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Review

Enhancing Groundwater Recharge Through Nature-Based Solutions: Benefits and Barriers

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Abstract: Nature-based solutions (NbSs) for water involve using or mimicking natural processes to contribute to the improved management of water. Although NbSs are gaining a significant amount of scientific attention, to ensure their wide usage for enhancing groundwater recharge, there is a need for clear documentation outlining their benefits and barriers. In this study, a systematic literature review was carried out to evaluate the application of NbSs for managing groundwater recharge. First, NbS approaches were classified into two broad groups: managed aquifer recharge (MAR) and ancillary recharge methods (ARMs). MAR includes all activities that intentionally enhance the recharge of an aquifer for later recovery, while ARMs include all the remaining NbSs wherein recharge enhancement is a secondary goal. In 50 out of 61 reviewed studies, MAR was reported to be successful in increasing recharge. However, in the remaining studies, reductions in recharge rates were reported. Most of the NbSs that failed to improve groundwater recharge were from the ARMs group. This group had little consensus among studies regarding the effectiveness of NbSs on groundwater recharge. In this study, we also identified opportunities and challenges, such as gaps in our knowledge of NbSs' effectiveness, their assessment in long-term, cost–benefit analysis and scalability. Addressing these challenges will further enhance the efficiency of NbSs, which indeed is a promising alternative for enhancing groundwater resources.

Keywords: nature-based solutions; ancillary groundwater recharge; managed aquifer recharges; effectiveness

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1. Introduction

Groundwater recharge is the downward movement of water that reaches the water table and replenishes groundwater storage [1]. Recharge occurs through diffuse and focused mechanisms [1]. Diffuse recharge occurs over large areas, often due to rainfall or melt, as soil water input infiltrates the soil and percolates into the water table. In contrast, focused recharge involves leakage from surface water bodies to an aquifer and tends to be localized and more spatially variable. In both these mechanisms, the recharge flux rate is largely driven by the head gradient and substrate hydraulic properties. Overall, groundwater recharge is one of the most important flux components determining the sustainability of aquifers. Estimation of contaminant transport into the subsurface is also critically dependent on reliable estimates of groundwater recharge. Despite its crucial importance, recharge estimates remain highly uncertain [2–6], both due to the challenges with measurements over large areas [1,7–9] at high spatiotemporal resolutions and due to parameterization and model structure errors inherent in subsurface components of hydrologic models [10–14]. With the continued depletion of groundwater in different regions of the world [15–17], there has been a dash for approaches to replenish groundwater recharge [18–24].

Nature-based solutions (NbSs) are one of the promising approaches for enhancing and/or sustaining groundwater recharge. According to Cohen-Shacham et al. [25], NbSs are interventions to protect, sustainably manage and restore natural or modified ecosystems.

NbSs encompass many previously known interventions and emerging solutions. For recharge, NbSs include methods that use or mimic natural processes for the management of recharge or mitigating risks to it. They have been gaining increased attention, in part due to their perceived environmental sustainability, climate resilience and, in some instances, also for the ancillary benefits that they can potentially provide. While NbSs for enhancing recharge have been studied in different parts of the world [26,27], there is a need to comprehensively study their effectiveness and understand the challenges and opportunities associated with them, especially with the goal of upscaling them for widespread use. This paper presents a systematic review of the effectiveness of NbSs for enhancing and/or sustaining groundwater recharge. This study aims to address three key questions: (1) How effective are different NbSs in recharging groundwater? (2) What are the key challenges that limit the widespread application of NbSs for groundwater recharge? (3) What opportunities exist to tackle the identified challenges?

This paper is organized into the following sections: Section 2 provides the review protocol followed by the comprehensive literature review of NbSs to improve groundwater recharge. A description of NbS concepts, their types and reported effectiveness are presented in Section 3. A summary and analysis of the reviewed papers, grouped by the types of NbSs they focus on, is also included. Section 4 presents key issues and challenges associated with different NbSs. It also outlines the current trends in NbSs for groundwater recharge improvement and gives perspectives on its future use. Finally, Section 5 details the conclusions and the path forward.

2. Literature Review Protocol

We performed a systematic literature review to identify, screen and filter peer-reviewed articles from the Scopus database. The search terms used in the database are as follows:

(((KEY (“groundwater recharge” OR “groundwater level”) AND TITLE-ABS KEY (“Nature based solution” OR “Nature based solutions” OR “nature-based solutions” OR “infiltration basins” OR “infiltration canal” OR “infiltration trenches” OR “sand dam” OR “sand storage dams” OR “wetlands” OR “forest” OR “trees” OR “terraces” OR “utfi” OR “field recharge” OR “ditch” OR “induced filtration” OR “spate irrigation” OR “crop rotation” OR “rotational cultivation” OR “tillage” OR “grasslands” OR “natural vegetation” OR “paddy fields” OR “hillslope trenching” OR “managed aquifer recharge” OR “Conservation” OR “restoration” OR “Enhancement through sustainable management” OR “low intensity grazing” OR “forest management” OR “vegetation management” OR “green infrastructure” OR “permeable surface” OR “riparian buffer” OR “floodplain restoration” OR “Agroforestry” OR “rainwater harvesting” OR “grazing management”) AND NOT TITLE-ABS-KEY (“quality” OR “Soil invertebrates” OR “recharge sites” OR “suitable sites” OR “linings” OR “nutrient” OR “land use change” OR “spectroscopy” OR “solvent” OR “dissolved oxygen” OR “potential sites” OR “chemical” OR “carbon dioxide” OR “sulphate” OR “hydrogen” OR “machine learning” OR “chloride” OR “phosphate” OR “valuing” OR “mineralization” OR “hindcasting” OR “LULC”)))).

Here, KEY field stands for keywords. It allows for searching for specific terms in the keywords of a document. The keywords are usually assigned by authors or generated by the publisher. The TITLE-ABS-KEY field searches for terms in the title, abstract and keywords of documents. This broadens the search but keeps it targeted to the aforementioned sections of a paper. OR, AND and NOT are the logical operators to broaden and/or narrow down the search domain defined based on the keywords.

