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Exploring Nature-based Solutions in Mountain Regions: A Review of Their Hydrological Functions

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Abstract. Mountain regions play a fundamental role in sustaining the water supply for many activities around the world. However, these ecosystems are under increasing pressure due to climate change, changes in land use, and socioeconomic stressors, threatening water security. Implementing Nature-based Solutions (NbS) in mountain catchments are considered and effective means to increase water security, in the mountain regions itself, but also downstream. Despite growing interest, the scientific evidence base on the hydrological impacts of NbS in mountain regions is limited and characterised by methodological inconsistencies and insufficient consideration of climate dynamics. This study aims to review the hydrological performance of NbS in mountain regions and identify key knowledge gaps. We present a typology covering Wetlands, Forest-based interventions (Afforestation, Reforestation, Forest Conservation, and Agroforestry), and Water Harvesting interventions highlighting their hydrological functions. The analysis revealed that the most frequently reported indicators included flow regulation, groundwater recharge, water retention capacity, and soil erosion control. Our findings emphasise the need for more standardised methodologies in this environment, to enable robust comparisons of NbS performance under future scenarios. Strengthening the evidence base will require methodological integration and multiscale analyses that incorporate climate variables, as well as the inclusion of local and indigenous knowledge in planning and evaluation processes. Such efforts are essential for enhancing the design, implementation, and long-term effectiveness of NbS strategies for safeguarding water resources in mountain regions.

1 Introduction

Mountains cover around 27% of the Earth's land surface and provide vital ecosystem services including supplying freshwater, conserving biodiversity, producing food, and generating energy (Romeo et al., 2020). Often referred to as the 'water towers' of the world, mountains are an essential source of fresh water for meeting basic human needs such as irrigation, municipal and industrial water supply, hydropower production, and environmental services (UN-WWDR, 2025; Viviroli et al., 2011). However, the unique characteristics of mountain environments, including steep topographic gradients, vertical climatic variability, and shallow soils, make these ecosystems highly vulnerable to external pressures (Jiao et al., 2024). The main

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drivers of stress are climate change and land use change negatively affecting mountain regions (FAO/UNEP, 2023) modifying precipitation patterns, snowmelt regimes and water temperature, while also amplifying the frequency and intensity of hydrometeorological extremes (Schmeller et al., 2022). These changes impact hydrological and ecological processes, directly affecting water security of communities living in mountain regions (Ruangpan et al., 2020).

NbS have emerged as a promising strategy for addressing these challenges. They offer the potential to maintain, enhance, and restore ecosystem functions, while delivering social and economic benefits (Lalonde et al., 2024). Inspired by and supported through natural processes, NbS aim to improve water management by using ecosystem services (WWAP, 2018). Their application in mountain regions for ecosystem restoration is becoming increasingly common (FAO/UNEP, 2023). Nevertheless, despite their growing popularity in research and practice, NbS studies remain methodologically fragmented, often focusing on individual components of the ecosystem services cascade (Boerema et al., 2017). To address the lack of clarity surrounding what NbS are and how they can be assessed and classified, the International Union for the Conservation of Nature (IUCN) developed the Global Standard for NbS (IUCN, 2020). This is a framework and tool for assessing, implementing and monitoring NbS based on eight evidence-based criteria and a total of 27 indicators. The Global Standard takes a comprehensive, scoreable approach and is structured around a rapid self-assessment tool that requires qualitative responses. However, the tool does not provide insights into the hydrological performance of NbS. Although the tool can be used in mountainous areas, it is not specifically designed for mountain regions. In the European Union, the Handbook on Evaluating the Impact of Nature-Based Solutions (NbS) (European Commission, 2021) provides an indicator-based classification for assessing the impact of NbS. This classification is based on a compilation of results from Europe-based research projects. The NbS Handbook includes a category on the 'water management' indicator and can be considered as providing input into methodological harmonisation. However, limited quantification is provided in the NbS Handbook. The handbook also does not specifically address mountain regions.

To improve understanding of the hydrological performance of NbS in mountain regions, this paper addresses the following research question: (i) How has the scientific evidence on the hydrological functions of NbS in mountainous regions evolved to date, and what methodological gaps remain? (ii) Should hydrological indicators for NbS be standardised to improve cross-regional comparability and applicability in mountain environments?

To address these questions, this study aims to: (i) summarize the current state of research on NbS for water security in mountain environments; (ii) examine the evolution of NbS research in these regions, emphasizing hydrological functions, methodologies, and spatial temporal patterns; (iii) identify research trends, knowledge gaps, and future directions to inform the development of NbS strategies for mountain water security; and (iv) identify the key parameters of NbS interventions, analyse their relationship with hydrological functions, and propose suitable indicators for assessing them in mountain contexts.

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2 Nature-based Solutions definition

The concept of NbS is widely applied in scientific and policy contexts, yet its definition varies among leading international organizations. The Organisation for Economic Cooperation and Development (OECD) (2020) defines NbS as "measures that protect, sustainably manage or restore nature, with the goal of maintaining or enhancing ecosystem services to address a variety of social, environmental, and economic challenges". According to Lalonde et al (2024), the OECD provides a comprehensive definition by combining the importance of ecosystem conservation, restoration, and sustainable management, with a broader perspective that incorporates social and economic dimensions of sustainability. For this reason, the present review adopts the OECD definition.

To evaluate the hydrological functions of NbS in mountainous regions, we apply the classification proposed by the World Water Assessment Program (WWAP) (2018) related to the primary service provision, in this case about water supply regulation (Table 1), which outlines three categories: (i) re/afforestation and forest conservation, (ii) wetlands restoration and conservation, and (iii) water harvesting. Within the water harvesting category, our focus is placed on four specific infrastructure types: (i) small reservoirs, (ii) diversion canals, (iii) infiltration trenches, and (iv) terraces. In this context, water harvesting is understood as the construction of elements that interact with natural features to enhance water related ecosystem services (Lalonde et al., 2024).

Table 1: Overview of NbS for water intervention types

NbS types	Solutions	Articles
Re/afforestation and forest conservation	Afforestation	Buendia et al., 2016; Castelli et al., 2017; Chen et al., 2016; Esquivel et al., 2020; Gallay et al., 2021; Hrabovský et al., 2020; Li et al., 2023; Liang et al., 2023; Martínez-Retureta et al., 2020, 2022; Pereira, 1967; Piégay et al., 2004; Rodríguez-Echeverry et al., 2018
	Agroforestry	Castelli et al., 2017; Denu et al., 2016; Jiao et al., 2024; Zuazo et al., 2011
	Reforestation	Gao & Yu, 2017; Ghimire et al., 2013; Holden et al., 2022; Kabeja et al., 2020; Kim et al., 2019; Molina et al., 2009
	Forest Conservation	Cervantes et al., 2021; Holden et al., 2022; Kim et al., 2019; Liang et al., 2023; Šach et al., 2014; Sun et al., 2002; Tiwari et al., 2009; vonHedemann, 2023; Wang et al., 2023

NbS types	Solutions	Articles
Wetlands restoration/conservation	Wetlands	Ahmad et al., 2020; Andreo et al., 2016; Baiker et al., 2022; Cao et al., 2020; Carlson et al., 2020; Carlson Mazur et al., 2014; Cervantes et al., 2021; Cooper et al., 2015; Cottet et al., 2013; Dwire et al., 2018; Frei et al., 2010; Leguizamon & Marín, 2017; B. Li et al., 2014; J. Li et al., 2013; J. Li & Shi, 2015; Mapeshoane & van Huyssteen, 2016; Monge-Salazar et al., 2022; Mosquera et al., 2015; Otto & Gibbons, 2017; Pitchford et al., 2012; Price et al., 2005; Pulido-Bosch et al., 2000; Rudolph et al., 2007; Scheliga et al., 2019; Shao et al., 2022; Shih & Hsu, 2021; Shih & Lee, 2023; Sun et al., 2002; Thompson et al., 2012; K. Wang et al., 2022; Y. L. Wang et al., 2012; Xu et al., 2009; Yang et al., 2023
Water harvesting	Small reservoirs	Craig et al., 2011; Guyassa et al., 2017; Jiao et al., 2024; Lane, 2014; Soomro et al., 2022
	Diversion canals	Baiker et al., 2022; Frot & van Wesemael, 2009; Jódar et al., 2022; Ochoa-Tocachi et al., 2019; Pulido-Bosch et al., 2000; Yair, 1983
	Infiltration trenches	Castelli et al., 2017; Guzman et al., 2017; LaFevor & Ramos-Scharrón, 2021; Li & Gao, 2019; Locatelli et al., 2020; Somers et al., 2018
	Terraces	Beckers et al., 2013; Bruins et al., 2020; Castelli et al., 2017; Gallart et al., 1994; Guzman et al., 2017; Herath et al., 2015; Huang et al., 2024; Jiao et al., 2024; Liu et al., 2022; Llorens et al., 1992; Paronuzzi & Bolla, 2023; Tiwari et al., 2009; Wang et al., 2024; Wei et al., 2024; Zhan et al., 2011; Zhao et al., 2023

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3 Methodology

The present review employs a scoping review approach to summarise the existing literature on the hydrological functions of NbS in mountain regions. The process followed the PRISMA Extension for Scoping Reviews (PRISMA-ScR) guidelines (Tricco et al., 2018), which provide a structured framework for identifying, screening, and reporting the literature.

The first step was to develop an NbS typology to guide the review process. Three major bibliographic databases were searched to identify potentially relevant documents: SCOPUS, Web of Science, and PubMed. The search took place between November 2024 to March 2025. A comprehensive search string (Table 2) was developed to encompass NbS intervention types and their synonyms, as well as key hydrological functions relevant to NbS performance, and mountain related terms to capture studies specific to mountain environments. The final search results were exported into a Zotero library and duplicates were removed manually.

Table 2: Search string and number of articles found per search

Database	Search string	Articles
Scopus	(TITLE ("nature-based solutions*") OR TITLE ("nature based solution*") OR TITLE (nbs) OR TITLE (reforestation) OR TITLE (afforestation) OR TITLE ("forest conservation") OR TITLE ("constructed wetland") OR TITLE (wetland*) OR TITLE ("wetland restoration") OR TITLE ("water harvesting") OR TITLE ("small depression*") OR TITLE ("diversion canal*") OR TITLE (trench*) OR TITLE (gullies) OR TITLE (ditches) OR TITLE (terrace) OR TITLE ("green infrastructure") OR TITLE ("blue infrastructure") OR TITLE ("ecosystem services") OR TITLE ("blue-green infrastructure") OR TITLE ("ecosystem based") OR TITLE ("ecological engineering") OR TITLE ("green-blue infrastructure")) AND (TITLE (hydrology) OR TITLE ("hydrological function*") OR TITLE ("hydrological model*") OR TITLE (runoff) OR TITLE (streamflow) OR TITLE (baseflow) OR TITLE (discharge) OR TITLE (transpiration) OR TITLE (evapo*) OR TITLE (infiltration) OR TITLE (storage) OR TITLE ("water management") OR TITLE ("peak flow*") OR TITLE (interception) OR TITLE (rainfall) OR TITLE (groundwater*) OR TITLE (recharge) OR TITLE (rainwater) OR TITLE (percolation)) AND (TITLE-ABS-KEY (mountain*) OR TITLE-ABS-KEY (cordillera*) OR TITLE-ABS-KEY (alpine) OR TITLE-ABS-KEY (alps) OR TITLE-ABS-KEY (sierra) OR TITLE-ABS-KEY (highland*))	137

