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Artificial recharge initiatives in India: Challenges and future scope

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ABSTRACT

Artificial recharge of aquifers is regarded as a fundamental supply-side strategy in India to address the prevalent issue of groundwater over-exploitation. Rainwater harvesting and artificial recharge are often implemented as cohesive sets of interventions because of the significant collateral benefits of rainwater harvesting. Central and state governments have implemented various schemes that incorporate rainwater harvesting and artificial recharge. Several studies are underway to investigate the optimal selection of construction sites, structural types, and designs based on local hydrogeology, groundwater flow patterns, terrain conditions, and water demand. These investigations aimed to assess the impact of these factors on resource replenishment and water quality enhancement. Studies have been conducted to determine the extent to which such initiatives yield socio-economic advantages. The discourse has encompassed crucial concerns, such as the accessibility of source water for recharge, conflicts between upstream and downstream stakeholders, and the increasing recognition of various demand-side measures for the sustainable administration of groundwater reservoirs. The paper highlights that there has been a rise in the number of studies regarding artificial recharge post-2020. Overall, this paper showcases the challenges for the implementation of artificial recharge structures with special focus on aspects such as site suitability, water quality concerns, operational problems and governance. The study also sheds light on the future scope of artificial recharge for the sustainable use of groundwater resources. More studies should be performed considering large-scale implications of artificial recharge structures considering resilience towards climate change and water quality and quality concerns.

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KEYWORDS GROUNDWATER RECHARGE, ARTIFICIAL RECHARGE, MANAGED AQUIFER RECHARGE, RAINWATER HARVESTING

HIGHLIGHTS

- The paper reviews the artificial recharge (AR) strategy of aquifers in India as a primary measure to combat the over-exploitation of groundwater.
- The review focuses on major issues: site suitability, water quality, post-construction challenges, and watershed-level impact assessment.
- The study focusses on the future scope and present development of artificial recharge for the sustainable use of groundwater resources.

1. INTRODUCTION

The expeditious and unregulated utilisation of groundwater has led to numerous challenges. The unrestrained exploitation of groundwater resources in various regions of the country has led to a depletion in groundwater levels and availability. Furthermore, the pristine quality of groundwater has been compromised. While the abundance of groundwater resources may appear ample at the state level, localised areas manifest adverse consequences from undue groundwater extraction. Artificial recharge mechanisms are employed to safeguard the sustainability of groundwater supplies. India's reliance on groundwater is unparalleled and highly significant in ensuring food and potable water security. According to recent estimations by the Indian Government, the nation extracted 248.7 km^3 of water from its aquifers in 2017. This quantity is the world's highest, exceeding the collective extraction of the United States and China (Saha et al., 2018). According to recent studies conducted by Malakar et al. (2021) and Singh et al. (2019), approximately 17% of the assessment units in India are characterised by over-exploitation, which occurs when the annual extraction of water surpasses the amount that is replenished to aquifers. The number of wells utilised for irrigation in the country increased from 62 lakh in 1986–87 to 205 lakh in the period of 2013–14. The extensive exploitation of groundwater has significantly reduced water levels and exhausted groundwater reserves in numerous regions in India (Saha et al., 2018). Rodell et al. (2009) conducted an international study utilising GRACE Tellus satellite data to evaluate the depletion of groundwater in the northwestern region of India, encompassing the states of western Uttar Pradesh, Haryana, and Punjab, as well as the adjacent Punjab province of Pakistan. According to Saha et al. (2018), most of the total extractions are attributed to irrigation, accounting for over 90%. Asoka et al. (2017) contended that the escalation in groundwater extraction in the nation could be attributed to the surge in demand and the irregularity of precipitation patterns resulting from climate change. The depletion of this crucial resource has necessitated the development of groundwater resilience by implementing strategies such as enhanced recharge and reduced extraction via water demand management. Such interventions are imperative for the preservation of Indian agriculture and the security of drinking water (Alam et al., 2020).