A search based on the aforementioned query resulted in 699 peer-reviewed articles and gray papers. The trends of the most common words in the title, abstract and keywords of the identified articles were processed using the Biblioshiny web page [28], which was accessed through RStudio (version 2022.02.3)and the Bibliometrix library. As shown in Figure 1, the usage rate of most terms significantly increased, starting in the late 2000s. This is unsurprising, as several studies in recent decades have performed detailed assessments of groundwater drought and depletion hot spots [15,16,29]. Additionally, there has been a growing emphasis on finding sustainable solutions [22,30–33].

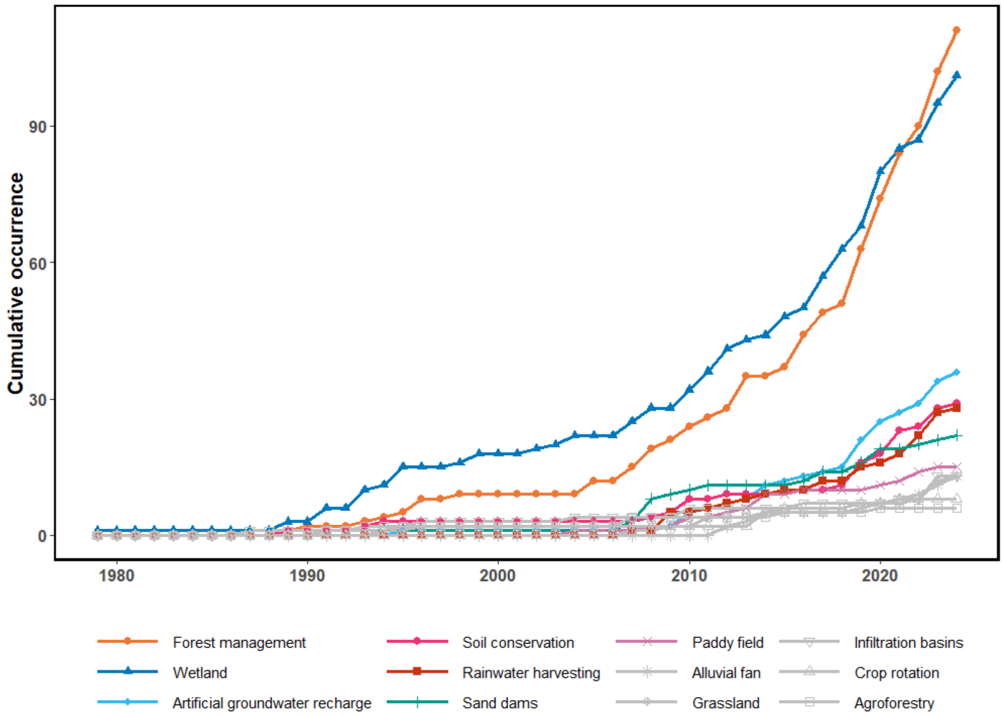

Figure 1. Cumulative occurrence of phrases in keyword, title and abstract of the total identified articles. The most frequently used search terms are plotted here.

After gathering the 699 articles, those that were directly related to our study objective were manually selected. The result of the selection is shown in the PRISMA flow diagram below. Figure 2 shows the number of articles removed and/or included while screening the identified articles. We reviewed the articles' keywords, titles and abstracts and found 61 articles to be eligible for full-text review. Some of the eligibility criteria for inclusion of articles in this review included the following: the article considers a conservation measure that fulfills the definition of NbSs set by our study, the effectiveness must be measured quantitively with sound methods and only already implemented NbSs, not mere proposals of such, should be considered.

A full-text review of each of the 61 articles was carried out to extract data. Studies that quantified the change in recharge rate due to NbSs application were thoroughly examined. Each paper was reviewed individually to extract specific features such as type of NbS deployment status, description of study area, size of intervention, main objective of the NbS, geographic area, scale of study (e.g., continental or basin scale, or a pilot study), source of water, effect on groundwater recharge and methods for response measurement/performance assessment. The 35 countries covered by the reviewed papers are shown in Figure 3. Despite our efforts to ensure comprehensiveness by utilizing the global Scopus database and considering a wide range of NbSs, it should be noted that certain regions, including Russia, Scandinavia and large areas of Africa and South America, remain under-represented in this study.

