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Research article

A framework for selecting Nature-based Solutions: applications and challenges at the catchment scale

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A R T I C L E I N F O

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Stakeholders
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A B S T R A C T

Nature-based Solutions (NbS) aim to address natural and anthropogenic risks, enhancing ecosystem-based approaches, biodiversity, human health, and socio-economic growth. Despite the growing interest in NbS applications, their integration into landscape planning at the catchment scale remains limited, given the multi-disciplinary comprehensive features related to them. To overcome this shortcoming, this study presents a multi-disciplinary GIS-based framework for identifying, selecting, and prioritizing NbS at the catchment scale, specifically focusing on water resources availability and management. The catchment is first categorized through a multi-level approach that considers the ecosystem types, climate class, and geomorphological characteristics (Stage 1). Through a literature review, an NbS catalog (Decision Matrix) was built, considering catchment classification (Stage 2). Finally, potential solutions from the decision matrix were mapped for each class (Stage 3). Stakeholder engagement was conceptualized by integrating the technical outcomes with the local perspectives to enhance the co-design and knowledge-sharing in the decision process. The framework was tested in the Bode River catchment (Germany), showing reliable results in detecting the potential areas for NbS implementation, and the framework's replicability to multiple contexts, given its ease of application and tailorable structure, even when different policy makers are involved in the process. The proposed framework supports baseline NbS map development to identify priority areas, engage stakeholders, and guide investments in alignment with long-term regional goals and the Sustainable Development Goals (SDGs).

1. Introduction

According to the International Union for the Conservation of Nature (IUCN), Nature-based Solutions (NbS) are “actions to protect, sustainably manage and restore natural and modified ecosystems in ways that address societal challenges effectively and adaptively, to provide both human well-being and biodiversity benefits” (Cohen-Shacham et al., 2016). This definition, commonly used to mean a wide range of ecosystem-based approaches, include additional concepts such as Natural Solutions (the role of protected areas in contrasting climate change); Ecosystem-based Adaptation (EbA); Ecosystem-based Disaster Risk Reduction (Eco-DRR); Green Infrastructure (for economic growth and investments, in the urban context); Natural Infrastructure (for a sustainable Integrated Water Resource Management); and Holistic or Regenerative Landscape management (IUCN, 2020) .

NbS has been recognized as a crucial tool for addressing climate change by mitigating carbon emissions (Pan et al., 2023), reducing disaster risks (Zhu et al., 2020) and enhancing biodiversity (Xie and Bulkeley, 2020), while strategically tackling various societal challenges, such as climate change mitigation and adaptation, disaster risk

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reduction, economic and social development, human health, food security, water security, and reversing environmental degradation and biodiversity loss (IUCN, 2020). Moreover, NbS plays a crucial role in building resilience to food and water insecurity by enhancing ecosystem services and supporting sustainable agricultural practices (Bommarco et al., 2013; Dunlop et al., 2024).

During the last decade, several approaches have been proposed to assess the main features of NbS across different scales (Dunlop et al., 2024; de Lemos et al., 2024). Many studies are devoted to presenting operative frameworks for urban and peri-urban areas (Fang et al., 2024). Sari et al., (2023) aimed to assess the NbS response to hydro-meteorological natural hazards. Lalonde et al., (2024) reviewed the hydrological impacts of NbS at the catchment scale, focusing on interventions like reforestation, wetland restoration, and water harvesting. They found that NbS effectiveness varies by location, design, and environmental factors. Integrated planning of NbS at the catchment scale can simultaneously enhance water availability, in terms of improving water infiltration and retention or groundwater recharge, elevate water quality, and manage floods, although there are inherent trade-offs between different objectives and building resilience to food and water insecurity (Haubrock et al., 2025; Liu et al., 2023).

Greater attention has been given to urban contexts in implementing NbS (Faivre et al., 2017; Fang et al., 2024), while simultaneously, there is limited focus on large-scale applications, such as at the catchment scale. Indeed, given the complexity and specificity of hydro-meteorological, geological, and socio-economic features, the criteria for NbS identification, design, implementation, and monitoring should target challenges (Perosa et al., 2021), such as specific natural hazards (Pignalosa et al., 2022; Zumpano et al., 2018), biodiversity enhancement (Spehn et al., 2011; Vaculisteanu et al., 2019), and socio-economic threats (Ingold et al., 2010). Simelton et al., (2021), under this umbrella of criteria, following a robust literature review, developed a technical framework based on the evaluation of four main functions, namely the sustainable practices, the green infrastructure, the amelioration, and the conservation, to overcome the limitations of the available approaches for the NbS investigation in agricultural areas. It relied on the integration of production and conservation functionalities. Nevertheless, stakeholder engagement was raised as the pivotal task for effective comprehensive assessment. Concerning rural and mountainous areas, Caroppi et al., (2024) implemented a hierarchical multi-level assessment framework tool (AFT) to quantitatively investigate the comprehensive outcomes of NbS and hybrid scenarios, based on the evaluation of a variable set of Key Performance Indicators (KPI) belonging to technical, environmental, socio-economic, and financial fields. The approach was tailored to compare at the ex-ante stage, namely before solution implementation, different NbS and hybrid scenarios, and at the ex-post stage, to monitor the effectiveness of the implemented solution. The tool was tested by Pugliese et al., (2022) on the Isar River case study to assess the overall reliability of the Isar River restoration in the areas surrounding the Municipality of Munich (Germany). The authors remarked on the stakeholders' relevant role in both selecting the most suitable KPI and properly weighing their relevance.

Concerning the catchment scale, despite some attempts made in literature, as it stands, an overall comprehensive framework for the quick and effective identification and selection of suitable NbS at the catchment scale remains a challenging, unresolved task. On the Scopus database, using "NbS" and "catchment" keywords, a set of 101 papers was found by 2024, especially focused on specific field applications or policy investigations. Nevertheless, there are very few proposed frameworks for the catchment scale (20 items). Among them, Liu et al., (2023) proposed an NbS optimization framework for urban and rural environments, based on a heuristic optimization algorithm for the qualitative-quantitative assessment of water resources. Sciuto et al., (2024) developed an integrated workflow for the investigation of NbS benefits against flood risk in urban areas by coupling different hydraulic solvers. Qiu and Schertzer, (2024) developed a scale-invariance framework to investigate hydrological performance and economic dimensions of NbS by integrating hydrological modeling with Life Cycle Costs (LCC) assessment. Through a cost-benefit analysis, Masiero et al., (2024) assessed the outcomes of riparian forest restoration against flood risk at the Koiliaris River Watershed in Greece. They proposed a multi-disciplinary workflow integrating empirical and scientific investigations with an integrated participatory process.

Notwithstanding, the above-referenced works show case-specific features that make them reliable when similar contexts are detected and a robust set of spatial and socio-economic data is available. To implement approaches that are effectively replicable in different spatial, geomorphological, and socio-economic environments while resulting in ease of application and integration, a comprehensive multi-level tool should be addressed. The absence of a holistic and streamlined framework for NbS selection at the catchment scale represents a critical bottleneck, leading to fragmented efforts, suboptimal outcomes, and missed opportunities in environmental management (European Environment Agency, 2023; Salafsky et al., 2021). While significant advancements have been made in understanding individual NbS benefits (Watkin et al., 2019), the challenge lies in effectively synthesizing this knowledge with socio-economic and hydrological data to guide rapid, multi-criteria decision-making across an entire catchment (IUCN, 2020). Addressing this unfulfilled need is paramount for realizing the full potential of NbS.

This study is thus an effort to fill the knowledge gap in existing literature about the NbS identification and selection at the catchment scale using a comprehensive approach, with the main scope to deal with the water availability and management challenge. The catchment scale emphasizes the systematic regulation of water for both rational utilization and combating soil erosion, as well as protecting against floods. The proposed catchment scale framework leverages free and publicly accessible data, thereby improving the potential for replication across various locations. This comprehensive approach ensures that water and soil management aspects are addressed effectively. The first objective is to define how a suitable NbS can be identified and selected according to the different ecosystems and geomorphological conditions across the catchment. The second objective is to build a catalog of solutions (Decision Matrix), which contains NbS that have been tested and validated, so that it can be used to select potential and context-specific solutions. The ultimate objective of the study is to present a workflow so that the framework can be adopted and applied to real-world case studies.

2. Methodology

2.1. General NbS framework

The general framework highlights the relevance of adopting a comprehensive strategy for the identification, selection, implementation, and long-term monitoring of NbS. The effectiveness of these solutions cannot be assessed without including behavioral, economic, political, and institutional challenges at each stage. Even the most technically robust solutions may fail to achieve their intended outcomes if these factors are not properly considered. A well-coordinated strategy relies on policy backing, financial incentives, active stakeholders' participation, and capacity-building to ensure the lasting impact and sustainability of NbS. The sketch in Fig. 1 gives an overarching view of activities, structured into three distinct levels.

Level 1 entails defining a baseline scenario, which primarily relies on defining the targeted challenges and co-benefits, as well as data collection, identification, and NbS selection. This process enables the categorization of NbS for varying ecosystems, climates, soil types, and topographies.

Level 2 encompasses the NbS design and implementation, entailing the integration of technical investigations with the assessment of the socio-economic and environmental co-benefits of the solution using KPI. Thus, through active engagement, gathering experience, and deep

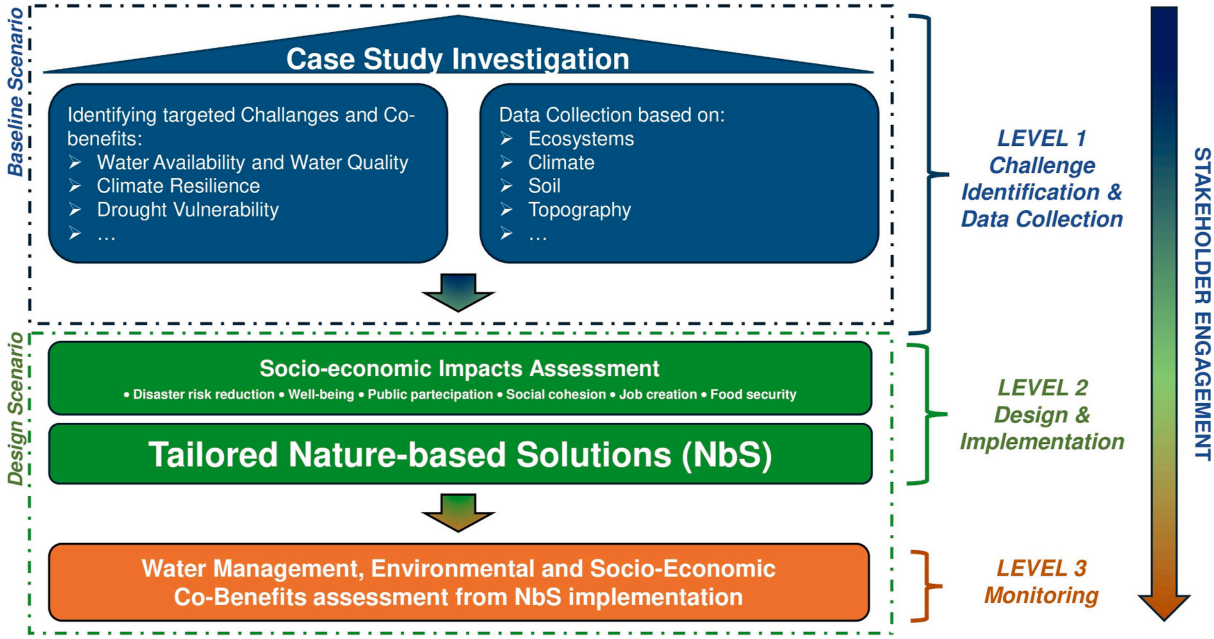

Fig. 1. General framework for NbS under baseline and design scenarios.

discussions (workshops, living labs, and training sessions) with stakeholders, solutions can be tailored to specific challenges, depending on the local specific needs and opportunities. The implementation phase focuses on executing the plan, allocating resources, and handling the practical aspects to bring the solution adopted to fruition.

