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Nature-based solutions can help reduce the impact of natural hazards: A global analysis of NBS case studies

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HIGHLIGHTS

- ~60 % of NBS case studies were from the EU, limited application in other regions.
- Most case studies were implemented to address natural hazards and climate change.
- Half of NBS is used in urban and river settings; green approach is the most used.
- Of 547 case studies, ~88 % of NBS implementations are supported by national policies.
- ~60 % of NBS supported SDGs (15, 13, 6) and 68 % aided biodiversity goals (B, D).

GRAPHICAL ABSTRACT

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ABSTRACT

The knowledge derived from successful case studies can act as a driver for the implementation and upscaling of nature-based solutions (NBS). This work reviewed 547 case studies to gain an overview of NBS practices and

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their role in reducing the adverse impact of natural hazards and climate change. The majority (60 %) of case studies are situated in Europe compared with the rest of the world where they are poorly represented. Of 547 case studies, 33 % were green solutions followed by hybrid (31 %), mixed (27 %), and blue (10 %) approaches. Approximately half (48 %) of these NBS interventions were implemented in urban (24 %), and river and lake (24 %) ecosystems. Regarding the scale of intervention, 92 % of the case studies were operationalised at local (50 %) and watershed (46 %) scales while very few (4 %) were implemented at the landscape scale. The results also showed that 63 % of NBS have been used to deal with natural hazards, climate change, and loss of biodiversity, while the remaining 37 % address socio-economic challenges (e.g., economic development, social justice, inequality, and cohesion). Around 88 % of NBS implementations were supported by policies at the national level and the rest 12 % at local and regional levels. Most of the analysed cases contributed to Sustainable Development Goals 15, 13, and 6, and biodiversity strategic goals B and D. Case studies also highlighted the co-benefits of NBS: 64 % of them were environmental co-benefits (e.g., improving biodiversity, air and water qualities, and carbon storage) while 36 % were social (27 %) and economic (9 %) co-benefits. This synthesis of case studies helps to bridge the knowledge gap between scientists, policymakers, and practitioners, which can allow adopting and upscaling of NBS for disaster risk reduction and climate change adaptation and enhance their preference in decision-making processes.

Abbreviations

NBS	nature-based solutions
SDGs	Sustainable Development Goals
OALs	open-air laboratories
HMHs	hydro-meteorological hazards
DRR	disaster risk reduction
CCA	climate change adaptation
OPERANDUM	OPEn-air laboRAtories for Nature baseD solUtions to Manage hydro-meteo risks
GeoIKP	Geospatial Information Knowledge Platform
EC	European Commission
ABT	Aichi Biodiversity Targets
UNGA	United Nations General Assembly
INSPIRE	Infrastructure for Spatial Information in Europe
IRDR	Integrated Research on Disaster Risk
EMDAT	Emergency Events Database
IUCN	International Union for Conservation of Nature
MAES	mapping and assessment of ecosystems and their services
EUNIS	European Nature Information System; Chanita conservation and restoration
WMQ	water management, protection of water-related ES and water quality
GSM	green space management
SMQ	soil management and soil quality
CCM	climate change mitigation
RR	rural regeneration and land-use
MITW	marine inlets and transitional waters
CCF	continuous cover forestry or forest cover retention
NRC	naturally resilient communities
LR	literature review
NH-NBS	natural hazards-nature-based solutions
SuDS	sustainable urban drainage system

1. Introduction

Nature-based solutions (NBS) are considered as a key priority by policymakers in Europe and beyond to address multiple societal challenges such as natural hazards, mitigate the impact of climate change, level up the agenda of sustainability, and support the achievement of the United Nations' Sustainable Development Goals (SDGs) (Faivre et al., 2017). NBS is a relatively new approach and concept that emerged from policy, which is increasingly being taken up by science (Nesshöver et al., 2017). NBS has the potential to provide multiple co-benefits for human health, the economy, society, and the environment, and thus they can represent more efficient and cost-effective solutions than the traditional engineering approach (EC, 2015). Furthermore, NBS planning should implement "no regret" options, meaning they should create strategies to maximise positive results and minimise negative consequences in the short- and long-term irrespective of climate change. This is especially crucial considering the longer time scales often required by the NBS to be effective, they have time pressures to adapt fast enough to reduce HMHs, and adapt to climate change, and the need of policymakers facing short elective cycles to respond to constituents' requirements. Therefore, NBS planning, designing, implementation/upscaling, evaluation, and monitoring depend on the type and robustness of nature-based interventions, their application, efficiency, temporal and spatial scale of implementations, and best practices (e.g., the learning of successes and failures from past projects and case studies).

A significant amount of scientific literature has been published on NBS. These focus on addressing knowledge gaps, co-creation, co-design, implementation challenges, monitoring, and evaluating the performance of NBS. For example, Frantzeskaki et al. (2020) studied that stakeholders need systems and solution-oriented thinking as a knowledge base. They argued that partnerships and collaborative governance models are crucial for executing the NBS project. Kumar et al. (2020) discussed the operationalisation and the wider acceptance of NBS for managing five types of hydro-meteorological hazards (HMHs; floods, droughts, landslides, coastal erosion, and storm surge, and nutrients and sediment loading). They exemplified the experience of seven European Open-Air Laboratories (OALs). Other works discussed the methods for designing, evaluating, and monitoring the efficiency of NBS (Kumar et al., 2021a, 2021b). Previous works highlighted the benefits, technical knowledge gaps and barriers in the implementation of NBS, highlighting the need for collaborative links between different municipality departments (e.g., urban greening and water) and the absence of effective communication strategies aimed towards citizens (Enzi et al., 2017; Sahani et al., 2019; Debele et al., 2019; Kabisch et al., 2016; Ershad Sarabi et al., 2019). The other barriers identified included uncertainty in the implementation process and the benefits arising from NBS, followed by inadequate financial resources, land and time availability, path dependency in decision-making, institutional fragmentation, and inadequate regulations. Ershad Sarabi et al. (2019) identified enablers that could accelerate the wider uptake of NBS such as partnerships, effective monitoring, knowledge sharing, financial instruments, supporting legislation, education, and training, combining with grey infrastructures, open innovation and experimentation, and appropriate planning and design. Therefore, a wealth of information on NBS concepts and knowledge gaps, design, evaluation, and monitoring are already available. However, such information is fragmented and there is a need for consolidating NBS case studies in one place in the form of a web platform that can present real-world examples as an enabler for the implementation of new NBS projects. The usability and functionality of the filter function in databases are particularly important as it offers users structured access to selected information. For example, there are only three studies in the current literature that discussed building an online data pool and methodology for the development of data and learning from existing NBS (Dushkova and Haase, 2020; Baills et al., 2021; Schroeter et al., 2021). For instance, Dushkova and Haase (2020) reviewed and developed the conceptual and methodological context and techniques for constructing a novel data and knowledge base that will systematically support the process of NBS monitoring and assessment for the CONNECTING Nature project. Baills et al. (2021) presented the structure of the PHUSICOS platform applications, which dealt with the risks triggered by HMHs and environmental issues in mountain landscapes. Schroeter et al. (2021) studied the knowledge transfer potential of online databases and platforms for implementing and upscaling NBS by comparing 21 online databases and platforms, presenting NBS case studies in terms of topics, availability, and quality of information on nature-based interventions. However, none of these or previous studies has comprehensively addressed the following topics that are the focus of this paper: (1) a thorough synthesis of the policies and legislations on which an NBS project depends; (2) a global review and analysis of NBS case studies for 22 HMHs and 26 societal challenges based on comprehensive metadata structure (presented in Section 2.5); (3) extensive classification of parent and sub interventions used by NBS; (4) systematic mapping of the contributions of NBS to Sustainable Development Goals and Aichi Targets; and (5) harmonisation of more than 400 case studies that included NBS examples for all main types of HMHs and societal challenges.

To fill this gap, the overall goal of this paper is to gather, consolidate and facilitate access to the largely dispersed evidence base on the benefits and co-benefits of NBS across the globe for reducing HMHs impacts on people and economic sectors. This, in turn, supports the design and implementation of climate proof NBS in DRR, CCA, and policy development worldwide. This goal is achieved by collecting, harmonising, and consolidating the NBS case studies from around the world following the comprehensive metadata structure to develop a solid evidence base on the multiple benefits, particularly the implementation and upscaling of nature-based approaches to gain their widespread global support. In particular, the following research questions have been addressed here through the evaluation of case studies: (1) Which HMHs and global challenges do the NBS case studies address? (2) In which ecosystem have these NBS been implemented? (3) Which policies are the NBS depending on?; and (4) What (co-)benefits do the NBS entail?

The scope of paper includes reviewing, collecting, consolidating, implementing, and facilitating access to the largely dispersed case studies on the benefits and co-benefits of NBS for reducing HMHs and climate change impacts on people and economic sectors to support the design and implementation of NBS for CCA and DRR agendas. It is worth noting that the specific details of identifying appropriate indicators and metrics for the social-ecological effectiveness of nature-based interventions, knowledge gaps, barriers, and enablers for NBS evidence-based implementation have been covered by earlier works (e.g. Calliari et al., 2019; Shah et al., 2020; Kumar et al., 2021a; Gonzalez-Ollauri et al., 2021; Sowińska-Świerkosz and García, 2021; Rödl and Arlati, 2022) and therefore are beyond the scope of this paper.

This paper is structured into four sections. Section 2 presents the methodology adopted to collect and review existing NBS case studies and policies relevant to NBS implications. Section 3 presents the results and discussion of the inventory of NBS case studies along with the limitation of the study in Section 3.7. Finally, Section 4 concludes the work by summarising the main findings and provides recommendations for future research (Section 4.2).

2. Methodology

Our methodology comprised the collection and selection of case studies (five stages), NBS-related policies and legislation, classification of NBS case studies, societal challenges and co-benefits, classification of natural hazards, ecosystem, typologies, geographic coverage, intervention, and approach of NBS.

2.1. Case studies selection strategy

We formulated a search and appraisal protocol based on 16 metadata elements to ensure a comprehensive overview of existing NBS case studies. Our approach employed a systematic review methodology, known for its rigorousness, comprehensive search strategy, and critical evaluation of included studies (Snyder, 2019; Dushkova and Haase, 2020). This approach enhanced the reliability, comprehensiveness, and value of the collected NBS case studies for researchers, policymakers, and practitioners in the field of DRR and CCA. Our methodology consisted of five main stages: (1) NBS case study identification, (2) quality check and analysis, (3) systematic analysis of contents, (4) charting/collating data, and (5) summarising and reporting results. Fig. 1 illustrates these stages, which involved a systematic online search to gather case studies from grey and peer-reviewed literature, databases, and platforms. We followed these stages to collect and select case studies focusing on single and multifunctional NBS, ensuring that the following criteria were fulfilled: (a) NBS addressed one or more HMHs as a main goal or co-benefit, (b) case studies provided clear information on the type, scale, intervention, geographical location, ecosystem of the NBS, societal challenges targeted by NBS, start and end dates of implementation, and original source/reference(s) of the NBS case study, (c) case studies were collected from the original source to eliminate duplication across databases and literature, and (d) the original or translated language of the case studies was English. These criteria were implemented to prevent the inclusion of duplicate case studies in databases/platforms such as PANORAMA and Oppla. To ensure that a case study is considered and catalogued, it underwent screening and must have met these criteria. Case studies that did not meet our criteria were discarded.