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Web of Sciences	(TI=("nature-based solutions*") OR TI=("nature based solution*") OR TI=(nbs) OR TI=(reforestation) OR TI=(afforestation) OR TI=("forest conservation") OR TI=("constructed wetland") OR TI=(wetland*) OR TI=("wetland restoration") OR TI=("water harvesting") OR TI=("small depression*") OR TI=("diversion canal*") OR TI=(trench*) OR TI=(gullies) OR TI=(ditches) OR TI=(terrace) OR TI=("green infrastructure") OR TI=("blue infrastructure") OR TI=("ecosystem services") OR TI=("blue-green infrastructure") OR TI=("ecosystem based") OR TI=("ecological engineering") OR TI=("green-blue infrastructure")) AND (TI=(hydrology) OR TI=("hydrological function*") OR TI=("hydrological model*") OR TI=(runoff) OR TI=(streamflow) OR TI=(baseflow) OR TI=(discharge) OR TI=(transpiration) OR TI=(evapo*) OR TI=(infiltration) OR TI=(storage) OR TI=("water management") OR TI=("peak flow*") OR TI=(interception) OR TI=(rainfall) OR TI=(groundwater*) OR TI=(recharge) OR TI=(rainwater) OR TI=(percolation)) AND (TI=(mountain*) OR TI=(cordillera*) OR TI=(alpine) OR TI=(alps) OR TI=(sierra) OR TI=(highland*) OR AB=(mountain*) OR AB=(cordillera*) OR AB=(alpine) OR AB=(alps) OR AB=(sierra) OR AB=(highland*))	101
PubMed	((nature-based solutions[Title]) OR (nature based solution[Title]) OR (nbs) OR (reforestation[Title]) OR (afforestation[Title]) OR (forest conservation[Title]) OR (constructed wetland[Title]) OR (wetland*[Title]) OR (wetland restoration[Title]) OR (water harvesting[Title]) OR (small depression*[Title]) OR (diversion canal*[Title]) OR (trench*[Title]) OR (gullies[Title]) OR (ditches[Title]) OR (terrace[Title]) OR (green infrastructure[Title]) OR (blue infrastructure[Title]) OR (ecosystem services[Title]) OR (blue-green infrastructure[Title]) OR (ecosystem based[Title]) OR (ecological engineering[Title]) OR (green-blue infrastructure[Title])) AND ((hydrology[Title]) OR (hydrological function*[Title]) OR (hydrological model*) OR (runoff[Title]) OR (streamflow[Title]) OR (baseflow[Title]) OR (discharge[Title]) OR (transpiration[Title]) OR (evapo*[Title]) OR (infiltration[Title]) OR (storage[Title]) OR ("water management"[Title]) OR ("peak flow*"[Title]) OR (interception[Title]) OR (rainfall[Title]) OR (groundwater*[Title]) OR (recharge[Title]) OR (rainwater[Title]) OR (percolation[Title])) AND ((mountain*[Title/Abstract]) OR (cordillera*[Title/Abstract]) OR (alpine[Title/Abstract]) OR (alps[Title/Abstract]) OR (sierra[Title/Abstract]) OR (highland*[Title/Abstract]))	6

The initial database search identified 244 scientific articles, all of which were published in either English or Spanish. This was supplemented by screening the reference lists of the identified papers, as well as additional reports and documents found

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through Google Scholar using targeted keyword queries related to mountains, NbS, and hydrological functions. This supplementary search yielded a further 20 articles and reports.

Following the PRISMA-ScR framework, the retrieved records were screened across three consecutive phases. First, the titles of the papers were screened to those that were clearly irrelevant. Secondly, the abstracts were screened to identify potentially relevant studies. Thirdly, a full text review was conducted in order to ascertain eligibility, with this process being based on predefined inclusion and exclusion criteria.

Studies were included if they: (i) were empirical studies, reviews, or modelling papers; (ii) explicitly analysed a specific NbS intervention; (iii) were located in a mountainous region, high mountain, or high plateau; (iv) measured or discussed at least one specific function of the hydrological cycle (iv) were published in English or Spanish.

Studies were excluded if they: (i) focused solely on non-hydrological ecosystem services (e.g. carbon storage) without a hydrological assessment; (ii) purely grey intervention (conventional civil engineering); (iii) were located in plains, coastal areas, or low altitude urban environments not connected to mountain ranges (iv) were published in any other language.

After this process, 85 documents met the inclusion criteria and were retained for analysis. LitMap software was used to visualise and map the selected literature (Fig. 2). This procedure enabled an evaluation of the current state of knowledge and identification of significant research gaps.

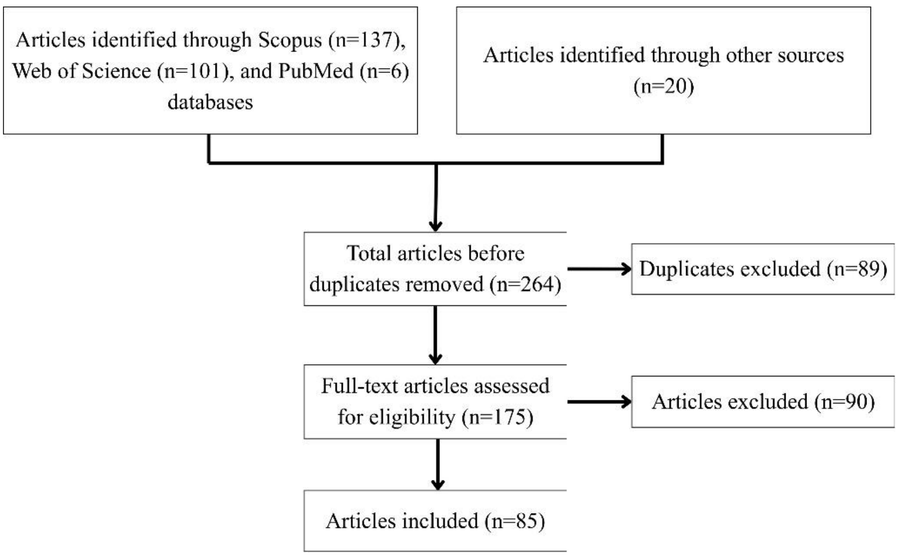

Figure 1: Flow chart of article screening based on the PRISMA-ScR methodology. The figure illustrates the selection process for the studies included in this review, as defined by the eligibility criteria.

Key information was systematically extracted for each included study using a data charting template (Supplementary material). This included bibliographic descriptors such as authors, year and journal; the type and spatial scale of the NbS intervention; the hydrological functions assessed and the step of the Ecosystem Services (ES) Cascade model addressed (Haines-Young & Potschin, 2010); the methodological approach used to quantify hydrological functions; geographical descriptors including

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location, country, and continent; and the condition of the ecosystem and the objective of the intervention, distinguishing between preservation, restoration from degradation, or human benefit. Additionally, the incorporation of climate change scenarios into the analyses was recorded.

4 Results

4.1 General overview

The screening process yielded 85 publications. A number of these articles evaluated multiple types of NbS. The literature map illustrates the distribution of studies addressing NbS in mountain regions by publication year and citation impact. The map also highlights limited interconnections among studies, as evidenced by the relatively few citation links, which suggests the presence of several independent research efforts. Furthermore, the most frequently cited publications were published around 2000 and are largely focused on wetland-related NbS. More recent publications demonstrate a broader diversity of interventions. However, these have not accumulated high citation counts, which may be attributed to their relatively recent appearance in the literature.

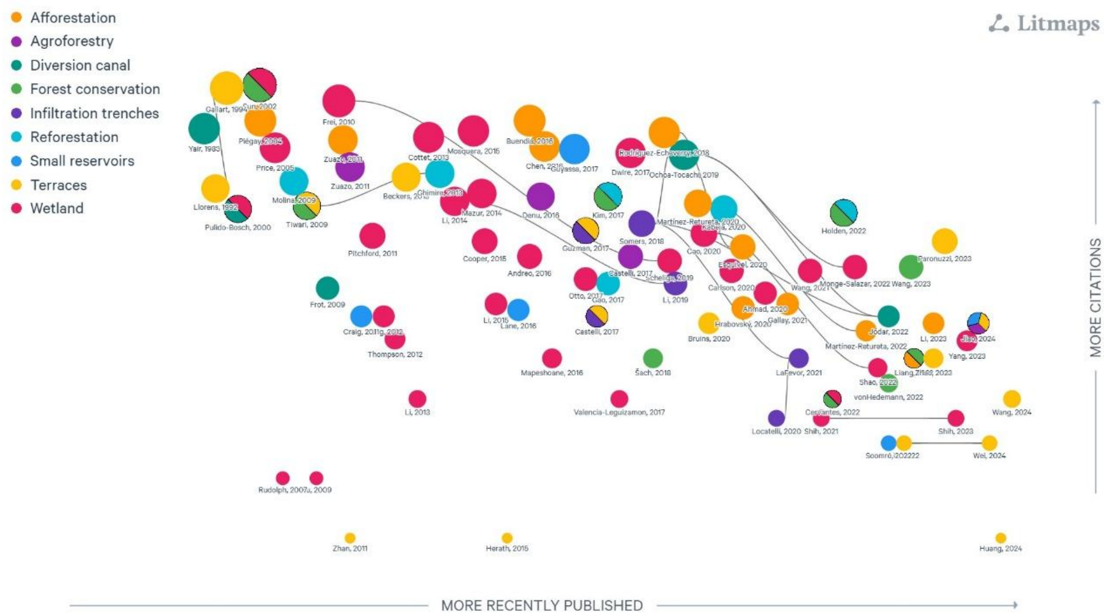

Figure 2: Literature map of hydrological functions in mountain regions, categorized by NbS type. Each node represents a reviewed paper. Node size is proportional to citation count, and colour indicates the type of NbS intervention. The lines represent citation links between studies. The figure illustrates research connectivity and academic influence over time.

The number of studies published in the field of NbS for water security in mountain regions has been increasing during the last decades. Figure 3 demonstrates that research has expanded considerably during the decade 2010-2020 with about 83% of the total research taking place from 2010 onwards. Moreover, the increasing number of studies after 2010 evidenced an increase in studies in Asia, with 35% of all studies since 2010. The second region with a large share of studies during this period are South-Central America and the Caribbean, with a combined 20% of all studies.

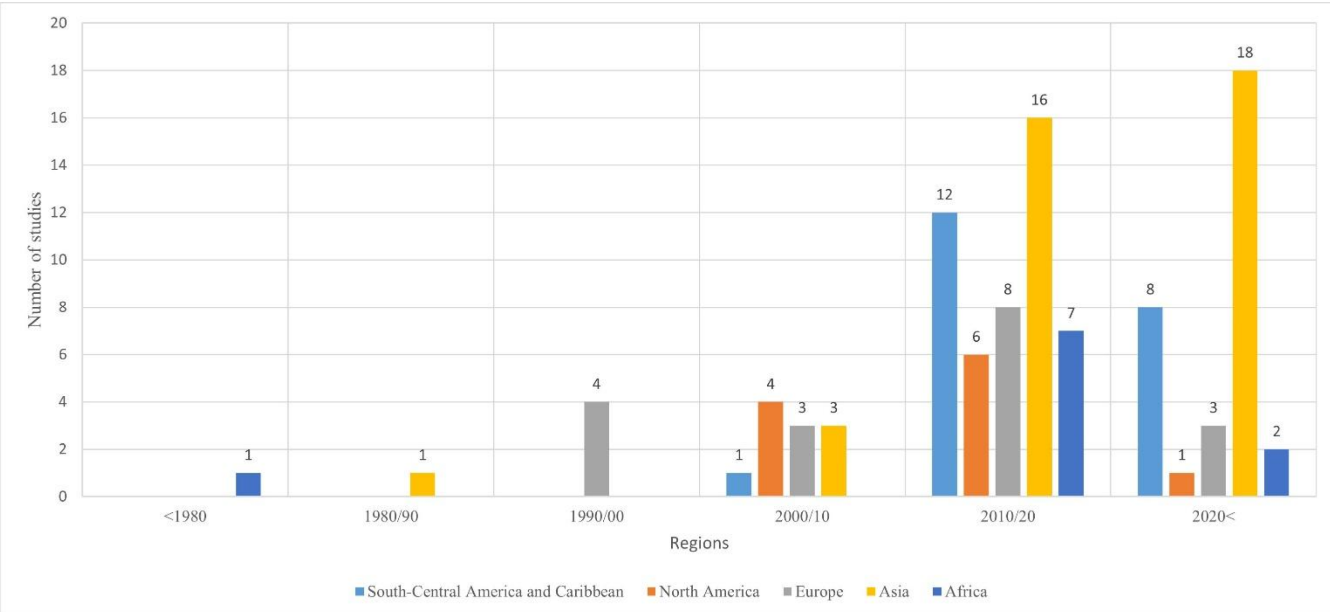

Figure 3: Number of publications by decade and geographic region. The figure illustrates the distribution of NbS studies over time. The bars represent the number of publications per decade, while the colour indicates the geographical region in which the studies were conducted.

Wetlands were the most frequently studied intervention, accounting for 33.7 % of all interventions. Terraces also represented a substantial proportion of the identified studies, with 16.3% of the total. Conversely, categories such as agroforestry (4.1%) and small reservoirs (5.1%) were comparatively underrepresented.