Level 3 aims to monitor the performance and effectiveness of NbS, highlighting their broader benefits and impacts. KPIs like economic impact, social well-being, and environmental benefits can be accounted for when assessing the effectiveness of a specific NbS intervention. The selected KPI must be measurable, straightforward, achievable, not overly time-consuming, and relevant to the project's objectives (Kumar et al., 2021; Wendling et al., 2019).

This manuscript is focused explicitly on identifying, selecting, and prioritizing potential NbS as depicted in Fig. 2.

2.2. *Multi-disciplinary NbS framework*

The multi-disciplinary NbS framework, built on the baseline scenario of the general framework of Fig. 1, is structured on the three stages shown in Fig. 2 and discussed in Sections 2.3, 2.4, and 2.5.

2.3. *STAGE 1 – catchment classification*

Stage 1 entails GIS-based data collection and processing to categorize catchment, based on a multi-step approach based on the classification of land use/land cover, soil type, climate, and topography data, as sketched

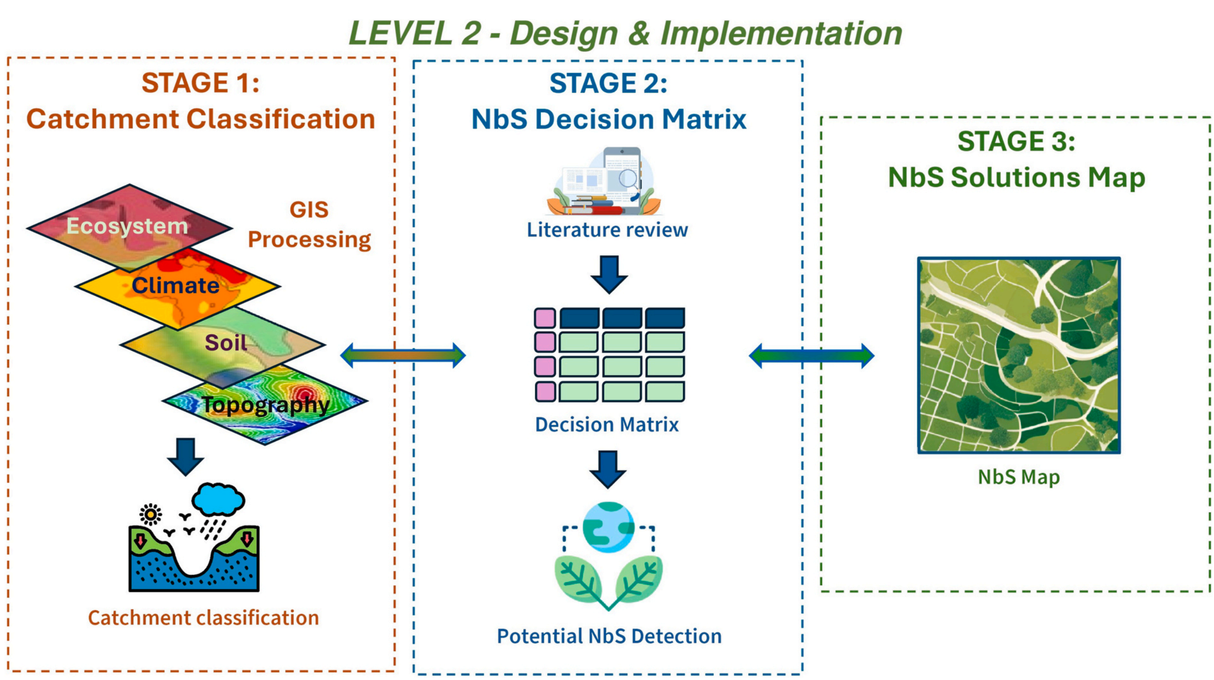

Fig. 2. Multi-disciplinary framework for mapping Nature-based Solutions (NbS).

in Fig. 3 and discussed below. The choice of these categories relies on their relevance in the initial assessment of NbS features dealing with water management in multiple environments (Lalonde et al., 2024; Jakubínský et al., 2021; Bayissa et al., 2025), as well as entailing ease of investigation in a GIS environment. Their integration can thus allow mapping homogenous areas potentially suitable for the implementation of specific NbS. It is worth remarking that other categories may result in the effective suitability for NbS investigation in specific contexts. As an example, for urban and peri-urban areas, along with land cover classification, the anthropogenic rate is also a critical task for detecting the suitability of green and blue infrastructures (GBI) or protection and restoration solutions (IUCN, 2020).

Nevertheless, the aim of the proposed framework relies on providing a practical tool giving specific insight into multiple environments at the catchment scale, mainly addressing the water management challenge. Thus, a more general structure allows for more flexibility and ease of application. It is worth remarking that, given its multi-level and flexible structure, further features can be properly addressed for an updated, tailored implementation. The output of STAGE 1 is a raster layer representing the catchment classes.

STEP 1: Ecosystems Classification

In chapter 2 of Nature Restoration Law (Regulation (EU) 2024/1991 on nature restoration and amending Regulation (EU) 2022/869) delineates restoration targets and obligations, specifying distinct ecosystems: terrestrial, coastal, and freshwater ecosystems (Article 4); marine ecosystems (Article 5); urban ecosystems (Article 6); agricultural ecosystems (Article 9); and forest ecosystems (Article 10), (European Union, 2024; Perissi, 2025). Aligned with this legislative framework, the methodology presented in this study classified ecosystems into five categories: agricultural, urban and peri-urban, forest, freshwater, and coastal ecosystems.

The Corine Land Cover 2018 dataset (CLC2018), produced by the Copernicus Land Monitoring Service and coordinated by the European Environment Agency (EEA), provides comprehensive and consistent information on land cover and land use across Europe for the year 2018. This dataset, with its spatial resolution of 100 m, significantly advances the legacy of the CORINE Land Cover Programme, enabling comprehensive analysis of land cover status and changes (Corine Land Cover, 2018). This dataset was used to define the ecosystem classes (Maes et al., 2016) detailed in Table 1.

i **Urban and peri-urban ecosystem:** cities and their surrounding socio-ecological systems, with a high urbanization rate (Maes et al., 2016). It represents a unique ecosystem category, predominantly artificial yet composed of various small patches of natural elements located in urban fringes, mainly strongly affected by human activities.

ii. **Agricultural ecosystem:** whether semi-natural or modified natural, is a human-managed environment designed for food and commodity production. Also known as “agro-ecosystem” ((Secretariat of the Convention on Biological Diversity Food and Agriculture Organisation of the United Nations, 1998), the EU is home to some of the continent’s most species-rich environments (Wilson, 2012); however, it affects both the ecosystem services and the socio-economic aspects (Tscharntke et al., 2005; Zhang et al., 2007).

iii. **Forest ecosystem:** dynamic integration of plant, animal, and microorganism communities interacting with their abiotic environment as a functional unit, with trees as pivotal components. Human presence, driven by cultural, economic, and environmental factors, is integral to many forest ecosystems (Mulligan, 2014; Rewald et al., 2020; UN Environment Programme, 2021).

iv. **Freshwater ecosystem:** refers to ecosystems found within terrestrial environments, including rivers, lakes, streams, wetlands, ponds, and groundwater systems. These ecosystems are

Table 1
Ecosystem classification based on Corine Land Cover 2018. .

Ecosystem	CORINE Land Cover Classes
Urban and Peri-Urban	111–142: Urban fabric, industrial areas, transport networks, green spaces, and recreational facilities.
Agricultural	211–244: Arable land, permanent crops, pastures, and heterogeneous agricultural areas.
Forest	311–335: Broad-leaved, coniferous, mixed forests, scrublands, and open natural spaces.
Freshwater	411–412, 511–512: Inland wetlands, rivers, and freshwater bodies.
Coastal	421–423, 521–523: Coastal wetlands, lagoons, estuaries, and marine waters.

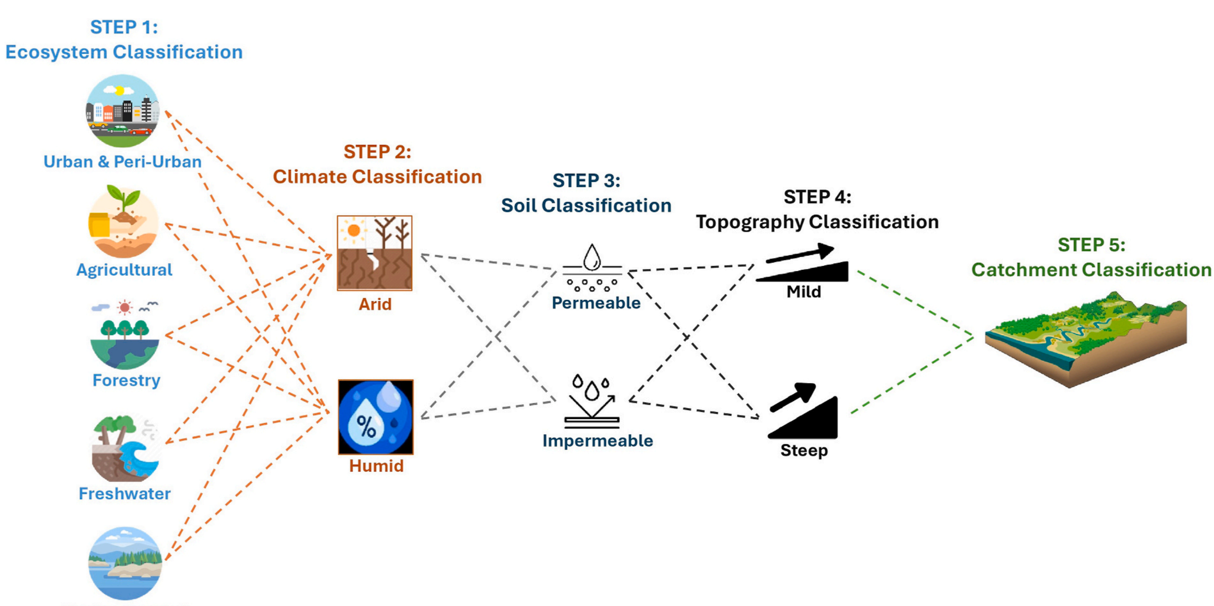

Fig. 3. Workflow for catchment classification and identification of NbS.

integral to the hydrological cycle and play a critical role in supporting biodiversity, regulating water quality, and providing essential ecosystem services such as flood control and water purification (Aylward et al., 2005; D'Alelio et al., 2021; Cohen-Shacham et al., 2016; Mukherjee et al., 2021).

v. **Coastal ecosystem:** local administrative units (LAU) where at least 50 % of their surface lies within 10 km of the coastline, which is the boundary where land and water surfaces meet (Eurostat European Union, 2013). The European Commission has adopted the use of the mean high tide (European Commission, 2000) as a standardized measure for delineating EU coastlines, despite variations such as mean or median tides.

STEP 2: Climate Classification

Climatic conditions affect the selection and design of NbS by dictating the types of interventions needed to adapt to specific climate conditions (Seddon et al., 2020; Sowińska-Świerkosz and García, 2021). Thus, selecting and designing NbS depending on the climate variable is pivotal. In this work, the aridity index (AI) is used to classify climate based on the ratio of precipitation to potential evapotranspiration. It provides insights into the dryness or moisture of a region (Kimura and Moriyama, 2019; Zomer et al., 2022). Specifically, for the sake of simplicity, two categories are accounted for: Arid ($AI \leq 0.65$) and Humid ($AI > 0.65$), as given in Table 1A (Appendix A).

