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Scientific evidence of the hydrological impacts of nature-based solutions at the catchment scale

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Abstract

The introduction of nature-based solutions (NbS) in catchments has the potential to increase the cost-effectiveness, flexibility, and reliability of water management practices aimed at improving water security. However, the scientific-evidence base of the hydrological impacts of NbS is still weak, and there is therefore a risk that catchment interventions might not lead to the desired hydrological outcomes. This is especially important when assessing NbS-based catchment interventions before their implementation, as this requires robust simulation tools capable of effectively managing the uncertainties associated with future forecasts. This study aims to review the hydrological impacts of different NbS intervention types for water management. First, we present an NbS typology and the corresponding dominant hydrological impacts. We then use this typology to review the strength of the current evidence of the effect of NbS interventions on the hydrological response at the catchment-scale. Our results demonstrate that the effectiveness of each NbS type hinges on specific conditions such as location, design, and environmental factors. For instance, micro-reservoirs notably enhance surface storage and evaporation, while infiltration trenches reduce runoff but can increase soil erosion. Our global analysis highlights the need for an improved understanding of NbS catchment impacts and careful planning of NbS interventions as a key for successful long-term implementation of NbS. These include participatory approaches with stakeholder involvement in NbS co-design, knowledge co-production, and novel data

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collection to support locally relevant adaptation strategies, and to increase water security on the long term.

This article is categorized under:

Science of Water > Hydrological Processes

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KEYWORDS

catchment interventions, hydrological processes, nature-based solutions, water security, water sustainability

1 | INTRODUCTION

Nature-based solutions (NbS) support the maintenance, enhancement, and restoration of ecosystems and their services to simultaneously address various social, economic, and environmental challenges. NbS offer effective measures to tackle and sustainably manage a broad range of social–environmental challenges, such as climate change mitigation and adaptation, disaster risk reduction, economic and social development, human health, food and water security, environmental degradation, and biodiversity loss (IUCN, 2020a; WWAP, 2018, 2020). They may also support ecological and economic recovery from global crises, such as the COVID-19 pandemic and the climate crisis (Davies et al., 2021; OECD, 2020). For these reasons, NbS are gaining traction in international research, policy, and business (Ara Begum et al., 2022; Seddon et al., 2020; WWAP, 2020). Governments, development organizations, corporations, and non-profit organizations are increasingly considering and promoting NbS for catchment conservation and management as well as for their role in transformational climate change adaptation and improved water security (Caretta et al., 2022; Fedele, 2019; Tellman et al., 2018).

NbS comprise a broad range of catchment interventions, and they need to be managed adaptively according to the understanding of the underlying ecohydrological processes. However, this understanding is often limited due to sparse observational data and process knowledge. This poses the risk that NbS may not produce the intended benefits or could lead to unexpected ecosystem responses with undesirable consequences for water security (IUCN, 2020a).

Because local and international policymakers are increasingly adopting NbS, there is an urgent need for improved understanding of the ecohydrological impact of NbS interventions. This includes stronger evidence of both the benefits and the limitations of NbS in hydrological processes, but also case studies of successful implementation and long-term outcomes (Bremer et al., 2016; IUCN, 2020b; Zhang & Chui, 2019). In addition, ecohydrological models that are able to simulate the impact of catchment interventions based on NbS are necessary to support ex-ante decision-making on aspects including the prioritization of investments, catchment monitoring, and adaptive management (Bremer et al., 2016; Davies et al., 2021; Nesshöver et al., 2017). However, one of the main challenges of building and improving such models is dealing with the diverse ecohydrological interactions (e.g., soil properties, vegetation cover, and water processes) of different NbS types and capturing the dominant modes of hydrological impact, while remaining sufficiently parsimonious in order to be robust and realistic in terms of data requirements. To build such models and tailor them to specific hydrological conditions, it is paramount to have a clear understanding of the robustness of the scientific evidence-base on NbS impacts at the catchment scale (Drenkhan et al., 2023).

To support this process, we review the hydrological impacts of NbS at the process level, considering surface runoff, baseflow, infiltration, evapotranspiration, floods, and droughts. To do so in a systematic way, we develop a typology of common NbS catchment interventions. We then identify consensus and knowledge gaps and compare the suitability of different NbS interventions for effective management and adaptation at the catchment scale.

2 | A TYPOLOGY OF COMMON NbS

The definition of NbS varies across the scientific literature, international reports, and regional reports, with some of the NbS requiring a unified and consistent definition of NbS (IUCN, 2020b). In Table 1, we present the most commonly

TABLE 1 Definitions of nature-based solutions (NbS).