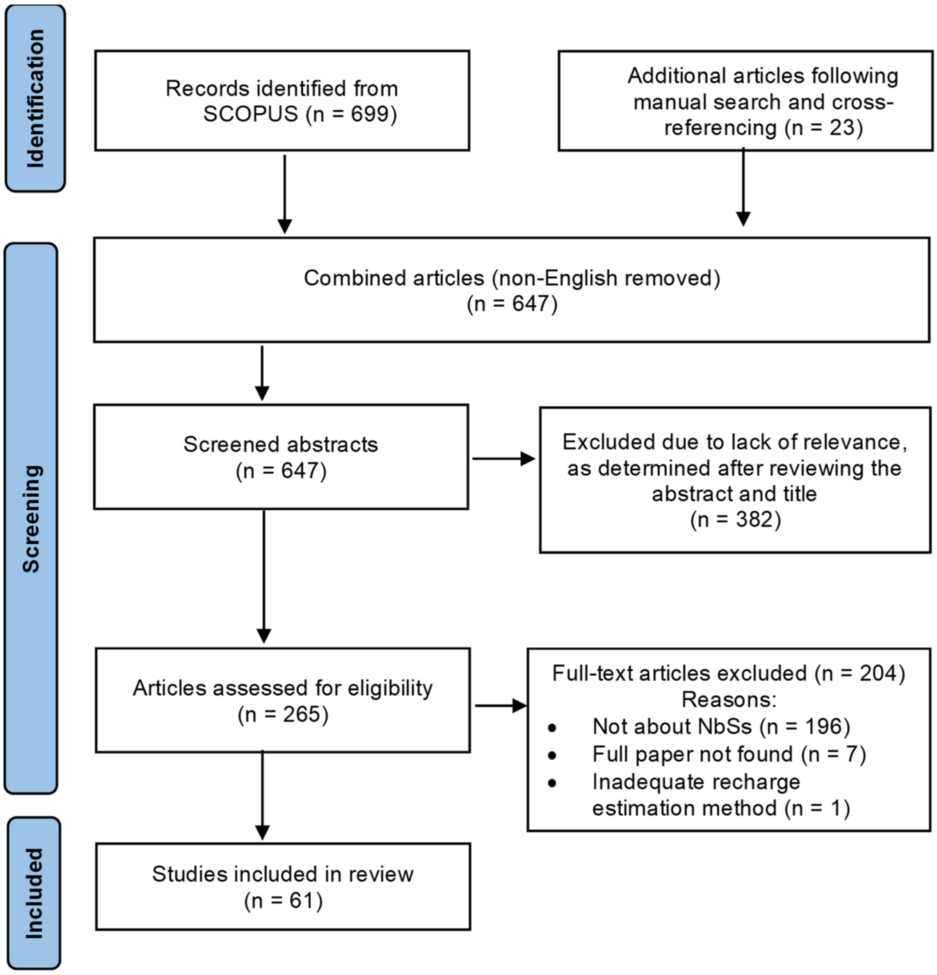

Figure 2. PRISMA flow diagram describing the different phases of the literature review.

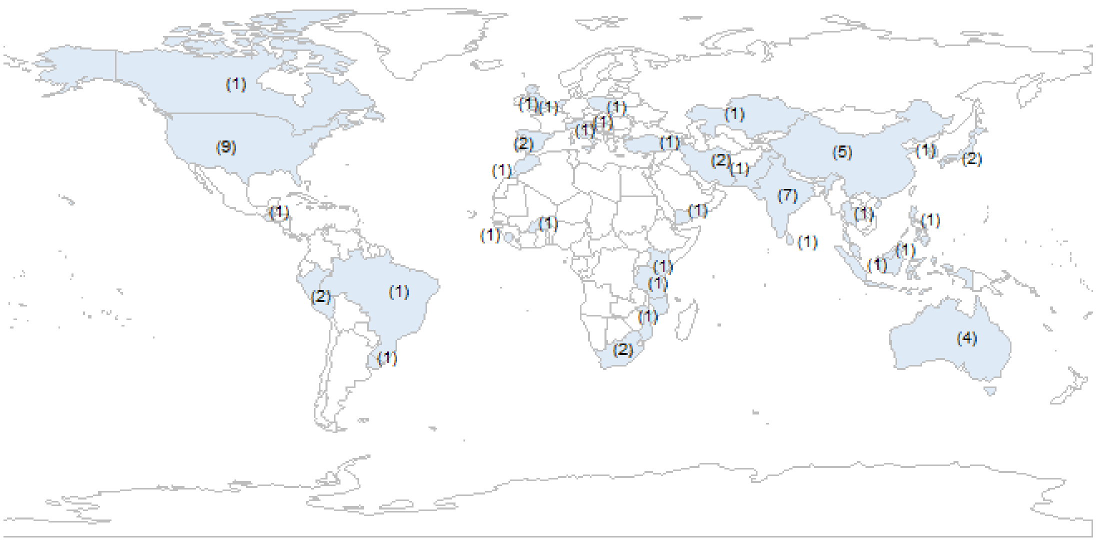

Figure 3. Spatial map of the study areas with the number of reviewed papers per country.

3. NbSs for Groundwater Recharge: Approaches and Their Effectiveness

As defined by the European Commission [34], NbSs are solutions inspired and supported by nature that are cost-effective and capable of simultaneously providing environmental, social and economic benefits and helping build resilience. In this review, we focus on two broad approaches of NbSs for aquifer recharge: managed aquifer recharge (MAR) and ancillary recharge methods (ARMs). MAR includes solutions specifically designed to intentionally enhance groundwater recharge as its primary goal [35]. In contrast, ARMs include all the remaining NbSs that are not primarily intended to improve groundwater recharge but still offer this benefit nonetheless. Previous studies [36,37] have used different approaches to quantitatively estimate the contribution of NbSs to groundwater recharge. Methods of assessment include long-term monitoring of groundwater table/recovered water volume, water balance analysis, stable isotopes and chloride balance, field investigation such as lysimetry and modeling. In the following sections, we briefly describe examples of the two NbS approaches for aquifer recharge, discuss how they lead to recharge improvement and highlight the methods used to assess their effectiveness.

This section has multiple subsections and provides a concise and precise description of the experimental results, their interpretation, as well as the experimental conclusions that can be drawn.

3.1. Managed Aquifer Recharge (MAR)

MAR is the type of NbS with a deliberate target of recharging aquifers. The recharged water could be recovered to fulfill water demand or serve as an environmental benefit [30,38,39]. Even though the major objective of MAR is to increase groundwater storage and minimize the temporal imbalance of water availability and water demand, it may also be used to mitigate saltwater intrusion in coastal aquifers [38,40], improve treated wastewater quality through soil aquifer treatment (SAT) and manage large-scale issues like land subsidence [41]. Globally, MAR projects are increasing in number by around 5% each year and currently, MAR has reached an estimated capacity of 10 km^3/year [30].

Types of MAR solutions that not only rely on built structures but also on natural systems fall under the vast umbrella of NbSs. These types of MAR typically make use of one big natural infrastructure, the aquifer. Even though NbSs are a relatively newer concept, MAR has been practiced for a long time, and different types and modifications of it exist. According to Dillon et al. [30], MAR can be classified into four major groups based on their objectives and the type of method used to achieve the objective. These are the spreading method, induced bank filtration, in-channel modification and artificial well/shafts/borehole recharge. Only the first three are considered in our study since those are the ones that heavily rely on natural processes and natural infrastructure. More details on these three different techniques, their advantages, limitations and overall effectiveness are summarized below.