The Global Aridity Index (Global-AI) v3 dataset offers high-resolution global raster data at 30 arc-seconds (~1 km at the equator), representing the long-term (1970–2000) annual AI. This index is calculated as the ratio of precipitation to reference evapotranspiration (ET_0) using the Food and Agriculture Organization (FAO)-56 Penman-Monteith method (Zomer et al., 2022). Following downscaling to a resolution of 100 m, the dataset was employed for climate classification. The climate was reclassified into two categories based on the Aridity Index: Arid ($AI \leq 0.65$) and Humid ($AI > 0.65$), as outlined in Table 1A (Appendix A).

STEP 3: Soil Classification

Soil characterization affects NbS by controlling water infiltration, retention, growth activity, and biodiversity (Fini et al., 2017; Spurgeon et al., 2013). Coarse-textured soils are prone to erosion, while fine-textured soils stabilize slopes and retain water for NbS projects (Andrés et al., 2021). Different soil types exhibit varying permeability capacities, affecting the water velocity (Gärttner et al., 2023).

The Soil Texture Classes dataset (Tomislav Hengl, 2018) provides a global classification of soil texture according to the USDA system, with a spatial resolution of 250 m. After downscaling the data to 100 m, soils were classified into two main categories based on USDA classification: soils with less than 20 % clay content are classified as permeable soils, while those with 20 % or more clay content are classified as impermeable soils (Thien, 1979; United States Department of Agriculture, 2022).

STEP 4: Topography Classification

Topography is crucial in NbS selection and implementation, especially for landslide risk reduction (Devanand et al., 2023; Dewi and Wijayanti, 2023). The NbS selection is significantly influenced by the specific type of topography (Zedek et al., 2024).

The Shuttle Radar Topography Mission (SRTM) Version 4 digital elevation model provides high-quality, near-global elevation data at a resolution of 90 m (Jarvis et al., 2008). After upscaling the data to 100 m for consistency, it was used to calculate slope percentages and classify the topography. Following the FAO soil slope classification (Jahn et al., 2006), the topography was simplified into two categories: Mild (0–5 %) and Steep (greater than 5 %), as shown in Table 2A (Appendix A).

STEP 5: Catchment Classification

An integrative approach is adopted to classify the catchment effectively based on ecosystem, climate, soil type, and topography. The classification workflow, as depicted in Fig. 3, enhances a systematic overlay of these geospatial layers to produce a refined classification output. This process is carried out within the GIS environment, defining 40 distinct categories, such as Agri-Humid-Imper-Mild, notably defining a catchment with an agricultural ecosystem, humid climate, impermeable soil, and mild slope. This detailed classification enhances the capability to identify and select suitable NbS tailored to the specific class of catchment area.

A spatial resolution of 100 m was used, which is a reasonable choice as it aligns well with the resolution of the land cover layer.

2.4. STAGE 2 – NbS catalog (decision matrix)

There are plenty of studies and resources in literature proposing and cataloging NbS. Notable examples include the comprehensive listings provided by Oppla (2023), Evaluating the impact of nature-based solutions: A handbook for practitioners (Dumitru and Wendling, 2021) and a catalogue of nature-based solutions for urban resilience (World Bank's Global Facility for Disaster Reduction and Recovery, 2021).

Nevertheless, most of these resources are tailored to specific projects, case studies, and ecosystems. However, a solution that is effective in one ecosystem and climate may not yield comparable benefits or effectiveness when applied to a different region. This inefficiency arises from the complex interplay of factors such as soil type, geographical characteristics, and localized environmental dynamics, which significantly affect the effectiveness and suitability of NbS. As NbS is a relatively new concept gaining significant attention over the past five years Fig. 4, there is a growing need to systematically categorize and assess existing solutions. To address these limitations, an extensive literature review was carried out to build a comprehensive catalog of NbS (Decision Matrix). This decision matrix categorizes potential NbS across various ecosystems. Additionally, it incorporates critical factors such as climate, soil type, and topography features to ensure a holistic and context-sensitive approach to NbS selection.

A comprehensive literature review was undertaken to develop the decision matrix. The methodology for this review encompassed several critical steps:

1. **Database Search:** Scientific databases, including Web of Science, PubMed, Scopus, and Google Scholar, were systematically searched using keywords "nature-based solutions," "ecosystem conservation," "ecosystem restoration," "ecosystem services," and specific ecosystem types (e.g., agricultural, urban areas, forests). The search criteria were restricted to peer-reviewed articles published in English-language journals between 2010 and 2024 to ensure the incorporation of contemporary research findings. 132 articles were found through the initial search criteria.
2. **Inclusion and Exclusion Criteria:** Studies were included if they (a) explicitly discussed NbS, (b) addressed their application within specific ecosystems, and (c) provided empirical evidence or case studies demonstrating their effectiveness. Articles that focused on theoretical frameworks without practical examples or those that lacked peer review were excluded. After this sorting, only 34 articles were identified, which explicitly discussed the implementation of NbS in these ecosystems.
3. **Data Extraction**: Data was extracted from the selected studies regarding the type of ecosystem, specific NbS implemented, geographic location, climate context, and observed outcomes. This process entailed thoroughly reading and analyzing the articles to ensure accurate and pertinent data collection.
4. **Categorization of Solutions:** The extracted data was categorized based on ecosystem types (e.g., agricultural, urban, forest), as well as

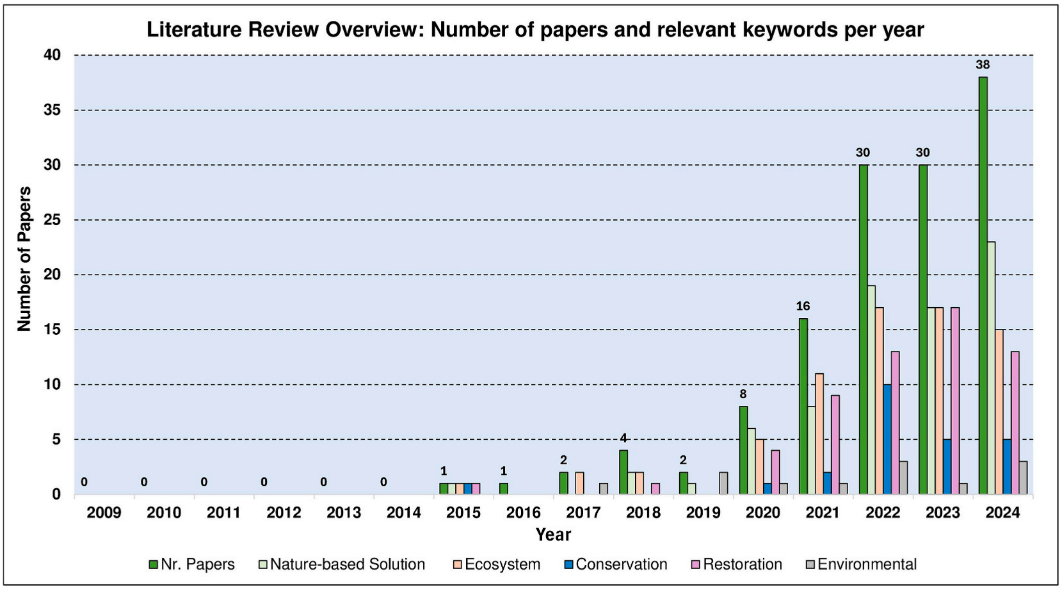

Fig. 4. Temporal distribution and increasing trend of publications on NbS.

climate and geographical contexts. This categorization was designed to build a matrix that aligns specific NbS with the classification frameworks.

5. **Decision Matrix Development:** The final step involved constructing a comprehensive matrix that categorizes the identified NbS according to ecosystems, climatic conditions, and geomorphological characteristics. Simultaneously, the matrix links these solutions to various co-benefits and societal challenges. This matrix acts as a practical tool to facilitate the selection of suitable NbS tailored to specific societal challenges and environments.
6. **Adaptability Assessment:** A qualitative assessment was conducted by the authors through an in-depth literature review, aiming to assign an adaptability score to the potential solutions. If a certain solution performs well in certain ecosystems, climates, and geomorphological conditions, it is assigned to have a higher adaptability in those specific conditions, and the same solution may have a lower adaptability in another ecosystem. Moreover, all the influencing factors, such as ecosystem, climate, soil, and topography types, were examined to determine their role in either supporting or restricting the adoption of solutions in those conditions. Then, based on this expert knowledge, solutions achieved low, moderate, or high adaptability, reflecting their likelihood of success in specific contexts (Tables 2-6).

Table 2
Potential NbS interventions/actions for urban ecosystems, arid and humid climates, permeable (Perm) and impermeable (Imper) soils, mild and steep topographies.

Potential NbS interventions/actions	Urban and Peri-Urban Ecosystems								References
	Arid				Humid				
	Perm		Imper		Perm		Imper		
	Mild	Steep	Mild	Steep	Mild	Steep	Mild	Steep	
Rainwater Harvesting and Infiltration Basins	•••	••	••	••	•••	••	••	••	(Blanco-Canqui, 2024; Nalluri and Karri, 2024; Recalde et al., 2024; Yimer et al., 2024)
Grassland Protection and Restoration	•	••	••	••	•••	••	•••	••	(Adil et al., 2022; Blanco-Canqui, 2024; Fernandes and Guiomar, 2018; Keesstra et al., 2018)
Permeable Pavements	•••	••	•	•	•••	••	•	•	(Gómez Martín et al., 2020; Hekrle, 2022; Huang et al., 2020; Krauze and Wagner, 2019; Liquete et al., 2016; Qi et al., 2020; Taylor et al., 2018; Tsatsou et al., 2023; Vojinovic et al., 2021; Yimer et al., 2024)
Creation of urban blue spaces	••	•	••	•	•••	••	••	•	(Bunclark and Hernández, 2022; Gómez Martín et al., 2020; Hekrle, 2022; Huang et al., 2020; Kabisch et al., 2016; Krauze and Wagner, 2019; Liquete et al., 2016; Nesshöver et al., 2017; Qi et al., 2020; Recalde et al., 2024; Tsatsou et al., 2023; Wolff et al., 2023; Woo, 2020; Yimer et al., 2024)
Urban Green Infrastructure and Urban Forests	••	••	••	••	•••	•••	•••	•••	(Bunclark and Hernández, 2022; Dunlop et al., 2024; Dumitru and Wendling, 2021; Faivre et al., 2017; Gómez Martín et al., 2020; Hekrle, 2022; Huang et al., 2020; Kabisch et al., 2016; Krauze and Wagner, 2019; Nesshöver et al., 2017; Qi et al., 2020; Tsatsou et al., 2023; Vojinovic et al., 2021; Wolff et al., 2023; Woo, 2020; Yimer et al., 2024)
Vegetated Swales and Filter Strips	•••	••	•	••	•••	••	•	•	(Albert et al., 2019; Blanco-Canqui, 2024; Huang et al., 2020; Keesstra et al., 2018; Thorslund et al., 2017; Vojinovic et al., 2021)
Constructed wetlands (Artificial wetland)					••		•••		(Blanco-Canqui, 2024; Bunclark and Hernández, 2022; Ferreira et al., 2023; Huang et al., 2020; Liquete et al., 2016; Motta Zanin et al., 2024; Nelson et al., 2020; Recalde et al., 2024; Taylor et al., 2018; Thorslund et al., 2017; Tsatsou et al., 2023; Wolff et al., 2023; Yimer et al., 2024)
Afforestation					•••	••	•••	••	(Hale et al., 2023; Keesstra et al., 2018; Taylor et al., 2018; Yimer et al., 2024)

Table 3
Potential NbS interventions/actions for agricultural ecosystems, arid and humid climates, permeable (Perm) and impermeable (Imper) soils, mild and steep topographies.