2.2. Collection and selection of case studies

The paper's methodological approach (Fig. 1) is based on a five-step linear analysis. The research documentation search was through four databases, including Science Direct, Scopus, Web of Science, and Google Scholar, to ensure better coverage (Fig. 1). For the database, platform, and literature search, we first conducted primary searches using the four databases utilising the following title/abstract/keywords search query to ensure better coverage. The keywords "nature-based solutions database" AND/OR "platforms", "nature-based solutions" AND "database" AND/OR hydro-meteorological hazard/risk OR "climate change", "Ecosystem-based Adaptation" OR "Ecosystem-based Disaster Risk Reduction" were included in the search and publishing year was chosen between 2008 and 2022 in all databases used. In the first step, using the search term the literature, databases, and platforms that recorded NBS case studies were identified. This involved identifying relevant online sources and evaluating their suitability based on predetermined criteria presented in Fig. 1 and carefully selected for step two. Furthermore, searching for relevant information on NBS case studies using Google Scholar yielded a large number of papers, making it challenging to review all the search results. To filter and obtain a comprehensive range of available evidence on NBS case studies, we searched through the first tens of pages. As we progressed through the search results, the relevance of the studies decreased, and hence we ceased our search after reaching 20 pages. This approach was taken to filter and gather as wide a range of available evidence on NBS case studies as possible while maintaining accuracy. In the second step, a quality check and analysis of the content was conducted based on the hazards, attributes, and NBS interventions

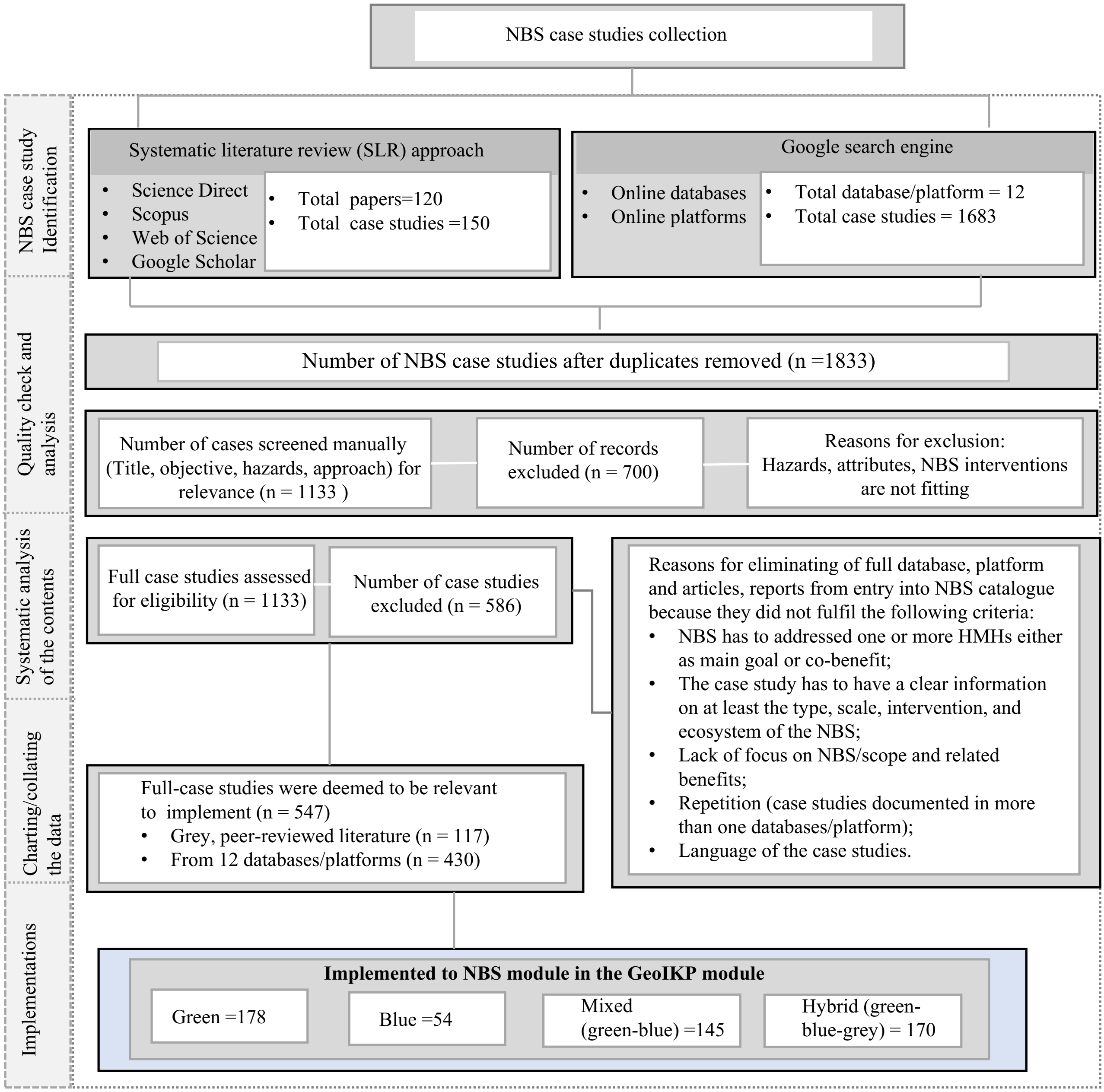

Fig. 1. The collection and screening procedures of NBS case studies.

not fitting the scope. In the third step, a systematic analysis of the content was conducted to assess both the quantity and quality of the data available, as well as the extent of the content covered. This involved reviewing the information provided by each database/platform, and papers and evaluating its reliability and relevance against the followed criteria (Fig. 1). In the fourth step, the full-text screening process, data from each database and platform, and paper were extracted and stored under 16 different metadata elements in an Excel database. Following the metadata elements, the following variables were mapped: (1) name of the case studies (e.g., study title in combination with NBS intervention, country), (2) geographical location of the NBS case study (lat and lon), (3) scale of the case study, (4) description of the case studies, (5) type of NBS used by the case studies, (6) approach(es) used by the NBS, (7) HMHs managed by the NBS, (8) intervention(s) used by NBS, (9) ecosystems where nature-based interventions are implemented, (10) societal challenges targeted by NBS case studies, (11) co-benefits provided by the NBS, (12) NBS ownership, (13) status of NBS implementation (planning, ongoing, and completed), (14) multiple hazards addressed by NBS, (15) picture of the case studies, (16) implementation start and end dates, (17) source/reference of the case studies, (18) policy and legislation NBS depends on, and (19) Sustainable Development Goals and Aichi Biodiversity Targets achieved by the NBS case studies. Finally, in the fifth step, the results were analysed, discussed, summarised, and implemented into the web platform GeoIKP (GeoIKP, 2022). Overall, the five-step linear data scanning (Fig. 1) used in the paper's methodological approach provided a comprehensive and structured framework for collecting and storing the NBS case studies in the GeoIKP.

Some relevant case studies might have been missed from our analysis due to the following reasons: (i) English language restriction, (ii) considered publishing timespan, and (iii) the specific set of keywords used for searches. Furthermore, there were several reasons for excluding many papers published in the field of NBS. Firstly, our research objectives focused on specific research gaps concerning the NBS case studies that were not addressed by existing studies in the literature. Secondly, our systematic review approach involved a comprehensive search strategy and critical evaluation of the contents, which resulted in the exclusion of certain papers. Thirdly, the use of keywords and inclusion criteria allowed us to filter out papers that did not report the necessary key elements and attributes of NBS. Lastly, our adopted metadata model required detailed information about the key elements and attributes of NBS, which led to the exclusion of papers that did not provide this required information. Most of the case studies collected were focused on the multidimensional benefits of NBS, such as hazard regulating functions, climate change adaptation (CCA) and mitigation, restoration of biodiversity, human well-being, economy, etc. around the world. This selection process led to a total of 547 case studies out of 1683 screened ones (Fig. 1). The majority of which (~65 %) were retrieved from four NBS databases/platforms, specifically, PANORAMA (~27 %), Oppla (~18 %), Climate-Adapt (~10 %), and Natural Hazards-Nature-based Solutions (9 %), while ~36 % were obtained from grey, peer-reviewed literature and other databases (Fig. 2b, c).

2.3. Collection and selection of NBS-related policies and legislation

Identifying and analysing the policies and legislations on which the NBS project depends are critical to translating NBS into actual implementation projects and strengthening the adaptation of NBS in national policies for disaster risk reduction (DRR), CCA, and land planning (Kumar et al., 2020). Furthermore, to understand NBS implementation at the local level, it is necessary to examine how the global frameworks are translated into national adaptation strategies and which additional policy instruments are relevant at the national, regional, and local scales. To collect the policy documents that support the implementation of NBS, we systematically reviewed the existing open-access information services on environmental legislation and regulations in combination with desk-based research. The database and platforms focused are: (1) the FAOLEX database on national legislation, policies and bilateral agreements on food, agriculture, environment, and natural resources management, (2) the Convention on Biological Diversity's country profiles, (3) the Biodiversity Information System for Europe, (4) the Climate-adapt database of country profiles, (5) the European Commission's published country reports of the Environment Implementation Review (EIR, 2022), and (6) the ECOLEX database for national and

