real-time monitoring of NbS performance, including assessments of real-time water and weather

data (RECONNECT, 2024). Furthermore, the ongoing WaterLANDS project focuses on NbS for wetland restoration and aims to develop a list of SMART indicators for assessing the resilience of wetlands and the services they provide (WaterLANDS <https://waterlands.eu/>, 2025). The projects, as well as the digital NbS decision-support tools, thus offer guidance on relevant NbS alternatives to address specific climate challenges, assisting with NbS assessment as they often include metrics that quantify the benefits that specific NbS yield. However, they do not examine how suitable specific criteria are to achieving set objectives, as done in the present study. Many of the projects also largely focus on addressing a smaller range of domains than the present study: they are mostly focused on environmental benefits provided by NbS, while the present study also incorporates social, economic and disaster risk-related benefits. Thus, future research directions can consider integrating the framework developed in the present study to ensure that NbS assessment and monitoring use the most relevant and suitable criteria for specific climate challenges, and address a wide range of domains, including environmental, social and others.

### 3.6. Limitations

This research provides a structured framework for evaluating NbS for

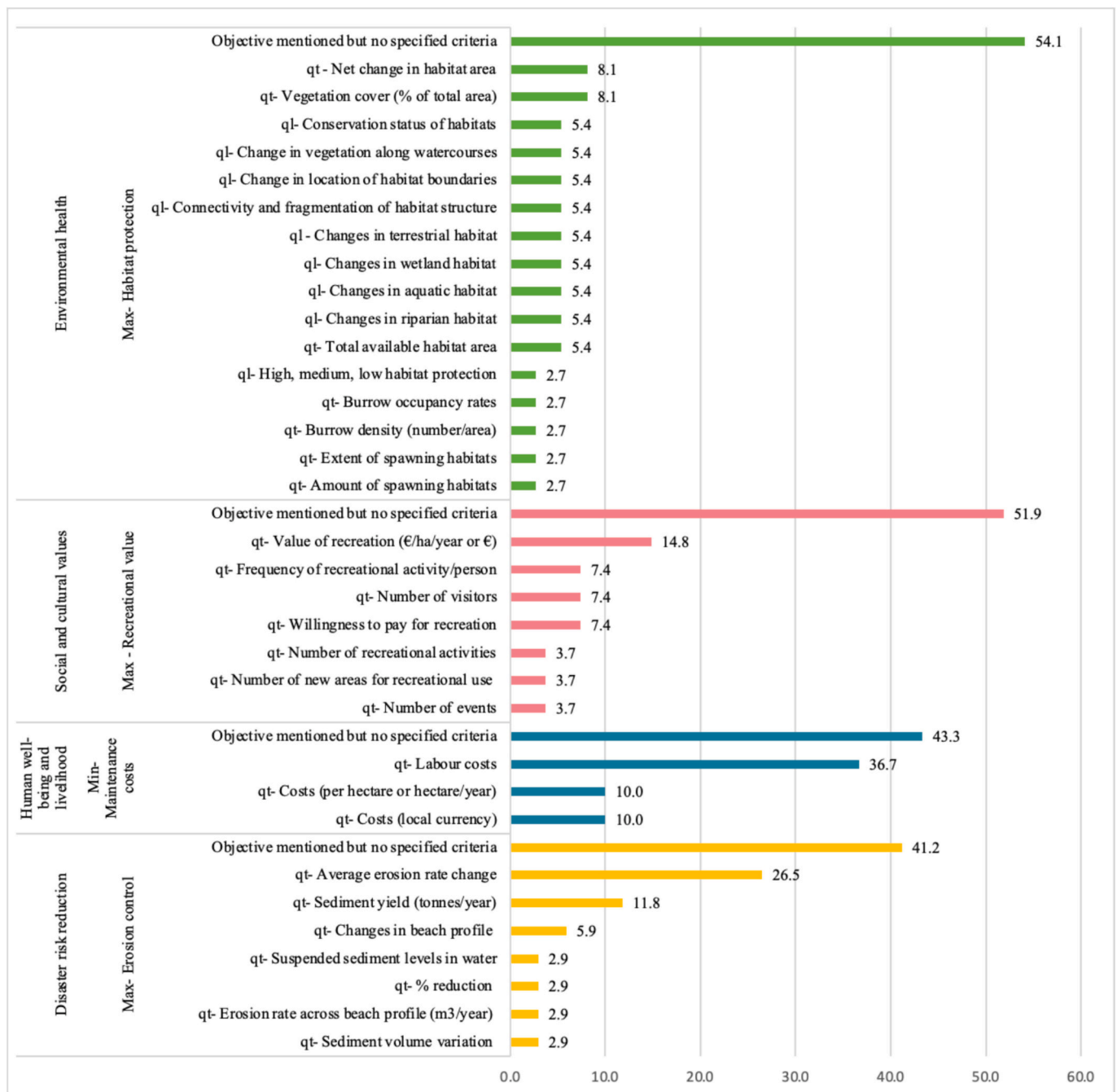


Fig. 6. Relative frequency distribution of criteria used to measure the domains' most frequently mentioned objectives. The frequencies are relative to the number of studies mentioning the objectives of focus.