Potential NbS interventions/ actions	Agricultural Ecosystems								References
	Arid				Humid				
	Perm		Imper		Perm		Imper		
	Mild	Steep	Mild	Steep	Mild	Steep	Mild	Steep	
Rainwater Harvesting and Infiltration Basins	•••		•		•••		••	•	(Blanco-Canqui, 2024; Nalluri and Karri, 2024; Recalde et al., 2024; Yimer et al., 2024)
Riparian Restoration	••	•	••		••	••	•	•	(Albert et al., 2019; Blanco-Canqui, 2024; Bunclark and Hernández, 2022; Miralles-Wilhelm, 2023; Recalde et al., 2024; Thorslund et al., 2017; Woo, 2020)
Conservation Tillage and Cover Cropping	•••	•••	•••	•••	•••	•••	•••	•••	(Adil et al., 2022; Blanco-Canqui, 2024; Keesstra et al., 2018; Miralles-Wilhelm, 2023)
Crop diversification and rotation	•••	•••	•••	•••	•••	•••	•••	•••	(Adil et al., 2022; Blanco-Canqui, 2024; Keesstra et al., 2018; Nalluri and Karri, 2024)
Regenerative Fertilizer Practices	•••	•••	•••	•••	•••	•••	•••	•••	(Adil et al., 2022; Blanco-Canqui, 2024; Keesstra et al., 2018; Miralles-Wilhelm, 2023)
Grassland Protection and Restoration	••	••	••	••	••	••	••	••	(Adil et al., 2022; Blanco-Canqui, 2024; Fernandes and Guiomar, 2018; Keesstra et al., 2018)
Contour Farming and Terracing		•••		•••		•••		•••	(Adil et al., 2022; Blanco-Canqui, 2024; Keesstra et al., 2018)
Efficient irrigation practices (Enhanced soil retention)	•••	•••	•••	•••	••	••	••	••	Pistocchi, (2022a)
Construct Check Dams (Natural barriers)		••		•••		•••		•••	(Liu et al., 2023; Turkelboom et al., 2021)
Natural hedge network restoration and protection		••	••	•••		••		•••	(Blanco-Canqui, 2024; Fernandes and Guiomar, 2018)
Reforestation	•	•	•	•	••	••	•••	•••	(Blanco-Canqui, 2024; Hale et al., 2023; Keesstra et al., 2018; Taylor et al., 2018; Thorslund et al., 2017)
Removing invasive species	•••	••	•••	••	•••	••	•••	••	(Adil et al., 2022; Keesstra et al., 2018)
Integrated pest management plans	••	••	••	••	••	••	••	••	(Adil et al., 2022; Keesstra et al., 2018)
Agroforestry and Soil Management Practices	••	•••	••	•••	••	•••	••	•••	(Blanco-Canqui, 2024; Dunlop et al., 2024; Fernandes and Guiomar, 2018; Hale et al., 2023; Keesstra et al., 2018; Miralles-Wilhelm, 2023; Nalluri and Karri, 2024; Recalde et al., 2024; Yimer et al., 2024)
Controlled Flooding to Replenish Nutrients in Floodplains	•	•	•	•	•••		••		(Adil et al., 2022; Blanco-Canqui, 2024; Keesstra et al., 2018)
Vegetated Swales and Filter Strips	•	••	•	••	•••	••	•	•	(Albert et al., 2019; Blanco-Canqui, 2024; Huang et al., 2020; Keesstra et al., 2018; Thorslund et al., 2017; Vojinovic et al., 2021)
Constructed wetlands (Artificial wetland)					••		•••		(Blanco-Canqui, 2024; Bunclark and Hernández, 2022; Ferreira et al., 2023; Huang et al., 2020; Liquete et al., 2016; Motta Zanin et al., 2024; Nelson et al., 2020; Recalde et al., 2024; Taylor et al., 2018; Thorslund et al., 2017; Tsatsou et al., 2023; Wolff et al., 2023; Yimer et al., 2024)
Afforestation					•••	••	•••	••	(Hale et al., 2023; Keesstra et al., 2018; Taylor et al., 2018; Yimer et al., 2024)

Table 4
Potential NbS interventions/actions for forest ecosystems, arid and humid climates, permeable (Perm) and impermeable (Imper) soils, mild and steep topographies.

Potential NbS interventions/actions	Forest Ecosystems								References
	Arid				Humid				
	Perm		Imper		Perm		Imper		
	Mild	Steep	Mild	Steep	Mild	Steep	Mild	Steep	
Rainwater Harvesting and Infiltration Basins	••		•		•••		••		(Blanco-Canqui, 2024; Nalluri and Karri, 2024; Recalde et al., 2024; Yimer et al., 2024)
Riparian Restoration	••	•	•	•	•••	•••	•	•	(Albert et al., 2019; Blanco-Canqui, 2024; Bunclark and Hernández, 2022; Miralles-Wilhelm, 2023; Recalde et al., 2024; Thorslund et al., 2017; Woo, 2020)
Grassland Protection and Restoration	••	•	••	••	•••	••	•••	••	(Adil et al., 2022; Blanco-Canqui, 2024; Fernandes and Guiomar, 2018; Keesstra et al., 2018)
Contour Farming and Terracing		•••		•••		•••		•••	(Adil et al., 2022; Blanco-Canqui, 2024; Keesstra et al., 2018)
Efficient irrigation practices (Enhanced soil retention)	•••	•••	•••	•••	••	••	••	••	Pistocchi, (2022a)
Construct Check Dams (Natural barriers)		•••		•••		•••		•••	(Liu et al., 2023; Turkelboom et al., 2021)
Natural hedge network restoration and protection	••	••	••	••	•••	•••	••	••	(Blanco-Canqui, 2024; Fernandes and Guiomar, 2018)
Reforestation	•	•	•	•	•••	•••	••	••	(Blanco-Canqui, 2024; Hale et al., 2023; Keesstra et al., 2018; Taylor et al., 2018; Thorslund et al., 2017)
Removing invasive species	•••	••	•••	••	•••	••	•••	••	(Adil et al., 2022; Keesstra et al., 2018)
Integrated pest management plans	•	•	•	•	•••	••	•••	••	(Adil et al., 2022; Keesstra et al., 2018)
Agroforestry and Soil Management Practices	•••	•••	••	••	•••	•••	••	••	(Blanco-Canqui, 2024; Dunlop et al., 2024; Fernandes and Guiomar, 2018; Hale et al., 2023; Keesstra et al., 2018; Miralles-Wilhelm, 2023; Nalluri and Karri, 2024; Recalde et al., 2024; Yimer et al., 2024)
Vegetated Swales and Filter Strips	••	•	•	•	•••	••	••	•	(Albert et al., 2019; Blanco-Canqui, 2024; Huang et al., 2020; Keesstra et al., 2018; Thorslund et al., 2017; Vojinovic et al., 2021)
Constructed wetlands (Artificial wetland)					••		•••		(Blanco-Canqui, 2024; Bunclark and Hernández, 2022; Ferreira et al., 2023; Huang et al., 2020; Liquete et al., 2016; Motta Zanin et al., 2024; Nelson et al., 2020; Recalde et al., 2024; Taylor et al., 2018; Thorslund et al., 2017; Tsatsou et al., 2023; Wolff et al., 2023; Yimer et al., 2024)
Afforestation					•••	••	•••	••	(Hale et al., 2023; Keesstra et al., 2018; Taylor et al., 2018; Yimer et al., 2024)

Table 5
Potential NbS interventions/actions for freshwater ecosystems, arid and humid climates, permeable (Perm) and impermeable (Imper) soils, mild and steep topographies.

Potential NbS interventions/actions	Freshwater Ecosystems								References
	Arid				Humid				
	Perm		Imper		Perm		Imper		
	Mild	Steep	Mild	Steep	Mild	Steep	Mild	Steep	
Removing invasive species	•••	••	•••	••	•••	••	•••	••	(Adil et al., 2022; Keesstra et al., 2018)
Controlled Flooding to Replenish Nutrients in Floodplains	•••		••		•••		••		(Adil et al., 2022; Blanco-Canqui, 2024; Keesstra et al., 2018)
Constructed wetlands (Artificial wetland)	•		••		•••		•••		(Blanco-Canqui, 2024; Bunclark and Hernández, 2022; Ferreira et al., 2023; Huang et al., 2020; Liquete et al., 2016; Motta Zanin et al., 2024; Nelson et al., 2020; Recalde et al., 2024; Taylor et al., 2018; Thorslund et al., 2017; Tsatsou et al., 2023; Wolff et al., 2023; Yimer et al., 2024)
Removal of Revetment (targeted removal of riprap or other hard surfaces from riverbanks)	•••	••	•	•	•••	••	•	•	(Albert et al., 2019; Miralles-Wilhelm, 2023; Vojinovic et al., 2021; Yimer et al., 2024)
Replacing Hard Surfaces with Natural Materials to Stabilize Banks	••	••	•••	•••	••	••	•••	•••	(Vojinovic et al., 2021; Woo, 2020; Yimer et al., 2024)
Adding In-stream Structures like Large Wood to Create Habitat Diversity	•••	•••	•••	•••	•••	•••	•••	•••	(Nalluri and Karri, 2024; Taylor et al., 2018; Vojinovic et al., 2021)
Floodplain Restoration (excavation/ Deepening/enlargement/widening)	••	••	••	••	•••	•••	•••	•••	(Adil et al., 2022; Albert et al., 2019; Keesstra et al., 2018; Taylor et al., 2018; Thorslund et al., 2017; Vojinovic et al., 2021)
Reconnecting rivers to floodplains, aquifers, oxbow lakes, and Re-meandering, Depoldering, natural features	•••	•••	•••	•••	•••	•••	•••	•••	(Albert et al., 2019; Recalde et al., 2024; Taylor et al., 2018; Vojinovic et al., 2021)
Removing Artificial Embankments (dams/obstacles/barriers)	••	••	••	••	•••	•••	•••	•••	(Albert et al., 2019; Taylor et al., 2018; Vojinovic et al., 2021)
Bio retention and detention areas (ponds/basins)	••	••	••	••	•••	•••	•••	•••	(Gómez Martín et al., 2020; Keesstra et al., 2018; Liquete et al., 2016; Thorslund et al., 2017; Tsatsou et al., 2023)
Lake Re-naturalization and restoration	••	••	••	••	•••	•••	•••	•••	(Belete et al., 2024)
River and stream renaturation/ restoration	••	••	••	••	•••	•••	•••	•••	(Albert et al., 2019; Bunclark and Hernández, 2022; Recalde et al., 2024; Taylor et al., 2018; Wolff et al., 2023; Woo, 2020)
Peatland protection, restoration, and creation	••	•			•••	••	•		(Blanco-Canqui, 2024; Bunclark and Hernández, 2022; Liquete et al., 2016; Motta Zanin et al., 2024; Tsatsou et al., 2023; Wolff et al., 2023)
Wetland protection and restoration	••	•	•••	•••	••	••	•••	•••	(Blanco-Canqui, 2024; Bunclark and Hernández, 2022; Faivre et al., 2017; Ferreira et al., 2023; Hekrle, 2022; Keesstra et al., 2018; Liquete et al., 2016; Miralles-Wilhelm, 2023; Motta Zanin et al., 2024; Radfar et al., 2024; Recalde et al., 2024; Taylor et al., 2018; Thorslund et al., 2017; Tsatsou et al., 2023; Wolff et al., 2023; Yimer et al., 2024)

Table 6
Potential NbS interventions/actions for coastal ecosystems, arid and humid climates, permeable (Perm) and impermeable (Imper) soils, mild and steep topographies.

