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Exploring the Hydrological Functions and Effectiveness of Nature-based Solutions in Mountain Environments: Evidence, Indicators, and Comparability

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Abstract. Mountain regions play a vital role in providing water resources, yet their hydrological systems are under threat from by climate change, land-use change, and socio-economic pressures. Although Nature-based solutions (NbS) are increasingly being considered as a means of ensuring water security, evidence of their hydrological performance in mountain environments is inconsistent and limited. This study presents a critical scoping review of the evidence on the hydrological functions of NbS in mountain regions, examining how reported hydrological effects can inform their contribution to water security objectives. A total of 106 studies were identified and classified into three groups: forest-based interventions, wetlands, and water harvesting. The four most frequently assessed hydrological functions were flow regulation, water retention, groundwater recharge, and soil erosion control. The evidence was unevenly distributed geographically, with studies concentrated in a limited number of countries. Forest-based interventions showed relatively consistent evidence for flow regulation, whereas evidence for groundwater recharge was more variable. Wetland studies reported effects on flow regulation and water retention, but these varied between sites and assessment approaches. Water harvesting interventions, particularly terraces and infiltration trenches, were frequently linked with runoff reduction and soil erosion control. However, their evidence base was predominantly local in scale and less extensive for several hydrological functions. The reported effect ranges varied within the NbS groups, highlighting the context-dependent nature of their performance and limiting the possibility of direct comparisons between cases. Overall, the review identified recurrent hydrological functions and conditioning factors relevant to mountain NbS, while highlighting important gaps in baseline conditions, methodological assessment, and spatial coverage. These findings establish a foundation for improving the assessment of hydrological evidence in mountain regions and for developing frameworks that demonstrate the contribution of NbS to water security.

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1 Introduction

Mountain environments are ecosystems vulnerable to natural hazards, climate extremes, and changes in land use. These stressors can alter the way in which ecosystems and hydrological processes function, affecting water availability and directly impacting the water security of populations that depend on mountain ecosystems (Adler, et al., 2022; Schmeller et al., 2022; FAO & UNEP, 2023).

NbS and ecosystem-based adaptation have emerged as promising approaches for addressing environmental and hydrological challenges. NbS have the potential to support water management by maintaining, restoring, or sustainably managing ecosystems and their associated services (Cohen-Shacham et al., 2016; Lalonde et al., 2024). However, despite growing interest, evidence on their hydrological performance in mountain environments remains limited across intervention types and environmental conditions. Previous reviews have acknowledged that the hydrological effects of NbS can vary according to the characteristics, location and design of the intervention (Ruangpan et al., 2020; Lalonde et al., 2024). However, they have not examined how consistently the reported evidence supports NbS performance across studies that differ in indicators, methods, scales, or climate change analysis.

The aim of this article is to conduct a critical scoping review of the scientific literature on the relationship between NbS and hydrological functions, with a focus on the comparability in reported effects on NbS performance across mountain environments. More specifically, we identify the current state of knowledge and the comparability of the hydrological evidence. We also highlight methodological gaps, and propose a minimum set of reporting information to strengthen future assessments. The analysis examines four recurrent hydrological functions: flow regulation, water retention, groundwater recharge, and soil erosion control, across three main groups of NbS interventions: forest-based interventions, wetlands, and water harvesting. This categorization follows the NbS approach presented by World Water Assessment Program (WWAP) (2018), while recognizing that other types of NbS may also be relevant in mountain environments.

2 Nature-based Solutions definition

The concept of NbS is widely applied in scientific and policy contexts, yet its definition varies among organizations. The International Union of Conservation of Nature defines NbS as “actions to protect, sustainably manage, and restore natural or modified ecosystems, that effectively and adaptively address societal challenges while simultaneously providing human well-being and biodiversity benefits” (Cohen-Shacham et al., 2016). The European Commission (EC) has provided a complementary definition, describing NbS as “actions inspired by, supported by, or copied from nature in order to achieve desired outcomes such as reduced disaster risk, improved human well-being, and socially inclusive green growth” (European Commission: Directorate-General for Research and Innovation, 2015). The Organisation for Economic Cooperation and Development (OECD) defines NbS as “measures that protect, sustainably manage or restore nature, with the goal of maintaining or enhancing ecosystem services in order to address a variety of social, environmental, and economic challenges” (OECD, 2020). For the purpose of this review, the OECD definition is adopted as the conceptual basis for identifying NbS, as

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it combines the two aforementioned definitions by connecting the protection, sustainable management and restoration of ecosystems with the provision of ecosystem services, as well as the addressing of environmental, economic, and societal challenges.

As this study focuses on the hydrological functions and effectiveness of NbS in mountain environments, the broad concept was narrowed to intervention types for which the reviewed literature could assess hydrological processes, functions, and outcomes. To structure the scope, we adopted the classification by the WWAP (2018), which identifies green infrastructure solutions at the catchment scale related to water supply regulation, including drought mitigation, erosion control, and moderation of extreme events. Within this framework, three intervention groups represented in the reviewed literature were considered: (i) re/afforestation and forest conservation; (ii) wetlands restoration and conservation; and (iii) water harvesting. Within the water harvesting category, four specific infrastructure types were considered: (i) small reservoirs; (ii) diversion canals; (iii) infiltration trenches; and (iv) terraces. Here, water harvesting is understood as the construction or modification of landscape features that interact with natural elements to improve water-related ecosystem services (Lalonde et al., 2024). These intervention groups do not represent a single hydrological function. Rather, depending on environmental and hydrological conditions, each may influence multiple hydrological functions. Accordingly, the analysis distinguishes between intervention types, hydrological functions, the indicators used to evaluate their effectiveness, and methods or tools used to assess them. This distinction provides the basis for examining evidence from different mountain environments and assessing the comparability of hydrological indicators and evaluation approaches.

3 Methodology

Following the PRISMA Extension for Scoping Reviews (PRISMA-ScR) guidelines (Tricco et al., 2018), the review provided a structured framework for identifying, screening, and reporting the literature.

The search strategy combined three components: (i) terms describing NbS interventions and their synonyms; (ii) terms describing hydrological processes, functions, and indicators; and (iii) terms identifying mountain environments. Three bibliographic databases were searched to identify potentially relevant documents: SCOPUS, Web of Science, and PubMed, using the search string in Table 1. The search strategy was developed to include studies that used the term “NbS”; as well as earlier studies that examined these interventions before the term became widely used, in order to avoid restricting the review to publications that adopted the terminology retrospectively. The search was restricted to intervention and hydrological terms in the title field only. This ensured that the retrieved studies focused centrally on the intervention and its hydrological assessment rather than merely mentioning them in passing in the abstract. While a title-based restriction increases precision, it may also exclude relevant studies in which the intervention is described in the abstract or keywords, but not the title. To mitigate this risk, we supplemented the database search by screening the reference lists of the included studies and conducting targeted Google Scholar searches applying the same eligibility criteria.

Table 1: Search string and number of studies found per search

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Database	Search string	Studies
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) OR TITLE ("soil erosion*")) 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*))	181
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) OR TI=("soil erosion*")) 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*))	136

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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]) OR ("soil erosion*")) AND ((mountain*[Title/Abstract]) OR (cordillera*[Title/Abstract]) OR (alpine[Title/Abstract]) OR (alps[Title/Abstract]) OR (sierra[Title/Abstract]) OR (highland*[Title/Abstract]))	23

The initial database searches identified 339 records, published in English and Spanish. The database search was supplemented by screening the reference lists of relevant studies, as well as targeted Google Scholar searches using combinations of terms related to mountain environments, NbS interventions, and hydrological functions. Following the removal of duplicates (240), screening of titles and abstracts, and assessment of the full texts, 106 documents met the predefined eligibility criteria and were retained for the synthesis. As individual studies could evaluate more than one intervention, they were assigned to all relevant NbS categories rather than being treated as different groups (Table 2). Consequently, the synthesis may report more specific records than the total number of unique studies included in the review.

Studies were included if they: (i) were peer-reviewed empirical studies, reviews, or modelling studies; (ii) assessed one or more predefined NbS interventions in accordance with the definition established in Chapter 2; (iii) were conducted in a mountain region or high plateau; (iv) measured, modelled, or discussed at least one hydrological process, function, or indicator relevant to the water cycle; and (v) were available in English or Spanish. For the purposes of this review, the concept of a mountain environment was adopted from (Kapos et al., 2000), who defined them based on elevation and terrain ruggedness.