3.1.1. Spreading Method

This method refers to the MAR application wherein water is infiltrated from the land surface to the underlying aquifers. There are different schemes of spreading the water such as infiltration basins with diverted water (infiltration ponds), buried trenches in the unsaturated zone to enhance infiltration (infiltration ditch), crops irrigated in excess or diffuse land infiltration by diverting flood water to specific areas (field infiltration). The spreading technique of MAR is the most versatile method. The water can either be retained in infiltration ponds or released to lands that are primarily used for other purposes. The spreading method is characterized by high area requirements, cost-effectiveness and high operational efficiency. It is the most commonly used type of MAR [30]. Using the spreading method, dune infiltration basins in the Netherlands managed to push back a seawater wedge, which helped the city to improve the water quality [42]. Although no quantitative assessments were reported, according to the operators of the scheme, this mitigation effort can serve for the coming centuries. This estimate aligns with other studies that have used physical and numerical models to show the reliable efficiency of the spreading method. When it comes to large-scale NbS applications, there are other alternative implementations of the spreading method, such as underground taming of floods for irrigation (UTFI).

UTFI recharge rate is two to nine times higher than the performance of infiltration ponds alone [43]. Strategically located UTFI schemes, such as upstream of major flood-prone areas, can not only readily recharge aquifers but also control downstream flooding [44,45].

Long-term measurement of recovered water volume has shown the high performance of the spreading method in sustaining the city's water supply demand over the last two decades [46]. The source for this recharge scheme is treated wastewater, which has helped to close water and other nutrient cycles. Groundwater level analysis before and after MAR scheme at installation in Iran showed that infiltration ponds helped to slow the rate of groundwater level decline [47], which further confirms the success of this technique in enhancing groundwater recharge. In another study, using monitoring well data, Iwasaki et al. [48] showed the positive impacts of field recharge on groundwater during the irrigation period. Mass balance around boundaries of the spreading system indicated more than 80% of inflow infiltrating in the subsurface [49]. In addition, model complemented mass balance analysis of the field recharge method has shown that declining groundwater level trends of up to 2.5 m/yr could be reversed through the spreading method of MAR. The study was carried out in Arizona and California using multi-decadal data from monitoring wells [50].

From all 61 implementations considered in this study, it was found that the spreading method failed only once in enhancing recharge [51]. A basin in Jordan showed no effect on recharge after two years of operation due to the clogging of ponds at earlier operation stages. Even though the success story of infiltration basins in increasing recharge is ubiquitous, clogging in the ponds has also been reported as a barrier to infiltration even at the early stage of the spreading system. While the latter stage of clogging is related to the design life of the ponds, early stage deterioration of infiltration rate is the result of poor characterization of hydrogeological structure and lateral heterogeneities [52]. This shows that the success of MAR can be highly site-specific. For instance, a previous study highlighted the need for comprehensive analysis before implementing an MAR system in a karst aquifer using the rechargeability index [53].

3.1.2. Induced Bank Filtration

In this method, water infiltrates from rivers and lakes to aquifers using hydraulic structures that induce vertical flow. The surface water loss is usually induced by a pumping well or weirs located a few meters away from the riverbanks. Natural filtration and attenuation occur as water moves in the subsurface. Induced bank filtration is usually used to improve water quality. There are several different studies regarding water quality improvement of induced bank filtration [51,54–58].

However, only a few of these studies performed a quantitative estimation of the contribution of bank infiltration to aquifer recharge [59,60]. This could perhaps be because the driving factor of induced bank filtration processes is water quality improvement rather than water storage [61].

Several factors control the success of induced bank filtration when they are intended as aquifer recharging schemes. Permeability of the river bed and bank formations, aquifer thickness, suspended matter of the surface water that could potentially accumulate and clog the riverbanks and bed [37] are some of the major factors that need to be considered to prevent rapid clogging. Due to the locally dependent efficiency of induced bank filtration and its potential for rapid clogging, previous studies have noted the restricted popularity [62] of this method despite being one of the oldest types of NbSs. Our review findings also align with this, as out of the 61 implementations we have reviewed (see Table 1), only two of them can be categorized as induced bank filtration. One additional study reported bank filtrate reduction immediately after flooding in induced bank filtration in Australia. However, the major objective of the study was to investigate the filter efficiency of the river bank [63].

Table 1. Papers reviewed in this study. Also noted are the NbS types (as discussed in Section 3), their impact on recharge and how the effectiveness was quantified.