Nature-based solutions (NbS) for adapting to water related risks (OECD, 2020)	NbS are 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.
Nature-based solutions and re-naturing cities (European Commission, Directorate General for Research and Innovation, 2015)	NbS are actions that are inspired by, supported by, or copied from nature. They have tremendous potential to be energy and resource-efficient and resilient to change: but to be successful, they must be adapted to local conditions.
Nature-based solutions for water (WWAP, 2018)	NbS are inspired and supported by nature and use, or mimic, natural processes to contribute to the improved management of water. The defining feature of an NbS is, therefore, not whether an ecosystem used is 'natural' but whether natural processes are being proactively managed to achieve a water-related objective.
Water and climate change (WWAP, 2020)	NbS which are inspired and supported by nature and which use or mimic natural processes, can contribute to the improved management of water while providing ecosystem services as well as a wide range of secondary co-benefits, including adaptation, mitigation and resilience to climate change.
Nature-based solutions to address global societal challenges (Cohen-Shacham et al., 2016)	NbS are actions to protect, sustainably manage, and restore natural and modified ecosystems in ways that address societal challenges effectively and adaptively, to provide both human well-being and biodiversity benefits.
Global standard for nature-based solutions (IUCN, 2020a)	<p>Criteria:</p> <ol style="list-style-type: none"> 1. effectively address societal challenges, 2. are informed by scale, 3. result in a net gain to biodiversity and ecosystem integrity, 4. are economically viable, 5. are based on inclusive, transparent, and empowering governance processes, 6. equitably balance trade-offs between achievement of their primary goal(s) and the continued provision of multiple benefits, 7. are managed adaptively, based on evidence, 8. are sustainable and mainstreamed within an appropriate jurisdictional context.

accepted definitions of NbS for water regulation from international key reports that target both the scientific and decision-making communities The International Union for Conservation of Nature (Cohen-Shacham et al., 2016; IUCN, 2020a, 2020b) defines NbS as a wide range of interventions for the protection, management, and restoration of natural and modified ecosystems. The definitions from the United Nations (WWAP, 2018, 2020), and the European Commission (European Commission, Directorate General for Research and Innovation, 2015) describes NbS as solutions inspired by or derived from nature. This definition is based on whether natural processes are actively managed in order to achieve water-related objectives, such as flood and drought mitigation, regardless of whether an ecosystem is "natural" or not. While the IUCN emphasizes the importance of ecosystem conservation and restoration in its definition (IUCN, 2020a), the European Commission offers a broader perspective also including social and economic aspects of sustainability (European Commission, Directorate General for Research and Innovation, 2015). The OECD (2020) suggests a combination of both definitions, emphasizing conservation and sustainable management as well as a broad sustainability perspective (Table 1). In this review, we adhere to the OECD definition.

In order to assess the hydrological impacts of NbS at the catchment scale (i.e., a broad range from small sub-catchments to large basins), we propose a detailed typology of NbS (Table 2) based on a previous classification suggested by WWAP (2018). To the best of our knowledge, this represents the only internationally published typology at the catchment scale, and outlines four categories: (i) re/afforestation and forest conservation, (ii) wetland restoration and conservation, (iii) construction of wetlands, and (iv) water harvesting (WWAP, 2018). Water harvesting refers to the construction of elements that interact with natural features to enhance water-related ecosystem services, aligning with the definition of green infrastructure provided by the OECD (2020). Such an infrastructure primarily focuses on

TABLE 2 Overview of nature-based solutions (NbS) for water intervention types.