Artificial recharge has gained global recognition as a significant measure for enhancing groundwater reserves. The above-mentioned process augments the infiltration capacity by accelerating the infiltration rates or extending the source water's temporal availability. The primary water source for recharge is precipitation, specifically rainwater collected from surface runoff. Alternatively, they may also be sourced from canals or treated wastewater. The supplementary recharge process contributes to the overall availability of groundwater in both spatial and temporal dimensions. According to Scanlon et al. (2006), the natural recharge process is characterised by a slow rate. It typically ranges between 0.15 and 5% of the long-term average yearly precipitation worldwide in arid and semi-arid regions. Regions such as the Indus-Ganga-Brahmaputra plains exhibit a greater replenishment rate primarily due to increased rainfall, improved permeability, and enhanced aquifer storage potential (Bhanja et al., 2019). Empirical data suggests that adopting flood irrigation-based agricultural practices has increased natural recharge.

Nonetheless, these regions frequently exhibit a reduction in water levels due to unfettered agricultural groundwater extraction (Scanlon et al., 2006). This study aims to comprehensively analyse the existing literature, executed projects, relevant policies, and other pertinent documents pertaining to diverse facets of India's artificial recharge, its challenges and future scope. This study will help assess the past developments in artificial recharge and how the technology has advanced, integrating the multifunctional aspects of watersheds for overall ecosystem development.

1.1. Trends in the development of artificial recharge in India

The escalating significance of the artificial recharge may be ascribed to the mounting withdrawal of water from the aquifers and, therefore, has been categorised into four distinct phases within the Indian context. Phase I pertains to the period preceding the mid-1960s when groundwater use was restricted. Indigenous communities were engaged in conventional water-harvesting methods funded or endorsed by regional monarchs or affluent individuals. Phase II, from the mid-1960s to 1990, was characterised by a significant surge in the utilisation of groundwater for various purposes such as irrigation, domestic and industrial applications. The fundamental cause of the increase in overexploitation may be traced to the development of cost-effective drilling and pumping technology and the government's supply of energy subsidies to customers (Saha et al., 2022). During this time, there was growing recognition of the significance of replenishing aquifers, which was subsequently incorporated into policy documentation. In 1987, the National Water Policy was framed, the first document that recognised water as a resource of national importance that requires perspective for management (Geethanjali & Rao, 2021). The period from 1990 to 2010, commonly referred to as Phase III, was characterised by a significant surge in the rate of groundwater extraction. Recently, there has been a substantial increase in the exploitation of groundwater resources, leading to the depletion of water levels and a decline in water quality across India (Saha et al., 2022).

In recent years, there has been a notable escalation in attention toward artificial recharge. Governmental bodies have undertaken pilot studies on artificial recharge to underscore its efficacy, enhance public awareness and foster proficiency within the populace. The impetus behind the government's emphasis on promoting artificial recharge infrastructures stems from the heightened strain on India's groundwater resources, as evidenced by the data presented in Table 1 and Figure 1, which is particularly prevalent in various regions across the country. The Indian government launched the National Watershed Development Programme in 1987 to optimise the utilisation of natural and social capital such as land, water, vegetation, livestock, and human resources (Sikka et al., 2014). Over time, these programs have increasingly prioritised artificial recharge to enhance groundwater levels and agricultural productivity. Several state governments have implemented water conservation programs, such as Mission Kakatia of Telangana, which aims to clean and remove silt from numerous tanks, thereby revitalising aquifers (Shah & Verma, 2018). Government agencies recognise the importance of sensitising, including society, the implementation and maintenance of artificial recharge structures, as noted by Shah et al. (1998). The central and state governments established groundwater authorities intended to regulate groundwater extraction. Singh et al. (2019) reported that the authorities had placed significant emphasis on the mandatory requirement of artificial recharge for issuing no-objection certificates (NOCs) for extracting groundwater to various sectors, including industrial units, infrastructure development projects, and mines. Lastly, phase IV denotes the time following 2012, as in this period, a notable transformation in attitude, strategy, and implementation towards addressing overexploitation was observed, wherein the government now accords equal emphasis to measures targeting both the supply and demand sides (Saha et al., 2022).