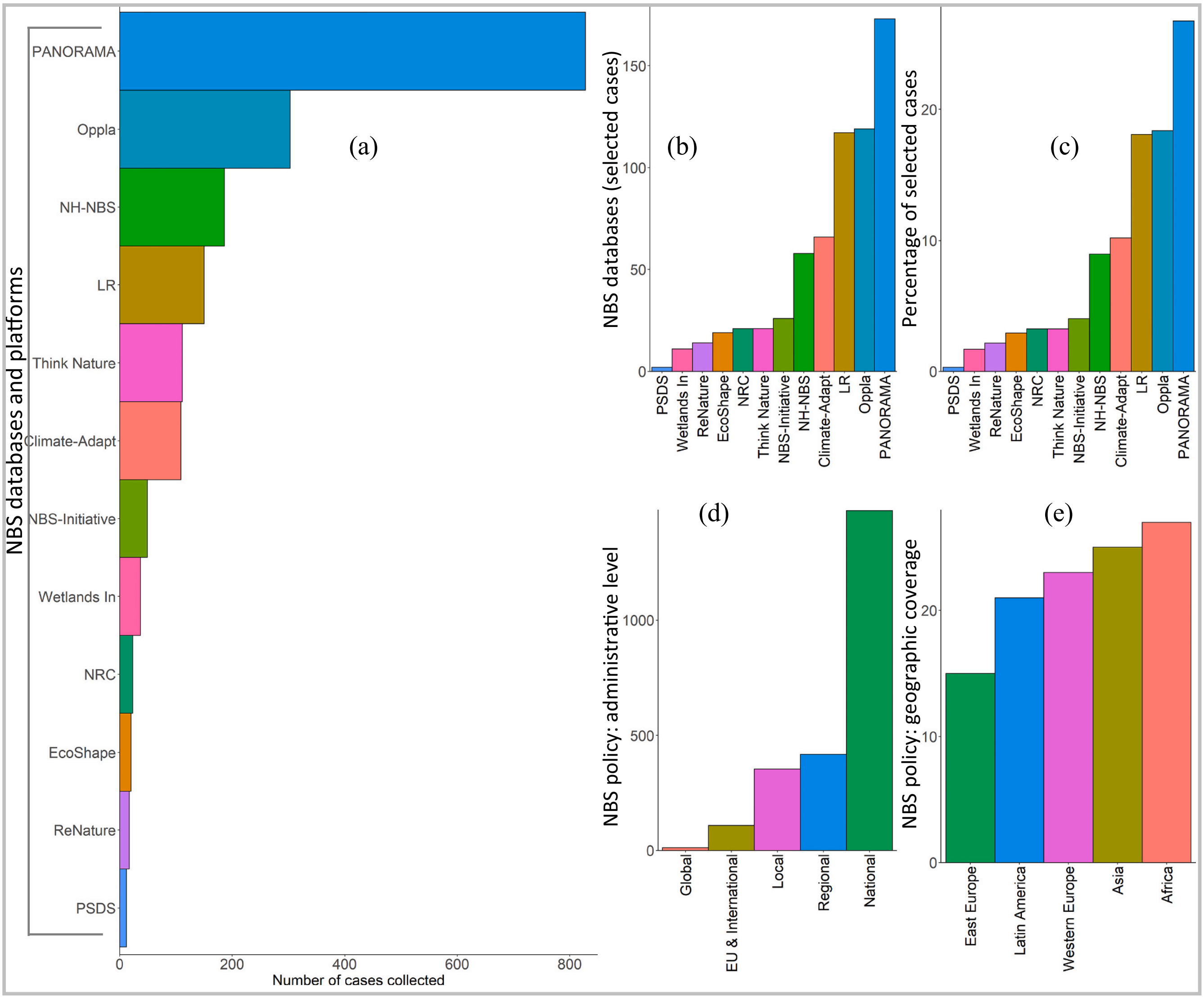

Fig. 2. The total number of case studies before screening (a), the total number after screening (b), the percentage after screening (c), NBS policy at the administrative level (d), and policy geographical coverage (e).

international environmental legislation. From these six-policy databases, more than 2000 policy documents were collected, analysed, and discussed in Section 3.

2.4. Classification of NBS case studies

To design the NBS platform, an in-depth review of 12 existing databases and platforms and 120 papers was carried out to design the NBS platform. Through this process, we collected 547 NBS case studies which were then classified to meet the following requirements: (1) NBS are implemented as suitable approaches for reducing vulnerability and risk of social-ecological systems to HMHs, and (2) simultaneously intended to deliver environmental, social, and economic co-benefits. The metadata model adopted in the OPERANDUM (OPEn-air laboRAtories for Nature baseD solUtions to Manage hydro-meteo risks) (OPERANDUM, 2023) project geo-catalogue consists of 16 different metadata elements (five key elements and 11 attributes), which encompass all different dimensions of NBS (e.g., geophysical, societal, environmental) (GeoIKP, 2022; Leo et al., 2022; OPERANDUM D7.16, 2022). The five key elements included: (i) hazards addressed by the NBS; (ii) types of ecosystems covered; (iii) driving policies of the NBS; (iv) global and societal challenges addressed by the NBS; and (v) indicators categories of NBS. The remaining eleven attributes included: (1) name; (2) type; (3) location; (4) description of NBS; (5) implementation dates (starting and ending); (6) NBS picture; (7) its approach; (8) geographical coverage; (9) type of intervention; (10) reference (i.e., source of NBS or authority of NBS); and (11) NBS ownership. This structure allowed to fully characterise each NBS case study and thus enabled the NBS catalogue to fulfil the specific information needs of different users and stakeholders for searching examples of NBS for HMHs reduction and managing societal challenges.

The 547 NBS case studies resulting from the search query were then evaluated with respect to the four objectives detailed in Section 1 and implemented into the web platform GeoIKP. The classification described in Sections 2.4–2.9 is based on the metadata model developed and implemented in the web platform as part of the EU H2020 OPERANDUM project. This classification is adopted here in order to analyse the case studies with respect to each of the aforementioned objectives.

2.5. Societal challenges and co-benefits

NBS are promoted as an approach to tackle single or multiple societal challenges such as climate change and resource (water, energy, and food) scarcity. In addition, an NBS is also expected to produce a range of co-benefits classified by Ommer et al. (2022) that contribute to the quality of life in cities, including positive side effects for the environment, society, and economy (EC, 2015). In this paper, the NBS case studies were classified into 13 macro categories and 27 associated subcategories of societal challenges (Fig. 3 and Table S1) aligned to Sustainable Development Goals (SDGs) and Aichi Biodiversity Targets (ABT).

Linking societal challenges, global goals, and targets with the case studies could help to highlight the major role of NBS in global sustainable agendas such as the 2030 Agenda for Sustainable Development, the Sendai Framework for DRR, and the Paris Agreement (Kumar et al., 2020; Faivre et al., 2018). The analysis from NBS that is designed to address several single or multiple societal challenges is presented in Section 3. Although NBS are not the only solutions to societal challenges, they may become part of a more strategic alliance of environmentally and socially healthy premises and aligned measures for shaping urban space, housing, and infrastructure and can serve for more than a “narrow and insufficient corridor of ecological modernisation” (Brand, 2016).

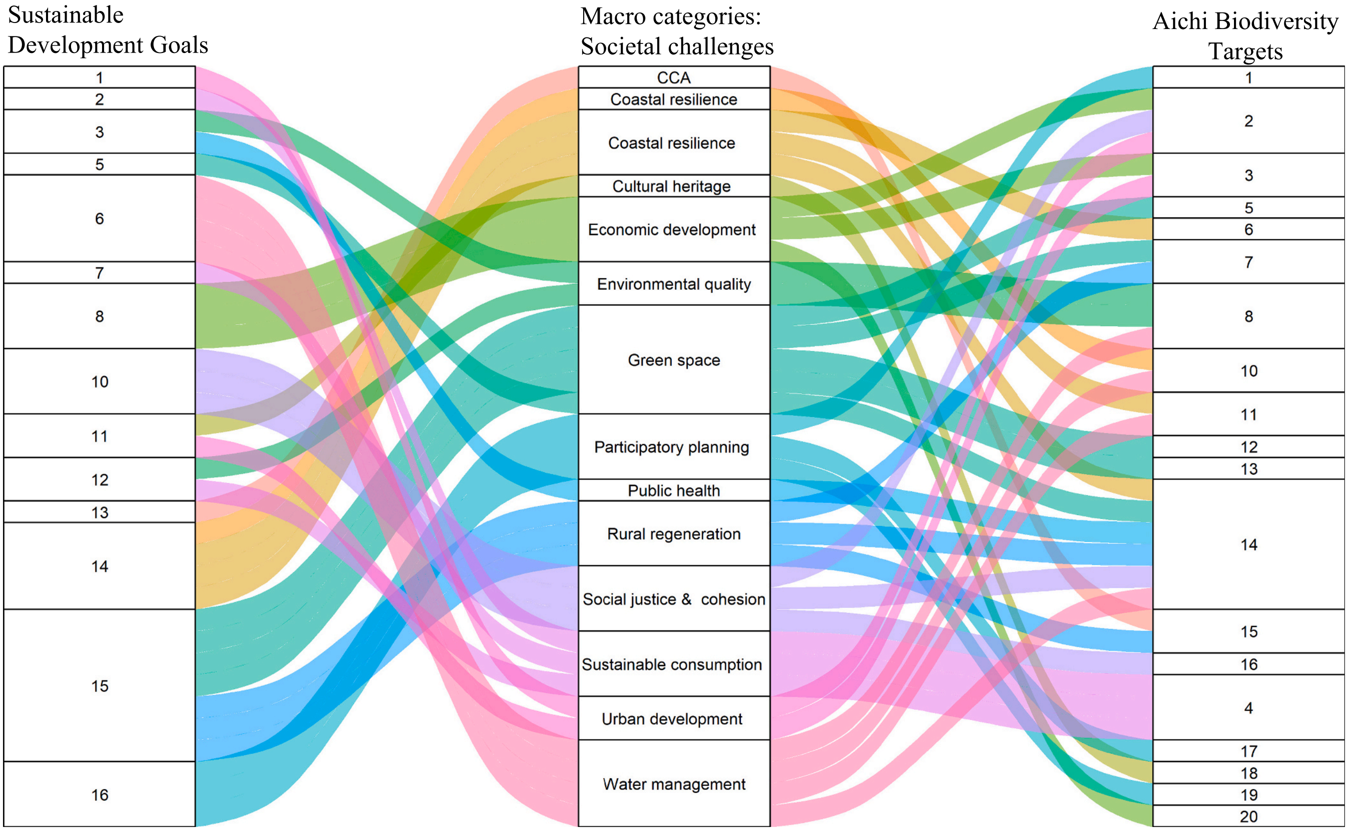

Fig. 3. A Sankey diagram showing the connection between NBS-related societal challenges, Sustainable Development Goals (SDG), and Aichi Biodiversity Targets (ABT).

2.6. *Classification of natural hazards*

The classification of natural hazards discussed in this paper follows a hierarchical structure, drawn from various sources such as INSPIRE (2012), Integrated Research on Disaster Risk (IRDR, 2014), and the United Nations General Assembly (UNGA, 2016). These classifications provide a comprehensive framework for categorising natural hazards, encompassing geological/hydrological, meteorological/climatological, and environmental hazards (Fig. 4). By integrating these classifications in combination with a literature analysis presented by Debele et al. (2019), four main families of natural hazards were developed (Fig. 4): fire, mereological/climatological, hydrological/geological, and environmental. Each family includes specific sub-categories of natural hazards. The classification also considers the distinction between single and multi-hazard, with multi-hazard referring to the simultaneous occurrence or coexistence of multiple hazards at one location (Fig. S1). Multi-hazard situations can arise through chain reactions or the interaction of climate drivers and with the triggering of primary hazard, resulting in compound events (Gill and Malamud, 2014; Zscheischler et al., 2018, Section S1). In response to these natural hazards and other societal challenges, NBS has proven effective due to their flexibility and diverse functionalities (Ruangpan et al., 2020). Therefore, when designing, implementing, and monitoring NBS, it is crucial to consider their suitability and scalability in relation to multi-hazard scenarios to ensure long-term effectiveness and mitigate any associated uncertainties/trade-offs.

2.7. *Ecosystem and typologies of NBS*

A comprehensive, concise, and user-friendly classification of NBS typology forms the foundation for collecting, evaluating, and categorising NBS case studies. NBS operates within the framework of ecosystems and their services, aiming to assist individuals in effectively and sustainably adapting to and mitigating the effects of natural hazards and climate change (Eggermont et al., 2015; Almenar et al., 2021).

Fig. 4. Classification of hydro-meteorological hazards and closely related hazards for the NBS case studies in the geo-catalogue based on the INSPIRE hazard classification and complemented with the updated Sendai Framework hazard classification (UNDDR, 2020).