Studies were excluded when they: (i) focused on non-hydrological ecosystem services without hydrological assessment; (ii) assessed grey infrastructure or conventional engineering interventions without NbS component; (iii) were conducted in lowland, coastal, or urban environments without a direct connection to mountain ecosystem; and (iv) were published in languages other than English or Spanish. While this enabled a consistent review across the selected sources, it may have introduced geographical and linguistic bias, as relevant studies in other languages were not considered.

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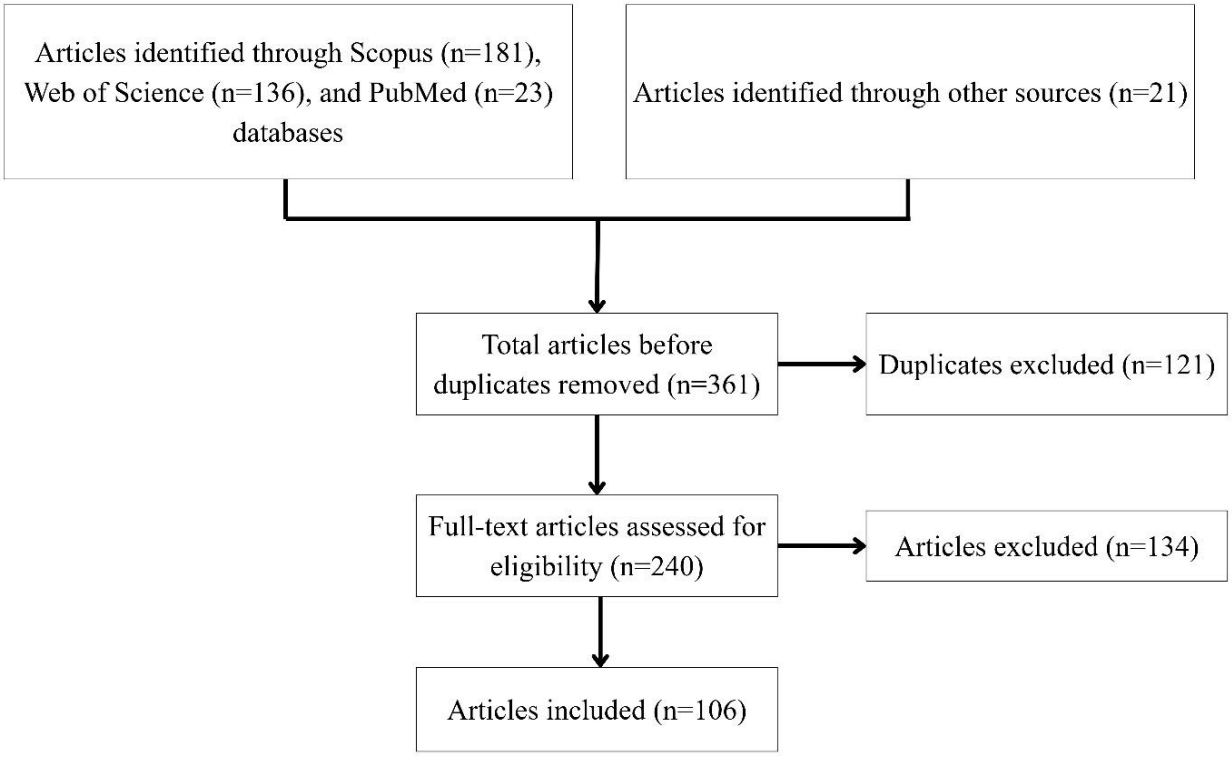


Figure 1: Flow chart of article screening based on the PRISMA-ScR methodology. The figure illustrates the selection process for the studies included in this review, as defined by the eligibility criteria.

Table 2: Overview of NbS for water intervention types

NbS types	Solutions	Studies
Re/afforestation and forest conservation	Afforestation	Buendia et al., 2016; Castelli et al., 2017a; 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: Martínez-Retureta et al., 2022; Pereira, 1967; Piégay et al., 2004; Rodríguez-Echeverry et al., 2018; Sisay, 2026
	Agroforestry	Castelli et al., 2017a; Jiao et al., 2024; Zuazo et al., 2011
	Reforestation	Fernández Velarde et al., 2026; Gao & Yu, 2017; Ghimire et al., 2013; Holden et al., 2022; Huang et al., 2018; Kabeja et al., 2020; Kim et al., 2019; Kim & Arnhold, 2018;

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NbS types	Solutions	Studies
		Molina et al., 2009; Rebelo et al., 2025; Vázquez-Ríos et al., 2025
	Forest Conservation	Cervantes et al., 2021; Holden et al., 2022; Kim et al., 2019; Liang et al., 2023; Meliho et al., 2021; Portalanza et al., 2025; Šach et al., 2014; Sun et al., 2002; Tiwari et al., 2009; vonHedemann, 2023; Wang et al., 2023; Yin et al., 2022
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; Chau et al., 2026; Cooper et al., 2015; Cottet et al., 2013; Dwire et al., 2018; Frei et al., 2010; Leguizamon & Marín, 2017; Li et al., 2014; Li et al., 2013; Li & Shi, 2015; Mapeshoane & van Huyssteen, 2016; Marti et al., 2025; 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; Seo et al., 2025; Shao et al., 2022; Shih & Hsu, 2021; Shih & Lee, 2023; Sun et al., 2002; Thompson et al., 2012; Wang et al., 2022; Wang et al., 2012; Xu et al., 2009; Yang et al., 2023
Water harvesting	Small reservoirs	Craig et al., 2011; Guyassa et al., 2017; Henchiri et al., 2026; Jiao et al., 2024; Lane, 2014; Soomro et al., 2022
	Diversion canals	Alcón et al., 2026; 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., 2017b; Guzman et al., 2017; Kagabo et al., 2013; LaFevor & Ramos-Scharrón, 2021; Li & Gao, 2019; Locatelli et al., 2020; Somers et al., 2018

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NbS types	Solutions	Studies
	Terraces	Beckers et al., 2013; Bruins et al., 2020; Camera et al., 2018; Castelli et al., 2017b; Chidi et al., 2022; Gallart et al., 1994; Guzman et al., 2017; Herath et al., 2015; Houshia et al., 2022; Huang et al., 2024; Jiao et al., 2024; Kagabo et al., 2013; Liu et al., 2022; X. Liu et al., 2021; Llorens et al., 1992; Meliho et al., 2021; Paronuzzi & Bolla, 2023; Rutebuka et al., 2021; Su et al., 2016; Subhatu et al., 2018; Tiwari et al., 2009; Wang et al., 2024; Wei et al., 2024; Zhan et al., 2011; Zhang et al., 2014; Zhao et al., 2023

The following information was recorded: (i) bibliographic information (authors, publication year and journal); (ii) geographical information (country, region and continent); (iii) NbS intervention type; (iv) spatial scale of the study, and where reported, the area of the intervention and/or study catchment; (v) hydrological functions assessed; (vi) hydrological indicators used to quantify these functions where applicable; (vii) methodological approach used for assessment (field observations, experiments, hydrological modelling, remote sensing, statistical analysis, or combinations); and (viii) additional contextual variables or information to support the interpretation of hydrological responses or functions.

Methodological comparability was assessed by analysing whether studies evaluating the same hydrological function employed comparable indicators, measurement approaches, and spatial scales. The aim was not to identify a single, universally applicable indicator or methodological approach, but rather to determine which indicators and approaches appear frequently in the literature and could form the basis of more comparable assessment frameworks in mountain environments depending on the type of intervention, or to address research gaps. Therefore, the evidence was organised according to their positive or negative relationship towards their effectiveness. The evidence was classified as positive (+) effect if it can increase or strengthen the hydrological response. For instance, a positive effect on flow regulation was indicated by a (+), meaning a reduction in a process linked to runoff. A negative effect (−) if the relationship was inverse. If the study did not specify an effect, but provided information about the role of the NbS intervention in relation to the hydrological function, it was also reported. The same applies to the functions of water retention, groundwater recharge and soil erosion control.