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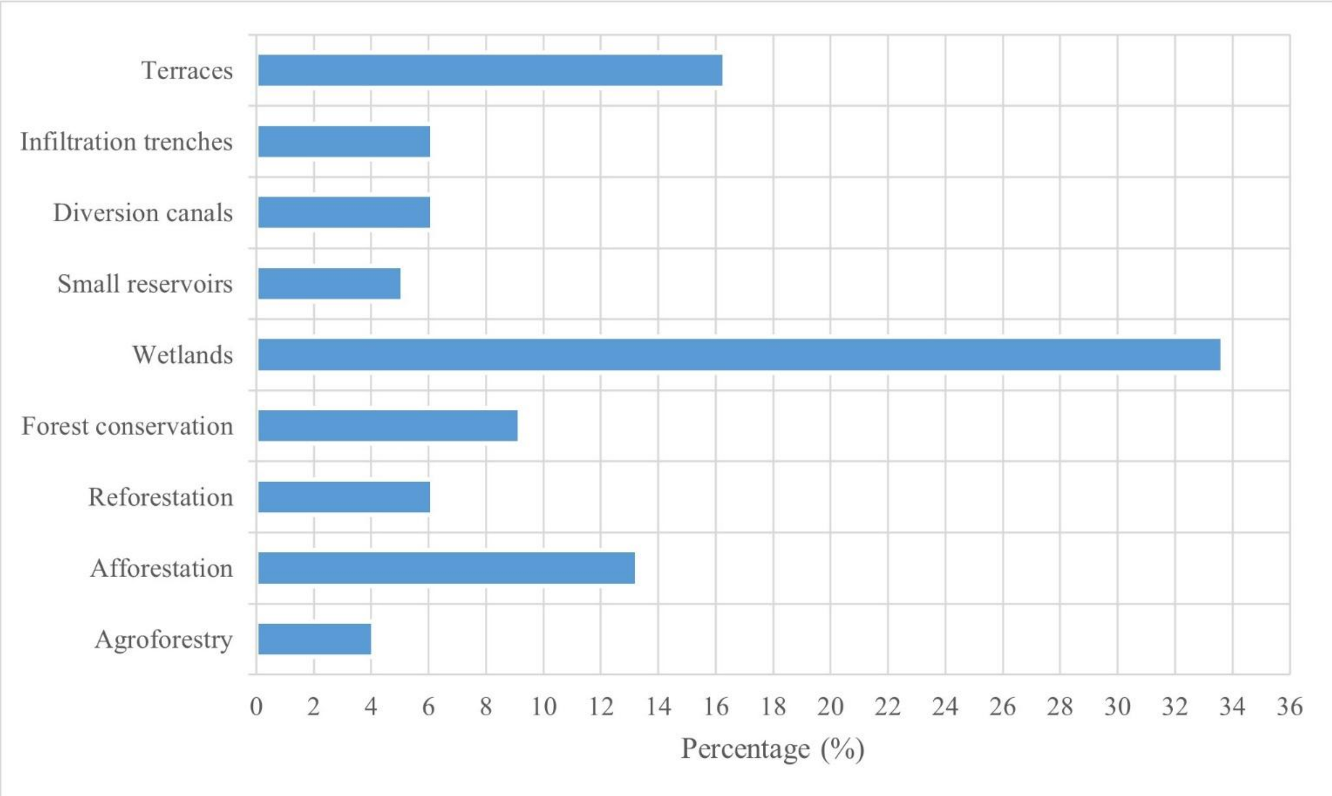

145 **Figure 4: Percentage of NbS studies assessing hydrological functions in mountain regions. Bars represent the proportion of reviewed studies according to the type of NbS intervention.**

The presence of any reference to social, political and/or economic aspects was examined. The result (Fig. 5) indicate that approximately 42% of the studies did not include any mention of these dimensions. Approximately 36% of the cases referred to social aspects, while the economic and political dimensions were each included in 24% of the studies. It is important to note that this analysis did not assess whether these dimensions were systematically evaluated within the studies; instead, it merely recorded whether they were mentioned. A more detailed examination is provided in the subsequent sections.

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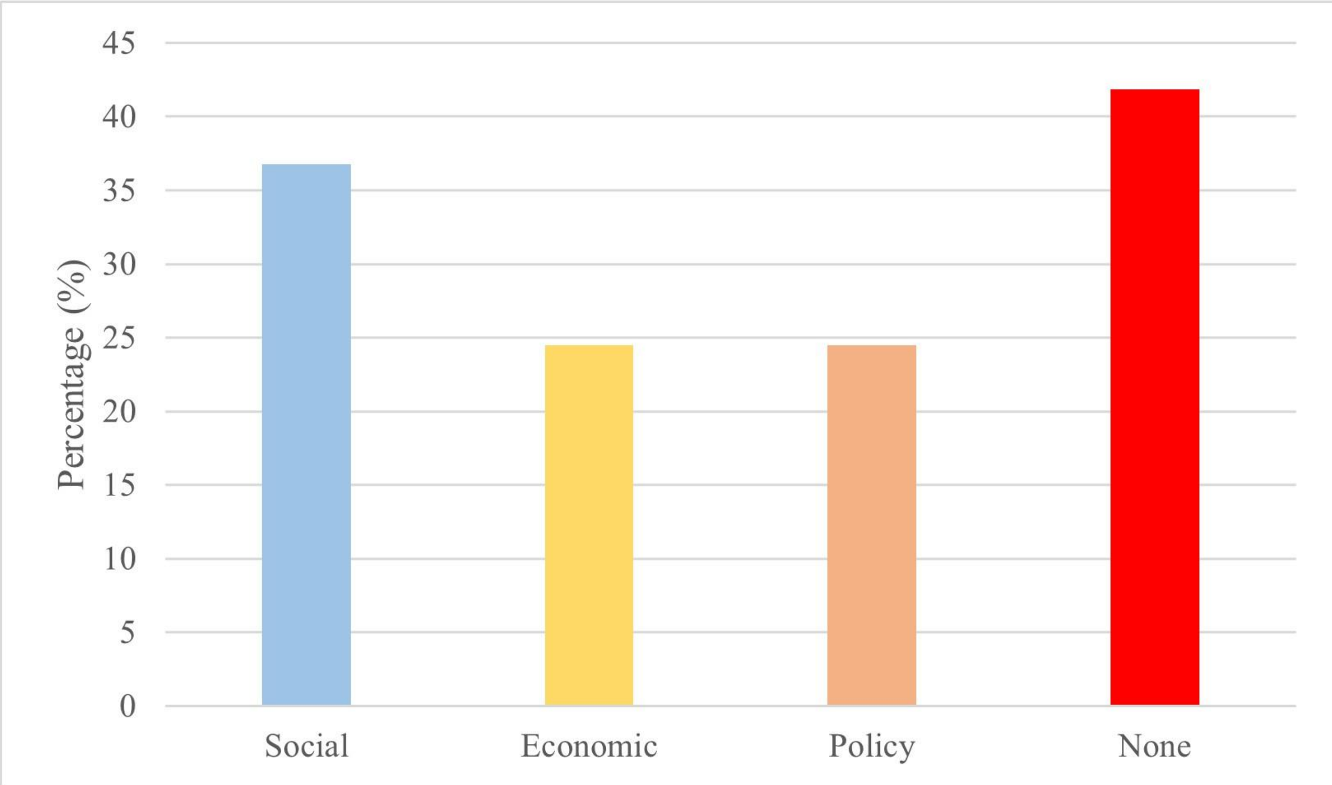
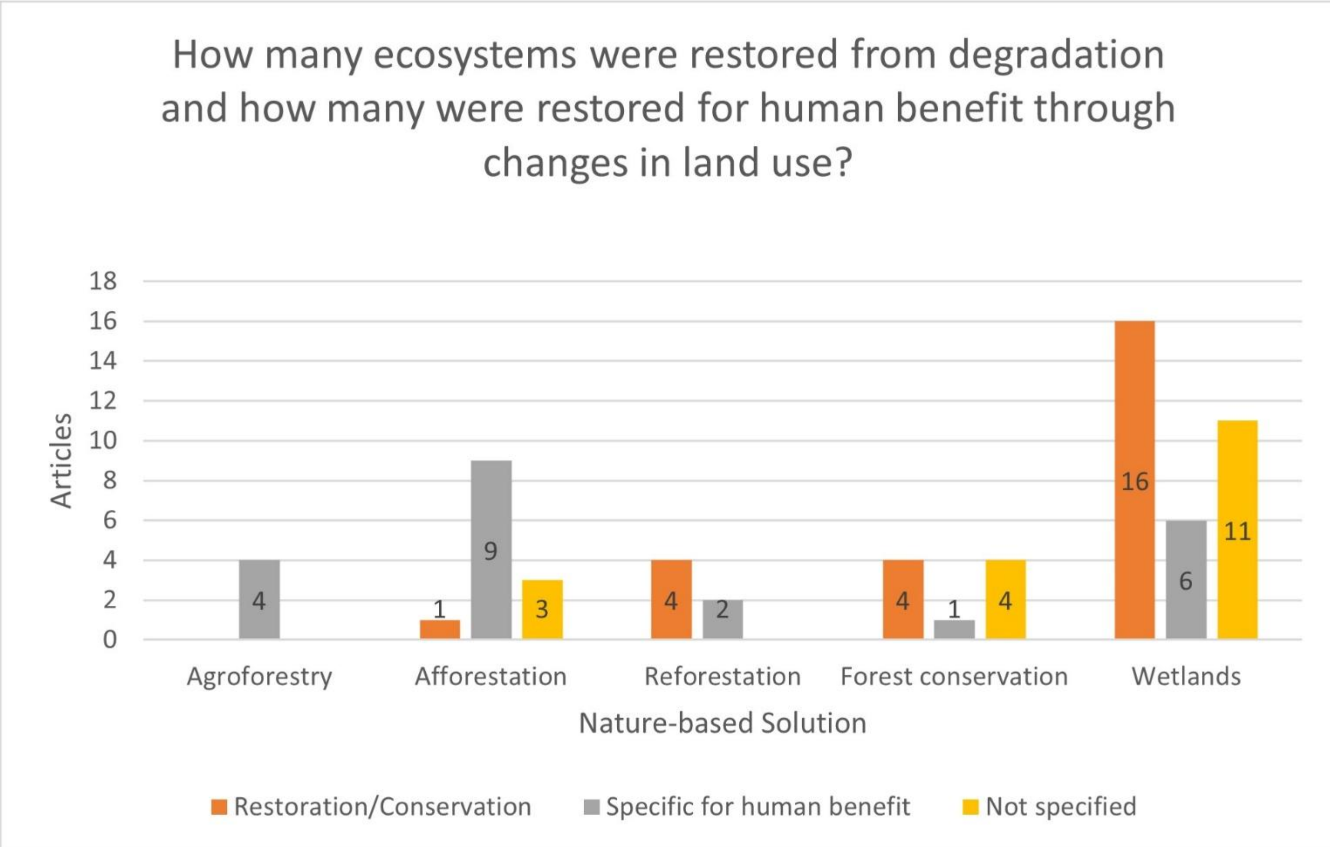


Figure 5: Proportion of reviewed studies referring to social, economic, or political aspects in the context of NbS in mountain regions. Bars indicate the proportion of reviewed papers mentioning these dimensions in mountain contexts.

The drivers of restoration varied across NbS interventions, with some implemented in response to ecosystem degradation and others primarily motivated by human benefits (Fig. 6). Most reported studies on agroforestry were associated with enhancing human benefits through land use change. For afforestation, a considerable number of studies indicated that this intervention was primarily aimed at altering vegetation cover for human purposes. Conversely, reforestation, forest conservation, and wetland interventions were more frequently linked to restoring degraded ecosystems or protecting vulnerable areas. Wetlands were the most frequently studied category, with 16 articles focusing on restoring degraded conditions. However, around 28% of the reviewed studies did not specify the purpose of the intervention, as shown in Figure 7.