2.7.1. *Ecosystem*

The concept of ecosystem services and NBS has been linked by the EC, the International Union for Conservation of Nature (IUCN), and other studies (e.g., Almenar et al., 2021). Eggermont et al. (2015) classified NBS into three main types based on their contribution to enhancing ecosystems and biodiversity: (i) improving the use of existing ecosystems, (ii) designing and managing newly created ecosystems, and (iii) sustainable management of ecosystems. The classification of NBS types depends on the specific ecosystem where they are planned or implemented (Almenar et al., 2021). In this paper, NBS has been categorised according to ecosystem types since they are solution driven and applied to ecosystems. The MAES ecosystem type classification (Maes et al., 2013) is adopted in this study because it offers a comprehensive categorisation and aligns with the European Nature Information System (EUNIS) classification. The MAES classification is also endorsed by the EC for evaluating ecosystem services (Almenar et al., 2021). Fig. 5a presents the ecosystem types analysed in this paper, while detailed information on the MAES ecosystem classification, its linkages to the EUNIS habitat classification, and the Marine Strategy Framework Directive marine habitat classification can be found in Fig. 5a and Table S2.

2.7.2. *Typologies*

The current classifications of NBS are primarily theoretical and challenging to grasp and apply when organising and implementing the gathered case studies within the NBS geo-catalogue (EC, 2015; Eggermont et al., 2015; Cohen-Shacham et al., 2016; Martin et al., 2020). To address this issue and facilitate the collection and implementation of NBS case studies, we utilised a modified version of the classification presented by Debele et al. (2019). This modified classification includes green (vegetation/plant-based), blue (water-based), mixed (green-blue), and hybrid (green-blue-grey) approaches (Fig. 5b). For detailed information on the classification, typologies, and examples of each NBS type, please refer to the SI Sections S2.

2.8. *Nature-based solutions case studies geographic coverage*

The success and impact of NBS in mitigating natural hazards and addressing climate change are significantly influenced by factors such as the size of the area (scale), local climate conditions, ecosystem characteristics, and the specific natural hazards being targeted. Therefore, the effectiveness of these solutions can vary based on the scale at which they are applied, meaning that their outcomes may differ depending on the size and scope of the area they are intended to cover. For example, NBS can be implemented, replicated, and upscaled on different scales depending on the effect they are expected to deliver. Following Haghighatafshar et al. (2018), the scale of the NBS intervention can be classified as (1) microscale/single/scattered/local (1 m–1 km) at which a single nature-based intervention (e.g. the green roof) could be investigated under site-specific conditions; (2) watershed/Mesoscale (1 km–100 km) where one or a group of several nature-based interventions are implemented at a catchment/neighbourhood scale (e.g. sustainable drainage systems); (3) landscape/macroscale/regional (100 km–10,000 km), where a combination of nature-based interventions is upscaled to a larger region (or the city level for urban NBS). The geographical distribution and typologies of the implemented NBS case studies have been presented in Fig. 6.

2.9. *Intervention used by nature-based solution case studies*

NBS interventions are nature-inspired work to provide environmental, engineering, and socio-ecological functions together with co-benefits such as biodiversity, quality of life, climate regulation, recreation, or new employment (Ommer et al., 2022; Souliotis and Voulvoulis, 2022). These can be applied at various scales (Section 2.8) to reduce HMHs at multiple spatial and temporal scales through the functions they provide (Raymond et al., 2017). Thus, the interventions were classified herein in light of the function they serve, although they also are integrated into the NBS types presented in Section 2.7. Through literature analysis and expert view, interventions were grouped into 10 main groups: (1) groundwater storage, (2) creation of green and built environments, (3) creation of blue-green space, (4) soil-water conservation, (5) afforestation and revegetation, (6) stream or river restoration, (7) infiltration and biofiltration, (8) streambank and slope stabilisation, (9) coastal protection and management, (10) sustainable drainage of urban runoff and surface water.

The functions by which the NBS interventions were classified also refer to multiple environmental compartments and to the ecosystem for which they are intended. For example, these ten interventions mentioned above can be implemented in urban areas, croplands, grasslands, woodlands, heathlands, wetlands, rivers and lakes, coastal regions, and even shelf and open ocean systems. Table 1 provides a comprehensive but not exhaustive list of interventions, while detailed definitions for each parent and sub-group intervention is presented in Table S3.

2.10. *Approach followed by nature-based solutions case studies*

Depending on the level of human involvement, NBS can have one or more approaches. These approaches are as follows: (1) Protection – this approach involves minimal or no intervention in ecosystems, with the objective of conserving and protecting existing ecosystems without extensive management or intervention. Examples include forest protection and aquifer protection (Eggermont et al., 2015; Martin et al., 2020); (2) Restoration – this approach focuses on assisting the recovery of degraded, damaged, or destroyed ecosystems. It includes various restoration methods and management interventions in agricultural lands, forests, river morphologies, grasslands, pastures, and meadows (Martin, 2017; Martin et al., 2020); (3) Sustainable management – this approach involves the sustainable and adaptive management of ecosystems. It encompasses practices such as continuous cover forestry, cropping management, grazing, residue management, and optimised forest management (Cohen-Shacham et al., 2019; Eggermont et al., 2015); and (4) Implementation – this approach entails significant alterations to existing ecosystems, or the creation of new ones designed and managed for multiple purposes, such as green roofs, basins, ponds, afforestation, and dune structures (Martin et al., 2020).

3. Results and discussion

3.1. *Synopsis of key findings*

Following the research methodology and criteria discussed in Section 2, a total of 547 case studies focused on the multifunctional benefits of NBS were collected and analysed. Fig. 7(a–e) and S2 provide a snapshot of these case studies with respect to (a) the single- or multi-hazard they target along with the type of social challenge being dealt with; (b), the types of policy and targets addressed by NBS (c), the types of the ecosystem where NBS are implemented, along with types of NBS, approaches, case studies locations, scales of intervention; (d) intervention types, and (e) the co-benefits provided by the NBS. To discuss the full functionality of NBS and address our research questions, the collected case studies were analysed based on the: (1) challenges/problems NBS is tackling, (2) policy and target/goal that support the implementations of NBS, (3) the ecosystems where NBS was belonged and implemented (NBS types, intervention, approach, location), (4) scale of NBS interventions, and (5) co-benefits provided by the NBS.

The majority of collected case studies (~82 %) were retrieved from 12 databases/platforms while the rest (~19 %) were obtained from scientific databases. Of HMH families, the majority of NBS case studies (~45 %) were used to tackle hydrological/geological, followed by meteorological/climatological (~30 %), environmental hazards (~24

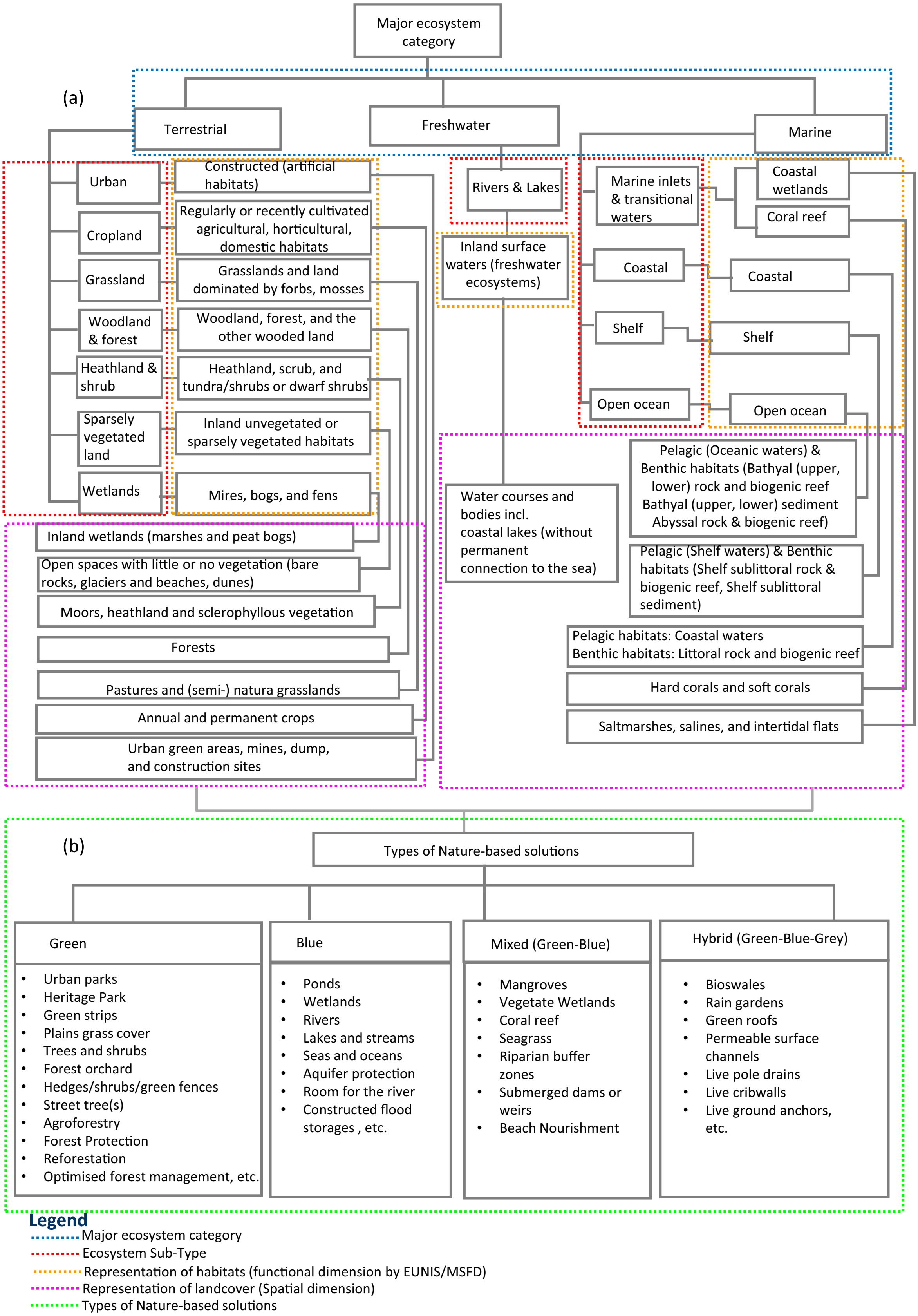

Fig. 5. The ecosystems covered by the implemented NBS in the context of the Mapping and Assessment of Ecosystems and their Services (MAES) are associated with (a) habitat types defined by EUNIS (MSFD), and (b) the specific types of NBS implemented within different ecosystems.