NbS types	Solutions	Definitions	Articles
Re-/ afforestation and forest conservation	Afforestation	Planting of trees where the species would not have occurred naturally, such as use of non-native species or planting any species on land that would have been grassland in the past.	(Acreman et al., 2021; Agnihotri & Yadav, 1995; Alves & Formiga, 2019; Z. Bai et al., 2018; Beets & Beets, 2020; Bonnesoeur et al., 2019; Breil et al., 2021; Buendia et al., 2016; Farley et al., 2005; Greenwood et al., 2011; Hejduk et al., 2021; Hou et al., 2023; Hrabovský et al., 2020; M. Huang et al., 2003; Ilstedt et al., 2007; Iroumé & Palacios, 2013; Krishnaswamy et al., 2012, 2013; Liu et al., 2016; McVicar et al., 2007; Mihalcea, 2017; Nadal-Romero et al., 2023; Ponette-González et al., 2014; Scott & Lesch, 1997; Takele et al., 2022; Teuling et al., 2019; Valente et al., 2021; Van Lill et al., 1980; Webb & Kathuria, 2012; Xu, Yang, et al., 2019; Xu, Liu, et al., 2019)
	Reforestation	Planting of native trees where they would have existed or allowing natural regrowth of native trees.	(Acreman et al., 2021; Bonell et al., 2010; Bonnesoeur et al., 2019; Borg et al., 1988; Bremer et al., 2019; Bruijnzeel, 2004; Eekhout et al., 2020; Galli et al., 2021; Groß et al., 2018; Holden et al., 2022; Z. Huang et al., 2010; Kabeja et al., 2020; Kirnbauer et al., 2013; Krishnaswamy et al., 2013, Krishnaswamy et al., 2013; Kuehler et al., 2017; Lukey et al., 2000; Meerveld et al., 2019; Page et al., 2020; Schooling & Carlyle-Moses, 2015; Shi et al., 2019; Tang et al., 2019; Teuling et al., 2019; Xu, Liu, et al., 2019; Zheng et al., 2008)
Wetlands restoration/ conservation	Wetlands	Areas of marsh, fen, peatland, or water, whether natural or artificial, permanent or temporary, with water that is static or flowing, fresh, brackish or salt, including areas of marine water, the depth of which at low tide does not exceed 6 m.	(Acreman et al., 2021; Amiri et al., 2022; Baiker, 2023; Bruland et al., 2003; Conn & Fiedler, 2006; Glas et al., 2019; Hunt et al., 1999; Jenkins et al., 2012; Liao et al., 2017; Milani et al., 2019; Mohamed et al., 2012; Patiño et al., 2021; Peck & Lovvorn, 2001; Polk et al., 2017; Queluz et al., 2018; Quin & Destouni, 2018; Rodríguez-Morales et al., 2019; Thorslund et al., 2018; Valois et al., 2020; Verzijl & Quispe, 2013; Watts et al., 2023; Wong et al., 2017; Wunderlich et al., 2023)
	Constructing wetlands	In constructed wetlands, essential processes that take place in natural wetlands are recreated through specific engineering designs.	
Water harvesting	Creation of small reservoirs	Dry detention basins, which are grassed depressions or basins created by excavation, into which runoff is channeled what facilitates the slow filtration of sediment and nutrient uptake by the vegetation.	(Costa et al., 2021; Djuma et al., 2017; Eekhout et al., 2020; Eisma & Merwade, 2021; Ferik et al., 2020; Galicia et al., 2019; Guyassa et al., 2017; Habets et al., 2018; Hayashi et al., 2003; Z. Huang et al., 2010; Itsukushima et al., 2018; Krol et al., 2011; Li et al., 2023; Liao et al., 2017; Perrin et al., 2012; Previati et al., 2010; Shi et al., 2019; Van Meter et al., 2016; Xu et al., 2013; Yuan et al., 2019)
	Diversion canals	Canals transporting water from a stream across hillslope to enhance infiltration and likely to supply small depression.	(Cárdenas Panduro, 2020; Ertsen & Van Der Spek, 2009; Ferreira et al., 2020; Kumar et al., 2010; Ochoa-Tocachi et al., 2019)
	Infiltration trenches	Excavations that are carried out on slopes in the form of channels of rectangular or trapezoidal section, which are built at contour lines to stop the runoff of rainwater.	(Abu-Zreig et al., 2020; Ahmed et al., 2015; Bergman et al., 2011; Błażejowski et al., 2018; Campisano et al., 2011; Cornelis et al., 2012; Cubides & Santos, 2018; De Carlo et al., 2020;

TABLE 2 (Continued)

NbS types	Solutions	Definitions	Articles
			Fach & Dierkes, 2011; Fan et al., 2022; Freni et al., 2009; Freni & Mannina, 2019; Greggio et al., 2018; Guzman et al., 2017; Heilweil & Watt, 2011; Kumar et al., 2022; LaFevor & Ramos-Scharrón, 2021; B. Locatelli et al., 2020; L. Locatelli et al., 2015; Lopes Bezerra et al., 2022; Mullins et al., 2020; Reinstorf, 2017; Somers et al., 2018; Taye et al., 2015; Widomski et al., 2010)
	Terraces	Sloped surface cut into flat layers by vertical or oblique walls usually made with stones.	(Agnihotri & Yadav, 1995; Arnáez et al., 2015; J. Bai et al., 2019; Baumhardt et al., 2020; Gallart et al., 1994, 1997; Gardner & Gerrard, 2003; Kendall & den Ouden, 2008; Khelifa et al., 2017; Li et al., 2023; Llorens et al., 1992; Lü et al., 2009; Madramootoo & Norville, 1993; Meerkerk et al., 2009; Qian et al., 2014; Romero-Díaz et al., 2019; Willems et al., 2021)

regulating water supply, and mitigating droughts and extreme events such as floods. Here, we focus on four water harvesting infrastructure types: (i) micro-reservoirs, (ii) diversion canals, (iii) infiltration trenches, and (iv) terraces.