Evidence for each hydrological function was also classified into four categories based on the direction and consistency of the reported effects: (i) Consensus, the majority of the studies reported an agreement of the hydrological function with limited conflicting results; (ii) Possible, effects were reported in a consistent direction, but by a limited number of studies, (iii) Controversy, studies reported limited agreement of the “positive” hydrological function effects; and (iv) Knowledge gap, insufficient studies were available to assess the function and limited agreement. This classification was built from the approach of Bonnesoeur et al., (2019). Studies were considered few if the combination was represented by 13 or fewer publications. It is important to note that these categories described the direction and consistency qualitatively. To visualise this classification,

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we plotted each combination of NbS intervention and hydrological function on a two-axis graph. The x-axis showed the total number of studies reporting a hydrological effect for each intervention and function. The scale was set according to the largest body of research (forest-based interventions) to represent the full range of the evidence base. The y-axis showed the level of agreement among the studies, expressed as a percentage. This was calculated by dividing the number of studies reporting a "positive" effect by the total number of studies assessing that combination. Agreement was considered high when more than half of the studies reported a "positive" effect. Quadrants were therefore defined by two thresholds: 13 studies (x-axis) and 50% agreement (y-axis). Combinations with ≥13 studies and >50% agreement were classified as "consensus"; combinations with ≥13 studies and ≤50% agreement as "controversy"; combinations with <13 studies and >50% agreement as "possible; and combinations with <13 studies and ≤50% agreement as "knowledge gap". Reported effect sizes were therefore presented as a range across studies and should be interpreted as an indication rather than a quantitative estimate of expected performance.

4 Results

4.1 Evidence base and geographical distribution

The 106 selected studies covered three main NbS groups: forest-based interventions, wetlands, and water harvesting. Of these, 36 studies from 18 countries evaluated forest interventions, 36 studies from 16 countries evaluated wetland interventions, and 42 studies from 17 countries evaluated water harvesting interventions (Table 3). The number of studies reported by intervention type should be interpreted as observations of interventions rather than as independent publications. This is because individual studies may assess more than one intervention and more than one hydrological function. Consequently, the total number of studies across intervention groups exceeds the number of unique studies included in the review.

Table 3: Distribution of selected studies according to NbS intervention

NbS intervention	Number of studies	Number of countries	Most represented countries
Forest	36	18	China (8); Chile (4)
Wetlands	36	16	China (9); USA (6); Peru (4)
Water harvesting	42	17	China (9); Peru (6); Spain (6)

The geographical distribution of the evidence was uneven across interventions. Studies on forest interventions were most frequently conducted in China (8) and Chile (4), while studies on wetlands were mostly conducted in China (9), the USA (6), and Peru (4). A similar pattern emerged in studies on water harvesting interventions, with China (9), Peru (6), and Spain (6) accounting for a substantial portion of the available evidence. Although the reviewed evidence covered a broad geographical range, a significant proportion of the studies were concentrated in just a few countries (Figure 2).

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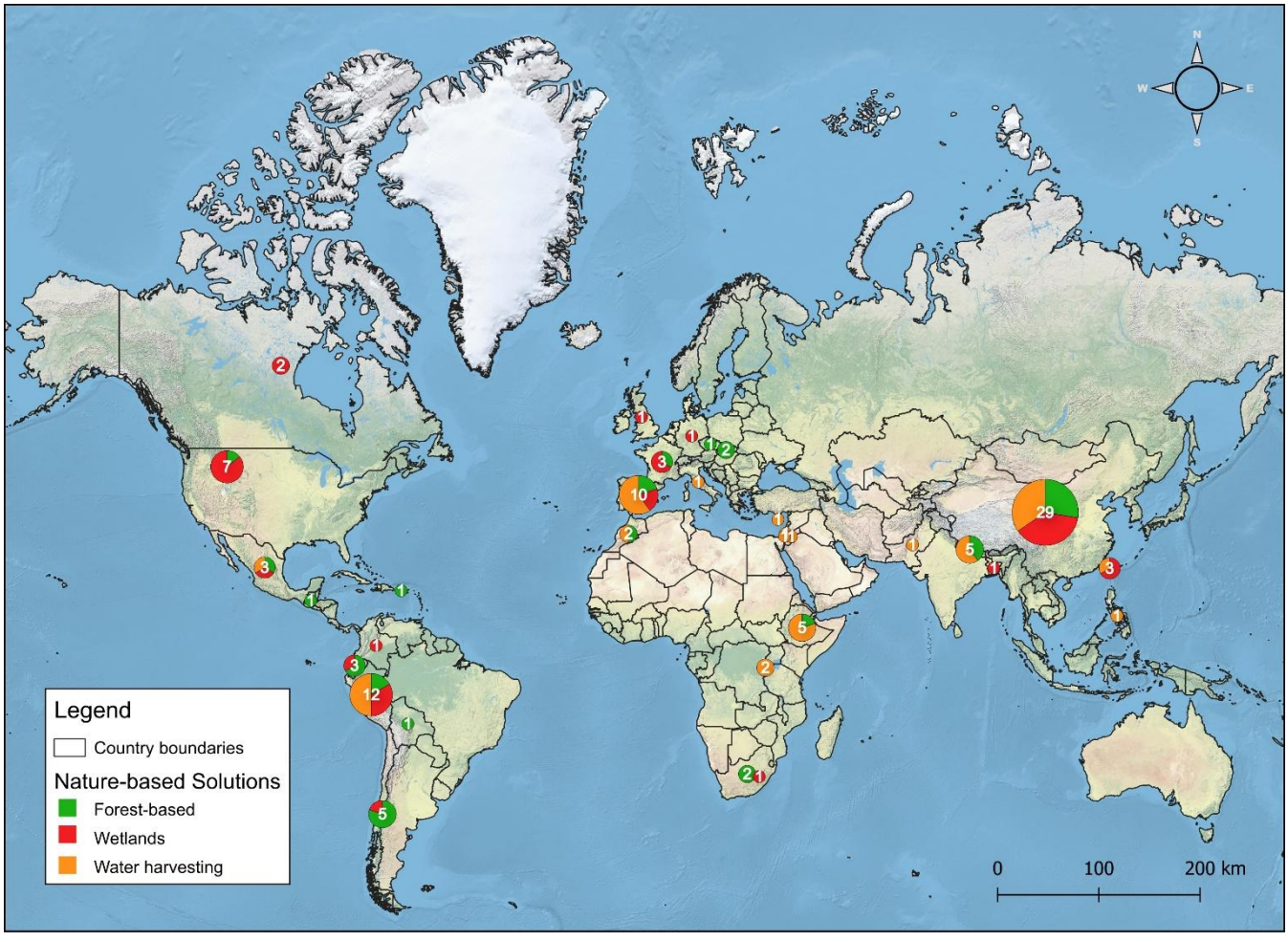


Figure 2:Geographical distribution of the evidence base for hydrological NbS studies in mountain environments. Base map: © ESRI contributors | Powered by Esri.

4.2 Hydrological functions assessed across NbS interventions

Four principal hydrological functions were identified for analysis based on the most frequently reported: flow regulation, water retention, groundwater recharge, and soil erosion control. For forest-based interventions, the most common assessment was flow regulation (26), followed by groundwater recharge (14), and soil erosion control (13) (Table 4). In wetland studies, a balanced distribution was seen between flow regulation (14 studies), water retention (10 studies) and groundwater recharge (13 studies). However, soil erosion control was assessed less frequently than the others (3). Finally, among the different individual interventions, water harvesting interventions were particularly researched in terms of flow regulation (24), groundwater recharge (24), and soil erosion control (22).

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Table 4: Quantity of studies that assessed hydrological functions across NbS interventions

NbS intervention		Flow regulation	Water retention	Groundwater recharge	Soil erosion control	Not specified
Forest	Agroforestry	1	-	-	1	-
	Afforestation	10	5	7	2	-
	Reforestation	7	1	3	4	-
	Forest conservation	8	4	4	6	-
Wetlands	Wetlands	14	10	13	3	14
Water Harvesting	Diversion canal	6	1	6	-	-
	Infiltration trenches	7	-	6	4	-
	Terraces	8	5	11	18	2
	Small reservoirs	3	3	1	-	-

The distribution of the individual intervention types that form the larger group of NbS interventions was heterogeneous. Studies of afforestation and reforestation predominantly examined flow regulation function. Within water harvesting, terraces were frequently associated with groundwater recharge and flow regulation; however, soil erosion control was the most widely studied function of these interventions. Conversely, infiltration trenches and diversion canals were the subject of fewer studies, which were more evenly distributed between flow regulation and groundwater recharge.

As several function categories were included in each piece of research, the results in this section describe the quantitative structure of the evidence base among the different NbS studies, rather than the importance of each function by intervention.