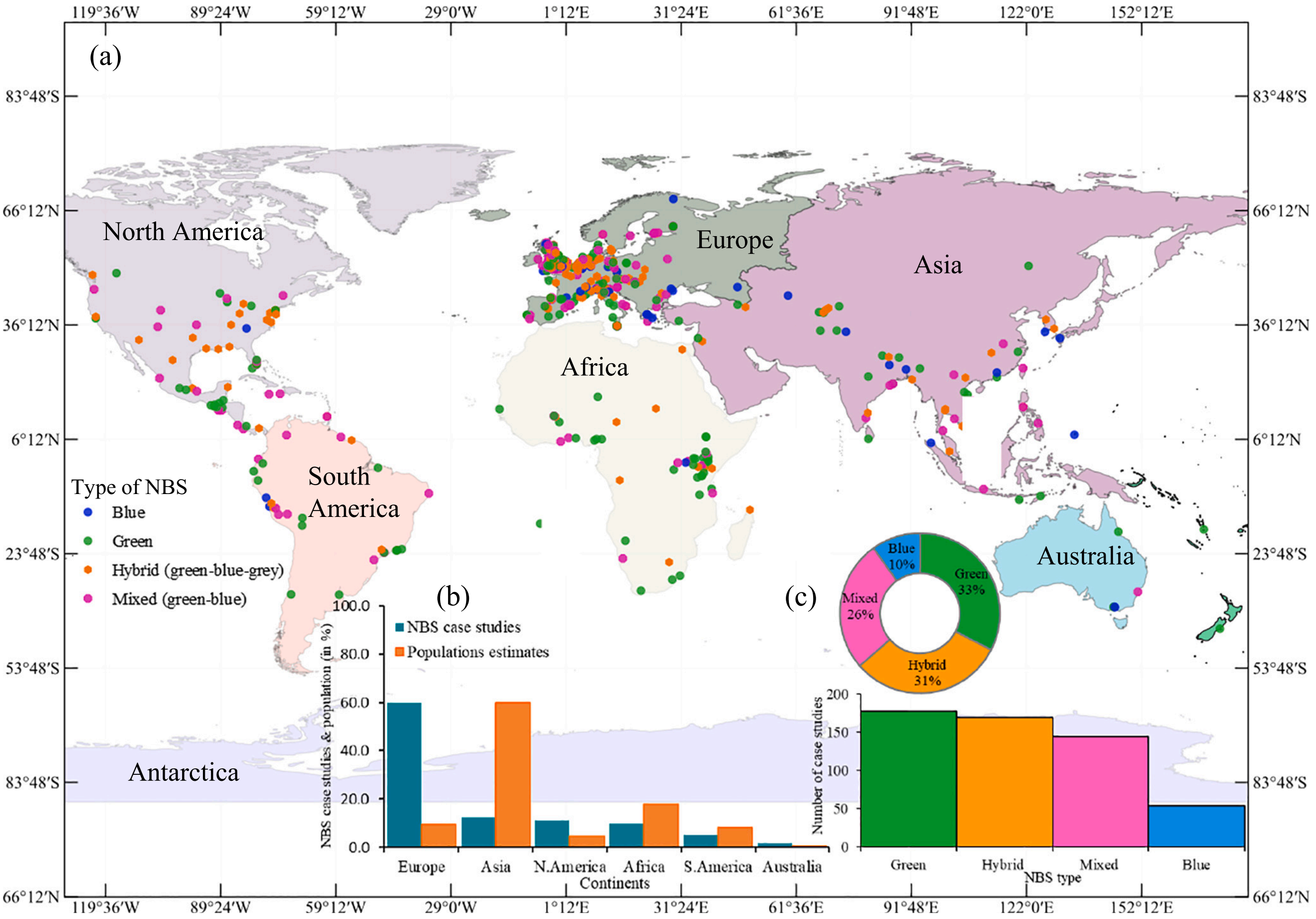

Fig. 6. (a) Global distribution of the NBS case studies by their types which are used to tackle HMHs (b) location of these NBS and distribution of the global population by continent, and (c) and percentage (pie-chart) and counts (bar-plot) of different types of NBS.

%), and fire (~1 %) hazards, respectively. Of the total case studies (*n* = 547), ~78 % were specifically designed to address one or more natural hazards, CCA, and resilience, while ~21 % (*n* = 116) were implemented to address other societal challenges such as loss of biodiversity, water, and air quality (Fig. S2). The distribution of the selected case studies (n = 547) by the type of NBS revealed that ~33 % of the case studies report green, ~31 % hybrid (green-blue-grey), ~27 % mixed (green-blue), and ~10 % blue approaches. The scale of intervention at which individual NBS actions become fully effective is essential to monitor and evaluate the effectiveness, usability/scalability, and transferability of NBS (Raymond et al., 2017). In addition to being a useful strategy to address societal challenges, NBS provides multiple co-benefits for both human well-being and biodiversity such as recreation, social cohesion, job creation, etc. (Ommer et al., 2022). For instance, from the analysis of the case studies NBS produced co-benefits for the society (~27), the economy (~9 %), and the environment (~64 %).

3.2. Societal challenge and hydro-meteorological hazards

3.2.1. Case studies addressing societal challenges

NBS are designed and implemented to address societal challenges (e.g., climate change, food, and water security or natural disasters) effectively and adaptively (Cohen-Shacham et al., 2016). Societal challenges can be environmental (e.g., climate change, water-related hazards, etc.), social (stakeholder engagement, social cohesion, cultural diversity, etc.), and economic (e.g., economic development, employment including green jobs, etc.) challenges. NBS is a multidisciplinary and cross-cutting concept that has the potential to facilitate cooperation among sectors and contribute to a more holistic approach to tackling environmental, social, and economic challenges. In this regard, the collected case studies revealed that about ~63 % of NBS addressed environmental issues followed by human well-being and development (~32 %), and economical (~6 %) challenges.

The collected NBS case studies were also implemented to solve several single or multiple societal challenges. An analysis (Fig. 7a) of such challenges revealed that CCA, mitigation, and resilience (~16 %) had been the most addressed challenge, while social justice and inequality, waste management, sustainable energy, employment (green jobs), marine protection, cultural diversity, DRR, and emergency and public services (in total ~4 %) are the least concerned to be solved by NBS. The type of challenge focussed in NBS design was CCA, mitigation, and resilience (~15 %), flood management (~8 %), biodiversity (~8 %), habitat conservation and restoration (~8 %), water management and quality (~7 %), quality of life (~7 %), green space management (~6 %), economic development (~5 %), stakeholder engagement (~5 %), soil management and soil quality (~5 %), urban development (~4 %), and health and safety (~4 %) which are in total ~ 82 % among many others (~18 % in total). Our analysis showed that only 22 % of the case studies addressed the social (e.g., social cohesion, social justice, and inequality, etc.) and health (e.g., health and safety, etc.) impacts. This is in line with conclusions from Dumitru et al. (2020) who reported that ~20 % of the total 65 studies took into account the intermediary pathways in their examination of the health and social impacts of NBS. Thus, a systematic evaluation of the impacts of NBS should contribute to the understanding of the conditions under which different types of NBS lead to specific health and social impacts. Dumitru et al. (2020) proposed four key categories - (1) conceptualising and testing of NBS, (2) evaluating environmental and social impacts of NBS, (3) including the magnitude of

Table 1
Nature-based solution intervention classification used in the OPERANDUM project.

Parent Intervention	Intervention
Groundwater storage	• Submerged dams or weirs
	• Controlled groundwater abstraction
	• Sustainable dams
	• Aquifer protection
	• Wetland restoration in areas of groundwater recharge
Green built environment	• Urban parks
	• Heritage parks
	• Rain gardens
	• Green strips
	• Vegetated drainage basins
	• Green walkways
	• Vegetated tracks
	• Green roofs
	• Green-blue roofs
	• Green walls/façades
	• Green alleys
	• Infiltration planters
	• Urban tree canopies
Blue-green space creation	• Riparian buffer zones
	• Mangroves
	• Saltmarsh/seagrass
	• Intertidal habitats
	• Dune structures
Soil water conservation practices	• Slope revegetation
	• Cover crops
	• Windbreaks
	• Conservation tillage practices
	• Permaculture
	• Deep-rooted perennials
	• Organic matter enrichment (manure, biosolids, etc.)
	• Inorganic soil conditioners and amendments (biochar, vermiculite, etc.)
	• Sustainable fertiliser use
	• Subsoiler use.
	• Cropping management
	• Plant cover crops in inter-row
	• Stone/earth terraces
	• Earth bunds/walls
	• Contour ditches
	• Grassed waterways.
	• Planting pits or vegetative strips
	• Agroforestry
	• Drainage trenches or terracing
	• Grazing and residue management
	• Perennial grasses
Forestry: Planting trees and shrubs	• Afforestation
	• Orchards
	• Vineyards
	• Hedges/shrubs/green fences
	• Street tree(s)
	• Mangrove restoration
	• Reforestation
	• High-density planting, afforestation
	• Continuous cover forestry or forest cover retention
	• Use of light machinery in forestry
	• Planting deciduous species
	• Forest Protection
	• Fire use restriction near forested area
	• Optimised forest management
Stream restoration or river restoration	• Surface wetlands (marshes)
	• Floodplains, floodplain reconnection with rivers
	• Restoration of degraded water bodies
	• Re-meandering of streams, river, and river daylighting
	• Retention ponds/wet detention ponds
	• Constructed wetlands or marginal wetlands.
	• Channel diversity creation
	• Re-introduce River sediments to coastal wetlands.
	• Riparian vegetation restoration
	• Locate access channels through reefs.
	• Construct emergency flood water storage (e.g., ponds, ditches)
Infiltration, filtration, and biofiltration structures	• River embankment
	• Infiltration basins
	• Vegetated filter strips
	• Rain gardens
	• Wet/dry grassed swales

(*continued on next page*)

Table 1 (*continued*)

Parent Intervention	Intervention
	• Surface ponds
	• Bioretention basins/bioretention cells
	• Planting floodplain or riverside
	• Sedimentation ponds and pits
	• Vegetation on steep slopes, margins of water courses
	• Maintain and enhance natural wetlands.
	• Revegetate bare peat.
	• Overland flow areas
Streambank and slope stabilisation techniques	• Branch packing
	• Brush layering
	• Brush mattress
	• Erosion control fabric
	• Joint planting
	• Live cribwalls
	• Live wattles and inert fascines
	• Live cuttings
	• Jute-mat logs
	• Live siltation
	• Live stakes, stakes fences, palisade
	• Breakwater logs
	• Plant mats, netting or blankets.
	• Rooted stock
	• Root wads
	• Living snow fences
	• Vegetated geogrids, vegetated gabions
Coastal management strategies	• Beach Nourishment
	• Sand dunes (repair and/or construction)
	• Clearing and restoration of seashores
	• Maintain intertidal muds/salt marshes/mangrove/seagrass beds.
	• Set back estuarine defences (sea walls, dike), and sea revetment.
	• Live pole drains
	• Live ground anchors
	• Sandscaping
Sustainable Urban Drainage System (SUDS)	• Retention ponds
	• Permeable paving
	• Bioswales
	• Detention basins
	• Rooftop rainwater harvesting
	• Reduce garden paving

NBS impact for different social groups, and (4) appropriate temporality and maintenance of evaluation (i.e., via the development of indicators) - to guide the development of robust impact assessment frameworks for NBS projects. These categories would also benefit NBS projects to develop clear conceptualisations of physical, societal, and economic impacts, as well as of the understanding of positive and negative interactions between them and their distribution across diverse socio-demographic groups. It is worth highlighting that since the social and health effects of NBS have not been evaluated in sufficient detail and quantities, there is a need for the conceptual development of the mechanisms through which diverse types and design characteristics of NBS influence various social outcomes. Such development should also focus on the variations in the impact of NBS on different demographic groups and the underlying reasons for those differences.