3 | METHODOLOGY

This scoping review follows a comprehensive approach to map and synthesize the existing literature on the hydrological impacts of NbS. First, we develop an NbS typology to guide the review process. Then, a comprehensive review of key literature is conducted using the Web of Science database. To this end, a search string was developed that covers the previously defined NbS interventions types (Table 2) and their synonyms including all hydrological key components of surface, runoff, baseflow, infiltration, evapotranspiration, floods and droughts, and storage and residence time, as follows: (TI=(Nature-based-solution*) 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 conservation) OR TI=(wetland restoration) OR TI=(water harvesting) OR TI=(small depression*) OR TI=(diversion canal*) OR TI=(trenches) OR TI=(gullies) OR TI=(ditches) OR TI=(terrace*)) AND (TI=(hydrology) OR TI=(runoff) OR TI=(streamflow) OR TI=(baseflow) OR TI=(discharge) OR TI=(transpiration) OR TI=(evapo*) OR TI=(infiltration) OR TI=(drought*) OR TI=(flood*) OR TI=(storage) OR TI=(residence)).

The search string identified a total of 1169 scientific peer-reviewed articles from research across the globe. As a second step, all articles underwent a thorough manual examination of title and abstract, and a final selection was made based on a full-text analysis. This procedure resulted in a total of 133 studies, most of them located in the Hindu Kush Himalaya, South Africa, Peru, the United States, and Alaska (Figure 1). All of the articles identified were synthesized according to our defined NbS typology and hydrological key components and processes analyzing the current state of knowledge as well as the related gaps.

4 | HYDROLOGICAL EVIDENCE OF THE IMPACTS OF NbS

The review was guided by four main questions regarding the hydrological role of NbS: (i) the influence on hydrological processes, (ii) the corresponding hydrological changes, (iii) potential limitations and risks, and (iv) remaining knowledge gaps. In the following, we bring together the main findings regarding the impacts of each NbS type on major hydrological processes (Figure 2).

subtropical, or Mediterranean climates (Borg et al., 1988; Bruijnzeel, 2004; Teuling et al., 2019). Yet, in some catchments located in hot climates and tropical savannas, the decrease in runoff is reported only as probable (Acreman et al., 2021), and in the catchments located in subarctic climates, this decrease is reported to be relatively unlikely (Groß et al., 2018). The decrease in surface runoff also depends on the catchment morphology and on the location of the reforestation activities in the catchment. For instance, a decrease in runoff is less pronounced in mountainous areas (Bonnesoeur et al., 2019), and it is also low when reforestation is implemented in low-elevation parts compared to higher and middle-elevation parts of catchments (Eekhout et al., 2020; Shi et al., 2019). In specific areas such as urbanized catchments, reforestation is not found to consistently decrease runoff (Schooling & Carlyle-Moses, 2015).

The effects of wetland interventions on runoff and baseflow are controversial. Some studies find that wetlands can reduce runoff and baseflow, while others report an increase (Baiker, 2023; Wunderlich et al., 2023) or no clear effect, regardless of the catchment size and climate (Jenkins et al., 2012; Thorslund et al., 2018). For instance, several wetlands in the Andes are predicted to buffer baseflow and interannual streamflow fluctuations (Glas et al., 2019; Patiño et al., 2021; Ross et al., 2023), while this effect is not confirmed in at least one other study (Rodríguez-Morales et al., 2019). Additionally, even if some studies report that wetlands regulate local flow, this conclusion cannot be systematically generalized to the catchment scale (Quin & Destouni, 2018).

The implementation of micro-reservoirs is reported to decrease in runoff in most of the studies we reviewed (Figure 2), and a literature review at the global scale underlines that runoff decreases depends on the specific hydroclimatic conditions (Habets et al., 2018). The observation of decreased runoff has not been made in other studies conducted in similar contexts to date, such as in large Mediterranean catchments (Eekhout et al., 2020) or in mountainous catchments (Shi et al., 2019; Xu et al., 2013). It is thus evident that there is a lack of understanding of the impact of micro-reservoirs on runoff across different catchment sizes and climates. Very few studies exist on diversion canals. Most of the research identified in the literature is located in the Peruvian Andes. While changes in runoff are not clear, two studies suggest an increase in baseflow (Cárdenas Panduro, 2020; Ochoa-Tocachi et al., 2019). One study in India found that the volume of water diverted also highly depends on the geometry of the canal and on the canal's rack slope, width, and spacing (Kumar et al., 2010). Infiltration trenches (or infiltration ditches, which are often used as a synonymous term) are found to have a reduction effect on runoff. A global literature review suggests there is agreement on an almost 50% decrease in runoff, with the strongest effects seen over natural cover rather than over cropland (Locatelli et al., 2020). Two case studies located in a desert climate confirm such a decrease in runoff only during remarkably wet events (Cornelis et al., 2012) or at an annual level (Guzman et al., 2017). In other contexts, such as a subalpine forested catchment in central Mexico and in urban areas of Copenhagen (Denmark), no significant changes were observed (LaFevor & Ramos-Scharrón, 2021; Locatelli et al., 2015). Hardly any studies have included baseflow and the effect of infiltration trenches on it. One study reports only a slight increase in baseflow in the mid-late rainy season, with minor effects on dry season baseflow (Somers et al., 2018). Three global literature reviews on terraces (Arnáez et al., 2015; Romero-Díaz et al., 2019; Willems et al., 2021) and several case studies confirm that they produce a decrease in runoff.