165 **Figure 6: Drivers of restoration in NbS interventions. The bars indicate the number of studies according to whether the intervention targeted a specific objective.**

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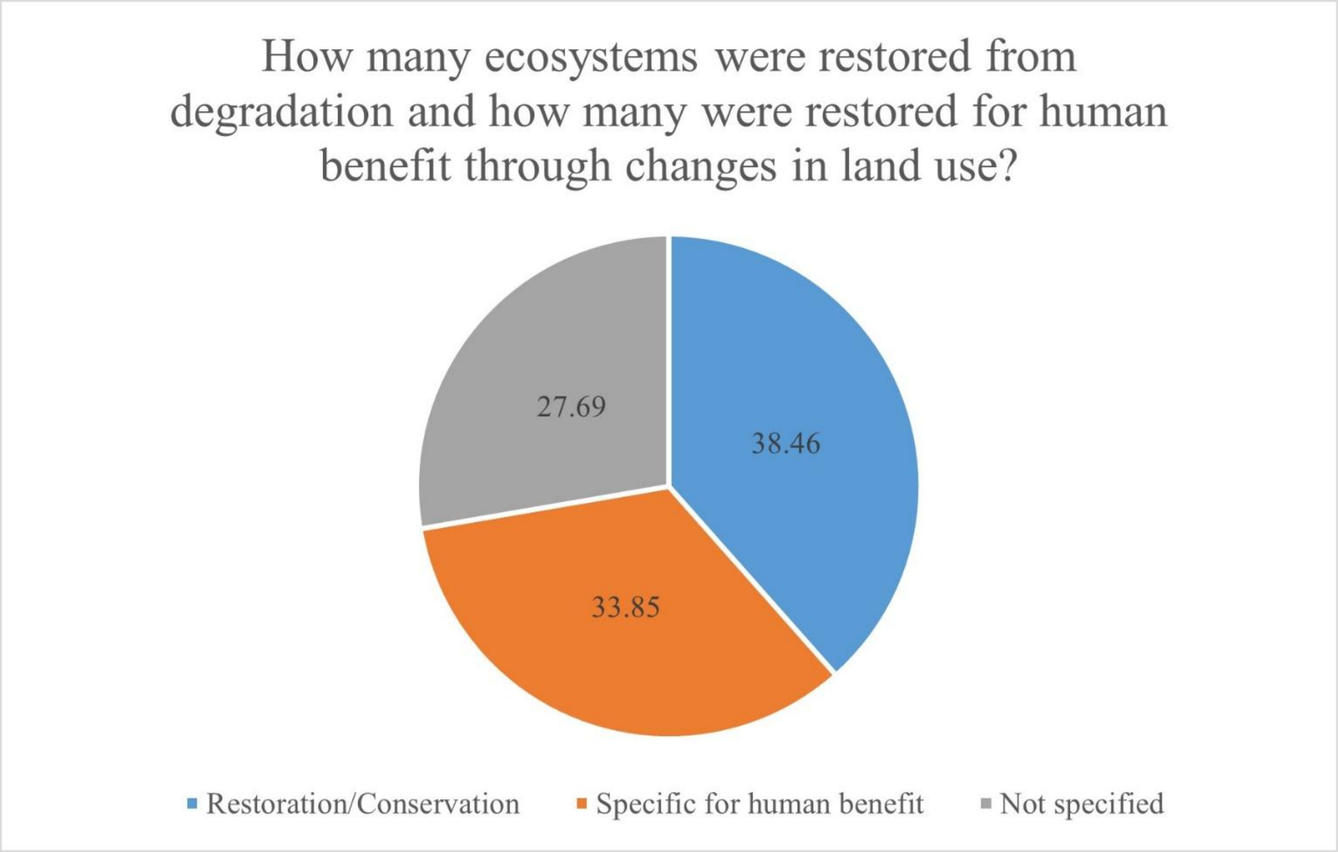

Figure 7: Percentage of reviewed studies reporting NbS interventions by restoration driver (ecosystem degradation, human benefit orientation, or unspecified).

A total of 29 different countries were represented in the reviewed studies. However, it is notable that 25% of the research came from China alone. Interventions related to forest NbS exhibited a relatively balanced distribution across Asia, Europe, and South-Central America and the Caribbean, whereas Africa and North America accounted for only a small number of studies (Fig. 8A). Water harvesting interventions (Fig. 8B) were most prevalent in Asia, where terraces were the most frequently studied practice. Wetland interventions (Fig. 8C) were more represented in North America and Europe, while in Asia and South America most studies were concentrated in specific countries, notably China and Peru. Research output from the African continent was comparatively lower than other regions on the subject of wetlands in mountain areas.

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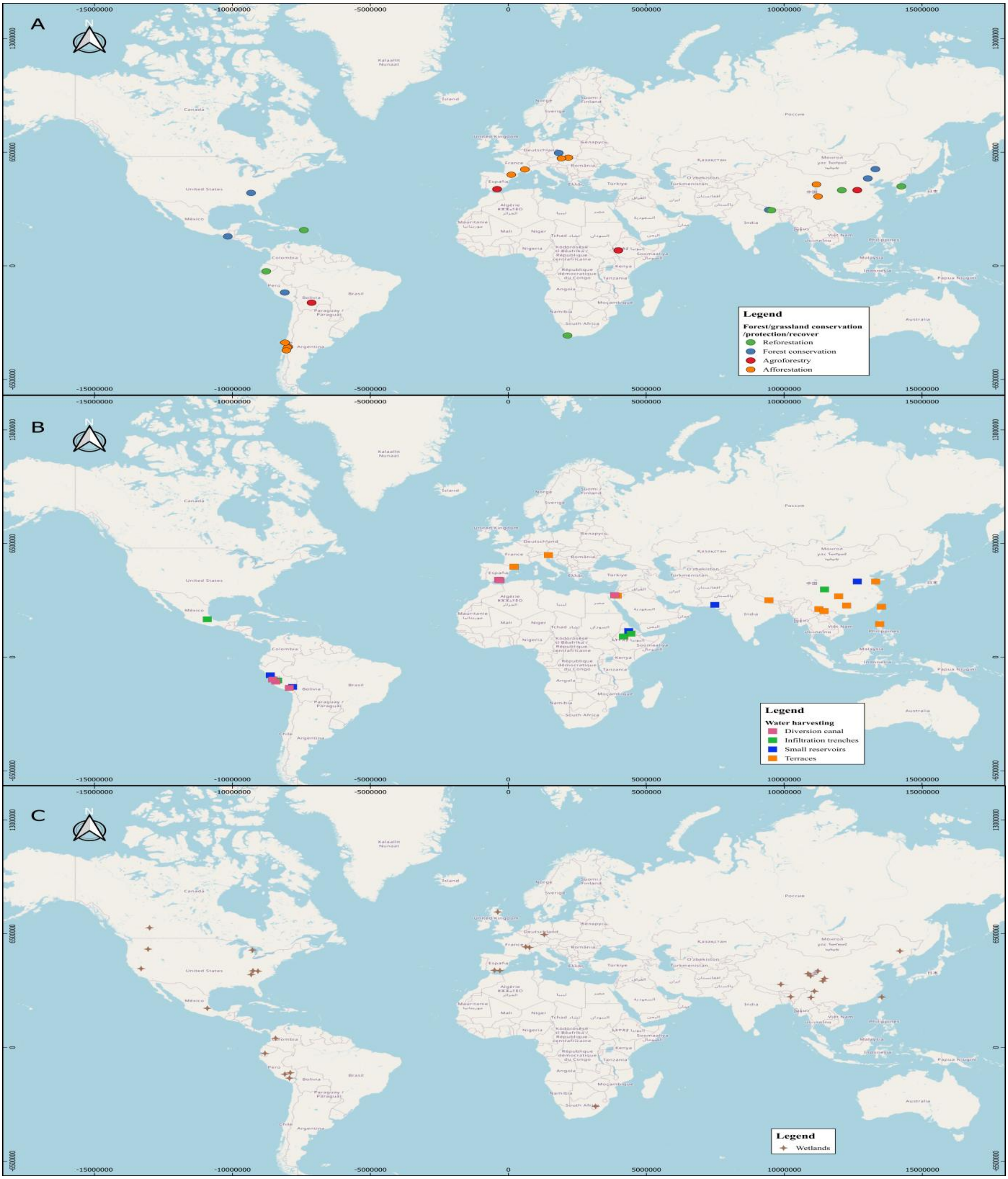

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Figure 8: Geographical distribution of NbS studies disaggregated by intervention type: (A) forest-based interventions, (B) water harvesting interventions, and (C) wetland interventions. Base map: © OpenStreetMap contributors.

4.2 Ecosystem Services (ES) cascade approach

The concept of NbS is closely related to, and influenced by, that of ES for the purpose of studying the interactions between nature and society (Welden et al., 2021). Therefore, it is important to understand how this concept has been analysed within the ES cascade conceptual framework.

The analysis indicates that most studies have focused on the ecological dimension of the cascade (Appendix A). The analysis (Figure 9) revealed that almost half (48%) of the reviewed literature focused on ecosystem functions, while ecosystem properties were also relatively well represented (25%). In contrast, a small number of studies explicitly quantified ecosystem services (14%), and an even smaller fraction addressed the value (2%). It is important to note that the benefits of the ES cascade were not directly quantified in any of the studies. This underscores a pronounced imbalance within the extant evidence base, with an overarching emphasis on ecological processes and an underestimation of socio-economic dimensions.

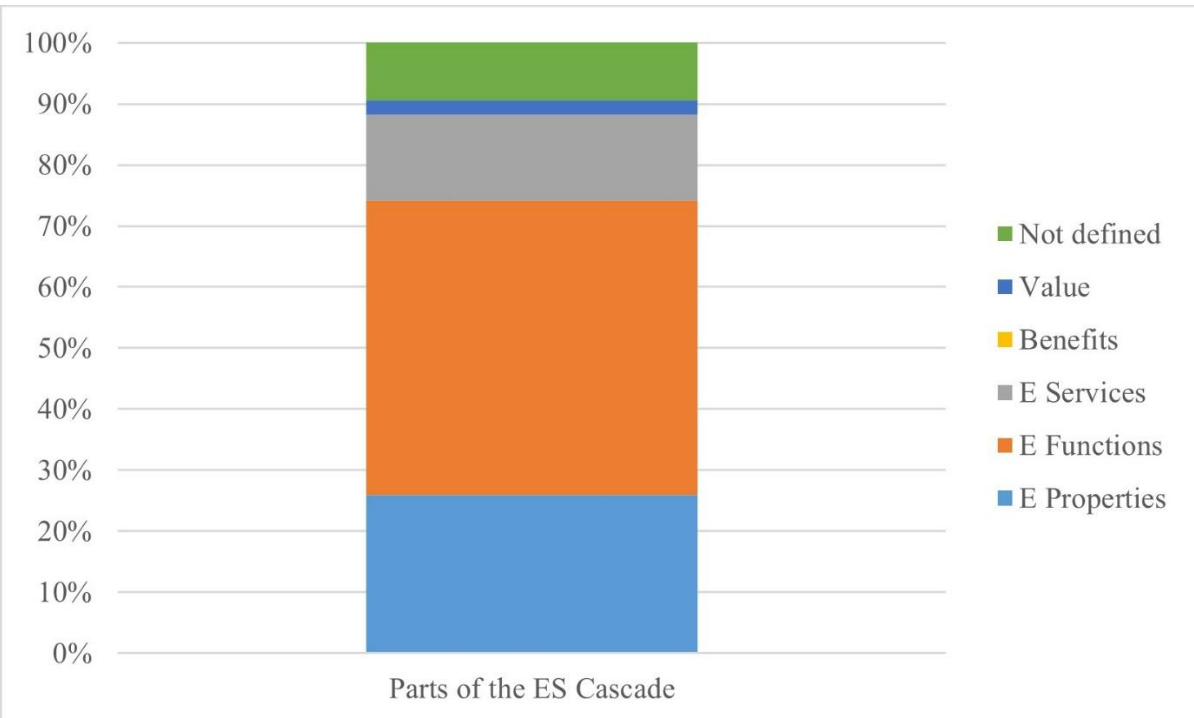

Figure 9: Percentage of reviewed studies that address each step of the ES Cascade in mountain regions.

4.3 Indigenous or/and local knowledge

This review also examined whether the studies explicitly incorporated local, traditional, or Indigenous knowledge in the design, implementation, or assessment of NbS. A total of 26 studies (31%) (Table 3) explicitly referenced community participation or the utilization of traditional knowledge. The remaining 59 studies (69%) either did not report the inclusion of these elements or they were not a part of the study.