An in-depth analysis of the case studies revealed that nature-based interventions are utilised more for CCA, mitigation, and resilience. For instance, Wada et al. (2017) have shown that in Hawaii, forest restoration effectively addresses societal challenges such as wildfire risk and reduced water availability varies between current and future climate change scenarios. Overall, collecting and analysing the case studies in future scenarios of nature-based intervention could provide a more holistic picture of the effectiveness of NBS for CCA across landscapes or larger scales. Many of the major international scientific organisations focusing on climate change and biodiversity acknowledge the potential effectiveness of NBS. There is also a growing agreement on the critical limitations of NBS for climate change mitigation, the potential negative impacts of certain actions on biodiversity and food security, and the necessity of coupling NBS with substantial reductions in fossil fuel emissions (Griscom et al., 2017; Seddon et al., 2021a, 2021b; Girardin et al., 2021). Thus, NBS has the potential to contribute to mitigating climate change, but it cannot be solely relied upon to solve the problem. Instead, they must be combined with rapid reductions in greenhouse gas emissions and augmented with engineered carbon removal methods to be effective. For instance, Girardin et al. (2021) highlighted that implementing NBS such as forest protection, large-scale restoration of ecosystems and improved land management would result in a 0.1 °C reduction in global warming if warming peaks at 1.5 °C by mid-century. On the other hand, if warming peaks at 2 °C later in the century, there would be more time for NBS to deliver their benefits, resulting in a 0.3 °C reduction in peak warming. Therefore, if NBS were scaled up to their maximum potential, they can make an important contribution to limiting climate change, especially in the latter part of this century. However, their potential is comparatively limited when compared to the substantial benefits that can be obtained by rapidly phasing out the use of fossil fuels. The rising frequency and intensity of climate extremes caused by climate change, coupled with other pressures such as land use changes and urbanisation are also limiting the effectiveness of NBS to climate change and other global challenges by recurring disturbances before the nature-based interventions have the opportunity to recover after major climate-related events such as droughts and fires (Seddon et al., 2020a, 2020b; Calliari et al., 2019). Such disturbances can severely reduce the adaptive capacity of specific nature-based interventions, potentially resulting in a shift to a new community of species or an entirely different ecosystem altogether (Seddon et al., 2020a, 2020b). Therefore, to fully leverage the advantages of NBS under the changing climate, they must be implemented within a systems-thinking framework that considers numerous ecosystem services and acknowledges trade-offs among them, as perceived by various stakeholders; otherwise, the complete benefits of NBS cannot be realised.

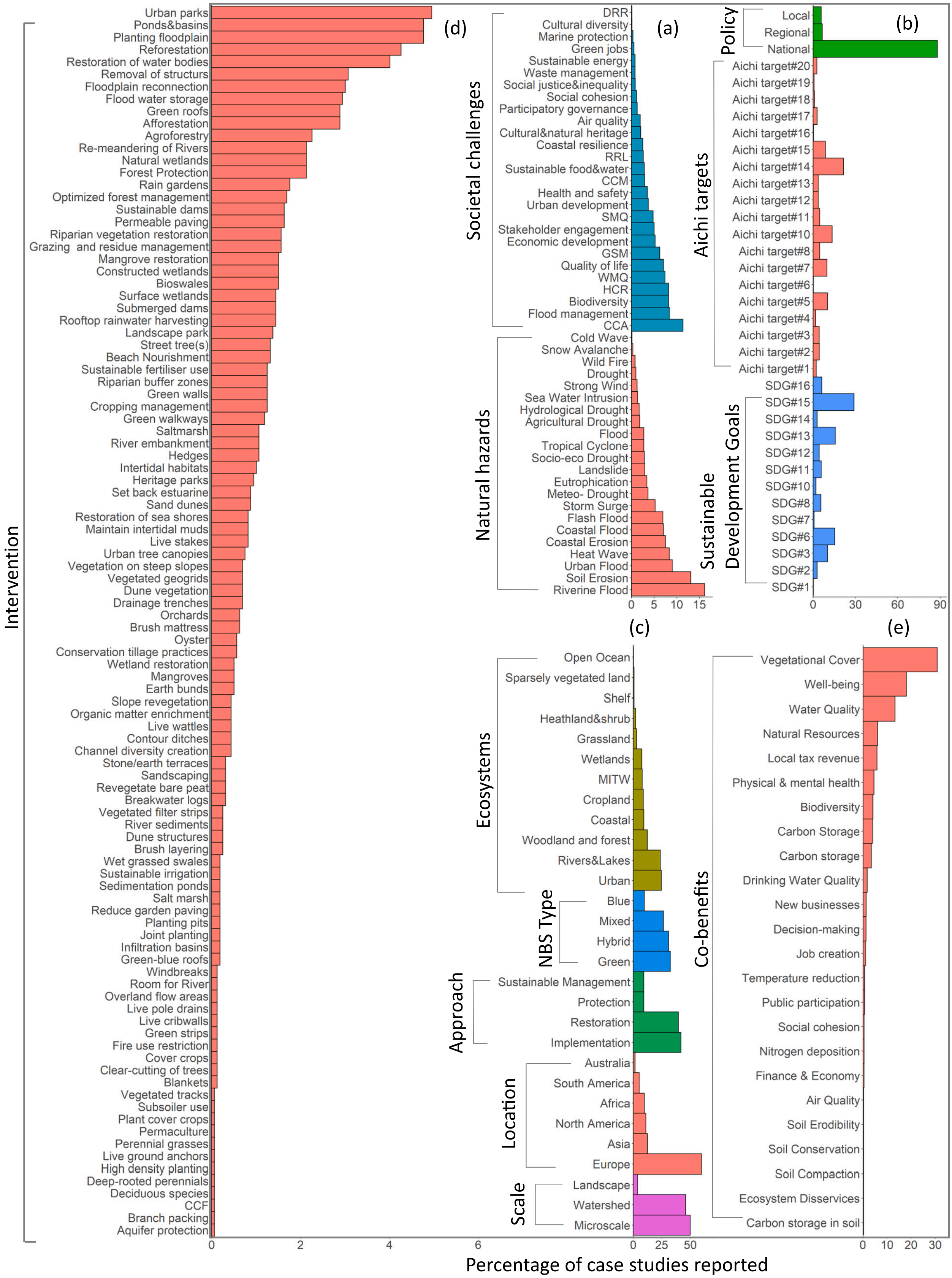

Fig. 7. The percentage of case studies that reported the effectiveness of NBS against HMHs, and societal challenges (a), NBS policies and targets (b), ecosystem, types of NBS, approach, location of NBS, the scale of NBS (c), NBS intervention type (d), and NBS co-benefits (e).

3.2.2. NBS case studies addressing single hazard

The case studies collected from the database and literature addressed a wide range of HMH impacts. These NBS case studies were implemented in response to different HMHs (Fig. 7a). It was found that most of the NBS was enacted in response to floods (~42 % of case studies implemented to manage fluvial floods, flash floods, urban floods, and coastal floods), erosion (~21 %), droughts (~11 %) (including agricultural, hydrological, meteorological, and socio-economic droughts), heatwaves (~8 %), followed by lesser traded storm surge (~5 %), eutrophication (~4 %), and landslides (~3 %) hazards, whereas wildfire, seawater intrusion, strong wind, wildfire, snow avalanche, cold wave (in total ~4 %) being the least focussed and addressed ones. This should be majorly due to the variation in the intensity of the damage caused by different HMHs, which points towards floods, heatwaves, and drought being the most severe while nature-based interventions are poorly utilised against seawater intrusion, strong wind, drought, wildfire, snow avalanches, and cold waves (4 % in total).

3.2.3. NBS case studies addressing multi-hazards

Among the total NBS case studies, ~48 % of case studies tackled multiple hazards and about ~44 % of case studies were implemented to address single hazards such as droughts, heatwaves, and landslides while ~8 % (#43) were used against consecutive (~5 %) and concurrent hazards (~3 %). In line with this, Ou et al. (2022) analysed and discussed integrated multi-hazard risk management using NBS as a novel approach to multiple climatic change-related risks. Nature-based interventions are designed to deliver multi-functional benefits to human needs and biodiversity. For instance, measures for water harvesting can be developed to deliver dual/multi-purpose flood and landslide prevention in addition to drought hazard management. Applying such multi-functional NBS can offer significant potential for multi-hazard-risk reduction, specifically under future climate change conditions (Hobbie and Grimm, 2020; Chausson et al., 2020).

3.3. Nature-based solutions policies and targets

3.3.1. Policies

NBS supports major policy priorities e.g., European Green Deal, biodiversity strategy, and climate adaptation strategy, as a way to foster biodiversity and make the world more climate resilient. These policies are helping to support the wider uptake, and upscaling of NBS through funding (EU's funding programme Horizon 2020, BiodivERsA ERA-Net). In this paper, the collection of NBS policies covers administrative levels (Fig. 2d) and all global regions (Fig. 2e). Most of the available information is currently related to policies at the national level (Fig. 2e). These policies depend on the spatial scale of implemented NBS, and stakeholders involved in the project can be local, regional, and national (Fig. 7b). The analysis reveals that in most of the cases (~88 %) the type of policy applied is at the national level, followed by regional (~6 %), and local (~6 %) policies.

The analysis indicates that there is very little support for mainstreaming the implementation of multifunctional and cost-effective NBS at the local and regional levels. These barriers can be explained by the lack of collaborative governance, inadequate knowledge, and limited funding availability (van der Jagt et al., 2023). To enable the barriers, nations/governments could play a vital role in breaking down these gaps by employing policy instruments and strategically merging these into policy mixes aiming at multiple regime structures. Our results confirm the previous finding presented by van der Jagt et al. (2023) in dictating that most of the implemented and mainstreamed NBS are supported by national governments, but they are not yet mainstream in urban development (e.g., at regional and local policy levels). Our results also agree with a recently published study by Calliari et al. (2022) who found that successful design and implementation of NBS are hindered by the lack of involvement of the private sector in financing NBS and opportunities for increasing stakeholder engagement at the local level.

3.3.2. Sustainable development goals, Aichi targets, and European green Deal

Nature is essential to support the achievement of the United Nations SDGs, ABT, and Paris Climate Agreement. In fact, the study shows that cost-effective and climate-proof NBS could contribute about 30 % of the mitigation required between now and 2050 to keep global warming below 2 °C (Agreement, 2015; Griscom et al., 2017). As a result, NBS is becoming increasingly popular in global policy and business discussions due to its vast potential to tackle the causes and effects of climate change, safeguard biodiversity, and ensure the continuity of ecosystem services that are critical for human well-being. For instance, estimates indicate that NBS has the potential to provide up to 37 % of the mitigation necessary by 2030 to meet the objectives of the Paris Climate Agreement (Seddon et al., 2020a, 2020b). For instance, Seddon et al. (2020a, 2020b) analysed the language around NBS in the 168 original nationally determined contributions, submitted by countries to the UN Framework Convention on Climate Change under the Paris Agreement and reported that 66.7 % of the signatories to the Paris Agreement included NBS in their climate adaptation and mitigation plans. In addition, the Science-Policy Platform on Biodiversity and Ecosystem Services, Intergovernmental Panel on Climate Change, and the Global Commission on Adaptation have all prioritised NBS as a key action track to climate change adaptation and mitigation.