NbS Type	Country	Hydrogeology/Hydrology	NbS's Main Target	Recharge	Effect Measurement Method	Year	Source
Sand dam	Kenya	Arid with erratic rainfall	livestock, irrigation	Improved	Groundwater level comparison	2013	[64]
Induced bank filtration	Slovenia	River with stable flow throughout the year	Groundwater recharge	Improved	Groundwater level comparison	2020	[59]
UTFI	India	Alluvial aquifer	Flood control	Improved	Relative mound height	2020	[43]
Infiltration pond	Iran	Overexploited aquifer	Mitigating drawdown	Improved	Mass balance/field measurement	2004	[49]
Infiltration system	Peru	Arid coastal region	Runoff harvesting	Improved	Tracer experiments	2019	[65]
UTFI	India		Flood control and recharge	Improved	Hydrologic simulation	2018	[45]
Forest patches	Indonesia	Tropical lowland/sandy clay loam soil	Ecosystem regulation	Improved	Hydrological model (SWAT)	2022	[66]
Trees	China	Semi-arid	Desertification prevention	Reduced	Field measurement/lysimeters	2021	[67]
Dune vegetation	China	Semi-arid region with deep aquifer	Erosion control	Reduced	Field measurement/lysimeters	2022	[68]
Trees	Guatemala	Tropical forestry pasture/scattered native trees	Erosion control	Improved	Isotopic measurement	2021	[69]
Infiltration pond	Iran	Alluvial aquifer in arid region	Flood control	Improved	Observed data from wells	2021	[47]
Paddy field	Japan	Confined alluvial aquifer	Improving farming system	Improved	Field measurement	2013	[48]
Infiltration pond	Netherlands	Coastal aquifer in dune area	Salt intrusion reduction	Improved	Insights of the scheme operators	2021	[42]
Continuous contour trench	India	Semi-arid watershed	Soil conservation	Improved	Hydrological modeling	2021	[70]
Trees	USA		Conserving natural forest	Improved	Water balance	2019	[71]
Trees	Burkina Faso	Semi-arid dryland with high rainfall condition	Agroforestry	Improved	Isotropic analysis	2020	[72]
Crop rotation	Spain	Semi-arid region	Soil fertility	Improved	Modeling/Water balance	2010	[73]
Grassland	USA	Unconfined aquifer	Soil erosion control	Reduced	Water table fluctuation (WTF)	2019	[74]
Ponds	USA	Intrusive rocks with moraine deposits	Conservation measure	Improved	Water balance	2011	[75]
Tree	USA		Afforestation	Declined	Chemical tracers	2015	[76]
Tree	South Africa	Sandstone/shale rock aquifer in subtropics	Conserving natural forests	Improved	Modeling using Hydrus 2D	2019	[77]
Crop rotation	Japan	Upland crop-rotated paddy fields/sandy aquifer	Improving farming system	Declined	Modeling using Hydrus 1D	2014	[78]
Phase farming with trees	Australia	Mediterranean/precipitation in growing seasons	Improving farming system	Declined	Numerical model	2006	[79]
UTFI	Thailand	Shallow alluvial aquifer	Flood control	Improved	Long-term measurement	2012	[44]
Trees	India	Highlands agro-ecological zone	Afforestation	Variable	Field measurement/modeling	2021	[80]
Infiltration pond	Spain	Alluvial aquifer prone to salt intrusion	Groundwater recharge	Low rate	ERT survey	2020	[52]
Bank filtration	Italy	Sand/gravel aquifer	Groundwater recharge	Improved	Numerical modeling	2020	[60]
Spate irrigation	Yemen	Unconfined, coastal quaternary aquifers	Irrigation	Improved	Water balance	2010	[81]
Trees	Australia		Logging and regeneration	Variable	Groundwater level	1988	[82]
Crop rotation	Pakistan	Arid region	Regenerative farming	Improved	Energy balance/modeling	2021	[83]
Sand dams	South Korea		Storage of ephemeral river	Improved	Numerical model (MODFLOW)	2020	[84]
MAR	India	Semi-arid region with hard rock basalt aquifer	Groundwater recharge	Improved	Water table fluctuation	2020	[85]
Forest	USA	Karst aquifer	Forest management	Improved	Isotopic analysis	2016	[86]
Wetlands	Canada	Prairie regions	Eco-change tracking	Improved	Isotropic analysis	2020	[87]

Table 1. *Cont.*

NbS Type	Country	Hydrogeology/Hydrology	NbS's Main Target	Recharge	Effect Measurement Method	Year	Source
Terraces flood irrigation	China	Loess area in a semi-arid region	Erosion control	Improved	ERT survey, field measurement	2021	[88]
National forests	USA	Mixed hydrogeological unit	Conservation measure	Variable	Hydrologic simulations	2021	[89]
Traditional rice terraces	Philippines	Wet region with high annual precipitation	Sustainable farming	Improved	Long-term field measurements	2018	[90]
Afforestation	Uruguay	Temperate region with shallow aquifer	Forest expansion	Variable	Hydrograph separation/WTF	2016	[91]
Eucalyptus Plantation	Brazil	Unconfined aquifer with sandstone layers	Forest expansion	Declined	Water table fluctuation	2019	[92]
Sand dams	Tanzania	Semi-arid region	Groundwater recharge	Improved	Groundwater level	2020	[93]
Forest	Poland	Clayey sand aquifer in a compacted forest area	Conservation measure	Variable	Water table fluctuation	2014	[94]
Forest management	USA	Arid land forests	Wildfire suppression	Improved	Process and statistical modeling	2020	[95]
Paddy fields/ crop rotation	Kazakhstan	Arid region	Improved irrigation	Improved	Groundwater table fluctuation	2014	[96]
Hillslope trench	Peru	Steep alpine grassland with seasonal rainfall	Glacier retreat adaptation	Improved	Hydrological models	2018	[97]
Trees	South Africa	Alluvium aquifer in arid region	Conservation measures	Declined	Groundwater level	2013	[98]
Forest	China	Temperate desert, desert–oasis transition zone	Conservation measures	Declined	Water balance/measurement	2023	[99]
MAR	China	Phreatic aquifer with coarse gravel soil	Groundwater recharge	Improved	Process- and data-based models	2023	[100]
Forestry plantation	Australia	Undulating coastal plain of marine origin	Conservation measures	Reduced	Empirical models	2024	[101]
Biodiversity conservation	Mozambique	Gently undulating terrain with tributary streams	Conservation measures	Improved	Hydrogeological inverse budget	2023	[102]
MAR	USA	Alluvium floodplain with well-drained soil	Groundwater recharge	Improved	Numerical modeling (Hydrus)	2023	[103]
Flow path interception	UK	Poorly draining soil with lower water storage	Runoff attenuation	Improved	Hydrological mode (MIKE-SHE)	2022	[104]
MAR	Morocco	Alluvium and underlying fractured aquifers with rare but intense rainfall	Groundwater recharge and floodwater harvesting	Improved	Measurement of piezometric variations in groundwater table	2024	[105]
Underground dam	Turkey	Alluvium aquifer	Groundwater recharge	Improved	Numerical modeling	2023	[106]
MAR	India	Basaltic and alluvium aquifer	Groundwater recharge	Improved	Numerical modeling	2024	[107]
In-channel modification	Sierra Leone	Inland valley swamp	Rainwater harvesting	Improved	Field measurement	2020	[108]
MAR	India	Semi-arid region with sandy/loamy soil	Groundwater recharge	Improved	Numerical modeling	2022	[109]
Flood irrigation	China	Closed-drainage depression in arid region	Groundwater recharge	Improved	Numerical modeling	2021	[110]
Wetland	Australia	Semi-arid and suburban area	Stormwater management	Improved	Isotopic measurements	2017	[36]
Riverbank filtration	Malaysia	Shallow alluvial aquifer	Groundwater recharge	Improved	Isotopic measurement	2018	[111]
Cascade tanks	Sri Lanka	Alluvium aquifer on weathered bedrock	Storing runoff	Improved	Water table fluctuation	2018	[112]

3.1.3. In-Channel Modifications

Unlike the first two types, these types of MAR use interception techniques. A structure such as a dam is built in channels to intercept and retain water. In-channel modifications are hybrid systems with natural and built structures. Recharge dams, sub-surface dams, sand dams or check dams are commonly used types of dams. In our review, we included methods that highly rely on natural processes, such as infiltration. As the source for subsurface dams is groundwater itself, those are not included here.