Table 3: Inclusion of local, traditional, or Indigenous knowledge in the reviewed NbS studies

	Indigenous, traditional, and/or local knowledge
Yes	(Baiker et al., 2022); (Beckers et al., 2013); (Bruins et al., 2020); (Craig et al., 2011); (Frot & van Wesemael, 2009); (Guyassa et al., 2017); (Guzman et al., 2017); (Herath et al., 2015); (Huang et al., 2024); (Jiao et al., 2024); (Jódar et al., 2022); (LaFevor & Ramos-Scharrón, 2021); (Lane, 2014); (Liu et al., 2022); (Llorens et al., 1992); (Locatelli et al., 2020); (Monge-Salazar et al., 2022); (Ochoa-Tocachi et al., 2019); (Tiwari et al., 2009); (vonHedemann, 2023); (Wang et al., 2024); (Wei et al., 2024); (Yair, 1983); (Zhan et al., 2011); (Zhao et al., 2023); (Zuazo et al., 2011)
No	(Ahmad et al., 2020); (Andreo et al., 2016); (Buendia et al., 2016); (Cao et al., 2020); (Carlson et al., 2020); (Carlson Mazur et al., 2014); (Castelli et al., 2017); (Castelli et al., 2017); (Cervantes et al., 2021); (Chen et al., 2016); (Cooper et al., 2015); (Cottet et al., 2013); (Denu et al., 2016); (Dwire et al., 2018); (Esquivel et al., 2020); (Frei et al., 2010); (Gallart et al., 1994); (Gallay et al., 2021); (Gao & Yu, 2017); (Ghimire et al., 2013); (Holden et al., 2022); (Hrabovský et al., 2020); (Kabeja et al., 2020); (Kim et al., 2019); (Leguizamon & Marín, 2017); (Li et al., 2014); (Li & Shi, 2015); (Li et al., 2013); (Li et al., 2023); (Li & Gao, 2019); (Liang et al., 2023); (Mapeshoane & van Huyssteen, 2016); (Martínez-Retureta et al., 2022); (Martínez-Retureta et al., 2020); (Molina et al., 2009); (Mosquera et al., 2015); (Otto & Gibbons, 2017); (Paronuzzi & Bolla, 2023); (Pereira, 1967); (Piégay et al., 2004); (Pitchford et al., 2012); (Price et al., 2005); (Pulido-Bosch et al., 2000); (Rodríguez-Echeverry et al., 2018); (Rudolph et al., 2007); (Šach et al., 2014); (Scheliga et al., 2019); (Shao et al., 2022); (Shih & Hsu, 2021); (Shih & Lee, 2023); (Somers et al., 2018); (Soomro et al., 2022); (Sun et al., 2002); (Thompson et al., 2012); (Wang et al., 2023); (Wang et al., 2022); (Wang et al., 2012); (Xu et al., 2009); (Yang et al., 2023)

4.4 Climate change analysis

No studies explicitly evaluating climate change were found in interventions such as agroforestry, small reservoirs, diversion canals and infiltration trenches. In contrast, 24% of studies on wetlands addressed this factor, making it the NbS category with the highest number of studies addressing climate change. Afforestation also demonstrated a relatively high level of climate change integration, with 4 of 13 studies addressing it, whereas only 22% of forest conservation studies did so.

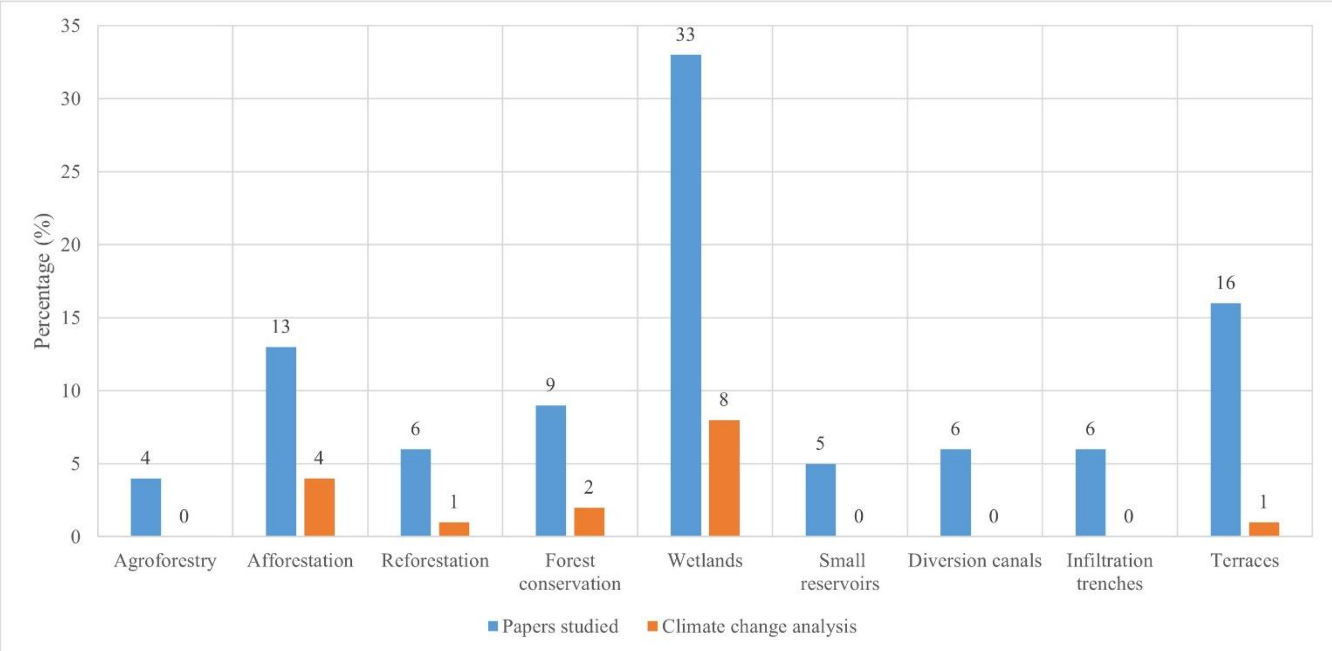

Figure 10: Number of studies on NbS interventions that included climate change scenarios or analyses when evaluating NbS interventions in mountain regions.

4.5 Assessment of NbS (Scale – models)

In terms of spatial scale of the analysis, the reviewed studies exhibited a wide range of scales, largely depending on the type of NbS intervention. Wetland studies covered the broadest spectrum, from local scales of 0.08 ha (Scheliga et al., 2019) to medium scale catchments of between 320 km2 (Pulido-Bosch et al., 2000) and approximately 7 000 km2 (B. Li et al., 2014; J. Li & Shi, 2015). Only 2 studies assessed wetlands at a regional scale, with study areas covering 11 957 km2 (Xu et al., 2009) and 20 930 km2 (Yang et al., 2023).

Of the studies on Agroforestry interventions, only 2 explicitly reported the spatial extent of the intervention: one at a small scale (Jiao et al., 2024b) and one at a medium scale (Castelli et al., 2017). Studies on afforestation and reforestation also tended to report on local to medium scales, while Forest Conservation interventions were mostly conducted on local scales. A single study on the subject was carried out on a regional scale (Wang et al., 2023).

Finally, Water Harvesting interventions were predominantly analysed at a local scale, with only one study examining the issue at a regional level (Li & Gao, 2019). It is worth noting that several studies did not report the spatial extent of their analysis. This limits the possibility of making comparisons between different cases.

The studies employed a variety of modelling and analytical approaches, which could be grouped into four main categories: (i) numerical or hydrological modelling; (ii) experimental, observational, or in situ methods; (iii) Geographic Information Systems (GIS) and remote sensing techniques; and (iv) statistical data analysis. Of the studies on Wetland interventions, the most frequently used approaches were hydrological modelling (44%) and experimental or in situ data collection (63%). Notably,

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28% of the studies combined modelling and field based approaches, while only one study (Wang et al., 2023) incorporated three methods by additionally using GIS analysis.

Of the 32 studies focusing on Forest-vegetation based interventions, the most applied approach was hydrological modelling (66%), followed by experimental or in situ data collection (50%). Overall, 28% of the studies combined hydrological modelling and field based data collection. GIS and remote sensing methods were less frequent (16%) and were always applied in combination with hydrological modelling. Only one study (Jiao et al., 2024b) integrated all three approaches in the context of Agroforestry. Additionally, the two studies that performed statistical analyses did so in combination with experimental data collection.

For Water Harvesting interventions, the most common approach was experimental or in situ data collection, reported in 79% of the studies. Hydrological modelling was employed in 39% of cases, while GIS and remote sensing methods were used in 21% of cases. Only two studies (Craig et al., 2011; Gallart et al., 1994) combined all three approaches. In most cases, GIS and hydrological modelling methods were implemented alongside experimental data collection rather than independent techniques.

4.6 Hydrological indicators and variables in mountain regions

A set of key performance indicators were identified to evaluate the effectiveness of NbS in mountain regions, based on the most frequently reported hydrological functions across the reviewed studies. These indicators include metrics related to runoff (e.g. discharge and peak flow reduction), groundwater recharge, water retention capacity, and soil erosion control. Additionally, a series of conditioning variables that influence these indicators were systematically extracted from the literature and summarised in conceptual maps (Fig. 11, 12, and 13). These maps illustrate the interactions among climatic drivers, catchment characteristics, and soil properties that collectively govern the hydrological functioning of wetland interventions in mountain environments. Positive relationships are denoted by a ('+') sign, indicating that an increase in the variable enhances the indicator, whereas negative relationships ('–') denote a diminishing effect on the indicator.

Most studies reported that wetlands were located in areas with gentle slopes, however, many studies did not provide explicit slope measurements, which limited comparability across sites. Topography was consistently identified as a critical factor in wetland function, influencing their roles as recharge zones, rainfall buffers, and structures that attenuate flow, regulate runoff dynamics, and water retention capacity. Catchment size also emerged as a critical driver because it largely determines the magnitude of inflows to the wetland system. Soil properties were also repeatedly emphasised as being essential for understanding wetland performance. The most reported attributes included infiltration rate, soil water holding capacity, soil moisture content, hydraulic conductivity, and porosity. These parameters are fundamental for quantifying the potential for groundwater recharge and capturing the capacity of wetlands to modulate runoff and reduce soil erosion.

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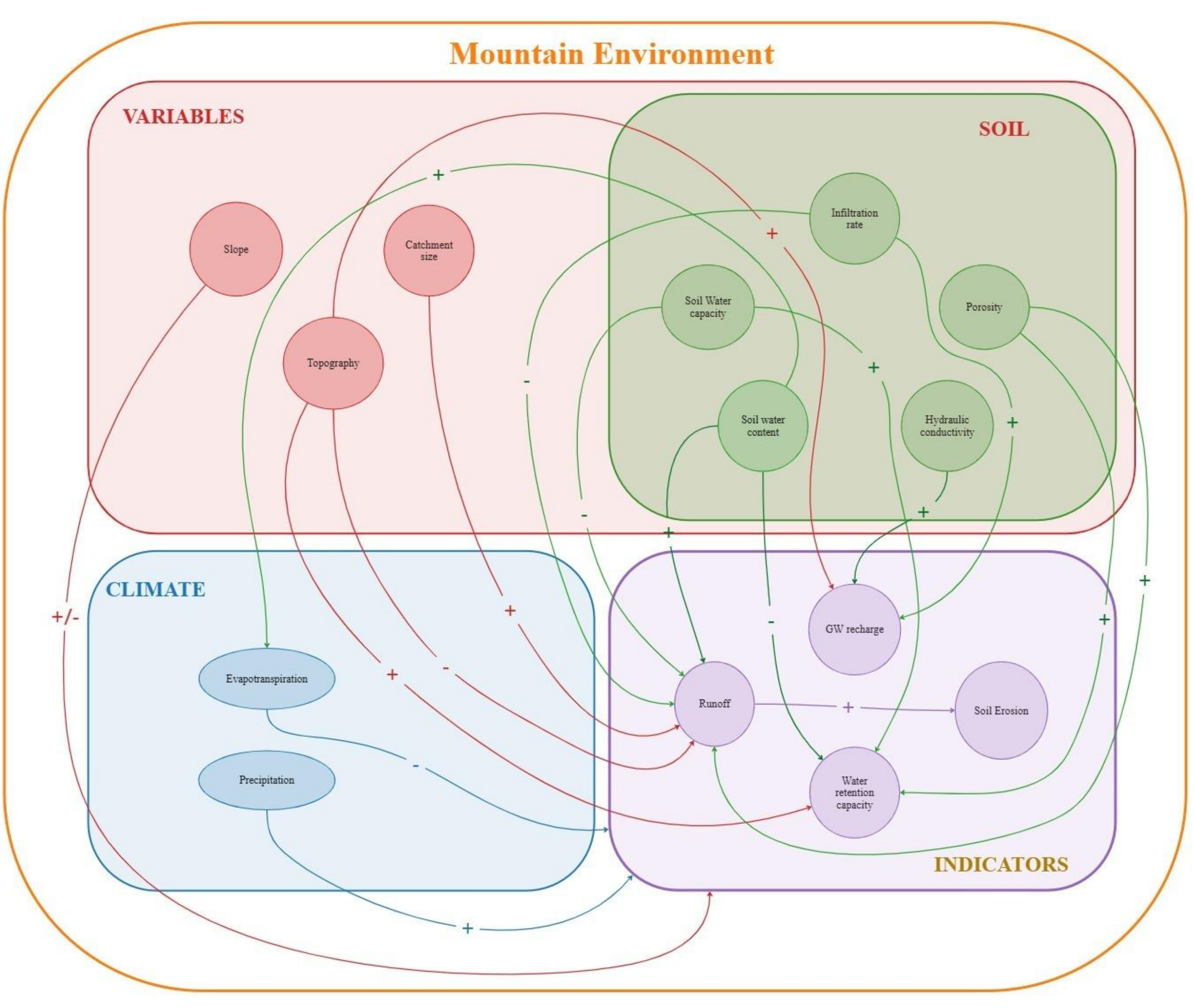

Figure 11: Conceptual map of the key hydrological indicators and conditioning variables for Wetland based NbS in mountain regions. The map illustrates the relationships between major hydrological indicators and the variables that influence them.