4.3 Reported hydrological effects and effectiveness

Although the magnitude of the effects varied considerably among studies (Table 5), forest-based interventions generally reported reductions in runoff and increases in water retention. Evidence concerning groundwater recharge was less consistent, particularly in the case of afforestation, where studies reported both increases and decreases in recharge.

Studies of wetlands reported reductions in runoff and flood peaks. However, the quantitative evidence was not consistently presented across studies. Some studies reported percentages of precipitation or flow, while others reported changes in discharge. Increases in groundwater recharge and water retention were also reported, but the evidence did not consistently support a single direction of effect across the reviewed cases.

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Finally, there was particularly strong evidence of reductions in soil erosion in terraces with 14 studies. Meanwhile, infiltration trenches were associated with reductions in runoff. In contrast, the responses of diversion canals and small reservoirs were limited and potentially dependent on the hydrological context and design.

Table 5: Agreement of the effect of NbS interventions according to the hydrological function

NbS intervention		Flow regulation			Water retention			Groundwater recharge			Soil erosion control			Not specified
		+	-	Qualitative	+	-	Qualitative	+	-	Qualitative	+	-	Qualitative	
Forest	Agroforestry	1	0	0	0	0	0	0	0	0	1	0	0	0
	Afforestation	7	1	2	4	0	1	3	3	1	1	0	1	0
	Reforestation	5	1	1	0	0	1	3	0	0	4	0	0	0
	Forest conservation	6	1	1	2	1	1	2	0	2	4	0	2	0
Wetlands	Wetlands	6	2	6	3	3	4	2	1	10	2	1	0	14
Water harvesting	Diversion canal	0	2	4	0	0	1	2	1	3	0	0	0	0
	Infiltration trenches	6	1	0	0	0	0	3	0	3	3	0	1	0
	Terraces	6	0	2	1	0	4	1	0	10	14	0	4	2
	Small reservoirs	1	0	2	1	0	2	1	0	0	0	0	0	0

Note: The reported effect is indicated by a plus sign (+) for a positive effect (e.g. reduction in runoff, increase in water retention, recharge or erosion control), and a minus sign (−) for a negative effect (e.g. increase in runoff or decrease in recharge). "Qualitative" refers to studies that describe the role in the hydrological function without quantifying the effect. "Not specified" indicates that the study did not report sufficient information to classify the hydrological effect within the four analysed functions.

Additionally, the hydrological functions were evaluated using indicators (Table 6). In this case, it should be noted that not all the reported studies quantified potential performance increases or reductions as a percentage.

Table 6: Effectiveness of reported hydrological functions related to NbS interventions

NbS intervention		Function	Indicator	Reported effect
Forest	Agroforestry	Flow regulation	Runoff reduction	11% - 94%
	Afforestation	Flow regulation	Runoff reduction	11% - 90%
			Water flow regulation	84%
			Increase of flow	3%
			Water supply capacity reduction	11%
		Groundwater recharge	Increase of recharge	3%
			Decrease of recharge	3% - 28%
		Water retention	Increase of water retention	18%-93%
	Reforestation	Flow regulation	Peak discharge reduction	6%-19%

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		Soil erosion	Soil storage	1% - 53%
			Soil erosion reduction	19%-25%
	Forest conservation	Flow regulation	Runoff reduction	6%-52%
			Percentage of flow generated from precipitation	3%-24%
		Groundwater recharge	Percentage of recharged water	15%
		Water retention	Percentage of water retained from precipitation	78%
		Soil erosion	Soil erosion reduction	30%-83%
Wetlands		Flow regulation	Percentage of flow generated from precipitation	25% - 75% of precipitation
			Runoff reduction	74.70%
			Flood peak reduction	21%
		Groundwater recharge	Percentage of groundwater recharged from precipitation	5% - 25%
		Water retention	Water retention from precipitation	90%
Water Harvesting	**Diversion canal**	Water retention	Storage frequency	0.3-1.7
			Increase storage	70%
		Flow regulation	Increase of runoff in dry season	3%-34%
			Flow diverted from precipitation	54%
		Groundwater recharge	Aquifer recharge	48%-70%
	Infiltration trenches	Flow regulation	Runoff reduction	0.08%-46%
		Groundwater recharge	Increase infiltration	1%-4%
			Increase recharge	4%
		Soil erosion	Soil erosion reduction	43%-57%
	Terraces	Flow regulation	Runoff reduction	6%-53%
		Soil erosion	Soil erosion reduction	30%-95%
	Small reservoirs	Flow regulation	Reduction of peak flow	8%-17%

Note: Single values indicate that only one study reported the effect for that indicator, whereas ranges aggregate values reported by multiple studies.

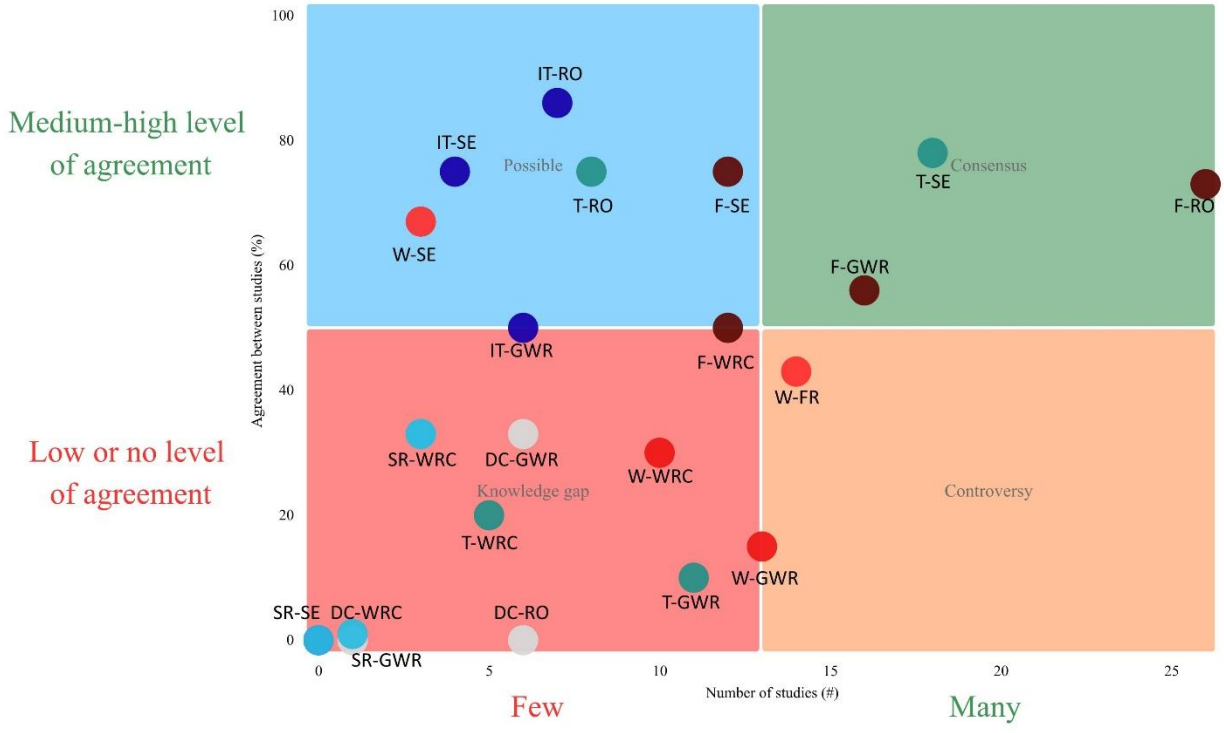
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The runoff reduction indicator for forest-based interventions was assessed through various interventions, with values ranging from 6% (Tiwari et al., 2009) to 94% (Zuazo et al., 2011). Furthermore, soil erosion reduction was consistently reported (Table 5), with values ranging from 19% (Kim & Arnhold, 2018) to 83% (Tiwari et al., 2009). The latter value represents the integration of forest interventions with terraces. Otherwise, the maximum value that could be achieved from the reported studies is 25% (Kim & Arnhold, 2018).

Quantitative evidence was not consistently presented across studies of wetlands interventions. Studies reported different indicators for the flow regulation function, which was the focus of most studies. The percentage of flow from precipitation was the most variable indicator ranging from 25% (Cervantes et al., 2021) to 75% (Sun et al., 2002).