TABLE 1. Annual groundwater recharge and extraction for India (CGWB, 2022).

1.	Total Annual Ground Water Recharge	437.60 km^3
2.	Annual Extractable Ground Water Resources	398.08 km^3
3.	Annual Ground Water Extraction	239.16 km^3
4.	Stage of Ground Water Extraction	60.08%

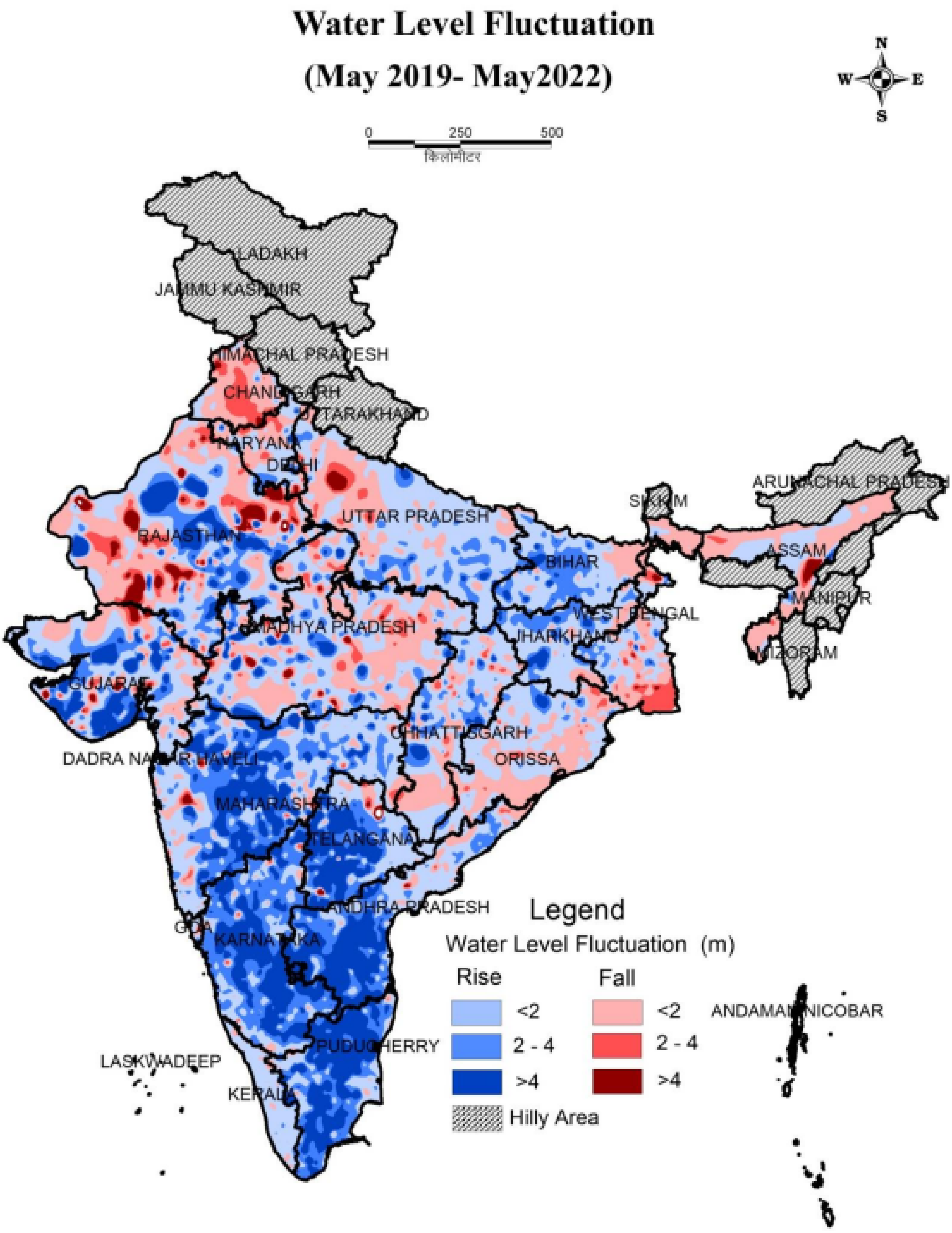

FIGURE 1. Water level fluctuation for India for the period 2019 to 2022 (CGWB, 2022).

The Central Ground Water Board (CGWB) launched the National Aquifer Mapping and Management Program (NAQUIM) in 2012, which aimed to map an area of 25.9 lakh km^2 that is hydrogeologically mappable to promote the sustainable management of groundwater resources (Saha & Ray, 2019). The primary aim of NAQUIM is to create a three-dimensional representation of aquifers and to develop a thorough understanding of their geometry, hydraulic properties, resource availability and chemical quality of groundwater in a specific aquifer setting. The program's output will aid in delineating appropriate regions that can be utilised for agricultural reclamation, determining the optimal structures to be implemented and specifying their designs. Apart from CGWB's initiatives, other Government of India schemes have primarily focused on water conservation practices. These schemes are namely Catch the Rain campaign (National Water Mission's campaign initiated by Ministry of Jal Shakti, Government of India), Jal Jeevan Mission (JJM) (an initiative of Ministry of Jal Shakti, Government of India) and Mission Amrit Sarovar (an initiative of Ministry of Rural Development, Government of India). These government initiatives primarily create awareness among the masses to conserve water and provide the rural population with access to clean and safe drinking water. There has been a significant increase in studies related to artificial recharge and rainwater harvesting. A rainwater harvesting system is one method of diversifying water resources and increasing water security (Marlow et al., 2013). Rainwater harvesting systems in cities and urban areas can contribute to mitigating the environmental