Potential NbS interventions/ actions	Coastal Ecosystem								References
	Arid				Humid				
	Perm		Imper		Perm		Imper		
	Mild	Steep	Mild	Steep	Mild	Steep	Mild	Steep	
Constructed wetlands (Artificial wetland)	••	••	•••	••	••	••	•••	••	(Blanco-Canqui, 2024; Bunclark and Hernández, 2022; Ferreira et al., 2023; Huang et al., 2020; Liquete et al., 2016; Motta Zanin et al., 2024; Nelson et al., 2020; Recalde et al., 2024; Taylor et al., 2018; Thorslund et al., 2017; Tsatsou et al., 2023; Wolff et al., 2023; Yimer et al., 2024)
Establishment of integrated coastal zone management plans	•••	•••	•••	•••	•••	•••	•••	•••	(Gómez Martín et al., 2020; Motta Zanin et al., 2024; Nelson et al., 2020; Tsatsou et al., 2023)
Coastal Vegetation Protection and Restoration	•••	•••	•••	•••	•••	•••	••	••	(Ferreira et al., 2023; Gómez Martín et al., 2020; Motta Zanin et al., 2024; Nelson et al., 2020; Tsatsou et al., 2023; Yimer et al., 2024)
Seagrass Meadow Protection and Restoration	••	••	••	••	•••	•••	••	••	(Ferreira et al., 2023; Hekrle, 2022; Nelson et al., 2020; Tsatsou et al., 2023)
Mangrove Protection and Restoration	••	••	••	••	•••	•••	•••	•••	(Ferreira et al., 2023; Hekrle, 2022; Motta Zanin et al., 2024; Nelson et al., 2020; Recalde et al., 2024; Tsatsou et al., 2023; Yimer et al., 2024)
Peatland protection, restoration, and creation	••	••	••	••	••	••	••	••	(Blanco-Canqui, 2024; Bunclark and Hernández, 2022; Liquete et al., 2016; Motta Zanin et al., 2024; Tsatsou et al., 2023; Wolff et al., 2023)
Community-based Coastal Management	•••	•••	•••	•••	•••	•••	•••	•••	(Faivre et al., 2017; Miralles-Wilhelm, 2023; Nelson et al., 2020; Recalde et al., 2024; Tsatsou et al., 2023; Yimer et al., 2024)
Wetland protection and restoration	••	••	•••	•••	••	••	•••	•••	(Blanco-Canqui, 2024; Bunclark and Hernández, 2022; Faivre et al., 2017; Ferreira et al., 2023; Hekrle, 2022; Keesstra et al., 2018; Liquete et al., 2016; Miralles-Wilhelm, 2023; Motta Zanin et al., 2024; Radfar et al., 2024; Recalde et al., 2024; Taylor et al., 2018; Thorslund et al., 2017; Tsatsou et al., 2023; Wolff et al., 2023; Yimer et al., 2024)

As an example, steep slopes and impermeable soils were often identified as limiting factors for certain solutions like wetlands. Conversely, areas with gentle slopes and permeable soils were highly suitable for solutions like rainwater harvesting and infiltration basin initiatives (Liang et al., 2019; Sayl et al., 2017). The primary objective of this assessment was to enhance the prioritization of solutions while providing multiple viable options tailored to specific contexts and societal challenges.

•	••	•••
Low Adaptability	Moderate Adaptability	High Adaptability

2.5. STAGE 3 – NbS mapping, societal challenges and Co-benefits

The spatial location of NbS, as defined in Section 2.4, is implemented in a GIS environment, mapping the identified potential solutions using the decision matrix

The decision matrix not only provides potential NbS but also allows users to select solutions associated with IUCN societal challenges (Cohen-Shacham et al., 2016) while highlighting the related co-benefits. This enables the decision matrix to provide tailored NbS to these societal challenges, specifically focusing on water security and disaster risk reduction at the catchment scale. The advantage of NbS relies on their capability to generate co-benefits while addressing a primary challenge. For instance, wetlands conservation enhances biodiversity and contributes to improved water quality, flood protection, shoreline erosion control, recreational opportunities, and aesthetic value. Therefore, it is crucial to consider these co-benefits, as they can simultaneously address secondary and tertiary issues within the selected area of interest. Table 7 provides a detailed interconnection of the relationship between NbS interventions and the co-benefits they offer, derived from the existing literature, which was used for the decision matrix. Each intervention, listed on the vertical axis, is analyzed against IUCN societal challenges and co-benefits, such as water security, disaster risk reduction, climate change mitigation, and adaptation.

Moreover, some interventions, such as reforestation, creating urban blue and green spaces, constructed wetlands, and floodplain restoration, emerge as highly versatile solutions, simultaneously addressing multiple co-benefits. These solutions could sometimes be used interchangeably, depending on the challenges.

3. The Bode River catchment

To showcase the practical implementation of the proposed framework, it was applied to the Bode River catchment, located in central Germany Fig. 5. The Bode catchment is approximately 3300 km^2, with significant topographic variation, with elevations ranging from 53 m to 905 m and higher elevations concentrated in the southwestern region. The catchment is a sub-part of the Harz Mountains natural drainage system and flows into the Saale River. The mountainous areas are mostly forested, while the fertile lowlands are intensively farmed. Around 66 % of the land is used for agriculture, 26 % is forest/seminatural, and 7 % consists of urban and industrial land (Wollschläger et al., 2017).

Bode catchment encompasses diverse ecosystems, each contributing uniquely to its ecological and hydrological status. Forest ecosystems in the Harz Mountains act as critical water catchments, stabilize soil, and support diverse biodiversity. At the same time, agricultural landscapes in the middle and lower reaches provide food while experiencing soil erosion and nutrient runoff. The Bode forest ecosystem was heavily impacted by the prolonged, Europe-wide drought conditions from 2018 to 2022 (Tripathy and Mishra, 2023). These droughts led to low water levels during the summer (Winter et al., 2023), algal blooms and water quality alteration (Musolff et al., 2024; Selle, 2024), reduced crop yields (Sodoge et al., 2023), and severe tree loss, approximately 72 % in 2022 (Lange et al., 2024). Urban ecosystems, centered around settlements like Quedlinburg, impact water flow and quality through impervious surfaces and pollution. Freshwater systems, including the Bode River and its reservoirs, are vital for aquatic biodiversity, freshwater supply, and recreation, yet face habitat fragmentation and pollution pressures. The interconnectedness of these ecosystems highlights the relevance of structuring catchment-scale, integrated management strategies to enhance ecological balance and sustainability.

STEP 1: Ecosystems Classification

The Bode catchment has several ranges of land use types, reflecting its ecological and agricultural significance. The catchment is classified into four distinct ecosystems, depending on the Corine land cover (Corine Land Cover, 2018). The catchment predominantly presents agricultural land use, interspersed with urban areas, extensive forest cover, and numerous water bodies, as illustrated in Fig. 6 (a).

STEP 2: Climate Classification

The Bode catchment climate was classified using the Global Aridity Index AI v3 (Zomer et al., 2022). The values range from 0.7 to 2.1; the predominant climate class identified is humid, according to the classification given in Table 1, as shown in Fig. 6 (b).

STEP 3: Soil Classification

The Bode catchment soil was categorized into two classifications based on permeability: permeable and impermeable, utilizing the Soil Texture Classes dataset (Tomislav Hengl, 2018). The soil clay content serves as the reference for this classification: soils with clay content up to 20 % are classified as permeable, whereas higher clay content (>20 %) entails the impermeable category. The dominant soil texture class identified in the central lowland areas is impermeable, as shown in Fig. 6 (c).

STEP 4: Topography Classification

The Bode catchment topography was classified into two categories based on the slope: mild (≤5 %) and steep (>5 %), utilizing the SRTM Version 4 digital elevation model (Jarvis et al., 2008). The Digital Elevation Model (DEM) allowed for the estimation of slope percentages and subsequent classifications according to framework classes. In the central lowland areas, the dominant slope class identified is mild. However, steep slopes were observed in the region's Harz part, as shown in Fig. 6 (d).

STEP 5: Catchment Classification

The predominant classes identified within the bode catchment include Agri-Humid-Perm-Mild (50.8 %), Agri-Humid-Imper-Mild (14.2 %), Forest-Humid-Imper-Mild (11.0 %), and Forest-Humid-Perm-Mild (9.7 %) as illustrated in Fig. 7. This segmentation provides a nuanced understanding of the catchment features, guiding the selection of practical solutions.

4. Results and discussion

4.1. Bode River catchment classification and NbS

The NbS integration within the Bode River catchment aligns with the declared need in Germany to optimize and refine strategic approaches to scale up NbS. Such a procedure is consistent with the German National Strategy on Biological Diversity (NBS) Report, which remarks on the ongoing decline in species richness and landscape integrity across the nation (BMUV, 2023). This deterioration varies regionally, but is consistently attributed to anthropogenic factors, most notably the

Table 7
Potential NbS interventions/actions, IUCN societal challenges, and co-benefits.

Potential NbS interventions/actions	**IUCN Societal challenges (co-benefits)**						
	Water security	Disaster risk reduction	Climate change mitigation and adaptation	Food Security	Human health	Economic and social development	Environmental degradation and biodiversity loss
Rainwater Harvesting and Infiltration Basins	🍃	🍃	🍃		🍃		🍃
Riparian Restoration	🍃	🍃		🍃	🍃		
Conservation Tillage and Cover Cropping	🍃		🍃	🍃			🍃
Crop diversification and rotation	🍃	🍃	🍃	🍃	🍃		
Regenerative Fertilizer Practices	🍃	🍃	🍃	🍃		🍃	🍃
Grassland Protection and Restoration	🍃	🍃	🍃	🍃			🍃
Contour Farming and Terracing		🍃	🍃	🍃			🍃
Efficient irrigation practices (Enhanced soil retention)		🍃		🍃			
Construct Check Dams (Natural barriers)		🍃	🍃				
Natural hedge network restoration and protection	🍃	🍃	🍃	🍃			🍃
Reforestation	🍃	🍃	🍃	🍃	🍃	🍃	🍃
Permeable Pavements	🍃	🍃					
Urban Green Infrastructure and Urban Forests	🍃	🍃	🍃		🍃		🍃
Creation of urban blue spaces	🍃	🍃	🍃		🍃		🍃
Vegetated Swales and Filter Strips	🍃	🍃	🍃				🍃
Constructed wetlands (Artificial wetland)	🍃	🍃	🍃				🍃
Removing invasive species		🍃		🍃			🍃
Afforestation	🍃	🍃	🍃			🍃	🍃

(*continued on next page*)

Table 7 (*continued*)

Integrated pest management plans	🍃		🍃	🍃	🍃		🍃
Agroforestry and Soil Management Practices	🍃	🍃	🍃	🍃			🍃
Controlled Flooding to Replenish Nutrients in Floodplains	🍃	🍃					
Removal of Revetment (targeted removal of riprap or other hard surfaces from riverbanks)	🍃	🍃					
Replacing Hard Surfaces with Natural Materials to Stabilize Banks		🍃	🍃				🍃
Adding In-stream Structures like Large Wood to Create Habitat Diversity							🍃
Floodplain Restoration (excavation/Deepening/enlargement/widening)	🍃	🍃					🍃
Reconnecting rivers to floodplains, aquifers, oxbow lakes, and Re-meandering, Dike removal/relocation, and Depoldering	🍃	🍃	🍃		🍃		
Removing Artificial Embankments (dams/obstacles/barriers)							🍃
Bio retention and detention areas (ponds/basins)	🍃	🍃	🍃		🍃		
Lake Re-naturalization and restoration		🍃				🍃	🍃
River and stream renaturation/restoration		🍃	🍃		🍃	🍃	🍃
Establishment of integrated coastal zone management plans		🍃	🍃				
Coastal Vegetation Protection and Restoration		🍃	🍃				🍃

(*continued on next page*)

Table 7 (*continued*)

Seagrass Meadow Protection and Restoration	🍃		🍃	🍃	🍃	🍃	🍃
Mangrove Protection and Restoration	🍃	🍃	🍃				🍃
Peatland protection, restoration, and creation			🍃				
Community-based Coastal Management			🍃			🍃	🍃
Wetland protection, restoration, and creation	🍃	🍃	🍃		🍃		🍃

intensification of agricultural practices, urban expansion, fragmentation of habitats, and widespread environmental pollution, including nitrogen surpluses (Mueller et al., 2016).

Specifically, the Bode River catchment was categorized into four ecosystems: urban, agricultural, forest, and freshwater. Each ecosystem was linked to specific interventions to enhance water management and security and promote climate resilience.