flood management, but it is not without limitations. First, the systematic literature review was limited to English-language articles and sourced from a single academic database, Web of Science, which may exclude relevant studies from non-English-speaking regions and grey literature sources. This constraint could result in a limited perspective, especially concerning cases from the Global South, where community-led and localised NbS initiatives may be underrepresented. Another limitation links to the fact that this literature review was performed in the course of 2023. To tackle this, another search with the same set of search terms was run in Web of Science on December 31st, 2024. When the search was rerun, 593 new records emerged between 2023 and 2024. Of these, numerous records described small-scale urban NbS or were review papers, which were beyond the study scope. Among the relevant new

records, Europe and the USA remained key locations for modelling and implementing NbS case studies. However, more studies from India, China, and other developing countries emerged, focusing particularly on coastal flooding vulnerabilities in these countries (Gupta et al., 2024; Wu et al., 2023; Chen et al., 2024). For example, Wu et al.'s (2023) study of isolated and riparian wetlands in China was highly relevant. They assessed wetland impacts on flood peak reduction and volumes and provided a detailed focus on wetland impacts on managing drought, which was infrequent among the studies reviewed in both runs of the searches. Along the same line, coastal flooding was more commonly addressed among all the studies regardless of location, although fluvial (river) flooding remained the most common type of hazard addressed by the studies. The land-use types for implementing the NbS were very