impact of buildings and towns. Additionally, they can enhance urban sustainability and help alleviate water stress caused by over-extraction in urban areas (de Sá Silva et al., 2022). A rainwater harvesting system for urban areas includes capturing and storing rainwater while preventing runoff, including collecting, storing, treating and distributing rainwater from roofs, terraces and other impermeable surfaces to be used on-site (Campisano et al., 2017; Lee et al., 2016). Figure 2 shows the number of research articles published from 2008 to 2022, indicating a substantial surge in artificial recharge-related studies from 2020 onwards. Figure 3 depicts the overall approach followed in this paper for selecting and reviewing the most relevant research papers on artificial recharge.

2. RESEARCH, REPORTS, AND DOCUMENTS ON ARTIFICIAL RECHARGE

The literature on aquifer recharge can be broadly classified into three categories: (i) site suitability for artificial recharge, (ii) water quality concerns for artificial recharge, (iii) operational problems and challenges, and (iv) impact assessment of recharge structures. Figure 4 shows the co-occurrence of keywords from articles published from 2017 to 2022. For this diagram, 311 papers were filtered on Scopus with primary search keywords such as "rainwater harvesting", "aquifer recharge" and "India", with a publication year limit from 2017 to 2022. The duration from 2017 to 2022 was selected to understand the recent trends in research as the number of research publications on artificial recharge has increased significantly from 2020 onwards. The keywords in Figure 4 indicate the dominance of rainwater harvesting, groundwater, groundwater quality, remote sensing, geographical information systems (GIS), climate change and aquifer properties. Further, a few studies also focussed on groundwater vulnerability, sustainability, water scarcity, water productivity and mitigation. However, the consideration of socio-economic aspects, indigenous knowledge about artificial recharge and multi-use services has been lacking.