Following the catchment classification, solutions were identified for these classes using the decision matrix developed in Stage 2 (see Tables 2-6). As multiple solutions were identified for different classes of catchment, they were then ranked from high to low adaptability (e.g., 1 = High Adaptability) by using the adaptability score to facilitate decision making for the stakeholders. For example, in the Urban-Humid-Imper-Mild category, urban green infrastructure and urban forests

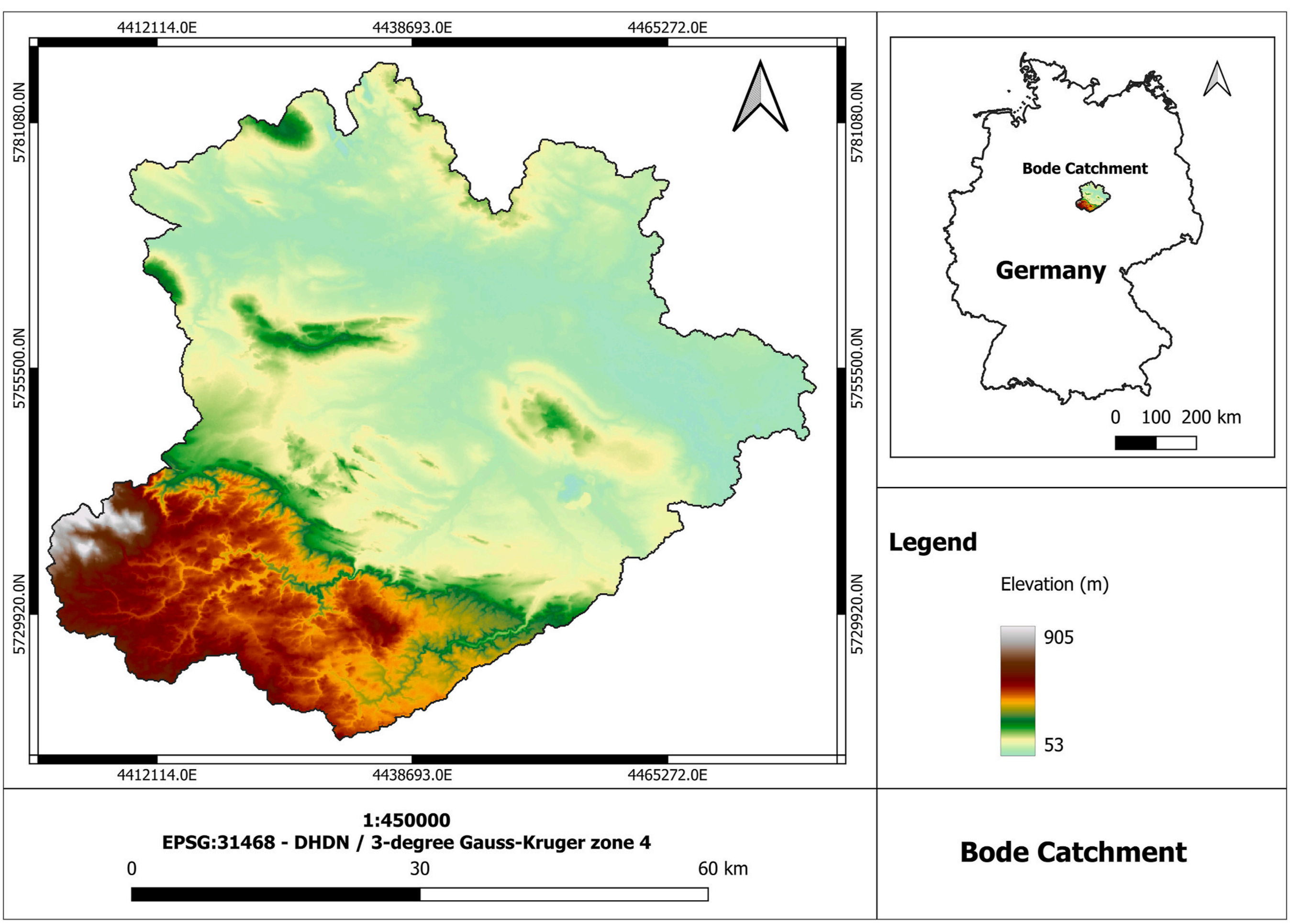

Fig. 5. Digital Elevation Model (DEM) of the Bode River catchment.

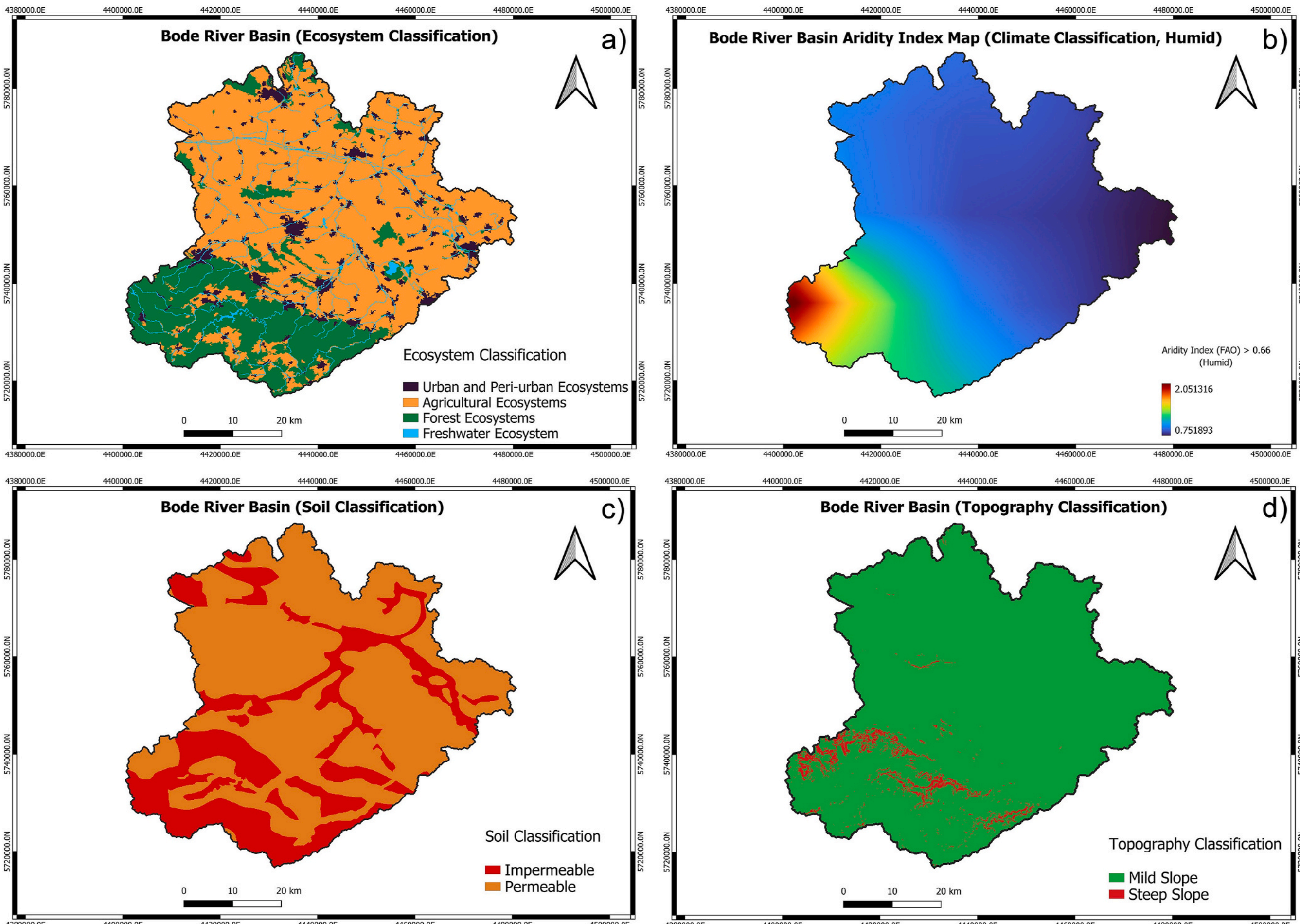

Fig. 6. The Bode River catchment: (a) Ecosystem, (b) Climate, (c) Soil, and (d) Topography classes.

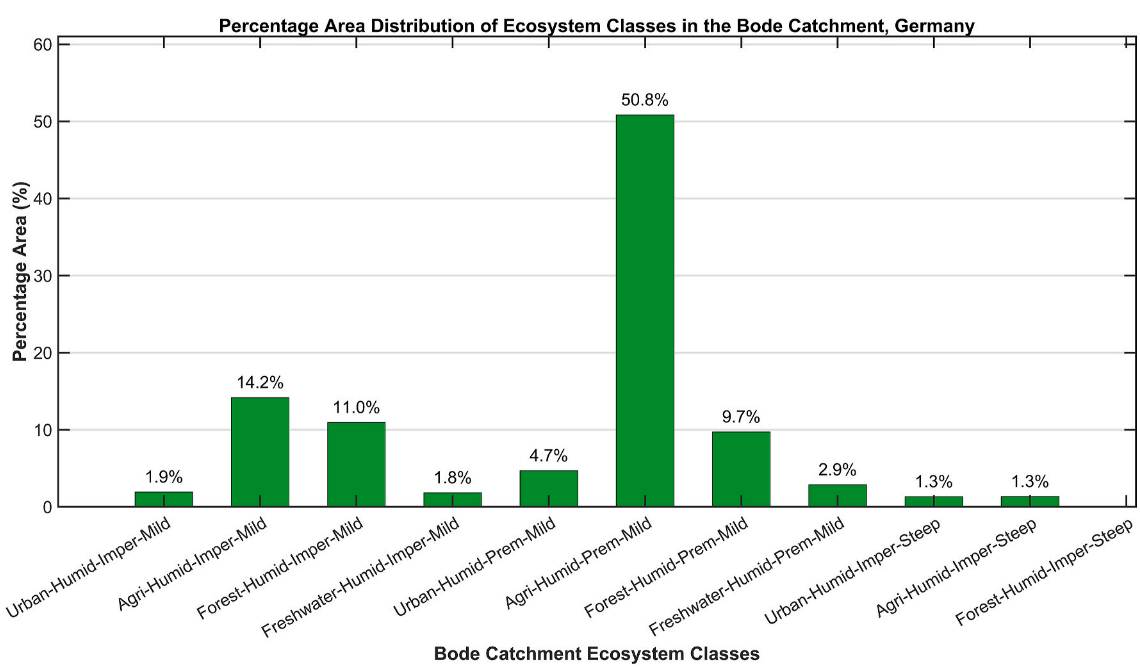

Fig. 7. Area distribution percentage of Ecosystem Classes for the Bode River Catchment, Germany.