4.2 | Infiltration

The majority of studies on afforestation suggest an increase in the total infiltrated volume of water and in the infiltration rate. An increase is observed in the Andes over degraded soils (Bonnesoeur et al., 2019), while in the tropics the same is observed for agricultural fields (Ilstedt et al., 2007). Another case is located in the Indo-Gangetic Plain which includes untreated ravine waste ground (Agnihotri & Yadav, 1995). However, some studies suggest a decrease in infiltration with afforestation, for example, over Slovakian vineyards and over Indian degraded tropical humid forests (Hrabovský et al., 2020; Krishnaswamy et al., 2012). Reforestation studies also mostly indicate an increase in infiltration, for both volume and rate (Figure 2). In urban or peri-urban areas, reforestation contributes to increasing the infiltration of runoff (Galli et al., 2021; Kuehler et al., 2017), which might be linked to stemflow, but also to local soil and climate (Schooling & Carlyle-Moses, 2015). In the Pacific, over the island of Maui, the total loss of groundwater recharge was very significant with a scenario of a yearly spread rate of reforestation at 10% (Bremer et al., 2019). However, the effects remain unclear in some areas, such as mountain regions where the effect of reforestation on infiltration represents a knowledge gap (Bonnesoeur et al., 2019).

Wetlands have increased infiltration in specific places, such as the high Andes (Valois et al., 2020). However, in most places, the effect is variable. For instance, even in studies conducted in agricultural and urban areas, some wetlands are found to increase infiltration, while other studies suggest a decrease (Liao et al., 2017; Peck & Lovvorn, 2001).

Some authors even found that the volume of infiltrated water is primarily driven by soil parameters (i.e., soil texture and associated capillary fringe) rather than by the inherent characteristics of the wetland (Hunt et al., 1999).

Micro-reservoirs are mostly reported to increase the infiltrated volume of water, but sometimes they are found to have no impact at all. This might be linked to the various materials used for their construction, with some materials being impervious while others are not (Previati et al., 2010). For instance, check dams (Djuma et al., 2017), micro-reservoirs located in hot climates (Krol et al., 2011), and micro-reservoirs built in urban areas (Liao et al., 2017) produce up to twice the previous recharge, whereas no change in infiltration is reported with earthen dams (Galicia et al., 2019) or in subarctic climates where the soil is partly frozen (Hayashi et al., 2003). Diversion canals located in Peru seem to increase the volume of water infiltrated, as reported in two observational studies (Cárdenas Panduro, 2020; Ochoa-Tocachi et al., 2019). However, a third study in the same location using modeling reported no changes (Ertsen & van der Spek, 2009). Infiltration trenches increase the volume and the rate of infiltration, as reported by both modeling and observational studies, for both volumes and rates. However, the only global literature review on infiltration trenches highlighted a knowledge gap regarding their impact on infiltration, only suggesting that there may be an increase because of a decrease in runoff (Locatelli et al., 2020). Some studies provide details on the rates of increased infiltration, which might also be dependent on the local water table, with the highest infiltration rates occurring when evapotranspiration is active and groundwater elevation is low (Mullins et al., 2020). Terraces have a more variable impact on infiltration according to the literature. One of the literature reviews (Willems et al., 2021), which was performed on a global scale, and two studies reported increases in infiltration. Yet, a study conducted in a tropical plain found hardly any impact on infiltration (Agnihotri & Yadav, 1995), and another found that the impact was mostly dependent on the crop (Qian et al., 2014). Finally, one study pointed out that the spatial distribution of infiltration capacities is controlled by the terrace patterns, being maximal in the outer parts of the terraces and minimal (even nonmeasurable) in the inner parts, where the deeper horizons of the soils are exposed (Gallart et al., 1997).

4.3 | Evaporation and transpiration

In afforestation and reforestation, the forest canopy intercepts a substantial amount of water that later evaporates, with the highest evaporation occurring during short, low-intensity storms and the lowest when rainfall volume and intensity increase (Bonnesoeur et al., 2019; Kirnbauer et al., 2013; Kuehler et al., 2017). Most studies and literature reviews focusing on the impacts of afforestation and reforestation, both global and regional, conclude that there is an increase in evaporation and transpiration after the implementation of NbS (Hou et al., 2023; Nadal-Romero et al., 2023; Ponette-González et al., 2014), but that this also depends on the species of trees used for the afforestation (Siriri et al., 2013). However, during European summers, a decrease in evaporation is found for afforestation over grasslands, due to the higher surface roughness of forest canopies and the more efficient transformation of solar radiation into turbulent sensible heat fluxes. These factors lead to lower surface temperatures that counteract the transpiration-facilitating characteristics of forests (Breil et al., 2021). For reforestation, there is consensus that this intervention increases evaporation and transpiration (Figure 2), but some studies argue that there is no modification of these fluxes, and that any increases might depend on different types of precipitation events (Krishnaswamy et al., 2013; Page et al., 2020). This means that the impact depends on the catchment climate, i.e. whether the occurring precipitation is, for instance, convective or stratiform.