Soil erosion in terraces was found to reduce by a greater amount, showing values of up to 95% (Llorens et al., 1992). Similarly, in terms of flow regulation, it was found that terraces reduced runoff by between 6% (Tiwari et al., 2009) to 53% (Rutebuka et al., 2021).

Effectiveness was also summarised based on the number of studies showing agreement based on the hydrological functions (Figure 3). Interventions supported by a consensus and a number of studies indicated that the potential role of terraces in controlling soil erosion is high. Forest-based interventions showed potential evidence for regulating runoff. Finally, this consensus section also includes groundwater recharge, although in this case it lay very close to the "controversy" quadrant. These classifications described the agreement of the available evidence in the reviewed literature and should not be interpreted as universal estimates of NbS performance across mountain environments.



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Figure 3: Level of agreement for NbS hydrological effects across all the interventions. The figure shows the level of evidence for key hydrological functions. This approach was adapted from Bonnesoeur et al., (2019). Table 7 shows the coding for the graph combinations.

Table 7: Coding for the different combinations from Figure 3.

Code	Intervention type	Code	Intervention type
F-RO	Forest based – runoff regulation	IT-RO	Infiltration trenches – runoff regulation
F-GWR	Forest based – groundwater recharge	IT-GWR	Infiltration trenches – groundwater recharge
F-WRC	Forest based – water retention	IT-WRC	Infiltration trenches – water retention
F-SE	Forest based – soil erosion control	IT-SE	Infiltration trenches – soil erosion
W-RO	Wetlands – runoff regulation	DC-RO	Diversion canal – runoff regulation
W-GWR	Wetlands – groundwater recharge	DC-GWR	Diversion canal – groundwater recharge
W-WRC	Wetlands – water retention	DC-WRC	Diversion canal – water retention
W-SE	Wetlands – soil erosion control	DC-SE	Diversion canal – soil erosion control
T-RO	Terraces – runoff regulation	SR-RO	Small reservoirs – runoff regulation
T-GWR	Terraces – groundwater recharge	SR-GWR	Small reservoirs – groundwater recharge
T-WRC	Terraces – water retention	SR-WRC	Small reservoirs – water retention
T-SE	Terraces – soil erosion control	SR-SE	Small reservoirs – soil erosion control

Five main combinations were identified in the quadrant with a "possible" effectivity. For forest-based interventions, there was close to a consensus within the quadrant on soil erosion control. However, the values for infiltration trenches and terraces in relation to runoff regulation, as well as erosion control for these trenches, remained in the central part of the quadrant. In the case of wetlands, the number of studies was too limited to reach a consensus on erosion control; however, they indicated a potential coincidence for it.

The knowledge gap and controversy quadrant revealed the studies that were more uncertain due to a lack of agreement in the reported responses or the limited available evidence. The combination of wetlands with the groundwater recharge role is located near the quadrant boundary having values close to the threshold. It showed that there is "controversy" regarding the flow regulation function. It is also important to note in this quadrant that water harvesting interventions were more abundant, highlighting the lack of studies determining the hydrological functions of different interventions. Terraces showed a low degree of agreement, but a relatively high quantity of studies were close to the controversy quadrant. Infiltration trenches showed a relatively high degree of agreement in the quadrant, but few studies. Finally, there were still few studies and a low level of coincidence regarding small reservoirs and diversion canals.

NbS interventions were also reported alongside other interventions. Water harvesting practices were frequently mentioned in conjunction with wetland 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 interventions, various interlinkages were also observed. Specifically, diversion canals were found to occur alongside small reservoir studies, for example those by Frot & van

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Wesemael, (2009) and Pulido-Bosch et al., (2000). Similarly, they were assessed in connection with infiltration trenches (Pulido-Bosch et al., 2000). In turn, infiltration trenches were linked with terraces in studies such as those by Castelli et al., (2017b) and Guzman et al., (2017), while terraces themselves were reported alongside small reservoirs 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., 2024; Zuazo et al., 2011), as well as forest conservation (Tiwari et al., 2009). Forest conservation interventions were also found to interact with wetlands (Cervantes et al., 2021; Sun et al., 2002). Furthermore, all forest based interventions were shown to be interdependent. Agroforestry was connected to afforestation (Castelli et al., 2017a), 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.

4.4 Conditioning factors and comparable methodologies of the hydrological evidence

The reviewed literature identified environmental and catchment characteristics associated with the reported hydrological responses of NbS. For wetlands, topography, catchment characteristics, and soil properties were repeatedly found to be associated with hydrological performance. However, the studies covered a range of scales, from the local scale of 0.08 ha (Scheliga et al., 2019) to medium scale catchments ranging from 320 km^2 (Pulido-Bosch et al., 2000) to approximately 7 000 km^2 (Li et al., 2014; Li & Shi, 2015). Only two studies assessed wetlands at a regional scale, with study areas covering 11 957 km^2 (Xu et al., 2009) and 20 930 km^2 (Yang et al., 2023). Furthermore, while most studies reported that wetlands were located in areas with gentle slopes, many did not provide explicit slope measurements, thus limiting comparability across sites. Topography was identified as a critical factor in wetland function, influencing their roles as recharge zones and rainfall buffers, as well as their ability to regulate runoff dynamics, and their 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 frequently reported attributes were infiltration rate, soil water holding capacity, soil moisture content, hydraulic conductivity, and porosity. Finally, wetlands appeared to be studied in climates ranging from arid and semi-arid to humid and tropical regions.

Forest-based studies revealed a relation between slope, vegetation characteristics, and soil properties. The reviewed studies indicated that, while some sites were located on gentler slopes, most were on relatively steep ones. This parameter was primarily associated with runoff generation, groundwater recharge, and soil erosion, reflecting its influence on key hydrological processes. Furthermore, the canopy's ability to intercept rainfall is a defining characteristic that directly affects the hydrological function of NbS. Soil properties were generally limited to measurements of hydraulic conductivity, soil water content, and infiltration rate. Of the agroforestry interventions, only two explicitly reported the spatial extent of the intervention: one at a small scale (Jiao et al., 2024) and one at a medium scale (Castelli et al., 2017a). Studies on afforestation and reforestation also tended to report on local to medium scales, while forest conservation interventions were mostly conducted at local scales. One study on the subject was conducted on a regional scale (Wang et al., 2023). Although

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reforestation studies were also carried out in semi-arid and dry regions, reported studies for forest-based interventions are mostly applied in warm and humid regions.

For water harvesting interventions, conditioning factors varied according to intervention type. 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° 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°. Infiltration trenches were reported to be particularly effective in areas with low infiltration capacity as they enhance groundwater recharge and increase infiltration rates. Regarding scale, these interventions were predominantly analysed at a local scale, with only one study examining these interventions at a regional level (Li & Gao, 2019). In terms of climate conditions, diversion canals were only studied in arid and semi-arid regions. In contrast, the climate in which terraces and infiltration trenches were used varies from humid and temperate to arid and Mediterranean.

The reviewed studies employed various types of analysis to evaluate the performance of hydrological functions. These approaches included field-based measurements, hydrological modelling and GIS or statistical analyses (Table 8). The flow regulation function was mainly assessed using the SWAT model in relation to forest-based interventions, with an important amount of research also applying experimental and field measures. Wetlands were mainly assessed using water balance models, while field measurements and experiments were the approaches used in more studies to assess water harvesting. Regarding the groundwater recharge function, the SWAT model was again the most widely used tool for assessing forest-based interventions, while MODFLOW was used for wetlands. However, field approaches appeared to be the most useful for water harvesting interventions, as was the case for flow regulation. The water retention function appeared to be balanced between the different approaches, with no predominant tool or methodology for forest-based or wetland interventions. Nevertheless, water harvesting interventions were still predominantly assessed using field approaches and GIS tools. Finally, soil erosion control appeared to be assessed more by field measurements and the RUSLE equation. It should be noted that other hydrological models could also be using the RUSLE equation, but we wanted to distinguish studies that explicitly mentioned the RUSLE equation from those that mentioned a hydrological tool in detail. InVEST also was an important tool for measuring this function for forest-based interventions.