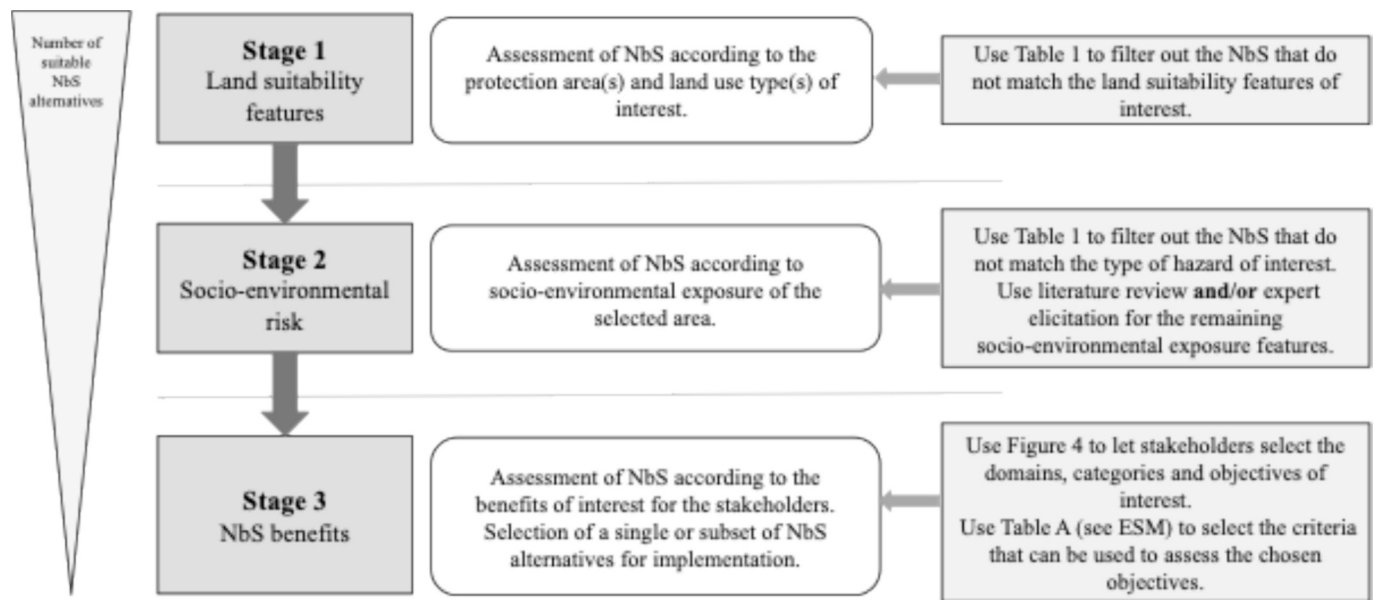


Fig. 7. Stepwise approach for the application of the framework to assess and select large-scale NbS for flood management.

varied, but many focused on agricultural areas. Coastal NbS were commonly assessed in estuaries. The studies largely focused on analysing criteria related to the objective 'Risk Reduction' in reference to the framework developed in the present study, focusing on managing peak discharge, area flooded or, in coastal areas, wave attenuation. A few studies focused on biodiversity and water quality benefits of NbS (Robotham et al., 2023; Paynter, 2025). Robotham et al. (2023), for instance, conducted a comprehensive study of watercourses that could absorb excess river flows during flood events. They assessed the potential of the NbS to reduce erosion and trap sediment, as well as improve water quality through trapping phosphorus and organic carbon by monitoring the relevant parameters in the Upper Thames River in the UK. Ruangpan et al. (2024) assessed the monetised value of benefits provided by various NbS including afforestation and floodplain restoration along an agricultural catchment in Serbia. They assessed values of carbon sequestration, biological control, habitat creation, air pollution reduction and education in Euros per year. Few other co-benefits were analysed and they rarely involved the social, cultural or economic benefits of NbS. Taylor-Burns et al.'s (2024) study emphasised the socio-economic values of NbS, focusing on the number of people who would be protected annually by NbS and the economic benefits of marsh restoration in the USA. Some studies that analysed other NbS co-benefits besides risk reduction monetised their values (Manes et al., 2024; Ruangpan et al., 2024). For example, Manes et al. (2024) assessed NbS in Brazil, determining the monetised value of carbon sequestration, non-woody products and wood production benefits provided by active restoration and natural re-vegetation of degraded urban forests and croplands. Notably, though, all the studies outlined quantitative criteria, with clearly defined indicators for measuring the criteria under risk reduction. Most of the studies implemented modelling approaches to assess the impact of NbS on disaster risk reduction and rarely assessed the performance of an existing NbS. Notably, Paynter (2025) conducted a long-term study that monitored the water quality impact of an existing seagrass plantation in the US. Similarly, Robotham et al. (2023) monitored the impacts of storage watercourses on sediment trapping and water quality. However, most other studies implemented hydrological or GIS models to assess the benefits a potential new NbS could provide in a high-risk area and how it would perform under various climate change scenarios. Nonetheless, the studies yielded valuable indicators and criteria for assessing flood reduction objectives for NbS.

Additionally, a solution that has not been specifically studied in this

review focusing solely on NbS is that of hybrid solutions. Hybrid solutions are solutions that offer a mix of green and grey infrastructure (Anderson et al., 2022). When compared with NbS and grey infrastructure, hybrid measures have been shown to be suitable solutions that would simultaneously fulfil the main disaster risk reduction objectives, provide co-benefits thanks to their natural elements, and satisfy stakeholders' preferences (Anderson et al., 2022; Arkema et al., 2017; Reddy et al., 2016; Huynh et al., 2024). Although their assessment was outside the scope of this research, focusing on hybrid solutions and comparing their benefits and their performance on benefits with those of NbS alternatives and grey infrastructure measures would provide additional insights into effective and appropriate measures for climate adaptation.

Another limitation links to the fact that the framework's structure and the allocation of objectives into the hierarchy of domains and categories were solely shaped by the research team. Furthermore, this study did not account for additional governance, political, and legal dimensions that could influence the effectiveness and social acceptance of NbS interventions. The framework also does not incorporate spatial and temporal dimensions, which are relevant to understanding the dynamic impacts of NbS on flood management and ecosystem resilience.