For Forest based interventions (Fig. 12), the reviewed studies indicated that most sites were located on relatively steep slopes, although some were located on gentler slopes. This parameter was primarily associated with runoff generation, groundwater recharge, and soil erosion, reflecting its influence on key hydrological processes.

Moreover, two forest-specific variables were found to be particularly relevant for quantifying the performance of hydrological indicators. The ability of the canopy to intercept rainfall is a defining forest characteristic that directly affects the hydrological function of NbS and forest cover.

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Soil properties were generally limited to measurements of hydraulic conductivity, soil water content, and infiltration rate. These are all relevant factors for understanding hydrological processes of runoff, groundwater recharge, and water retention capacity in forested environments.

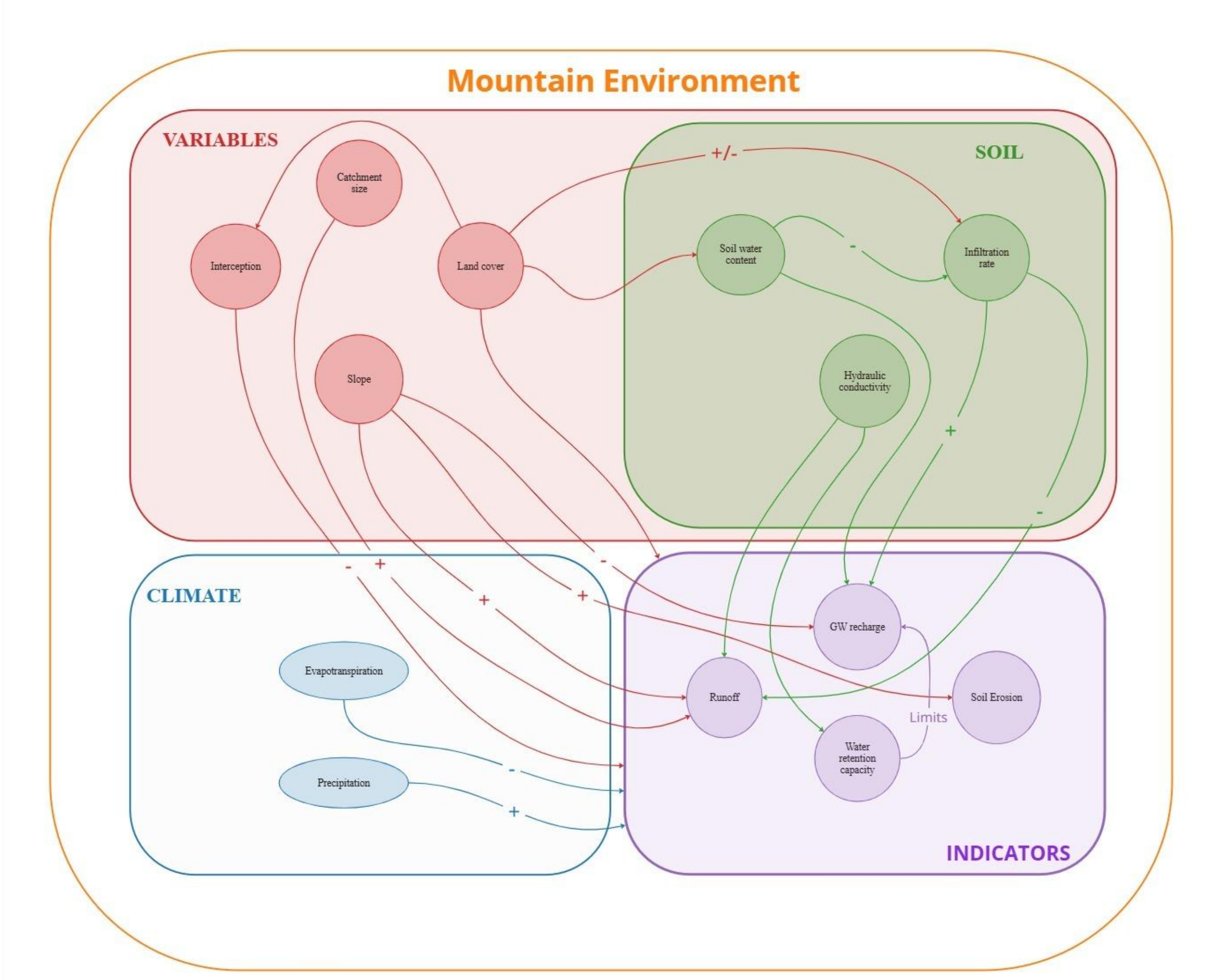

Figure 12: Conceptual map of the key hydrological indicators and conditioning variables for Forest based NbS in mountain regions.

For Water Harvesting interventions (Fig. 13), the interactions with mountain ecosystem parameters reported in the literature were more diverse and complex. This is because the four types of intervention (small reservoirs, diversion canals, terraces, and infiltration trenches) respond differently to site characteristics.

Concerning slope, Diversion Canals were found to be effective in sloping mountain areas with values ranging from 12% to over 50%, favouring water conveyance. Infiltration Trenches were found to function on both gentle and steep slopes. Terraces are designed to manage steepness and have therefore been reported to operate across a wide range of slopes, from as low as 1°

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to over 40°. Information on the slope requirements for small reservoirs was scarce, with only two studies reporting values, one of which indicated slopes of up to 66°.

Small reservoirs were consistently associated with increased water retention capacity, reduced surface runoff and soil erosion, and enhanced infiltration and groundwater recharge in the intervention area. The effects of diversion canals on groundwater recharge were reported to be variable depending on their design and purpose, but they generally contributed to water retention.

Terraces were the most extensively studied Water Harvesting intervention, and the evidence showed that they increased the residence time of rainwater on the land surface, improved infiltration rates and reduced soil erosion. Land cover was identified as a key parameter influencing runoff reduction.

Finally, Infiltration Trenches were reported to be particularly effective in areas with low infiltration capacity as they enhance groundwater recharge and increase infiltration rates. They also contribute to reducing soil erosion and surface runoff. The performance of Infiltration Trenches was also found to be influenced by land cover.

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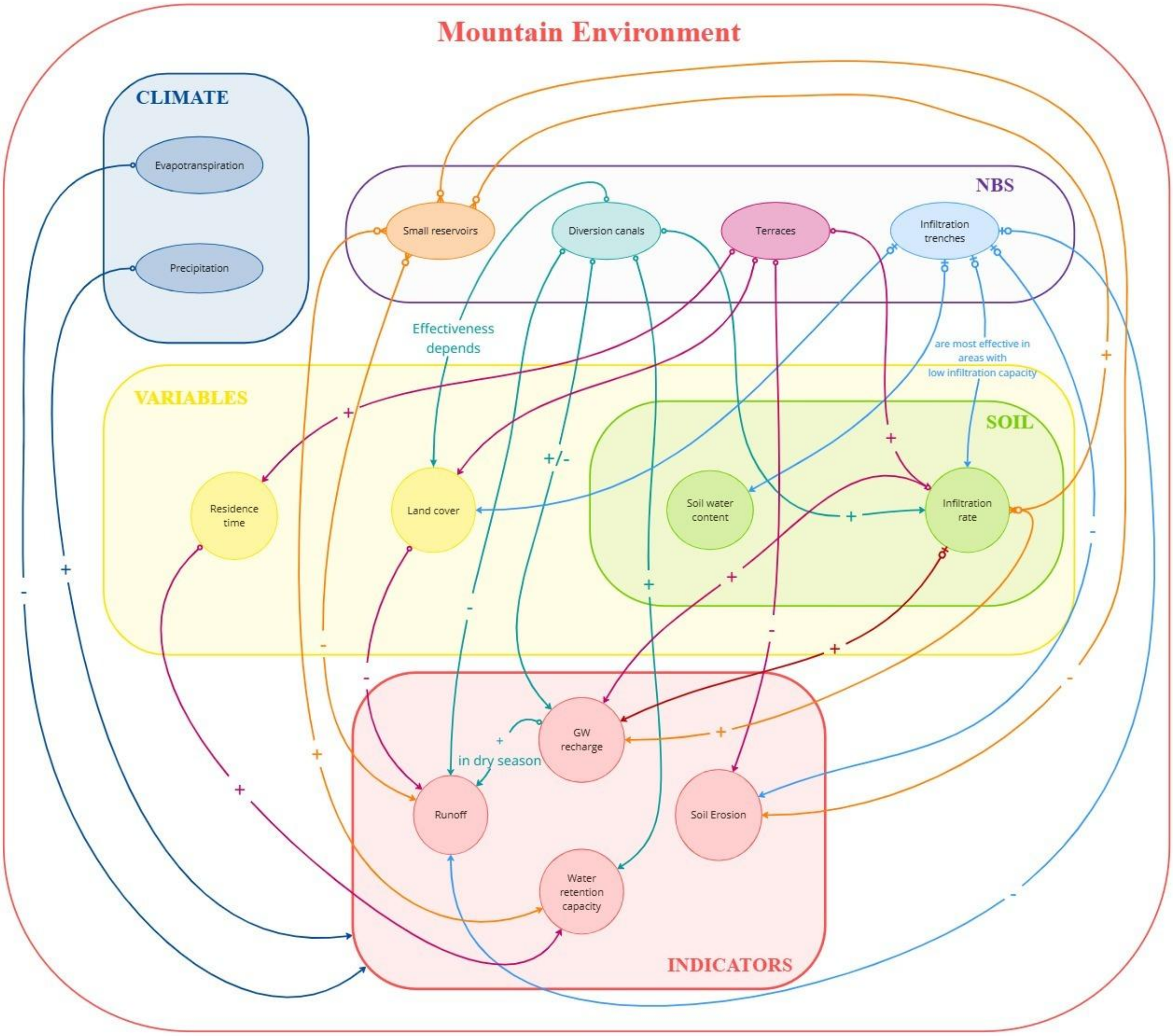

Figure 13: Conceptual map of the key hydrological indicators and conditioning variables for Water Harvesting based NbS in mountain regions.

4.7 Effectiveness of NbS for water security in mountain environments

The reviewed studies were further analysed based on the proposed water security indicators to evaluate the reported effectiveness of each NbS intervention. In this context, 'effectiveness' was defined as an intervention's ability to deliver measurable improvements in the selected indicators. The interventions were categorised by type (Table 1) and their supporting evidence was classified according to the number of available studies and the degree of agreement among their conclusions. The results were then represented using a colour coded scheme to indicate whether each intervention-indicator combination was well supported (consensus), suggested as potentially effective (possible), the subject of conflicting evidence (controversy) or the subject of a knowledge gap due to a lack of sufficient studies (knowledge gap) (Fig. 14).