Table 8: Detailed approaches for assessing hydrological functions

Hydrological function	NbS interventions	Measurements	Hydrological Modelling	Data analysis

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Flow regulation	Forest-based	Field measures (6); monitoring stations (2)	SWAT (7); MIKE-SHE (2); Water balance equation (2); HEC-RAS (1); InVEST (1); RS-Gash model (1); Dooge hydroclimatic model (1); N-SPECT (1); Linear model (1); HEC-GeoHMS (1); Semivariogram models (1); WRSM Pitman (1); ACRU4 (1); Hydrobal (1)	GIS (6); Satellite images (2); Regression method (1)
	Wetlands	Field measures (3); monitoring stations (3)	Water balance model (3); Hydrobal (1); Conceptual model (1); Water budget model (1); HydroGeo-Sphere (1)	Statistical analysis (1); Remote sensing (1)
	Water harvesting	Experimental measure (9); Field measures (10)	STREAM model (1); MODFLOW (1); TOPMODEL; PED model (1)	GIS (2)
Groundwater recharge	Forest-based	Field measurements (3)	SWAT (3); RS-Gash model (1); WEAP model (1); HEC-GeoHMS; Hydrobal (1)	ARCGIS (1); satellite data (1)
	Wetlands	Experimental measures (1)	MODFLOW (2); Regional Gravity-Driven Groundwater Flow Model (1); Hydrobal (1); Wetlands Hydrologic Model (1)	
	Water harvesting	Experimental measure (7); Field measures (3)	STREAM model (1); MODFLOW (1); PED model; SHER model (1)	GIS (1)
Water retention	Forest-based	Field measure (2); monitoring stations (1)	InVEST (2); Water Balance model (2); SWAT (1); HECRAS (1); RS-Gash model (1); Dooge hydroclimatic model (1)	GIS (2)
	Wetlands	Monitoring stations (3); Field measure (1)	Water balance model (2); HydroGeo-Sphere (1); Matlab (1)	ARCGIS (1); Remote sensing (1); Water budget Analysis (1)
	Water harvesting	Field measure (5)	TOPMODEL (1); Hec-HMS (1); Geology-based model (1)	GIS (6); Remote sensing (1)
Soil erosion control	Forest-based	Field measures (4); monitoring station (2)	RUSLE equation (4); InVEST (3); linear model (1); numerical model (1); SWAT (1)	Satellite images (2); Land use projections (1); statistical analysis (1)
	Wetlands	Monitoring (1)	Conceptual model (1)	-
	Water harvesting	Experimental measure (10); Field measure (6)	RUSLE model (4); PED model (1); TOPMODEL (1)	GIS (4)

298 Only a limited number of studies reported an analysis of NbS performance under climate change scenarios. As shown in Figure
299 4, the highest number of analyses for this scenario were reported for wetlands, reflecting the larger number of studies available
300 for this intervention type. Of the water harvesting interventions, terraces were the only ones to show effects under climate

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change scenarios, albeit in very low numbers. This is despite the many articles that reported on the hydrological functions of these interventions under current conditions.

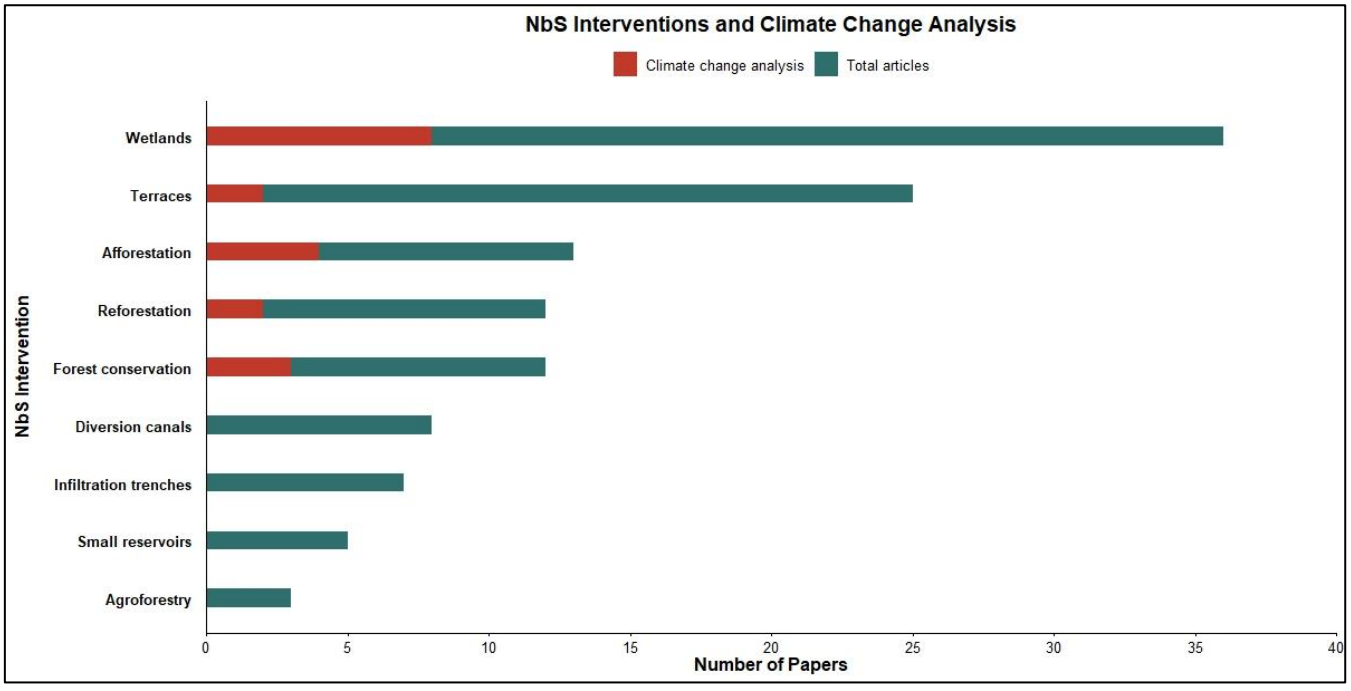


Figure 4: Number of articles that included a climate change analysis scenario for the NbS intervention.

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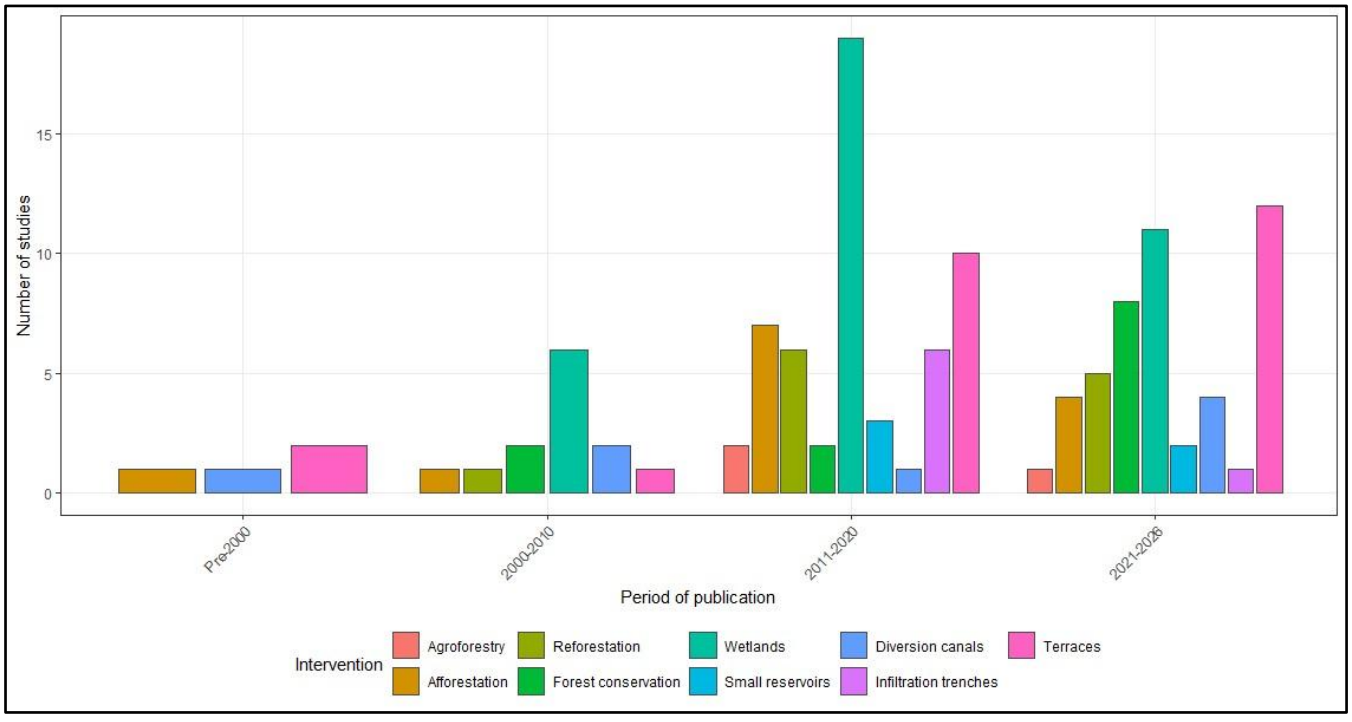


Figure 5: Period of publication of the review studies.