Most studies on wetlands agree that they increase evaporation and transpiration (Amiri et al., 2022; Mohamed et al., 2012; Queluz et al., 2018; Rodríguez-Morales et al., 2019; Valois et al., 2020; Wong et al., 2017). Some studies also point out that the effect depends on the plant species growing in the wetland (Milani et al., 2019). Studies on micro-reservoir impacts on evaporation and transpiration are still lacking. Some studies report no significant changes, for instance in tropical savanna climate with rain water harvesting at different places in the catchment (Van Meter et al., 2016), while others report significant increases in semi-arid catchments with a single micro-reservoir (Perrin et al., 2012). For diversion canals, one study suggests no effects on evaporation and transpiration using modeling (Ertsen & van der Spek, 2009). For terraces, only two modeling studies find an increase in evapotranspiration while an observational study suggests no effect. In their global review, Willems et al. (2021) report only a probable increase in evaporation.

4.4 | Floods and droughts

Various studies on afforestation, carried out in different climatic and geographic conditions, agree on a reduction in the number of floods as well as on a delay and reduction in peak flow (Alves & Formiga, 2019; Bonnesoeur et al., 2019;

Buendia et al., 2016; Mihalcea, 2017). However, one study reports an increased magnitude of high flows and a higher risk of flooding brought about by afforestation with fruit tree planting in a subtropical catchment of about 10 km² (Xu, Liu, et al., 2019). An increasing severity of droughts has been reported for most catchments, yet this trend is not consistent across all regions; specific catchments, such as those in subtropical areas, have not experienced any significant changes in drought conditions (Farley et al., 2005; Xu, Liu, et al., 2019). Although the general consensus seems to be that reforestation decreases floods and peak flow (Bonnesoeur et al., 2019; Bruijnzeel, 2004; Kabeja et al., 2020), a few studies that focused specifically on drought reported opposite trends (Galli et al., 2021; Xu, Liu, et al., 2019). Wetlands in headwater catchments are found to increase floods and droughts in Africa (Acreman et al., 2021). In urban areas, on the other hand, wetlands are found to decrease peak flows up to 70% (Conn & Fiedler, 2006; Jenkins et al., 2012; Liao et al., 2017). Additionally, Andean wetlands (*bofedales*) are found to buffer floods (Valois et al., 2020), and this also occurs in New England where the wetlands increase the residence time of surface water (Watts et al., 2023). However, knowledge on the effect of wetland restoration and construction on droughts is still missing.

There is agreement in the literature on the role of micro-reservoirs in decreasing floods. However, sometimes micro-reservoirs do not mitigate floods at the catchment scale but at the local scale, such as in the Netherlands (Costa et al., 2021). In small to medium-sized catchments in Hungary and Slovenia, the effect on decreasing floods is limited (Ferk et al., 2020), while in Ethiopia, in a medium-sized catchment, the effect reduces peak flow by up to 17% (Guyassa et al., 2017) and even by up to 60% in small Chinese catchments (Yuan et al., 2019) or 90% in urban areas (Liao et al., 2017). Diversion canals might reduce drought periods since they increase baseflow and the residence time of shallow water on hillslopes (Ochoa-Tocachi et al., 2019). There is no quantification of the influence of infiltration trenches on droughts. However, regarding floods, modeling studies do not seem to find any impact, although one observational study in Colombia reported a reduction (Cubides & Santos, 2018). According to the results of one review and two studies (Romero-Díaz et al., 2019), terraces lead to a decrease in floods, whereas, another review concludes that there are not enough data on the effect of terraces on floods (Willems et al., 2021). However, three studies found an increase in floods, in the Pyrenees; the magnitude of floods increased with the use of abandoned terraces (Gallart et al., 1994, 1997; Llorens et al., 1992). We did not find any quantification of the impact of terraces on droughts.