Among the analysed case studies, ~29 % of the nature-based interventions are used to achieve SDG 15 ("protect, restore and promote sustainable use of terrestrial ecosystems, sustainably manage forests, combat desertification, and halt and reverse land degradation and biodiversity loss"). About ~15 % of the case studies address SDG 13 which is "Take urgent action to combat climate change and its impacts". While ~15 % of the case studies "ensure availability and sustainable management of water and sanitation for all" (SDG6). About ~27 % of nature-based strategies are used to solve human-related Sustainable Development Goals (SDGs) such as good health and well-being (~10 %, SDG3), promote peaceful and inclusive societies (SDG 16, ~6 %), productive employment, and decent work (SDG 8, ~6 %), zero hunger (SDG2, ~3 %), etc. Among the 17 SDGs published by United Nations, SDG# 4, 5, 9, and 17 are not mentioned in any of the NBS case studies. Still, NBS has to contribute to the achievement of these goals through time or by 2030 (Fig. 7b) after the implementation of the strategic plan for biodiversity 2011–2020 or ABT – "a ten-year framework for action by all countries and stakeholders to save biodiversity and enhance its benefits for people". Nature-based interventions are contributing to 20 different targets under four strategic goals. For instance, most (~69 %) of nature-based interventions are used to address the strategic goals B and D ("reduce the direct pressures on biodiversity and promote sustainable use", ~38 % and "enhance the benefits to all from biodiversity and ecosystem services", ~30 % respectively). While the cause of biodiversity loss (strategic goal A, 12.6 %), improving biodiversity by safeguarding ecosystems, species, and genetic diversity (strategic goal C, ~12 %) and enhancing the implementation of biodiversity through a participatory approach (strategic goal E, ~7 %) are still the least addressed biodiversity goals by NBS. Looking into the individual target under strategic goal B, ~22 % of NBS case studies contributed to the achievement of target #14 which is aimed by 2020 to restore and protect the ecosystem functions such as services related to water and health, livelihood, and well-being by taking into consideration poverty, vulnerability, local and indigenous communities (Fig. 7b). Similarly, three targets i.e., #16, #18, and #19 are the least biodiversity targets under strategic goals D and E that received very poor contributions from planned and implemented NBS (in total ~1.9 %), Fig. 7b.

Overall, the analysed case studies could support the achievement of climate policy (e.g., Paris Agreement, COP27), European Union released Biodiversity Strategy for 2030 – Strategy on Adaptation to Climate Change and Forest Strategy which all represent major pillars of the ambitious European Green Deal which depend on NBS to both restore and preserve ecosystem integrity and enhance climate adaptation and resilience. Furthermore, the research and policy in Europe have advanced the conceptualisation and implementation of NBS, so the best practice from this study could help to achieve the ambitious goals of the European Green Deal and fulfil its vision of transforming into a climate-neutral, sustainable, climate-proof, fair, and prosperous European Union by 2050.

3.4. Ecosystems and nature-based solutions used by the case studies

3.4.1. Ecosystems used by case studies

Most of the case studies (~48 %) were implemented in the urban, and river and lake ecosystems. Nature-based interventions were primarily implemented in urban areas (~24 %), rivers and lakes (~24 %), and woodland and forest (~12 %) comprising a total of ~60 %. While sparsely vegetated land (~0.6 %), shelf (~0.6 %), and open ocean (~0.2 %) are the least utilised ecosystems, among others, e.g., coastal (~10 %), cropland (~9 %), marine inlets and transitional waters (~8 %), wetlands (~7 %), grassland (~3 %), and heathland and shrub (~2 %) (Fig. 7c). A similar study by Chausson et al. (2020) found that about ~53 % of nature-based interventions are implemented in the woodland and forest ecosystem which is the third most utilised ecosystem in this paper.

3.4.2. Types of nature-based solutions used by the case studies

NBS have been categorised based on their definition, typology, functions, services, and the component of nature/ecosystems involved in them, i.e., blue, green, mixed, and hybrid (Section 2.6). Figs. 6c and 7c concludes that most of the NBS implemented were green (#178, ~33 %), followed by hybrid (#170, ~31 %), and mixed (#145, ~27 %). However, blue NBS was noted to be the least implemented one (#54, ~10 %). This can be concluded from the analysis that NBS is still in the maturity and competition phase with the engineered solutions to be fully included in CCA planning and DRR (Tye et al., 2022). Therefore, to avoid any failures of NBS implementation and upscaling, stakeholders have promoted green and hybrid NBS taking precautions for any failure of NBS due to lack of evidence on the blue approach or any other unknown reasons, since research and evidence on NBS full-proof safety and benefits are still progressing (Dumitru et al., 2020).

Furthermore, the effectiveness of NBS relies on their specific type and the socio-ecological context in which they are applied (Martin et al., 2021). For instance, the trade-offs can arise due to the definition of NBS which is often intertwined with ecosystem-related approaches such as ecosystem-based adaptation, ecosystem-based disaster risk reduction, community-based natural resource management, and others. This overlap has sparked debates about whether NBS should be viewed as a part of these interventions or as a distinct approach. The International Union for Conservation of Nature has positioned NBS as an umbrella concept, but some question its added value to existing ideas. Ambiguity and optimality of biodiversity benefits, as outlined in the NBS definition, are also among the trade-offs. For example, if policies promoting climate mitigation prioritise NBS with low biodiversity value such as monoculture afforestation with non-native species, these may result in the failure of selected trees to thrive in future climates or compromise the broader health of the ecosystem into which they are introduced (Findlater et al., 2022). This can result in maladaptation or benefit only some people at the expense of others, which is particularly problematic in a rapidly changing world where resilient ecosystems and multi-functional landscapes that rely on biodiversity are critical (Seddon et al., 2020a; Wamsler et al., 2020; Seddon et al., 2021a, 2021b; Seddon, 2022). As a result, poorly designed NBS project implementation can result in maladaptation, where exposure and sensitivity to climate change impacts and loss of biodiversity are instead increased as a result of action taken. Therefore, the design and implementation of NBS need to be inclusive to capture the different spatial scales, social-ecological dimensions, and effectiveness of natural climate solutions and reduce the chance of unforeseen consequences or maladaptation.

3.4.3. Type of interventions implemented by the case studies

The type of NBS intervention varied following the type of challenge, location, approach, and type of NBS (green, blue, etc.). Most of the case studies (around one-fourth, ~25 %) in our database accounted for the restoration of water bodies such as rivers, streams, etc. The parent interventions included stream restoration or river restoration (~25 %), soil water conservation practices (#232–14 %), green built environment (~14 %), forestry: planting trees and shrubs (~13 %), Sustainable Urban Drainage System (SUDS) (9 %), infiltration and biofiltration structures (~8 %) comprised a total of ~84 % of total interventions. While others, such as groundwater storage, blue-green space creation, streambank and slope stabilisation techniques, and coastal management strategies covered ~16 % (in total, Fig. 7d).

Restoration of degraded water bodies and floodplains, removal of structural elements, and floodplain reconnection with rivers were the most used interventions from stream restoration or river restoration intervention. Similarly, afforestation and drainage trenches or terracing are the most utilised from soil water conservation practice intervention while urban parks and green roofs are widely used from green built environment intervention. From green intervention to reforestation/ forestry (planting trees and shrubs), reforestation is the most implemented solution against different societal challenges (Fig. 7d). Overall, ~67 % of the case studies used water and soil-related interventions to tackle the associated hazards such as floods, soil erosion, droughts, shallow landslides, etc. while the remaining ~34 % are applied to tackle wind-related hazards such as cyclones, tornadoes, heat, and cold waves.

3.4.4. Approaches followed in the nature-based solution case studies

NBS are site-specific; thus, the success of any measure is strongly associated with the environmental and socio-economic conditions of the area in which they will be implemented. To effectively evaluate the potential multiple benefits which an NBS can produce, in addition to hydrological, climatic, and socio-economic studies, it is important to consider the type of approaches targeted by NBS. Fig. 7c provides the NBS case studies classified by their approach: implementation (~42 %) and restoration (~40 %) are the most popular approaches used by the NBS case studies while protection (~9 %) and sustainable management (~9 %) are equally used in the case studies. This implies that the major approaches of NBS are focused on the implementation of new solutions and the restoration of existing ones. This is due to the fact that the European Commission and the UN's ambition and goals are increasingly supporting and prioritising the implementation and restorations of ecosystems in urban environments.

This result is consistent with the study by Martin et al. (2020) who highlighted that in recent years, the creation of new ecosystems that are cost-effective, climate-proof, and flexible to deal with multiple-societal challenges are increasingly considered in urban development planning (e.g., green roofs, permeable surface channels) by the European Commission. Our analysis also agrees with the conclusion of Rivière et al. (2022), who found that ecological restoration and urban environment management are the urgent priority of the UN and EC that fulfil five fundamental IUCN NBS criteria.

3.4.5. Location and distribution of NBS case studies

Fig. 6a shows the global distribution of case studies examining the benefit of NBS to address ~22 HMHs and ~26 societal challenges. The dots represent the location of the case studies and the NBS types used against ~22 HMHs and ~26 societal challenges. These NBS evidence were collected from seven continents with a concentration of case studies from Europe (~60 %), Asia (~13 %), North America (~11 %), Africa (~10 %), South America (~5 %) and Australia (~2 %; Fig. 6c). Europe, although being the second smallest continent, has encouraged the maximum number of NBS case studies. This may be due to the fact that several databases and case studies are part of Horizon 2020 projects. In addition, the EC launched a special program for NBS in rural and urban areas and is promoting the concept and the wider uptake in general. So far, the term NBS is mostly dominated within the EU while other areas refer to NBS measures sometimes with different connotations, like "water-sensitive urban design" in the case of Australia among others (Fletcher et al., 2015). Furthermore, Kabisch et al. (2022) discussed how the design and implementation of NBS are particularly relevant in the urban context where there is a high population density and vulnerability to natural hazards. With respect to this, most of the NBS project funders are supporting projects that focus on urban settings. Comparing the implemented NBS case studies with the distribution of the population by continent, Asia is having the largest population (59.7 %) with the smallest number of case studies (12.5 %) compared with Europe which is the third populated continent (9.4 %) has the largest number of case studies (59.8 %), see Fig. 6b.

Our analysis is similar to a study by Schroeter et al. (2021) and Debele et al. (2019) who found that most of the implemented NBS case studies are unevenly distributed and Eurocentric while there is a huge gap and need to focus on documenting NBS case studies in Asia, North America, Africa, South America, and Australia. Considering the size of these continents, it seems there is a wide scope of NBS development in other large continents. Overall, most of the case studies (~73 %) came from nations classified as high-income and upper-middle-income continents such as North America, Australia, and Europe (World Bank, 2020) and ~29 % were from low-income and lower-middle-income continents.