Figure 5 shows that the evidence base is concentrated in the most recent decades. Only three studies were published before 2000, focusing on afforestation, diversion canals and terraces. The number of studies then increased markedly from 2000 onwards. This temporal pattern was relevant to interpreting the climate change gap identified in this review.

5 Discussion

5.1 Evidence base and geographical distribution

Despite the diversity of NbS interventions in mountain environments and their context dependency, the reviewed literature provides relatively consistent evidence on flow regulation, water retention, groundwater recharge, and soil erosion control. These functions are also among the most frequently considered in broader assessments of the hydrological impacts of NbS (Lalonde et al., 2024). The evidence base was unevenly distributed geographically, with China accounting for the largest number of studies across the three main intervention groups, followed by Peru and Spain. In contrast, comparatively few studies were identified from several African mountain regions. Similar geographical imbalances have been reported in broader assessments of NbS effectiveness (Chausson et al., 2020; Lalonde et al., 2024). This geographical concentration is important to consider when interpreting the transferability of reported hydrological responses. Evidence generated from a limited number of environmental and climatic contexts may not represent the range of conditions across mountain regions. Furthermore, the review revealed that the quality of evidence varied not only among intervention types and hydrological functions, but also in

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how these functions were measured and reported. These characteristics of the reviewed studies are closely related to the knowledge gaps illustrated in Figure 3. The limited range of regions in which the evidence has been produced and reported, and the scarcity of studies for certain combinations of intervention and function, are partly a consequence of each other. Therefore, it is important to strengthen evidence from underrepresented mountain regions and improve the comparability of hydrological assessments in order to determine whether reported NbS functions can be transferred across mountain environments and used to support water security objectives.

5.2 Hydrological functions and effectiveness of NbS interventions

The results show that hydrological responses vary according to the type and purpose of the intervention, the biophysical characteristics of the site, and the socio-ecological context in which NbS are implemented. Similar variability has been reported in previous studies about hydrology and NbS (Lalonde et al., 2024; Ruangpan et al., 2020). This variability is important for decision-making purposes because the suitability of an NbS intervention depends on its ability to provide a specific hydrological function, as well as on the comparability of the supporting evidence. Therefore, when making these decisions, it is helpful to consider the conditions under which an effect has been documented. While there is no one-size-fits-all solution that can be transferred from one mountain context to another without modification, this does not diminish their potential value. Investing in these measures can be worthwhile, but realising their potential requires investment in parallel studies and monitoring to determine their most effective application, likely through integrated approaches within specific programmes under development.

The reviewed evidence showed comparatively consistent effects for runoff regulation and water retention in forest-based interventions, while groundwater recharge exhibited greater variability. Water harvesting interventions, particularly terraces and infiltration trenches, were frequently associated with runoff reduction, increased infiltration, and soil erosion control. Wetland interventions showed evidence of effects on runoff regulation, groundwater recharge and water retention, although some functions were less consistently assessed. The conditioning factors identified for wetlands help to explain the dispersion observed in the controversy quadrant. Differences in wetland type, topographic position, and soil properties can show "opposite" direction of the hydrological response. This means that a lack of agreement is more accurately interpreted as a sign of context dependency. Notably, the magnitude of the reported effects varied substantially even within the same NbS category. These ranges should therefore not be interpreted as general effect sizes for NbS, but rather as an indication of the variability reported across different interventions. This reflects the methodological differences in how effects were measured and context-specific factors. As most studies did not report reference conditions, it is not possible to separate these sources, meaning that the ranges represent the possible responses rather than a single estimate of effectiveness. It is important to make this distinction when using the evidence to inform NbS selection, because a reported effect in one mountain environment cannot necessarily be assumed to occur with the same magnitude under different conditions.

The variability was also influenced by the methodological approaches used to quantify these functions. The reviewed studies employed a variety of methods, including field measurements, hydrological modelling, GIS and remote sensing, as well as

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statistical analyses, either independently or in combination. While these approaches provide complementary information, they are not directly interchangeable. Field measurements can provide direct evidence of local hydrological processes, whereas hydrological models can extend observations across spatial and temporal scales and evaluate processes that are difficult to observe directly. Hydrological modelling was crucial for evaluating flow regulation in forest-based interventions, whereas field methods were more prevalent for water harvesting interventions. Therefore, when comparing reported effects across studies, methodological differences should be considered rather than treating all reported measurements as equivalent evidence of effectiveness. In addition, a key consideration in the methodological approach is the exposure–effect relationship that characterises NbS. These interventions have a finite storage or retention capacity, and their effectiveness is non-linear when performing a specific hydrological function. Therefore, measured efficiency depends on the magnitude and intensity of the hydrological input during the assessment and on how efficiency changes across events of different magnitudes. When exposure is higher, efficiency drops. This implies that the reported effect ranges cannot be interpreted without reference to the exposure conditions under which they were assessed, which highlights the importance of reporting these conditions.

5.3 Evidence gaps and comparability of hydrological assessments

The main gap identified across the evidence base was the lack of comparability between their hydrological assessments. The studies varied in terms of the indicators selected, the assessment techniques employed, spatial and temporal scales adopted, the baseline conditions considered, and how intervention characteristics were reported. Importantly, the information needed to contextualise these studies in relation to one another was often incomplete. This is not merely a methodological inconvenience. It directly affects how the evidence can be interpreted. For example, two studies of the same intervention may report different effects without contradicting one another because they address different hydrological questions. Both may be valid, but neither can be used to benchmark the other. These differences prevent direct comparisons of hydrological responses across studies, and overcoming them could lead to more comparable hydrological assessments while retaining the heterogeneity of interventions that characterises NbS in mountain regions.

The need for comparability is not just a scientific concern, it also has direct implications for implementation. Without comparable evidence, decision-makers cannot evaluate whether a reported hydrological effect on water security is likely to occur in their own context and therefore cannot justify investing in NbS. The European Environment Agency (2023) has identified the lack of standardised methods for assessing and monitoring NbS as a major challenge for their wider replication and application. This leaves decision-makers uncertain about what works where, for whom, and how reliably over time (Dayananda, 2026). Comparable assessments would facilitate the transferability of hydrological responses across mountain regions, enable interventions to be prioritised according to local and regional conditions, and allow NbS to be designed and monitored more confidently.