4.5 | Additional water-related benefits

Our review has focused on how NbS modulate the hydrological processes within a catchment as a way to enhance downstream ecosystem services related to water quantity. However, various NbS produce several other water-related benefits that are out of the scope of this study. Nonetheless, we briefly summarize the most important benefits related to water access and quality. For local water access, examples are direct water extraction from micro-reservoirs and diversion canals for irrigation of high-Andean wetlands (Monge-Salazar et al., 2022), livestock watering systems, and domestic use of water. For water quality, wetlands are widely recognized as buffers (Kingsford et al., 2016; Verhoeven & Setter, 2010). This includes processes such as decreasing the sediment yield (Acreman et al., 2021), reducing bacterial loads, and removing micropollutants, microplastics, antibiotics, and a variety of water contaminants in a wide range of ecosystem environments (Álvarez-Rogel et al., 2020; Ávila et al., 2021; Haddis et al., 2020; Jamwal et al., 2021; Sossalla et al., 2021; Wang et al., 2020). Micro-reservoirs can have similar functions (Ferk et al., 2020; Quin & Destouni, 2018), while the impact of infiltration trenches is mostly restricted to nutrient removal (Yano et al., 2019). Lastly, reforestation can mitigate hillslope soil erosion and stream bank erosion which in turn decreases sediment yield (Acreman et al., 2021; Eekhout et al., 2020; Zaines et al., 2021).

4.6 | Limitations and risks

The implementation of NbS may also lead to undesired hydrological outcomes, including the creation or enhancement of hydrological risks. For instance, wetlands need careful (local) management and maintenance to prevent flood peaks from increasing (Kingsford et al., 2016; H. Li, 2015). The long-term extension of wetlands is also challenging and often requires long-term sustainable management by local communities including protection and investments (FAO, 2022; Monge-Salazar et al., 2022). This is a particularly critical point, as the restoration of dried-out wetlands and the artificial extension of wetlands is a long-lasting and challenging process (Verzijl & Quispe, 2013). Micro-reservoirs can produce chemical or biological contamination of the groundwater (Ferk et al., 2020; Massoudieh et al., 2017). If micro-reservoirs

are abandoned or under poor management conditions and low investment, they are at risk of destabilizing the hydrological and agricultural system and even increasing the chances of floods and droughts (Ferk et al., 2020). Check dams suffer from a similar problem of decommissioning, as they are short-lived interventions (Shi et al., 2019).

The construction of infiltration trenches, despite their function of decreasing soil losses by erosion on the long term, can also cause a temporary increase in slope erosion, with an increase in sediment concentration in catchment outflow for up to 2 years (Guzman et al., 2017). Moreover, infiltration trenches are often filled with sediments within a few years, which decreases infiltration capacities and requires long-term strategies and maintenance (Locatelli et al., 2020). For instance, studies in Ethiopia and Mexico reveal that infiltration trenches lost efficiency after only 2–3 years and 11 years, respectively, due to high sediment deposits. In addition, few studies have analyzed the effect of abandoned infiltration trenches with high sedimentation, or of hillslopes with low infiltration capacity, on the infiltration capacities of infiltration trenches. Reduced infiltration can lead to water ponding damaging the trenches and increasing evaporation rates (Locatelli et al., 2020). Terraces potentially face similar issues with long-term maintenance, including negative effects on water regulation and soil degradation, when lacking appropriate management (Willems et al., 2021).

5 | DISCUSSION

This study synthesizes the current scientific knowledge of the hydrological impacts of different NbS types through a scoping review. Despite the complex nature of a wide range of NbS types and the limited evidence available, consensus in observations and process understanding can be found regarding some key hydrological impacts. For instance, micro-reservoirs and the restoration of natural vegetation cover tend to decrease runoff and low flows, while diversion canals and irrigated wetlands increase infiltration rates. However, for most hydrological impacts of NbS, clear and consistent specific evidence is still lacking due to missing or ambiguous data on specific intervention types and catchment processes or due to unclear results.

Another limitation relates to the fact that the definition of NbS tends to be a broad and sometimes vague concept, which is often used as an umbrella term to highlight the similarity of various conservation approaches, such as natural infrastructure, blue and green infrastructure, or natural solutions (IUCN, 2020a). This overlapping and inconsistently applied terminology hampers reliable analyses of the impact of NbS under a unified modeling framework across research fields. Besides, our definition of a common NbS typology excludes some NbS intervention types, particularly those which have emerged in the past few years. For instance, in Northern India, ice stupas were developed to limit the negative impact of rapid glacier retreat on local water availability. Ice stupas consist of the construction of ice reservoirs during winter that will melt in the spring when agriculture depends on irrigation (Nüsser et al., 2019). This NbS intervention matches with the water harvesting type of intervention, but it has not yet been described as a common NbS type. Green infrastructure, such as green roofs and permeable pavements, are gaining traction in urban water management, but they are not investigated at the catchment scale. Additionally, in this review, we did not select NbS that primarily focus on water quality, but we acknowledge the influence of the selected NbS on it.