3.5. Scale of nature-based solutions used by the case studies

For the systematic monitoring, evaluation, replication, and upscaling of NBS, research should address the scale that matches the scale of hazards and impact posed by climate change (Hobbie and Grimm, 2020; Martin et al., 2020). The implementation of multi-functional NBS may range from local scale (e.g., green infrastructures, such as green roofs, green walls, and rain gardens) to whole catchment or regional scale (e.g., using natural and constructed wetlands for flood control). Such scaling issues need to be addressed in the contexts of the individual location of implementations - their local biome, climate, and hydrogeology; the magnitude and types of HMHs under investigation (e.g., droughts, floods); their specific social, ecological, and technical characteristics (e.g. spatial segregation of risks, the age, type, and distribution of green-blue and grey innervations, and the social barriers to implementation of NBS); and opportunities to integrate green-blue with grey interventions. On this basis, the analysis from the 547 case studies revealed that the majority of the NBS (~96 %) were implemented to tackle societal challenges such as HMHs, DRR, urbanisation, and climate change at micro/scattered (~50 %) and *meso*/watershed (~46 %) scales while very little (~4 %) nature-based interventions were utilised at macroscale/landscape scale to manage the large-scale societal challenges (Fig. 7c). NBS often works best and effectively against climate change-induced natural hazards when implemented at larger scales (across whole landscapes or cities) (Swann et al., 2021). Our analysis, therefore, supports the evidence for the application and scaling up of NBS at a large/landscape scale to reduce the hydro-meteorological risk (HMR) which is still behind and received little attention.

3.6. Co-benefits produced by nature-based solutions

NBS is designed to deliver direct, measurable, and multiple (co-) benefits for nature and society in a sustainable and cost-effective manner. The rationale for the implementation of NBS as a measure to handle societal challenges (e.g. natural hazards and climate change) alone or in combination with the grey measures is that they provide a wide range of expected benefits (e.g., reduction of floods, droughts, heatwaves) and co-benefits (e.g., improving vegetation cover and biodiversity, carbon storage in soil, job creation, physical and mental health, (Fig. 7e)) while generating limited disbenefits (e.g., increased pollen in the air, mosquitoes), thus proving cost-effective on a medium-to-long term perspective (EC, 2015). For instance, the collected case studies that are implemented to manage HMHs and climate change as a direct benefit addressed about ~64 % environmental co-benefits (e.g., improving biodiversity, air quality, drinking water quality, carbon storage, etc.), ~27 % social co-benefits (e.g., human well-being, job creation, social cohesion), and ~9 % economical co-benefits (e.g., local tax revenue, new businesses).

Fig. 7e, summarises numerous co-benefits provided by NBS. It was found that ~34 % of the NBS delivered co-benefit to increase vegetational cover and biodiversity, followed by human well-being, i.e., humidex and recreational area (~18 %), water quality (~13 %) and the other ~35 % of co-benefits are generated to manage environmental (e.g., carbon storage in vegetation, drinking water quality), human (e.g. social cohesion, increase public participation), and economic related issues (e.g., local tax revenue, new businesses), Fig. 7e. The results of this finding are consistent with the recent study by Neumann and Hack (2022) and Curt et al. (2022) indicating that NBS is a holistic approach to help societies to adapt to and mitigate the impact of climate change and natural hazards while providing co-benefits to the environment (e.g., improved biodiversity), society (e.g., recreational services), and economy (e.g., local tax revenue).

3.7. Limitations

Several limitations were identified through reviewing the NBS case studies that can guide future research. The monitoring and evaluation frameworks for NBS, like the EU Handbook (Dumitru and Wendling, 2021), are available but there is a need to identify and utilise appropriate metrics and indicators to assess the socio-ecological effectiveness and limitations of NBS in the face of future climate change. This gap hinders the development of a comprehensive understanding of the broader socio-ecological benefits of NBS and the ability to accurately evaluate their true impact. Developing indicators and metrics to assess the socio-ecological effectiveness of NBS can provide, a more comprehensive understanding of the broader socio-ecological benefits and true impact of NBS under the changing climatic conditions. Additionally, there are challenges related to data availability and accessibility, as well as potential variations in data quality from different sources. Despite efforts to examine comprehensive databases and platforms, further research is needed to address these limitations. This can be achieved by enhancing the quality of data for NBS case studies. It is important to note that the reliability and accuracy of the data collected for NBS case studies depend on the quality and consistency of the original sources. There may be variations in the quality, depth, and detail of the data across different sources. Furthermore, funding sources can also influence the implementation of NBS case studies and the origin of associated databases/platforms.

4. Conclusions and recommendations

NBS has emerged as the best, sustainable, and cost-effective solution to address multiple societal challenges. Currently, the information about their usability and effectiveness is largely scattered. The aim of this study was to consolidate, analyse, and facilitate access to the largely dispersed evidence base on the effectiveness of NBS for managing societal challenges and their impacts on people such as climate change, DRR, biodiversity loss, human health, and well-being. In this study, 547 NBS case studies were collected, harmonised, analysed, and discussed to support the implementation of climate-proof NBS for DRR and policy development.

4.1. Conclusions

The following conclusions were drawn:

- In the collected case studies ~63 % of NBS were planned and implemented to address environmental issues (natural hazards, climate change, loss of biodiversity). The remaining ~37 % were utilised to manage socio-economic challenges e.g., social justice, inequality, social cohesion, and economic development. When analysing case studies as per single- and multi-hazard categories, it was found that ~44 % and ~56 % of the case studies across the world were implemented to reduce the risks posed by single and multiple HMHs, respectively.
- The majority of collected NBS case studies were deployed against HMHs (floods, landslides, and snow avalanches: ~45 %) followed by meteorological/climatological (droughts, heatwaves, and others: ~30 %) and environmental hazard families (soil erosion, eutrophication: ~24 %) while very little NBS were used to manage natural fires such as wild and forest fires (~1 %).
- ~88 % of NBS studies were supported and integrated into national policies, while regional and local policies accounted for only about 12 % (6 % each). These NBS are instrumental in advancing major policy goals and UN agendas, including the SDGs and the ABT. ~ 60 % of implemented case studies contributed to achieving SDG15 (29 %), SDG13 (15 %), and SDG6 (15 %), while the remaining 41 % supported other SDGs (2, 3, and 16). The role of NBS in biodiversity restoration and loss reduction, with mention of ABT, was assessed. About 69 % contributed to strategic goals B and D, while the remaining 32 % supported goals A, C, and E.
- NBS effectiveness varies across ecosystems. Urban and rivers/lakes ecosystems account for ~48 % of NBS implementations. Woodland/forest, coastal, cropland, marine inlets/transitional waters, wetlands, grassland, and heathland/shrub ecosystems make up ~51 %, while continental shelf, sparsely vegetated land, and open ocean are poorly represented at 1 %. Four types of NBS (blue, green, mixed, and hybrid) are used within these ecosystems. Green (~33 %) and hybrid (~31 %) measures make up ~64 % of implemented case studies, while ~27 % use a mixed approach, and ~10 % provide limited evidence of the blue approach.
- This paper presents ten parent interventions from collected NBS case studies. ~84 % of the studies focused on six interventions – stream restoration, soil water conservation, green built environment (green roof, walls, rain gardens), forestry (afforestation, reforestation), SuDS, and infiltration/biofiltration structures. The remaining 16 % accounted for four other interventions (which ones). The findings highlight a neglect of nature-based interventions in coastal management, with a strong emphasis on urban areas, rivers, lakes, woodlands, and forests (~60 % in total). These interventions were implemented at different scales, including single/local (50 %), watershed (46 %), and landscape/regional (4 %) scales, to address climate change and HMH impacts.
- Three main co-benefits (environmental, social, and economical) provided by nature-based innervations were discussed in this study. Most of the case studies (~64 %) delivered environmental co-benefits such as improving biodiversity, carbon storage, water, and air quality, etc. ~27 % and ~ 9 % of the case studies reported social (job creation, social cohesion) and economic (local tax revenue) co-benefits, respectively. Nonetheless, the economic co-benefits of NBS are poorly recognised and documented by the reviewed case studies.

4.2. Recommendations

Based on the analysis and findings reported in this paper, the following recommendations can be provided for future research:

- The establishment of a global NBS database that encompasses diverse case studies and best practices is crucial for both research and implementation purposes. This is particularly important in addressing the limitation of the current Europe-concentrated NBS databases, such as GeoIKP, Oppla, Climate-Adapt, and NBS Evidence Platform. By incorporating case studies and best practices from various regions including Asia, North America, Africa, South America, and Australia, a more comprehensive understanding of NBS effectiveness worldwide can be achieved. Having a global NBS database can facilitate the dissemination and implementation of NBS under different climate and socio-economic conditions. It can provide a broader perspective on the effectiveness of NBS globally. To enhance the connection between NBS and global policy, it is recommended to integrate such a global database with existing EU-funded project databases. This integration would create a unified platform that serves as a central hub for NBS case studies, enabling the cataloguing of information, leveraging best practices, and long-term monitoring of NBS effectiveness across continents.
- **NBS indicators play a crucial role in evaluating the effectiveness in climate adaptation from a social-ecological perspective.** However, there is currently a lack of standardised indicators that can be used to assess the effectiveness of NBS across different scales and dimensions. As a result, it is necessary to develop context-specific indicators that are tailored to the specific circumstances in order to ensure the usability, scalability, and transferability of NBS. This approach will help minimise unintended consequences and enhance understanding at the local level, particularly in the face of changing climate conditions.
- **NBS plays an important role in achieving Net-Zero emissions by simultaneously reducing fossil fuel emissions.** While NBS can contribute to mitigating the impact of climate change, it is important to prioritise further research on integrating them with solutions that result in significant reductions in greenhouse gas emissions and engineered carbon removal methods. This requires studying the interactions and synergies between NBS and traditional engineering solutions, as well as investigating the specific role of NBS in aligning with international agreements like the Paris Agreement and the SDGs. By focusing on these areas, we can better understand how NBS can effectively contribute to the overall goals of climate action and sustainable development.

CRediT authorship contribution statement

SD: Conceptualisation, Collecting the NBS case studies, Data quality control & analysis (Figures, Tables), Writing - Original Draft, Writing - reviewing & editing. **LSL**: Conceptualisation of the NBS classification (metadata model) adopted in GeoIKP and used in this paper, Quality Checking of NBS case study, Supervision, Writing - reviewing & editing. **PK**: Conceptualisation, Supervision, Project Administration, Funding, Collecting NBS Case Studies, Analysis, Writing - Original Draft, Writing - reviewing & editing. **JS**: Collecting NBS case studies, Writing - review & editing. **JO:** Collected information for the classification of hazard, multi-hazard, ecosystem, and co-benefits, Writing - review & editing. **EB**: collected information related to co-benefits, Writing - review & editing. **SV**: Quality checking and approving of the implanted NBS case studies, Writing - review & editing. **ZA & IP**: Collected policy & societal challenges data, Writing - reviewing & editing. **MARS & AG:** Collected information related to ecosystem and intervention, Writing - reviewing & editing. **SDS**: Conceptualisation, Funding, Supervision, Writing - reviewing & editing. All authors commented on the draft manuscript and assisted in the conceptual development of the text, tables, figures, and the overall cohesiveness and proofreading of the paper.

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

No data was used for the research described in the article.

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Appendix A. Supplementary data

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