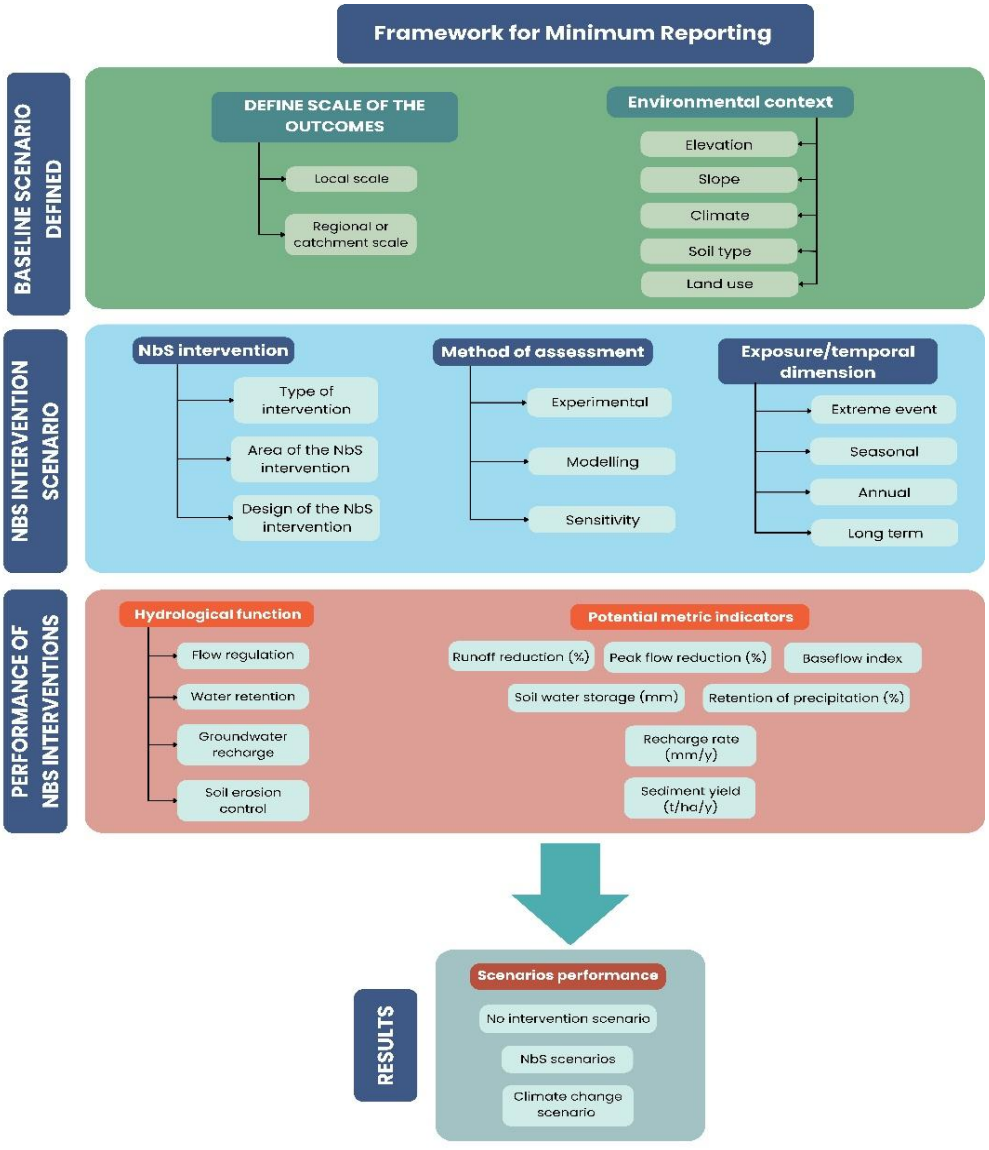
This problem is particularly significant in the context of climate change. Although NbS are increasingly being promoted as tools for addressing climate-related water challenges (da Silva Bezerra, 2025; United Nations Environment Programme and International Union for Conservation of Nature, 2021), only a limited number of the reviewed studies have examined their

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performance in climate change scenarios. As most of the studies were published after 2000, this limited inclusion of climate change scenarios cannot be attributed to the age of the studies. This gap reflects the complexity of assessing these future scenarios rather than a lack of research effort. As discussed in section 5.2, the nonlinear response of NbS to exposure suggest that its efficiency may vary in more extreme conditions expected in the context of climate change. Consequently, the available evidence provides limited insight into whether the hydrological functions of NbS will be maintained, enhanced, or diminished under future climatic conditions, precisely the conditions on which water security decisions are ultimately depend. The need for more consistent assessment has been recognised more broadly within the NbS literature, with systematic reviews continuing to highlight the lack of scalable approaches to NbS design and monitoring, particularly with regard to hydrological performance (Calliari et al., 2022; Ruangpan et al., 2020). This does not weaken the case for investing in NbS, as extreme events are difficult to avoid through any single measure.

To address these gaps, we propose a minimum information framework for hydrological assessments of NbS (Figure 6). This specifies the information that future studies should report, including intervention design, environmental context, reference condition, hydrological function and indicators, spatial and temporal scale, methods, exposure conditions under which effects are measured, and uncertainty. This would allow results to be presented in a way that facilitates the evaluation of the most suitable NbS intervention for particular contexts, scales, and stages of water security assessment. This would enable future stakeholders to identify potential NbS interventions for their own context from a range of information without the interventions themselves being standardised. This information is relevant for future assessments that seek to connect hydrological evidence with the broader contribution of NbS to water security.

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406

407 **Figure 6: Proposed minimum reported information to enhance the comparability of hydrological assessments of NbS in mountain**
408 **regions.**

409 This would be a consequential step, as it would enable future reviews to distinguish more clearly between differences in NbS
410 performance and differences arising from how effects are measured, providing the basis for assessing NbS effectiveness under
411 the climatic conditions for which they are most needed. Future research should focus not only on increasing the number of
412 studies and but also on developing approaches that allow evidence generated at different spatial and temporal scales to be
413 integrated. Similar challenges regarding the scaling up and integration of evidence have been identified in previous assessments
414 of NbS for hydrological hazards (Ruangpan et al., 2020).

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6. Limitations

The evidence base was constrained by the fact that the studies identified were only available through selected bibliographic databases, supplementary searches, and the restriction of the string in the title field. Publications in languages other than English and Spanish were not systematically included. This may have introduced geographical and linguistic bias, particularly in mountain regions where relevant evidence may be published in different languages and some relevant studies may have been overlooked.

The classification of the evidence in Figure 3 relied on the thresholds set for this review. These thresholds were chosen to distinguish between combinations supported by substantial literature and those supported by only a few case studies. However, they should be treated as an analytical method rather than as a universal criteria.

Moreover, the review focused on the hydrological aspect of NbS effectiveness. Consequently, the social, economic, and governance dimensions of NbS were not evaluated. While these dimensions are important for determining whether hydrological benefits can be realized, their integration would require a broader interdisciplinary assessment beyond the scope of the present study.

Finally, the synthesis was limited by the way in which the literature reported hydrological effects. The few studies classified in the "controversy" quadrant in our classification (Figure 3) suggested that studies tend to agree on the direction of hydrological effects where sufficient evidence exists, even though the magnitude varies. However, studies may be more likely to report positive or expected effects than neutral or negative outcomes, which could influence the apparent direction of the evidence. Explicit reporting of negative, null, and divergent responses would provide a more balanced evidence base, improving future synthesis and comparability.

7 Conclusions

This article provides a critical scoping review of the literature on NbS and the effectiveness of hydrological functions in mountain regions. It brings together evidence on intervention type, hydrological function, reported effects, conditioning factors, and methodological approaches, providing a basis for interpreting the hydrological performance of NbS for stakeholders.

Among the hydrological functions assessed, forest-based interventions showed consistent evidence for flow regulation. Although the magnitude of reported effects varied substantially among specific intervention types and study conditions, the evidence for this function was comparatively more abundant. In contrast, evidence on water retention in forest-based interventions remained limited. Wetland interventions showed mixed evidence for flow regulation and groundwater recharge, potentially due to differences in soil properties, topography, and hydrological connectivity among wetland systems. Water harvesting interventions were predominantly assessed at local scales, with relatively consistent evidence for the role of terraces in soil erosion control. Infiltration trenches also demonstrated a correlation between reported effects for erosion control and runoff regulation, although the number of available studies was limited. Together, these findings can inform the selection of

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NbS according to specific hydrological objectives, while highlighting areas where the available evidence was insufficient or context-dependent.

Throughout the review, the reported ranges of effects should be interpreted as evidence of the variability observed in the literature rather than as general estimates of NbS effectiveness. This contextual dependency is particularly important in mountain environments, where variations in factors such as topography, climate, soil types, land cover, and hydrological connectivity can affect the outcome of the same intervention. Another source of this variability lies in the exposure–effect conditions, meaning that reported effects should be interpreted in relation to the events and monitoring periods from which they were derived. Therefore, a key challenge is the inconsistent reporting of these factors, which limited our ability to understand the performance of reported responses across studies. Improving the reporting and harmonisation of these factors could enhance our understanding of the underlying processes and enable more meaningful comparisons to be made between different mountain environments. In order to enable more comparable assessments, this review proposes a minimum reporting framework for the hydrological evaluation of NbS in mountain environments. This would help to better inform decision-making for future NbS projects related to hydrology.

From a water security perspective, the hydrological functions identified in this review are important biophysical processes through which NbS can contribute to water security. However, this review focused on hydrological functions rather than evaluating water security outcomes directly. Future research should therefore strengthen the connection between measurable hydrological responses and water security indicators, while taking into account the environmental, climatic, and intervention conditions that determine their effectiveness. Developing more comparable hydrological evidence could provide a basis for incorporating these indicators into water security assessments and identifying situations in which NbS could effectively address specific water resource challenges. Integrating hydrological evidence with social and economic dimensions, alongside stakeholder and community involvement in the selection, design and long-term management of NbS, would facilitate more contextual applications and robust assessments of their contribution to water security.

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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