2.1. Site suitability for artificial recharge

The Central Ground Water Board (CGWB) has formulated a comprehensive plan for artificial recharge (CGWB, 2007) covering the entire nation. The project identified an area of 0.9415×10^5 km^2 appropriate for artificial groundwater recharge. The plan was formulated considering various factors such as the type and characteristics of aquifers, the decadal average of post-monsoon water levels and the ease of access to non-committed surface water sources. As per the Master Plan, a total of 111 lakh structures of various types, such as recharge shafts and wells, check dams, contour bunds, and sub-surface dykes, can facilitate the recharge and storage of approximately 85.6 km^3 of water. These structures are designed to be compatible with local hydrogeology and groundwater regimes. The assessment of these structures in terms of their site suitability has also been done in the past. Anbazhagan and Ramasamy (1997) used geophysical surveys, such as electrical resistivity and water level maps, to identify fractures and determine appropriate locations for aquifer recharge in the hard-rock regions of Tamil Nadu.

The fractures were overlaid onto groundwater level maps to demarcate suitable sites for aquifer recharge. Further, Wada et al. (2012) applied quantitative morphometry and hydrogeological analysis to identify suitable locations for artificial recharge in the Almorah region of Uttarakhand. Using remote sensing data in conjunction with geoinformatics analysis can evaluate the magnitude of runoff and site selection in diverse terrains encompassing soft and hard rock regions (Sharma & Thakur, 2007). Sahu et al. (2022) employed hydrogeological, geospatial and multi-criteria decision analysis methodologies in their research to identify groundwater recharge potential zones and appropriate recharge structures for the Tapi River basin in north Maharashtra. Moharir et al. (2023) recently employed GIS and Analytical Hierarchy Process (AHP) methodologies to identify potential

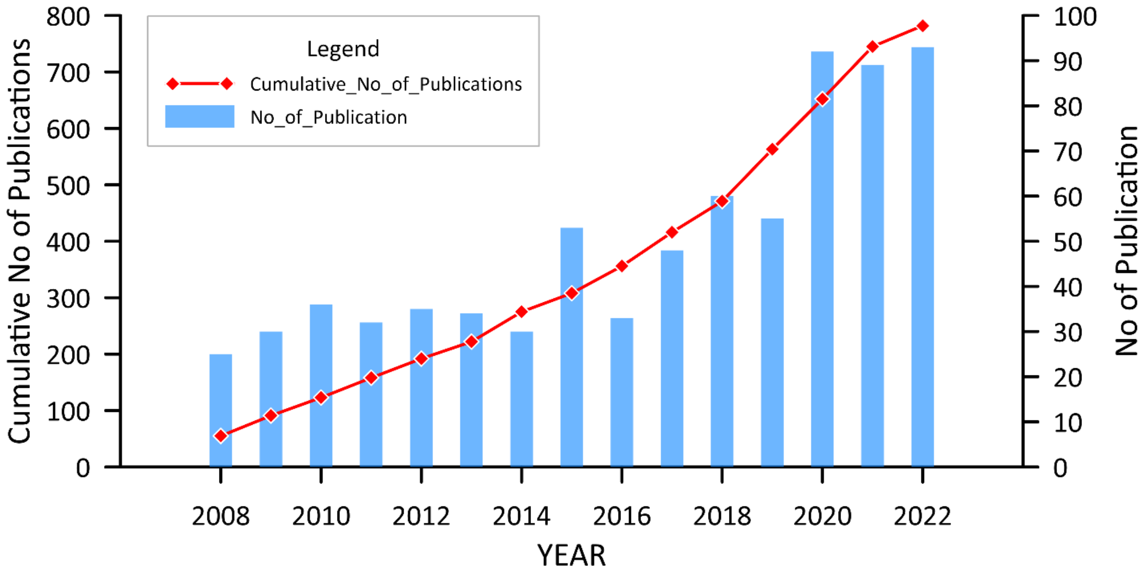

FIGURE 2. The number of peer-reviewed publications on artificial recharge year-wise for the period 2008–2022.