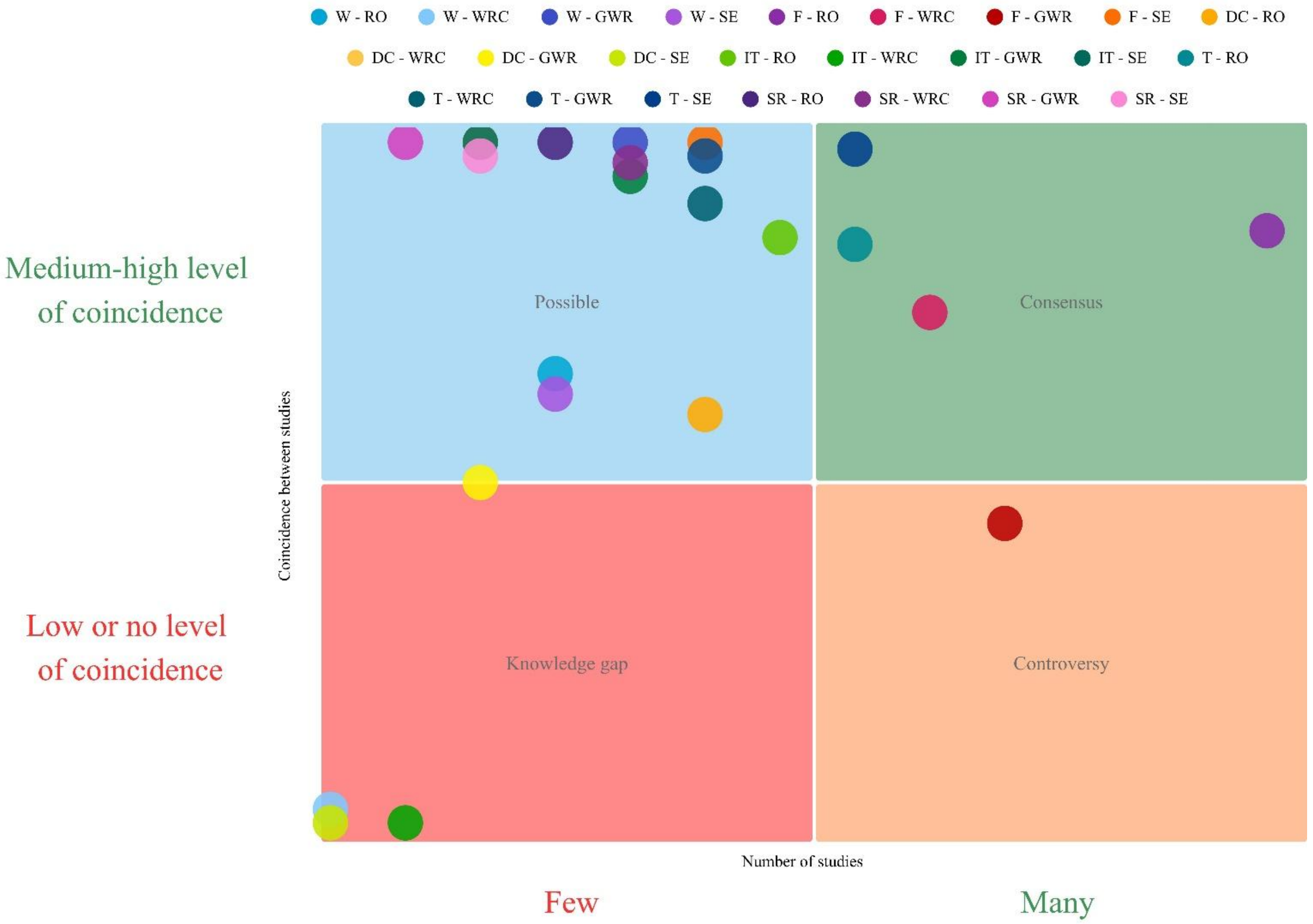

Figure 14: Level of evidence for NbS hydrological effects across all the interventions. The figure shows the level of evidence for key hydrological indicators, such as runoff reduction, increased groundwater recharge, increased water retention capacity and controlled soil erosion, based on the percentage of studies reporting each effect within each NbS intervention. This percentage reflects the "coincidence" of reported effects across studies. Higher percentages indicate that a greater proportion of studies found the same effect, representing stronger evidence. Studies were considered "few" when a given NbS intervention was reported on by six or fewer publications. This approach was adapted from Bonnesoeur et al., (2019).

Wetland related NbS (W) showed 'possible' evidence of reducing runoff (RO), improving groundwater recharge (GWR), and soil erosion control (SE). However, no studies were found that explicitly evaluated the effectiveness of the water retention capacity (WRC) function (knowledge gap).

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Forest interventions (F) had the strongest evidence base, with a consensus that they effectively regulated runoff (RO) and enhanced WRC. However, GWR outcomes were marked as controversial, reflecting inconsistent findings across studies. SE control was classified as 'possible'.

For the Diversion Canals (DC), both GWR and SE were identified as areas of uncertainty, whereas RO and WRC were considered possible. For Infiltration Trenches (IT), RO, GWR and SE were all considered possible, while WRC again represented a knowledge gap.

Terraces (T) were found to be effective in reducing runoff and controlling soil erosion, while GWR and WRC were both classified as possible.

Finally, all four hydrological functions indicators (RO, WRC, GWR and SE) were classified as possible for Small Reservoirs (SR), indicating moderate evidence but no clear consensus regarding their effectiveness due to the few studies found in the review.

Therefore, based on the previous analysis, we were able to identify specific ranges of effectiveness for the hydrological functions where consensus was reached, as evidenced across the reviewed studies. For example, in the reduction of soil erosion in Terraces, a reduction of up to 95% was reported (Llorens et al., 1992). Similarly, in the case of flow regulation, it was found that terraces reduced runoff by between 10% (Guzman et al., 2017; Tiwari et al., 2009) and 25% (Zhan et al., 2011).

There was broad consensus that NbS interventions related to forests or vegetation can enhance WRC, with Šach et al., (2014) reporting values of up to 78% of precipitation retained in forest soils. However, the extent of this effect will depend on vegetation type and other parameters, as mentioned in Section 4.6. Finally, runoff regulation within this category also showed a strong level of consensus across the reviewed studies. Reported effects included reductions in peak discharge ranging from 6 to 14% (Kabeja et al., 2020). In terms of total reduction, outcomes varied considerably, ranging from between 2% (Ghimire et al., 2013) to 90% (Gallay et al., 2021).

It is also important to note that many NbS interventions have been reported as being implemented alongside other interventions. As illustrated in Figure 15, interventions were categorised according to their conditions and combinations. For example, Water Harvesting practices were often reported alongside Wetland based interventions (Baiker et al., 2022; Lane, 2014; Monge-Salazar et al., 2022; Price et al., 2005; Pulido-Bosch et al., 2000). Within the category of Water Harvesting measures, various interlinkages were also observed. Specifically, DC were found to occur alongside SR in studies such as those by Frot & van Wesemael, (2009) and Pulido-Bosch et al., (2000). Similarly, DCs were assessed in connection with IT (Pulido-Bosch et al., 2000). In turn, IT were linked with Terraces in studies such as those by Castelli et al., (2017) and Guzman et al., (2017), while Terraces themselves were reported alongside SR in studies by (Craig et al., (2011); Jiao et al., (2024), and Lane, (2014).

In terms of Forest based interventions, agroforestry was employed alongside Terraces (Jiao et al., 2024b; Zuazo et al., 2011), as well as Terraces and Forest Conservation (Tiwari et al., 2009). Forest Conservation was also found to interact with Wetlands (Cervantes et al., 2021; Sun et al., 2002). Furthermore, all Forest based interventions were shown to be interdependent. For example, Agroforestry was connected to Afforestation (Castelli et al., 2017), while Reforestation (Holden et al., 2022; Kabeja et al., 2020; Kim et al., 2019) and Afforestation (Liang et al., 2023) relied on the Forest Conservation as a foundational measure.

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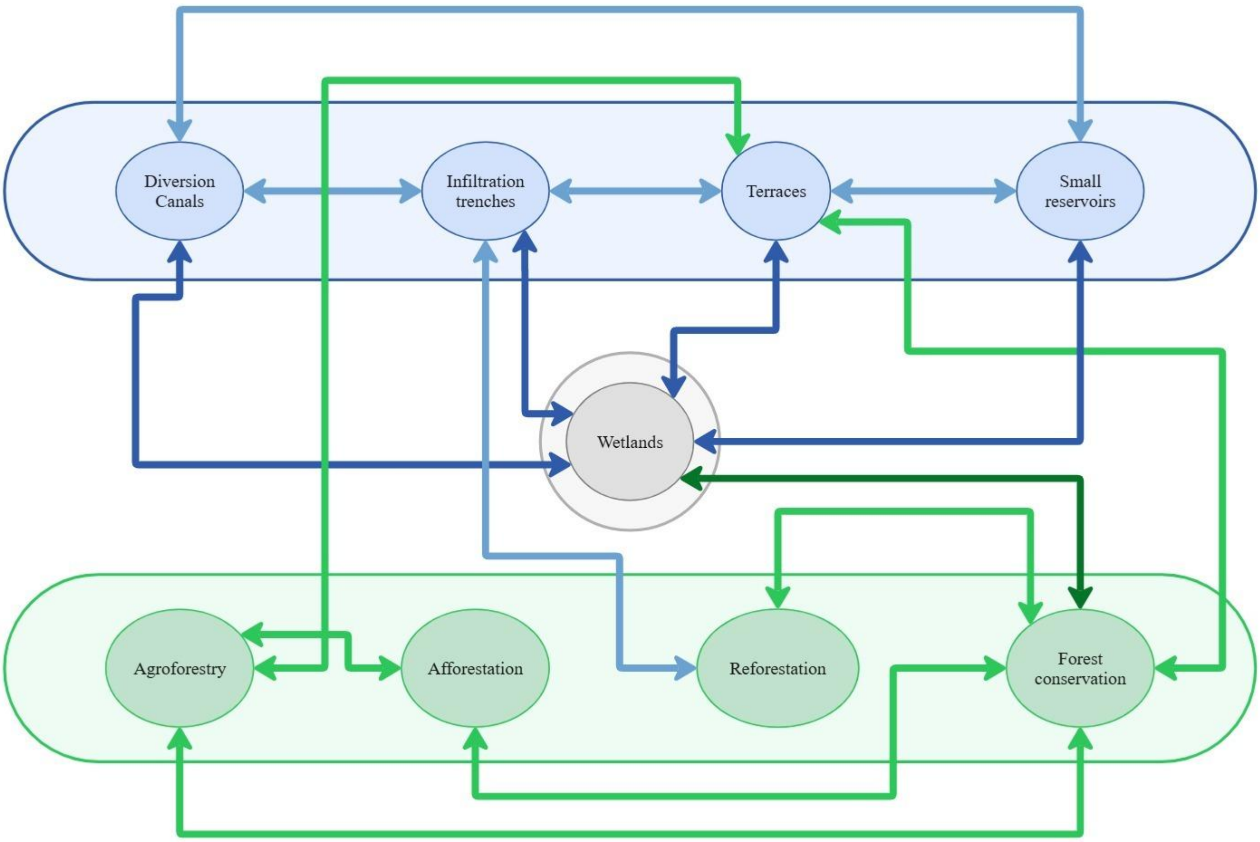

340 **Figure 15: Reported interactions among different NbS interventions in mountain regions. These were identified in the reviewed literature. The arrows highlight the potential synergies among the NbS types in mountain environments, indicating a reported relationship between them.**

5 Discussion

345 ## 5.1 General overview

This study summarises the current scientific knowledge on NbS types related to hydrological functions in mountain regions. Despite the complexity of these interventions and the limited evidence available for such environments, there is a general consensus on key hydrological indicators, including runoff regulation, increased water retention capacity, enhanced groundwater recharge, and controlled soil erosion. However, the limited interconnection among studies suggests that NbS research in mountain regions has largely developed through isolated efforts. Nahlik et al. (2012) also identified this lack of integration as a concern within the field of ecosystem services, citing the absence of a unified conceptual and methodological framework.

Nevertheless, this diversity of approaches reflects the adaptable nature of NbS and the flexible application of the ecosystem services concept, which can be considered a strength due to its capacity to accommodate different contexts and worldviews (Ainscough et al., 2019). However, the conceptualisation of NbS has also been criticised for being vague, with links to existing concepts often being superficial (Nesshöver et al., 2017). This flexibility carries the risk of overlooking opportunities to strengthen natural resource management, as the concept may be overshadowed or subsumed by others (Waylen et al., 2014). In this context, Ainscough et al., (2019) argue that conducting policy related assessments requires the development of standardised classification systems, conceptual frameworks, and related methodologies. However, such standardised practices may also reinforce specific worldviews, thereby sidelining alternative perspectives and limiting discussion of the underlying value assumptions.

It should also be noted that the increase in publications after 2010 reflects the global rise of NbS in political and academic fields (Cohen-Shacham et al., 2016). However, the disproportionately high number of studies conducted in Asia, particularly in China, indicates that research efforts in mountainous regions are not evenly distributed. This regional bias raises concerns about the transferability of findings to underrepresented areas, such as Africa, where mountain hydrology, NbS implementation and socio-economic contexts may differ substantially. This uneven distribution emphasises the importance of comparative studies that consider the regional specifics of mountain hydrological systems while following standardised methodological guidelines (Ainscough et al., 2019; Nesshöver et al., 2017) to ensure analyses remain comparable without constraining local variability. Furthermore, the high concentration of earlier studies focusing on Wetlands reflects the historical importance of this type of intervention. By contrast, more recent research exploring a broader range of NbS has not yet achieved a comparable level of influence. This imbalance highlights potential knowledge gaps in the literature. For instance, despite having been extensively studied in relation to its functions in other environments (Janzen et al., 2024; Mbow et al., 2014), the role of Agroforestry in mountain regions with regard to water security remains under researched. These gaps highlight the importance of expanding the research portfolio beyond Wetland approaches, in order to enable a more comprehensive understanding of the effectiveness of NbS with regard to hydrology.