The effectiveness of in-channel modifications on groundwater recharge has been assessed using numerical models and groundwater level field data [113]. In Kenya, hydrological processes around sand dams of arid regions have been modeled to assess their long-term impact on groundwater levels. Besides the approximation of the model used and assumptions made in the study, recharge improvement was highlighted [113]. The scope of their study was only assessing the relative improvement of recharge rather than quantifying it. Dashora et al. [114] estimated the mean annual recharge volume of structures with known capacities, such as sand dams, to be one to two times its detention capacity. Their studies were based on long-term farmer's water level records. All reviewed studies regarding in-channel modification reported groundwater table rise, although the extent of influence was variable based on seasons [115] and the site hydrogeology [116]. Indirect evaluation of sand dams' impact on recharge has been performed using vegetation cover as an indicator. In Kenya, areas with higher sand dam density have shown higher vegetation cover based on Normalized Difference Vegetative Index (NDVI) values [117]. Although check dams are not widely discussed in published articles [118], a recent review found that most check dams are effective in improving groundwater recharge [119].

3.2. Ancillary Recharge Methods (ARMs)

Alternative NbS approaches whose main goal is not to enhance the recharge, but may still provide ancillary benefits of enhancing recharge, include source water protection, watershed management, wetlands restoration, protection, construction, water harvesting, agricultural best management practices, afforestation, sustainable drainage systems and protecting mangroves [120]. Although most of the aforementioned NbSs may fall under the ARMs category, only those with enough groundwater recharge studies are included in this review. These are afforestation, wetlands restoration and regenerative agricultural practices that improve soil moisture. The selected ARMs and groundwater recharge responses to them are discussed below.

3.2.1. Afforestation

Afforestation has been used as a large-scale NbS not only for the water sector but also for land, biodiversity and agriculture disciplines. Trees can increase or decrease groundwater recharge according to their type, density, location, size and age [35]. For instance, Ilstedt et al. [121] showed how intermediate tree cover can maximize groundwater recharge in the seasonally dry tropical country in West Africa. The main method used in this study was groundwater budget modeling. However, the negative impact of eucalyptus trees on aquifer recharge has been repeatedly reported [76,92,122–124]. Chausson et al. [125] recently also highlighted that the eucalyptus tree plantation, used as an NbS in Portugal, has been uprooted due to its negative impacts on groundwater. In another case study that assessed the effect of heavy selective logging on the water resources, it was found that the water level rose immediately after logging, remained at an elevated but fairly constant level for three years and then declined again as the forest regenerated [82]. Silveira et al. [91] estimated change in groundwater recharge due to the substitution of natural grassland with forest plantation, by summing change in groundwater and stream base flow. By assuming that the variation in unconfined aquifer levels is only due to the groundwater recharge, change in groundwater storage was estimated using water table fluctuation data. Stream baseflow was found using the hydrograph separation method. Although stream discharge was reported to be less in the forested watershed, groundwater recharge was almost similar in both natural and forested watersheds. These results show the dynamic and non-linear response of the natural systems.

3.2.2. Wetlands

Wetlands have previously shown their potential to be an effective NbS by regulating flooding and securing water quantity and quality. However, studies about the relationship between wetlands and groundwater recharge have shown contradicting results.

Large-scale restoration and desilting of abandoned wetlands in the Godavari River basin has been found to have successfully stored water and recharged the aquifer to meet the agricultural demand of the community [126]. Similarly, Staes et al. [127] highlighted, using distributed hydrological models, how the restoration of wetlands promotes groundwater recharge. In the Mississippi alluvial plain, strong evidence from field measurements has highlighted that an Oxbow Lake wetland system was the primary source of groundwater recharge [128]. Another recent example is the application of wetlands for flood reduction and groundwater recharge in the Sponge City Construction (SPCC) of China. The SPCC in Jinan uses wetlands in the city as temporary stormwater storage space and later recharges groundwater through grass swales [129]. While these success stories and reports of wetlands acting as a "sponge" exist, depending on the different hydrological properties, location and type, sometimes these wetlands may act as a barrier to aquifer recharge [130]. In particular, headwater wetlands can saturate and rapidly convey stormwater to surface water. Moreover, many wetlands exist since they are on impermeable soil. Even if wetlands interact with groundwater, the direction of water movement between wetlands and aquifers was found to be interchangeable in different seasons [31,130]. However, for areas where wetlands are proven to be focal points for groundwater recharge, they have a significant economic value. Acharya and Barbier [131] highlighted that the reduction in recharge from wetlands could lead to substantial welfare losses for farmers.

The conflicting results of previous studies show that wetlands may not always recharge groundwater. Even in cases wherein successful groundwater recharge from wetlands is reported, most of the groundwater recharge could likely flow to the moist margins surrounding the wetlands rather than the regional groundwater levels [132]. These contrary results call for further studies that consider large-scale water fluxes and balance to understand these interactions better [132,133].

3.2.3. Regenerative Agricultural Practices

Land use and land cover change due to agricultural management practices alter groundwater recharge in both quantity and quality. Irrigation areas have a higher recharge rate than watersheds dominated by rainfed agriculture [134]. In addition to irrigation, other agricultural practices such as crop rotation and conservation tillage that improve soil moisture have been proven to be effective in recharging aquifers of different depths. Furthermore, traditional agricultural practices utilize physical storage units, such as tank cascade systems, to store water during the monsoon season, which has been found to enhance groundwater recharge [112,135].