#### 4. Conclusion and recommendations for future research

In the face of climate change, hydrometeorological hazards such as floods and droughts threaten vulnerable populations globally. NbS have been proposed as climate change adaptation measures that enhance community and ecosystem resilience. However, a gap remained concerning the range of benefits, or objectives, provided by these NbS targeting hydrometeorological hazards. By conducting a systematic literature review of 132 case studies, this research started by mapping land features and hazards targeted by a range of NbS alternatives for flood management. The mapping of these features revealed that certain protection areas (such as fluvial floods and river basins) have received the most attention, whereas others (such as mountainous regions) remain underrepresented. This was also the case for targeted hazards, where flash floods and sea-level rise were less analysed in our sample. Secondly, the study provided a comprehensive framework including environmental, socio-cultural values, well-being and livelihood, and risk reduction objectives, as well as the criteria used to measure these objectives. The final framework contains 62 objectives structured into 12 categories across four domains. The operationalisation of the objectives

is enabled by 327 criteria, which can be chosen by project analysts and stakeholders according to their resources and interests. Third, we also proposed a three-stage approach for applying this framework to assess and select large-scale NbS alternatives for flood management. The tiered approach helps choose NbS that matches the preferences of the stakeholders and the context-specific requirements of the project. As each step is followed, the number of suitable NbS alternatives decreases. First, options are filtered based on the land features of the area. Then, they are further narrowed down using a set of socio-environmental risk features. Finally, they are filtered according to objectives and criteria chosen by the stakeholders. This approach allows practitioners to select NbS alternatives tailored to their specific area efficiently.

To further refine the framework, future research could expand the search for case studies working with hybrid solutions and to additional databases such as Scopus ([www.scopus.com](http://www.scopus.com)) or Lens ([www.lens.org](http://www.lens.org)) and include grey literature, thereby capitalising on the efforts of organisations like the International Federation of the Red Cross and Red Crescent Societies, WWF, and International Union for the Conservation of Nature (DeWit et al., 2022; Doswald et al., 2021). Additionally, similar methodologies could be applied to other types of NbS targeting different hazards or socio-ecological challenges, especially in Global South regions. The framework could further be enhanced by incorporating governance, political, and legal aspects, to provide a more comprehensive understanding of NbS impacts and benefits. This could include the assessment of the extent to which NbS initiatives respect indigenous land rights, support of the implementation of international environmental treaties, or contribution to the resolution of conflicts over natural resource management (Anguelovski and Corbera, 2022). Future research should explore how situational stakeholder engagement can be systematically integrated into NbS implementation across diverse contexts, and how VFT can be employed to that end. In particular, comparative studies are needed to examine the influence of varying stakeholder interests and expertise on the effectiveness and equity of NbS outcomes. It could expand on the three-stage approach to NbS implementation by clarifying which stakeholders should be engaged, during which stage, why their involvement is important, and how to best facilitate participation at each stage.

Future research could also account for the spatial and temporal dimensions of NbS interventions to accurately capture their impacts and effectiveness (Sowińska-Świerkosz and García, 2022). Lastly, looking at this work from a decision science side, new research could involve expert collaboration to refine these criteria and develop comprehensive decision support tools that compare NbS with hybrid solutions and grey infrastructure. Such tools, potentially integrated with existing platforms like the NbS Benefits Explorer (Brill et al., 2022), would help DM select NbS alternatives based on specific land features and performance outcomes, thereby facilitating the scaling up of NbS initiatives.

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### CRedit authorship contribution statement

**Lorette Gallois:** Writing – review & editing, Writing – original draft, Validation, Methodology, Formal analysis, Data curation, Conceptualization. **Elisabeth Hirtz:** Writing – review & editing. **Marc van den Homberg:** Writing – review & editing, Supervision, Methodology, Conceptualization. **Jeewanthi Sirisena:** Writing – review & editing, Formal analysis, Data curation. **Shreya Mozumdar:** Writing – review & editing, Formal analysis, Data curation. **Marco Cinelli:** Writing – review & editing, Supervision, Methodology, Conceptualization.

### Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

### Data availability

Supplementary data to this article can be found online at <https://doi.org/10.1016/j.scitotenv.2025.180948>.

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