Finally, distinguishing between interventions motivated by ecosystem restoration and those primarily intended to benefit humans highlights the diverse rationales underpinning the implementation of NbS and its conceptual framework. This can be understood through the lens of the human–nature dichotomy (Welden et al., 2021). It raises a fundamental question: does nature have intrinsic value and merit understanding within a horizontal human–nature relationship, or is the NbS framework essentially anthropocentric, valuing ecosystems only when they provide humans with tangible benefits? Further analysis revealed that interventions such as Afforestation and Agroforestry were predominantly classified as human-oriented, whereas Wetland interventions were more often associated with ecosystem restoration. This suggests a divergence in how different types of intervention are conceptualised.

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However, this interpretation should be approached with caution. Many of the reviewed studies did not explicitly adopt an NbS framework; rather, they were classified as NbS during the screening process based on the type of intervention analysed. Consequently, ecosystem restoration efforts may be overrepresented under the NbS terminology. Additionally, the predominance of biophysical and properties analyses limits our understanding of whether NbS are primarily designed for human utility or ecological restoration. This underscores the need to clarify whether NbS are primarily implemented for ecological restoration, socio economic benefits, or both, an issue that directly influences their design, implementation, and long-term sustainability. In addition, the substantial number of studies that fail to report the initial state of ecosystems or specify the purpose of the intervention reflects a methodological limitation that constrains rigorous assessment of NbS effectiveness.

5.2 ES cascade approach

The uneven distribution reflects a dominant research orientation that prioritises biophysical processes while overlooking socio economic dimensions. This pattern aligns with the findings of Boerema et al., (2017), who noted that ecosystem services (ES) are often not adequately quantified. They argued that at least two complementary measures are required when assessing ES: one to capture ecosystem functions (the supply side), and another to reflect the benefits to humans (the demand side). Therefore, this study highlights the importance of methodologies that integrate both dimensions of the ES cascade in order to improve the quality and comprehensiveness of assessments of NbS mountain areas regarding water security.

5.3 Indigenous or/and local knowledge

Many non-Western cultures hold a worldview in which nature and humanity are understood as interdependent and inseparable, existing within a horizontal and integrated relationship (Welden et al., 2021). Such perspectives are characteristic of many Indigenous and rural communities inhabiting mountain regions. However, the traditional practices of these communities are under significant threat from multiple pressures, including climate change, increased competition for water from more powerful users, the introduction of commercial crops and associated agrochemicals, tourism, urbanisation, deforestation, and global market forces. These dynamics drive migration and endanger the continuation of traditional practices, along with the transmission of the knowledge and values that sustain them (Cassin & Ochoa-Tocachi, 2021).

The potential loss of traditional knowledge could also weaken citizen participation in water management, reducing the capacity of local communities to contribute actively to water governance. The findings of this review show that the majority of studies did not explicitly incorporate community participation or traditional knowledge. However, this gap also presents an opportunity: as society seeks resilient and sustainable solutions, it becomes increasingly important to recognise and integrate the perspectives and horizontal worldviews of local communities to strengthen collective action. Community-led initiatives that use traditional NbS solutions to protect resources through collective action can generate benefits that extend beyond the local scale (Cassin & Ochoa-Tocachi, 2021). Given the limited attention currently given to community participation and traditional knowledge in research, standardising methodologies for assessing NbS in mountain areas, where communities often face greater water security challenges, could be a key tool for increasing both scientific output and social inclusion in water resource management.

5.4 Climate change analysis

Although a larger number of studies address climate change and NbS in relation to Wetlands and Afforestation, a substantial gap remains between these and the total number of analysed studies. The limited inclusion of future climate scenarios may prevent NbS research from effectively informing adaptive water management strategies in mountain regions. This is of particular concern in mountain regions, where changes in the hydrology, the environment, and their impact on society, require climate considerations to be integrated into NbS assessments. This methodological limitation highlights the need for more diverse and forward looking research that incorporates climate change into larger NbS interventions more frequently.

5.5 Assessment of NbS (Scale – models)

The results reveal that NbS research is more prevalent at local scales than at regional levels. Although Wetland interventions encompassed a broader range of spatial analyses, studies at the regional level were still scarce. A similar pattern was observed for Agroforestry, Afforestation, and Reforestation, which were predominantly studied at local and medium scales. The same pattern emerged for Water Harvesting interventions. The absence of multiscale analyses restricts our ability to evaluate NbS effectiveness, hydrological impacts and their interactions with broader socio-ecological systems. While local-scale studies are fundamental for understanding site-specific dynamics and performance differences across NbS types, larger-scale assessments are necessary to capture natural processes interactions and how they change over time (Ruangpan et al., 2020).

In terms of methodological approaches, the review reveals a strong focus on hydrological modelling and experimental methods. Only a small number of studies combined three or more methods, indicating that methodological integration remains limited. This pattern may reflect researchers' preference for methods with proven versatility and effectiveness in NbS assessments. For Wetland interventions, in situ evaluations were the most frequently employed approach. For Forest based interventions, hydrological modelling was the preferred method, though in situ data collection was also widely used. In both cases, around 28% of studies combined modelling and field methods. Finally, experimental approaches dominated for Water Harvesting interventions, which may be linked to the practical and site-specific nature of these systems, and the complexity of adequately representing them in hydrological models.

These findings underscore the need to address methodological gaps to support more robust, scalable and transferable NbS assessments, particularly in mountain regions. They also highlight the main methodologies that can be applied to research specific interventions.

5.6 Effectiveness of NbS

The effectiveness of NbS varies considerably depending on their purpose of implementation, the biophysical characteristics of the site and the socio-ecological context in which they are applied (Ruangpan et al., 2020). Despite this variability, the results of this review demonstrate a consistent pattern among NbS types, while also highlighting significant methodological gaps. Overall, Forest based interventions have relatively consistent hydrological effects, particularly about flow regulation and erosion control. This aligns with the findings of Bonnesoeur et al., (2019). However, the limited assessment of other hydrological indicators, similarly observed in Wetlands based interventions, reveals an absence of standardised methodologies for comprehensively evaluating NbS performance. Similarly, Water Harvesting interventions show mixed results, indicating persistent knowledge gaps regarding their influence on hydrological regulation and subsurface flow processes (Locatelli et al., 2020). This methodological and thematic heterogeneity restricts cross context comparison and limits the scalability of results. Several patterns emerge when comparing NbS types and mountain contexts. Forest based NbS are more effective at regulating surface runoff and reducing peak flows, in a manner similar to water harvesting practices implemented on steep mountain slopes. In contrast, although they are less studied, Wetland based NbS demonstrate greater effectiveness in arid and semi-arid mountain regions, where their lower antecedent soil moisture enhances their capacity to retain and infiltrate precipitation. Water harvesting interventions, which are usually found on steeper slopes, play a more significant role in controlling soil erosion compared to wetlands, which are generally located in gentler terrain and for which there is limited evidence regarding sediment regulation.

In terms of groundwater recharge, afforestation was found to have a negative impact in several cases, particularly when exotic species such as eucalyptus were involved. Conversely, reforestation using native species was associated with improved recharge groundwater. The common assumption that wetlands enhance groundwater recharge was supported by only a few studies, specifically those conducted in North America and the Central Andes. This suggests that evidence of this relationship is currently limited to specific geographical areas and is not yet generalisable.

Finally, Forest based interventions consistently outperformed others in terms of interception processes, highlighting the importance of canopy structure and vegetation type in influencing hydrological dynamics. Regardless of humidity conditions, both forest and water harvesting interventions demonstrated robustness in regulating runoff and erosion across climatic gradients, suggesting their potential for application in diverse mountain climates.

To address the current gaps, future studies should adopt more robust, standardised methodological approaches that account for the multiscale nature, and hydrological complexity of mountain environments. Integrating broader, comparable indicators would strengthen the basis for evaluating the effectiveness of NbS by type and context, ultimately supporting their incorporation into adaptive water resource management strategies.

6 Conclusions

This paper provides a critical scoping review of the literature on NbS for ensuring water security in mountain regions. It identifies future research directions based on current knowledge gaps. The review highlights several key deficiencies, including the limited incorporation of climate change scenarios in evaluations, the lack of basin-scale studies assessing NbS performance, and the insufficient integration of local and traditional knowledge.

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With respect to ecosystem services, we call for the development and testing of indicators that capture the components of the ES cascade, encompassing both ecosystem functions and human benefits, as recommended by Ainscough et al., (2019). These indicators should be incorporated into future methodologies for evaluating NbS in mountainous contexts to improve the consistency and comparability of assessments.

Standardising methodologies that address these gaps is essential for advancing NbS research and enhancing the resilience of water resources in mountain regions. The first step towards this goal is identifying indicators of hydrological functions. The literature suggested that NbS interventions have impact on flow regulation, groundwater recharge, water retention capacity, and soil erosion control. Future research should initially focus on quantifying these indicators within a robust methodological framework and subsequently integrate social and economic indicators to capture the full range of benefits provided by NbS more effectively.

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7 Appendices

7.1 Appendix A

Table A. 1: Studies organised by ecological dimension of the ES Cascade

Ecosystem Properties	Ecosystem Functions	Ecosystem Services	Benefits	Value	Not defined
22	41	12		2	8
(Andreo et al., 2016); (Chen et al., 2016); (Cooper et al., 2015); (Craig et al., 2011); (Li et al., 2014); (Mapeshoane & van Huyssteen, 2016); (Martínez-Retureta et al., 2022); (Otto & Gibbons, 2017); (Paronuzzi & Bolla, 2023); (Rudolph et al., 2007); (Shao et al., 2022); (Shih & Hsu, 2021); (Shih & Lee, 2023); (Soomro et al., 2022); (Sun et al., 2002); (Thompson et al., 2012); (Wang et al., 2024); (Wang et al., 2022); (Wang et al., 2012); (Xu et al., 2009); (Yair, 1983); (Yang et al., 2023)	(Ahmad et al., 2020); (Buendia et al., 2016); (Cao et al., 2020); (Carlson et al., 2020); (Carlson Mazur et al., 2014); (Denu et al., 2016); (Dwire et al., 2018); (Frei et al., 2010); (Frot & van Wesemael, 2009); (Gallart et al., 1994); (Ghimire et al., 2013); (Guyassa et al., 2017); (Guzman et al., 2017); (Herath et al., 2015); (Holden et al., 2022); (Hrabovský et al., 2020); (Huang et al., 2024); (Jódar et al., 2022); (Kabeja et al., 2020); (LaFevor & Ramos-Scharrón, 2021); (Leguizamon & Marín, 2017); (Li & Shi, 2015); (Li et al., 2013); (Li et al., 2023); (Li & Gao, 2019); (Liu et al., 2022); (Llorens et al., 1992); (Martínez-Retureta et al., 2020); (Molina et al., 2009); (Mosquera et al., 2015); (Ochoa-Tocachi et al., 2019); (Piégay et al., 2004); (Pitchford et al., 2012); (Šach et al., 2014); (Scheliga et al., 2019); (Somers et al., 2018); (Tiwari et al., 2009); (Wei et al., 2024); (Zhan et al., 2011); (Zhao et al., 2023); (Zuazo et al., 2011)	(Baiker et al., 2022); (Castelli et al., 2017); (Castelli et al., 2017); (Cervantes et al., 2021); (Esquivel et al., 2020); (Gao & Yu, 2017); (Kim et al., 2019);(Liang et al., 2023); (Monge-Salazar et al., 2022); (Rodríguez-Echeverry et al., 2018); (vonHedemann, 2023); (Wang et al., 2023)		(Gallay et al., 2021); (Jiao et al., 2024)	(Beckers et al., 2013); (Bruins et al., 2020); (Cottet et al., 2013); (Lane, 2014); (Locatelli et al., 2020); (Pereira, 1967); (Price et al., 2005); (Pulido-Bosch et al., 2000)

Author contributions

Fernández Velarde, Michell Andree: Conceptualization, Data curation, Formal analysis, Funding acquisition, Investigation, Methodology, Validation, Visualization, Writing – original draft. **Cools, Jan:** Conceptualization, Funding acquisition, Methodology, Project administration, Supervision, Validation, Writing – review & editing. **Staes, Jan:** Conceptualization, Funding acquisition, Methodology, Project administration, Supervision, Validation, Writing – review & editing. **Yepez, Santiago:** Supervision, Validation, Writing – review & editing.

Competing interests

The authors declare that they have no conflict of interests.

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