Groundwater recharge increased from soil moisture improvement through the restoration of grassland and shrubs [61] or better management of irrigated fields such as using spate irrigation [81]. The effect of crop rotation on recharge rate has been studied using a semi-distributed model and it was found that the continuous rotation of crops with high irrigation rates and shallow roots increases recharge [136]. An isotopic fractionation study showed that the change of native grassland to wheat reduced groundwater recharge [64]. Recharge rate improvement due to cultivation and conservative tillage application has been reported as one explanation for long-term groundwater table rise in arid regions [137]. Conservation tillage changed the hydraulic properties of the top of the soil of the area which consequently affected the recharge rate. These variations show that generalization and assumptions about the ARMs' response on recharge should be avoided as it is highly site-specific and needs knowledge of hydrology and hydrogeology of the field to be deployed on.

4. Challenges and Opportunities

While several NbSs have shown a potential to improve groundwater recharge, their implementations still face challenges. The following subsections explore a few of these challenges and present opportunities to alleviate them.

4.1. Quantification of the Effectiveness of NbSs in Short and Long Term

Previous studies have mostly used groundwater levels and water budgets to monitor the effectiveness of NbSs for groundwater recharge [44,49,70,81,82,90,92,93,96,98,99,105,112]. However, significant uncertainties abound in the usage of these methods for quantifying the effectiveness of NbSs. For example, the water table fluctuation (WTF) method, which is often used to evaluate groundwater recharge, requires data on specific yield, a variable whose estimates remain highly uncertain [6,138–140]. In addition, factors that affect groundwater levels, other than recharge, such as pumping, tides and surface loads are often neglected in recharge estimation using the WTF method. This limitation significantly affects results for NbSs with active groundwater pumping, such as cascade tanks. A few other studies [88,117,141–143] have also used remote sensing tools, models and chemical tracers. In addition to models, indirect methods such as electrical resistivity analysis have also been used to complement the direct methods [52]. Depending on the remote sensing data choice and the scale of impact, remote sensing data fail to measure the effectiveness of NbSs on groundwater recharge. According to Eisma and Merwade [117], impact assessment using Gravity Recovery and Climate Experiment (GRACE) data could not detect any significant impacts of dams on water storage, likely due to the limitation of the spatial resolution of GRACE and/or the small magnitude of the sand dams' impact on groundwater storage.

Both data-based and physically based models have been used in the past to study wetland dynamics [144–150], which can be used to estimate dynamic groundwater recharge from wetlands. However, these models are often affected by uncertainties in model structure and parameterization [151–154]. Spatially explicit estimation is also often limited by computational demand [155,156], which can be significant especially while obtaining estimates for smaller-sized wetlands. Model results are highly sensitive to assumed boundary conditions. For example, ill-matched assumptions during model construction resulted in exaggerated water levels and impacts of sand dams [113]. Chemical tracer methods have limitations regarding input tracer and tracer transport process estimation [134,157,158]. Shamsuddin et al. [111] highlighted the advantage of integrating different methods while assessing the effectiveness of aquifer recharge by combining the result of stable isotopes and chloride mass balance.

The relationship between groundwater recharge and afforestation has been studied using methods such as water budget [71], groundwater fluctuation [91,94,98,99], hydrochemistry (stable isotope) [69,72,86] and mathematical models [89,95,101]. Other studies used a solute mass balance [76,159,160] and aquifer water budget [82,92]-based approaches to estimate recharge. Groundwater recharge, as the "residual" of water budget, is one of the most commonly used methods in the reviewed articles. Parameters in these methods, such as specific yield, are one of the major uncertainties of the approach. Individual components of the water balance are estimated through models or field measurements, such as using hydraulic structures and lysimeters [121,161].

Another challenge in the evaluation of the effectiveness of NbSs over the long term is the cost and effort associated with measuring these impacts over the analysis period. The fact that recharge varies temporally, and its pattern is affected by seasonal and long-term trends of climate, adds to the challenge. Performing such evaluations over large scales, at resolutions at which NbSs are applied, makes the endeavor even more challenging. Most studies we reviewed reported observations at plot scale and for the short term (<1 year). Although hydrodynamics models developed for catchment scale are less prone to plot scale measurement limitations, Kumar et al. [162] recently highlighted that these models hardly capture spatially discrete changes in the hydrological and energy balance that resulted from NbS implementation.

Opportunities exist to reduce the uncertainties of measurement methods' by using multiple methods of estimation [163–167] and scaling them over larger areas. Robustness of estimates of recharge using hydrologic models can be improved by constraining parameter uncertainties by using and/or assimilating data from various sources including in situ products and remote sensing [141,142], improving the representation of physiographic data [168] and through the reduction in structural constraints [169,170].

4.2. Scalability of NbS

To benefit a large number of people, NbSs must be applied at a larger scale or over a range of settings. However, both science and implementation challenges exist in this regard. For example, NbSs implemented to enhance aquifer recharge may be hindered by unfavorable geological and local environmental conditions within large areas. Moreover, the scalability of NbSs is often complicated by the complexities of planning and implementation. There is also a historical inertia against NbS upscaling, with the prevailing assumption that gray infrastructure is superior and faster. NbSs are still considered by many as a less efficient or risker than a gray system [35]. All of these factors restrict NbSs' upscaling, preventing them from reaching their full and significant potential. To alleviate the aforementioned challenges, there is a need to not only develop methods that can evaluate the effectiveness and efficiency of NbSs at different scales but also implement specific NbSs at various scales. This would allow for a more comprehensive understanding of the scientific, management, planning and economic challenges therein.

4.3. Lack of Stakeholders' Engagement and Collaboration

Broader stakeholder involvement and participation are crucial for the successful implementation of NbSs for groundwater recharge. When applied at scale, NbS success requires the involvement of various institutions and stakeholder cooperation. However, this is hard to achieve given that success stories at different scales are few and far between, which makes it difficult to be considered as a preferred option for stakeholders. Stakeholders generally prefer tested and conventional solutions, which makes building consensus among stakeholders hard. The problem is in a way compounded by the fact that the hydrological functions of aquifer-based NbSs are less understood, leading to their neglect in policy appraisal and planning. Capacity and knowledge must be enhanced by promoting research that fills this gap. This may raise stakeholder awareness of NbSs' potential and help NbSs become a part of policies and regulatory frameworks.