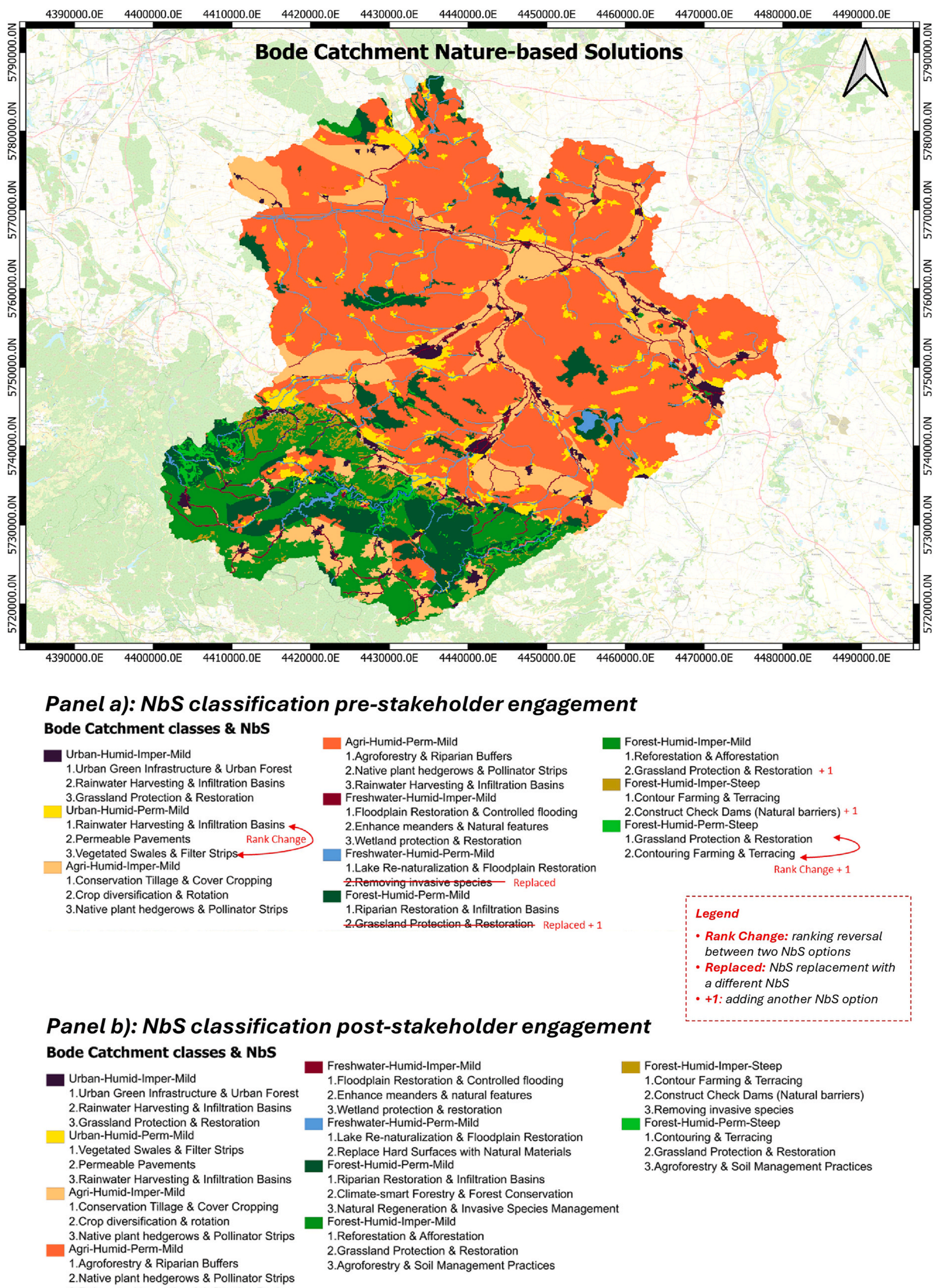

Fig. 8. NbS identified in the Bode River catchment, Panel (a) and Panel (b) show the integration of NbS proposed for the Bode Catchment pre- and post-stakeholder engagement. Panel (a) represents the initial analysis output, while the updates suggested by stakeholders are included in red. Panel (b) gives the refined and finalized configuration post-stakeholder engagement.

Table 8
SWOT analysis of the proposed framework.

Strengths	Weaknesses
- Simplicity of approach - Ease of application for large (catchment) scale case studies - Required readily available datasets (Low data demand) - Decision Matrix (based on extensive literature review) - Provide solutions for multiple ecosystems - It could be applied over different climatic regions - It fosters the co-design through direct stakeholder engagement in the whole process	- Semi-qualitative assessment of NbS outcomes - Difficulty in identifying tailored NbS in some specific cases - Framework and adaptability score not completely validated through stakeholder interaction yet
Opportunities	**Threats**
- Map visualization enables dissemination even to non-professional citizens - Open technical discussions with stakeholders - Sharing knowledge about NbS - Co-design with central authorities, starting from societal issues - Improving awareness among citizens and associations about environmental challenges - Driver for engagement with stakeholders	- Low stakeholders' interest - Numerous frameworks already exist in the literature - Incompetence of stakeholders to use GIS, lack of resources, or data - Change of stakeholders after local elections - Lack of knowledge about NbS processes - Lack of a structured business model to support NbS implementation - Path-dependency

were ranked as the first choice. Conversely, rainwater harvesting and infiltration basins got the second rank due to the high adaptability of the first option in similar environments, as aligned with the literature. This prioritization provides a structured method for selecting effective and context-appropriate solutions, further facilitating stakeholders' decision-making. These solutions were thus mapped at the catchment scale, showing the spatial distribution of NbS across the catchment. The map, given in Fig. 8, provides a clear and practical overview of the potential NbS that can be implemented after considering policy and economic targets.

The goals set out in the German National Biodiversity Strategy (BMU/Bundesministerium für UmweltNaturschutz und Reaktorsicherheit, 2007) aim to bring significant changes in land use across all identified ecosystem types (Wüstemann et al., 2014). In an urban ecosystem, controlling the overdevelopment of sealed surfaces, which disrupts natural water infiltration and degrades local ecosystems, is essential, while requiring integrated innovative solutions, such as integrating green elements into energy-efficient building upgrades. So, in the urban ecosystem, the framework was able to select solutions such as urban green infrastructure, rooftop rainwater harvesting, and infiltration basins. These interventions aim to enhance resilience against flooding, improve water management, and mitigate urban heat island effects, thereby contributing to a more sustainable and adaptive urban microclimate.

In an agricultural environment, the conservation and enhancement of biodiversity represent core objectives of the agri-environmental programme and are integral to the strategic goals outlined in the German National Strategy on Biological Diversity (BMUV, 2023). The solutions selected by the framework for the agricultural ecosystem were consistent with biodiversity goals. Effective solutions include adopting conservation tillage, establishing pollinator-friendly hedgerows, and implementing riparian buffers. These measures enhance soil health, reduce nutrient runoff, and support biodiversity.

To preserve and promote biodiversity in forests, encouraging natural forest regeneration and creating ecosystems that closely resemble native conditions are key strategies for achieving the German National Biodiversity Strategy (BMU, 2007; BMUV, 2023) . The solutions like reforestation, afforestation, grassland protection, and restoration were identified for forested zones to promote carbon sequestration and maintain watershed stability, ensuring long-term ecosystem resilience.

Whereas the status of freshwater ecosystems fluctuated over time, showing no clear long-term trend. To meet biodiversity goals by 2030, focused restoration of rivers and floodplains is essential, as remarked by the EU Water Framework Directive (European Commission, 2000) and Germany's Blue Belt initiative (BMUB and BMVI, 2015), which promotes stronger ecological integrity and healthier habitats. Aligned with these policy goals for freshwater ecosystems, optimal solutions include floodplain restoration, controlled flooding, wetland protection and restoration, and re-meandering. These interventions aim to reestablish the natural features and hydrological balance, enhancing water retention, facilitating sediment deposition, and restoring ecosystem functionality. Additionally, removing artificial structure and re-naturalizing stream meandering were prioritized over other NbS options to promote ecological integrity and improve the resilience of aquatic systems.

These solutions are advantageous as they properly account for the area's topography. The focus is on erosion control in steeper terrains, while lowland areas prioritize water retention and riverine restoration. This spatially explicit approach demonstrated the synergy between ecological restoration and sustainable land use. It also serves as an example for aligning ecosystem functions with localized ecological conditions, showcasing how such integration can offer climate adaptation and biodiversity conservation.

Another key advantage of these solutions is their multifunctionality, as they provide multiple co-benefits simultaneously. For example, biodiversity enhancement supports ecosystem health and contributes to carbon sequestration, making these solutions economically viable over extended periods, given their self-sustaining abilities. For freshwater ecosystems, the conservation and restoration of wetlands address water quality issues and deliver a broad spectrum of additional benefits. While wetlands are traditionally valued for enhancing biodiversity and improving water quality, they also offer significant benefits such as flood protection, recreational opportunities, and habitat provision for fish species. This multifunctionality makes wetlands substantially more cost-effective and beneficial than single-purpose infrastructure solutions, reinforcing their long-term value.

4.2. Stakeholder engagement

The suitability of NbS implementation significantly varies depending on public acceptance, cost, and impact, which are influenced by the specific location. Thus, engaging stakeholders is crucial to ensure the solutions are well-received, economically feasible, and effective (Ferreira et al., 2020; Singh, 2025). To assess the proposed framework, strategies like focus groups, living labs, online forums, webinars, and live streams strengthen the stakeholders' involvement through interviews and discussions, thus capturing a wide range of viewpoints within a small group (Corbin and Strauss, 1990). Additionally, applying the interest-influence matrix (Murray-Webster and Simon, 2006) enhances the assessment of stakeholders' roles and their relevance across the design, implementation, and monitoring phases. Besides local stakeholders such as representatives from the agricultural sector, forestry, and civil society, high-level policymakers and planning experts will be identified through stakeholder mapping (Saysel et al., 2021), ensuring a diverse representation of viewpoints: government authorities, associations, academia, civil society, private investors, and media. For each stakeholder group, it is worth establishing a position about the issues, future perspectives, and the level of interest, as well as defining contribution or resistance (conflicting interests, economic or social concerns) to change. Academia is a key participant in stakeholders' mapping (Lupp et al., 2021), alongside regional planners, civil society organizations, and farmers. However, academia is generally less affected by natural hazards and has limited direct influence on NbS implementation, thus assuming a neutral, observer role rather than a core actor in collaborative planning processes (Zingraff-Hamed et al., 2020a). To achieve higher levels of engagement, it is crucial to conduct open discussions, implement transparent communication strategies, and establish conflict resolution protocols to address disagreements and find mutually acceptable solutions. The stakeholder interviews should also explore the proposed solutions, emphasizing their appropriateness and the potential obstacles to their implementation, whether social, political, institutional, or financial. For instance, farmers and landowners, operating as private businesses, could hesitate to adopt NbS due to fears of potential economic compromises. NbS are often viewed as restricting revenue-generating possibilities on productive land. This hesitation is compounded by the absence of a structured business model to support NbS implementation, alongside sporadic policy measures and incentives. When scientists and technical watershed specialists team up with local leaders, they help citizens deeply understand their watershed's identity. This collaboration also facilitates sharing new information, emerging scientific discoveries, and technical solutions, encouraging people to adopt new practices and inspire others to follow suit (Morton et al., 2011).

Following the above criteria, in the frame of the current work, a workshop was held to facilitate engagement with local experts of the Bode River catchment. The group consisted of five highly experienced professionals, each possessing extensive expertise in various aspects of water resource management. Their collective backgrounds include hydrology, environmental science, policy development, and engineering. With a wealth of knowledge gained from years of working in academia and industry, they were well-suited for framework validation. The NbS map of the Bode River catchment, Fig. 8 (Panel a), was shown to stakeholders during a 90-min interactive session, structured to encourage intensive discussion for the investigation and adjustment of the developed scenario by detecting potential constraints, issues, and limitations. The group generally accepted most of the proposed solutions but raised some concerns. They suggested adjusting the ranking of solutions in urban areas to prioritize solutions related to water quality, such as vegetated swales and filter strips. Additionally, they expressed concerns about certain options, like replacing hard surfaces with natural materials, as this could lead to flooding in urban environments.

After the discussion session, the consensus regarding several selections was documented. Participants also proposed additional localized solutions to be included in the revised version of the selection, as shown in Fig. 8 (Panel b). Additionally, a SWOT analysis was applied to give a thorough understanding of the framework, highlighting the main strengths and shortcomings raised.

4.3. SWOT analysis

The framework application to the Bode River catchment allowed assessing its robustness, shortcomings, and potentialities for improvement. To make the evaluation more consistent, a SWOT analysis (Gürel and Tat, 2017) was carried out to account for the Strengths, Weaknesses, Opportunities, and Threats of the approach. This entails a comprehensive understanding of the framework's potential and areas for improvement, ensuring its effective application and adaptability. In the following Table 8, a set of relevant items for each category of the SWOT matrix is listed and then properly discussed.