Moreover, several specific hydrological impacts are barely understood including both the benefits and the adverse or undesired outcomes of NbS interventions. Modeling these impacts would therefore inevitably result in high uncertainties. As an attempt to quantify these uncertainties, we gathered information from various literature reviews and studies. Nonetheless, we had to exclude the often ambiguous or unknown effects of NbS on precipitation. Yet, some studies state that, for instance, reforestation might increase precipitation over South Asia (Bruijnzeel, 2004), or that evaporation from wetlands in South Sudan would enhance rainfall in the Ethiopian Highlands (Acreman et al., 2021). From a modeling and assessment perspective, further research and model improvements are needed to evaluate the specific hydrological impacts of NbS, considering different hydroclimatic and ecological environments. Our study therefore represents a first attempt to improve systematic assessments and future evidence bases of the specific benefits and risks of NbS implementation for improved catchment management and adaptation in view of the increasingly adverse impacts from global change.

An improved understanding of NbS catchment impacts and a successful long-term implementation requires further efforts. This includes stakeholder and citizen involvement in NbS co-design with novel approaches to hydrological data collection and participatory methods (Pagano et al., 2019) in order to increase local relevance and knowledge co-production (Baiker & Farfán Flores, 2023; Buytaert et al., 2014; Oshun et al., 2021). Additionally, assessment models for the potential location of NbS in the catchment need to be further developed (Al-Khuzai et al., 2020) including a better understanding of their impacts in a changing climate (Alamdari et al., 2018). Such an approach can help to

achieve and to maximize the principal benefits expected from NbS such as climate resilience, human health, and well-being, which are systemic strategies associated with the adoption of a participatory approach. This has the potential to increase local communities' autonomy over water resources, thereby contributing to co-production of diverse knowledge and water sustainability.

6 | CONCLUSION

Successful implementation of a variety of NbS types for adaptive water management depends on the specificities of each NbS, which requires consideration of appropriate locations, dimensions, and construction materials within a wider catchment context. In this study, we provide a synthesis of the specific benefits, impacts, and knowledge gaps related to NbS.

Reforestation and afforestation interventions affect the evaporative fluxes through transpiration and interception. Their impacts on soil infiltration and runoff generation can be complex and need to be assessed according to vegetation type and density, soil type, and soil moisture dynamics. However, subsurface flows and deep percolation tend to be limited and might be neglected in specific contexts. Wetlands increase baseflow, promote evaporation, and decrease the potential of floods and droughts. The residence time of infiltrated water is likely to depend directly on the depletion induced by drought and is therefore a key characteristic that needs to be assessed for the quantitative evaluation of the catchment-scale impact of these wetlands in order to evaluate the hydrological benefits of such an intervention. Micro-reservoirs generally enhance surface storage, retention, and evaporation rates. From a management perspective, undesired increased evaporation can be offset by additional surface storage where possible. Evaporation rates tend to scale linearly with the number and size of reservoirs implemented in the catchment and this function can be used to maximize storage benefits at the lowest evaporative losses. In addition, permeable micro-reservoirs can increase baseflow. Diversion canals seem to efficiently infiltrate water, with an increase in low flows. Major process-uncertainties relate to the partitioning of evaporation and recharge as well as to the residence time of subsurface flows. Such analyses have barely been performed and they are complex particularly when multiple flow pathways occur, such as shallow hillslope flow and deep percolation. Infiltration trenches reduce runoff but their capacity to increase infiltration remains highly uncertain and site-dependent. These intervention types can include undesired outcomes, including losses from soil erosion and evaporation. The specific effects on erosion, evaporation, subsurface flows, and residence times are not well understood for infiltration trenches, and their quantification them in a model will therefore be highly uncertain without local field data. Terraces increase infiltration which is particularly important for their agricultural purpose, and their effect is more straightforward to estimate or quantify. Their impact on evaporation is complex and depends on the location (exposure to the sun) of the terrace with different micro-climatic conditions and land use. The magnitude of subsurface flows and deep percolation mainly depends on the terrace structure and geology.

An improved understanding of NbS catchment impacts and a successful long-term implementation of NbS require further efforts. These include stakeholder and citizen or community involvement in NbS co-design and knowledge co-production with novel data collection and participatory approaches in order to support locally relevant adaptation strategies and to increase water security on the long term.

AUTHOR CONTRIBUTIONS

Morgane Lalonde: Data curation (equal); formal analysis (equal); methodology (equal); writing – original draft (lead); writing – review and editing (equal). **Fabian Drenkhan:** Conceptualization (equal); methodology (equal); resources (equal); supervision (equal); writing – original draft (equal); writing – review and editing (equal). **Pedro Rau:** Resources (equal); writing – review and editing (equal). **Jan R. Baiker:** Resources (equal); writing – review and editing (equal). **Wouter Buytaert:** Conceptualization (equal); methodology (equal); resources (equal); supervision (equal); writing – original draft (equal); writing – review and editing (equal).

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CONFLICT OF INTEREST STATEMENT

There is no conflict of interest.

DATA AVAILABILITY STATEMENT

Data sharing is not applicable to this article as no new data were created or analyzed in this study.

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