4.4. Cost

Although small-scale NbSs can be implemented for no or at a low cost, aquifer-based NbSs can be costly, especially at scale [171,172]. The general assumption about NbSs is that they are more cost-effective than gray (built) systems. A more efficient recharge scheme could be more sustainable and cost-effective than a built infrastructure such as dams. However, the overall management cost is influenced by the local landscape and its hydrological responses.

NbSs for groundwater recharge are often considered cost-effective, offering multiple co-benefits related to climate resilience, public health and job security. However, there is usually a threshold wherein an NbS reaches its optimum cost efficiency and ceases to return the large investment, particularly for NbSs at scale [173,174]. Before making broad assumptions about the cost-effectiveness of NbSs, a comprehensive assessment is required that takes into account not only the conventional cost–benefit terms but also hydrological and other co-benefits. Monetizing co-benefits has been stated as the greatest uncertainty in previous studies [175]. To reduce uncertainty, all involved stakeholder groups can potentially identify and quantify benefits and costs. Identifying the threshold and optimum mix of gray infrastructure and NbSs also calls for further research. Such research could possibly give common performance indicators and frameworks.

4.5. Lack of Guidance

Although new emerging NbSs are being implemented for groundwater recharge, there is a lack of data, information and documentation. Many new technologies with no documented manuals are being constructed at the pilot scale [35], which limits their adaptive capacity. In addition, methods, guidelines and evidence that justify investment and impacts of NbS schemes on groundwater recharge are rarely available. Tools and approaches that help to determine the optimum mix of gray infrastructures and NbSs for groundwater recharge are still lacking. These situations are the results of insufficient research and development in NbSs. Documenting investment, effectiveness and cost–benefit analysis of already deployed NbSs helps to have a well-established, capable and informed subsequent NbS planning and implementation. Moreover, standard regulations, technical guidelines and tools that are common and based on quantifiable benchmarks must be developed. This would facilitate the easy adaptability of NbSs for groundwater recharge. It is to be acknowledged that there could be cases wherein human-made infrastructure may be better suited than NbSs in enhancing recharge.

4.6. Uncertainties with NbSs

NbSs's effectiveness relies on the substrate ecosystem [176], which is dynamic in nature with a certain capacity threshold. A natural ecosystem's response changes over time and location. Due to this, the efficiency of the NbS varies from high to incompatible based on the location, climate and ecosystem type it is implemented in. Additionally, the performance of the NbS varies and is influenced by local hydrology, management and the overall ecosystem [34,35,177]. The box plot in Figure 4 shows the effectiveness and their range for different NbSs. It can be noted that there is little consensus among studies regarding the range of their effectiveness.

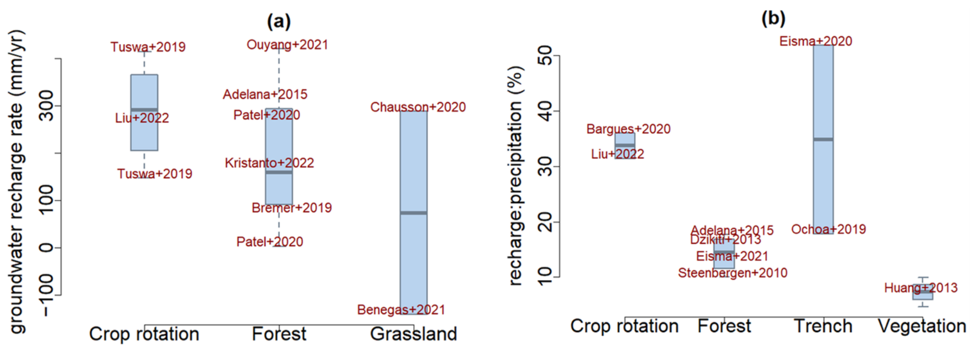

Figure 4. Mean effectiveness measurements of groundwater recharge from NbSs: (**a**) Annual groundwater recharge rate; (**b**) groundwater recharge to precipitation proportion in percentage. The *x*-axis labels in (**a**,**b**) correspond to the NbS considered in the reviewed studies. Forest category includes afforestation, forest restoration, forest management and tree cutting and thinning. Trench includes hillslope and contour trenching methods. The vegetation category corresponds to sand-stabilizing vegetation implementation. The labels of the data points in the box plots correspond to the citation of the studies being considered [64–66,68,69,71,72,77,81,85,89,93,98,117,122,125].

5. Conclusions

This study provides a comprehensive review of NbSs in improving groundwater recharge. The goals were to assess the effectiveness of NbSs as recharge enhancement methods, identify key challenges in their widespread applications and finally recommend opportunities to reduce the barriers.

Our review of 61 studies showed that NbSs have been successfully applied to increase groundwater recharge in most of the reviewed studies. The managed aquifer recharge approach had a positive effect on recharge consistently, while ancillary recharge methods had mixed results. However, large variations exist in the performance of the same or similar methods across studies.

Key barriers regarding the widespread implementation of NbSs have been identified, which includes challenges related to performance quantification, scalability and stakeholder engagement. This study underscores the uncertainties in determining the efficacy of NbSs on groundwater recharge, revealing substantial knowledge gaps regarding their long-term and large-scale impacts. In addition, as an emerging concept, NbSs face research gaps in areas such as scalability, cost–benefit assessment and lack of technical guidance and tools. Addressing these issues through further studies is crucial for a full successful use of NbSs in improving groundwater recharge. Despite these challenges, NbSs can be considered as a promising alternative for enhancing groundwater resources. Continued and improved planning and funding to support research on NbSs will enable a more robust quantitative basis regarding their effectiveness and costs across a range of scales, settings and methods. This should eventually lead to NbS design and implementation strategies with sound scientific evidence.

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