- **Strengths**

One of the most relevant strengths of the proposed framework relies on its simplicity while assuring a comprehensive and flexible structure which helps its application to multiple environments and climate conditions, as required by European Environment Agency, 2023 report on scaling nature-based solutions for climate resilience and nature restoration, which stresses the relevance of developing tools that are both tailored to specific contexts and applicable across European terrains (European Environment Agency, 2023). As remarked in the introduction section, despite several available frameworks in the literature for the NbS selection at the catchment scale, providing an operative approach, able to couple a robust literature review with quite basic GIS processing and low data demanding, makes it a reliable tool for NbS investigation at different contexts and stages. In addition, the general features and the flexible structure of the tool allow its application to wide contexts and configurations, while allowing it to be properly tailored when applied to specific environments. As an example, in urban and peri-urban ecosystems, including the assessment of the anthropogenic land transformation, effectively increases the robustness of the investigation. In addition, consistent with further approaches available in the literature (de Lima et al., 2022; Caroppi et al., 2024), the multi-level structure allows it to be suitable at both design and monitoring stages. Then, the creation of the NbS catalogue (Decision Matrix), as well as the identification of societal challenges and co-benefits, gives a holistic overview of NbS selection (Dumitru and Wendling, 2021). Indeed, the decision-support process employs a Decision Matrix (solution catalogue), co-benefits mapping, and ecosystem-service linkages to help evaluate trade-offs and synergies. This clear and thorough approach makes it easier to understand and make decisions by considering different factors and outcomes, consistently with EU Water Framework Directive (WFD) (European Commission, 2000), which calls for integrated, participatory water management at the river basin scale, and with the EU Strategy on Adaptation to Climate Change (European Commission, 2021), which identifies NbS as a cornerstone for building resilience.

The framework's relevance in various ecosystems, as shown by its use in the Bode River catchment, strengthens its adaptability. This ability is also strengthened by the evidence that the reliance on widely accessible datasets - such as land cover, topography, and soil type - struggles with the persistent challenge of data scarcity in local-level NbS implementation (Pistocchi, 2022b). Lastly, providing the direct involvement of stakeholders at the different stages of the process enhances the co-design feature, which is the cornerstone of the effective NbS integration (Strout et al., 2021; Mickovski et al., 2024).

- **Weaknesses**

One of the main concerns of the framework relies on its semi-qualitative features in assessing the solutions and presenting challenges in terms of precise measurement. Against further approaches, more numerically consistent (Caroppi et al., 2024; Chairat and Gheewala, 2024), the semi-qualitative property of the proposed approach assures the easy and quick application, while detecting the tailored NbS in complex and heterogeneous environments, where a nuanced understanding of local environmental and socio-economic dynamics is significantly challenging, even considering the multi-disciplinary perspectives required for the comprehensive assessment of the NbS effectiveness.

Furthermore, stakeholder engagement, which results in a primary strength of the approach, can potentially represent a consistent barrier when limited interaction with stakeholders and policymakers occur (Zingraff-Hamed et al., 2020b; Enu et al., 2025). Another shortcoming of the procedure is the NbS ranking, which comes from the adaptability scores based on the experts' opinions and is thus affected by their evaluation, skills, and expertise. Integrating a robust stakeholder engagement within the process can yield a more consistent evaluation while resulting in a time- and cost-demanding process for finalization.

- **Opportunities**

A spatial distribution map of potential NbS was successfully produced using this framework. This method enables rapid mapping of the possible options using simple and readily available data, even for non-professional stakeholders. The resulting maps give a macroscopic view of potential solutions, providing a strategic advantage in addressing societal challenges and enhancing resilience to climate change. This visualization could make informed decision-making easier by highlighting the spatial alignment of NbS. By translating complex environmental assessments into accessible visual outputs (e.g., spatial prioritization maps), it facilitates both awareness-raising and co-design. This communicative potential is essential to advancing NbS, particularly in light of the General Union Environment Action Programme 2030 (European Parliament and Council of the European Union, 2022), EU Biodiversity Strategy for 2030 (European Commission, 2020), European Green Deal (European Commission, 2019) and Nature Restoration Law (European Union, 2024), which stresses the role of ecosystem-based approaches in meeting conservation and climate objectives simultaneously. Moreover, the developed NbS Catalog (Decision Matrix) has the potential to be used for large-scale mapping of NbS. This resource will help us upscale the framework on the regional scale. Additionally, integrating this framework with stakeholders' engagement can significantly improve the status of the approach by fostering inclusivity, enhancing solution acceptance, and leveraging local expertise, thus increasing the awareness among citizens and associations about environmental challenges. All these aspects consistently fit with regional Sustainable Development Goals (SDG) adopted by the United Nations in 2015, aligning with SDG 6 (Clean Water and Sanitation), SDG 11 (Sustainable Cities and Communities), SDG 13 (Climate Action), and SDG 15 (Life on Land), aimed to enhance resilience, sustainability, and ecosystem restoration.

The proposed approach is grounded in scientific knowledge and currently lacks the integration of interaction with stakeholders, which is an important aspect for NbS design, planning, and implementation. There is a pressing need to develop a scientifically robust management plan for stakeholder involvement to increase the framework's impact and accuracy. Future research will be focused on effectively organizing and incorporating stakeholders and framework into the decision-making process, ensuring that both are context-specific and scientifically grounded. This participatory method aims to bridge the gap between theory and practice, ultimately fostering a robust framework for the successful design and implementation of NbS.

The framework contributes to addressing the current gap in harmonized methodologies for NbS mapping at the catchment scale. By operationalizing ecosystems, integrating co-benefit evaluation, and aligning with EU-level policy frameworks, it offers a foundation for standardization without losing contextual flexibility. The framework presented here offers an actionable pathway toward this integration, provided that future refinements incorporate participatory mechanisms, multi-level governance coordination, and adaptive learning cycles. Ultimately, the success and long-term effectiveness of NbS depend on environmental awareness and on socio-economic benefits (Gómez Martín et al., 2020; Chatelier et al., 2025).

- **Threats**

Among the potential threats of the procedure, key concerns include the possible stakeholders' and policymakers' lack of expertise and knowledge; they may not own the essential technical competencies (Martin et al., 2025), such as proficiency in GIS software, programming skills, or access to adequate resources and data, to effectively leverage the capabilities of the framework. The EEA's 2021 report on NbS highlights that a lack of familiarity with spatial planning software, insufficient institutional mandates, and fragmented funding landscapes all impede the mainstreaming of NbS (Castellari et al., 2021).

Although NbS offers substantial benefits to ecosystems, many stakeholders had limited familiarity with the concept, especially in rural contexts, thus sometimes making the co-benefits hardly detectable (Welden et al., 2021; Sarwar et al., 2024). While certain solutions were already being applied in practice, they were neither explicitly identified as NbS nor evaluated for their capacity to replicate natural processes. This lack of understanding can hinder the broader adoption of NbS. Additionally, shifting political priorities and administrative discontinuities, especially in regions experiencing high electoral turnover, can destabilize long-term ecosystem planning (Zandersen et al., 2025; Tedeschini et al., 2024). These barriers denote the potential shyness to invest and enhance a quite young approach against the usual ones (grey solutions), according to the so-called path-dependency trend (Martin et al., 2025). In addition, the lack of politically supportive policies, coupled with the possible lack of funding, may limit the NbS implementation, as well (Scolobig et al., 2021).

5. Conclusions

This study introduces a holistic GIS-based framework for the systematic identification and selection of NbS at the catchment scale. By integrating ecological, climatic, and geomorphological parameters into a structured decision matrix, the approach offers a replicable methodology for evaluating NbS suitability across heterogeneous landscapes. Its application provides stakeholders and decision-makers with a comprehensive overview of spatial priorities, enabling the strategic deployment of NbS tailored to diverse hydrological and ecological conditions.

The application of the framework to the Bode River catchment shows that it effectively identifies NbS at the catchment scale; those identified solutions were further validated and tailored by co-designing them with local experts, which could significantly enhance the adoption of those solutions. Integrating NbS into catchment management can contribute to climate resilience, water security, and ecosystem restoration. Beyond addressing water-related challenges such as flood risk, erosion, and drought, the proposed framework fosters the multifunctionality of NbS, including co-benefits like biodiversity enhancement, carbon sequestration, and improved water governance. This aligns with the EU Green Deal, the EU Biodiversity Strategy for 2030, and the Nature Restoration Law, all of which advocate for integrated, ecosystem-based management approaches.

Nevertheless, the selection and design of NbS remain inherently complex, requiring sensitivity to local environmental characteristics and socio-political dynamics. The findings underscore the critical relevance of stakeholder engagement and local knowledge in identifying feasible, context-specific solutions. Institutional support and policy alignment are equally essential, especially when ensuring that NbS are sustained over time and integrated into broader governance frameworks.

The presented framework offers a valuable foundational tool for the development of baseline maps. It can assist in identifying priority areas, facilitating stakeholder engagement, and guiding investment decisions. To expand on that, the framework can streamline the identification and selection process of NbS at the local and regional scale, greatly aiding stakeholders and policymakers with a quick decision support tool and proving NbS maps to be considered in future planning of projects for restoring balance to nature and addressing climate change outcomes. The finalization and implementation of these solutions will not only depend on the long-term objectives of the region and relevant government agencies, but also crucially on the engagement and ownership of local communities, whose participation is essential in ensuring context-appropriate and sustainable outcomes, ensuring alignment with the SDGs.

CRediT authorship contribution statement

Awais Naeem Sarwar: Writing – review & editing, Writing – original draft, Methodology, Investigation, Formal analysis, Conceptualization. **Cristina Caramiello:** Writing – review & editing, Methodology, Conceptualization, Writing – original draft, Formal analysis. **Francesco Pugliese:** Writing – review & editing, Methodology, Formal analysis, Conceptualization. **Seifeddine Jomaa:** Writing – review & editing, Supervision, Project administration, Methodology, Funding acquisition, Conceptualization. **Anis Guelmami:** Writing – review & editing,

Methodology, Data curation. **Michael Ronse:** Writing – review & editing, Methodology, Data curation. **Pier Paolo Roggero:** Writing – review & editing, Supervision, Investigation, Conceptualization. **Nunzio Marrone:** Writing – review & editing, Methodology, Formal analysis. **Francesco De Paola:** Writing – review & editing, Supervision, Methodology, Conceptualization. **Irem Daloglu Cetinkaya:** Writing – review & editing, Supervision, Methodology, Formal analysis. **Nadim K. Copty:** Writing – review & editing, Supervision, Methodology, Conceptualization. **Michael Rode:** Writing – review & editing, Supervision, Investigation. **Salvatore Manfreda:** Writing – review & editing, Writing – original draft, Supervision, Project administration, Methodology, Funding acquisition, Formal analysis, 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.

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Appendix A

Table 1A
Global Aridity Index (Global-AI) classification and reclassification scheme.

Aridity Classification	Aridity Index (AI) Range	Reclassification
Hyper-arid	AI < 0.05	Arid
Arid	0.05 ≤ AI < 0.20	
Semi-arid	0.20 ≤ AI < 0.50	
Dry sub-humid	0.50 ≤ AI < 0.65	
Sub-humid	0.65 ≤ AI < 0.80	Humid
Humid	0.80 ≤ AI < 1.5	

Table 2A
FAO soil slope classification and reclassification scheme.

Class	Description	% Slope	Reclassification
1	Flat	0–0.2	Mild
2	Level	0.2–0.5	
3	Nearly level	0.5–1.0	
4	Very gently sloping	1.0–2.0	
5	Gently sloping	2–5	
6	Sloping	5–10	Steep
7	Strongly sloping	10–15	
8	Moderately steep	15–30	
9	Steep	30–60	
10	Very steep	>60	

Data availability

Data will be made available on request.

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