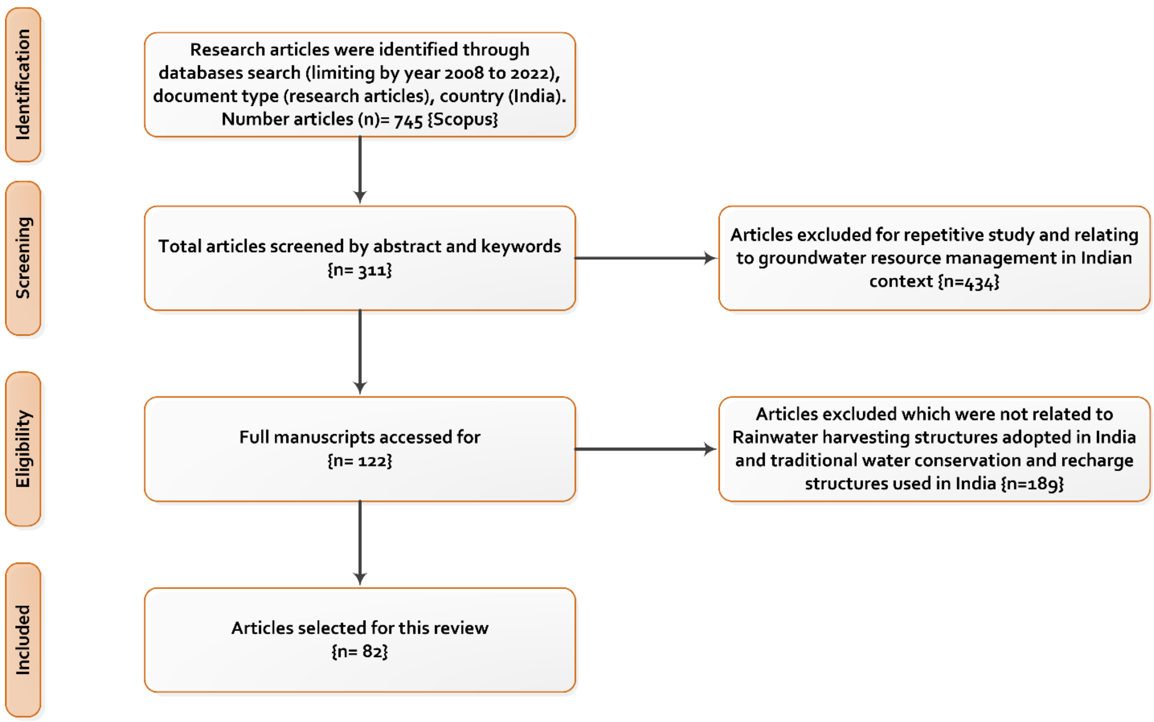

FIGURE 3. Flowchart reflecting the methodology of screening the papers used for the review.

groundwater zones in the Damoh region in Central India. They employed geology, geomorphology, slope, aspect, drainage density, lineament density, topographic wetness index, topographic roughness index and land use land cover to identify possible groundwater zones. These zones are critical in developing the groundwater table by building artificial recharge structures. Rawat et al. (2023) used a GIS and Multi-Criteria Decision Analysis (GIS-MCDA) approach to create rainwater harvesting (RWH) suitability maps in Rajasthan. According to their findings, 3.6%, 8.2% and 27.3% of their study area were highly, partly and inappropriate for rainwater harvesting structure implementation, respectively. A Google Earth Engine and Multi-Criteria Decision Analysis (GEE-MCDA) tool for site suitability mapping of managed aquifer recharge (MAR) structures was tested for the Ganga-Yamuna doab region, India. The tools found 82% of the area under suitable, 12% very suitable and 5% moderately suitable

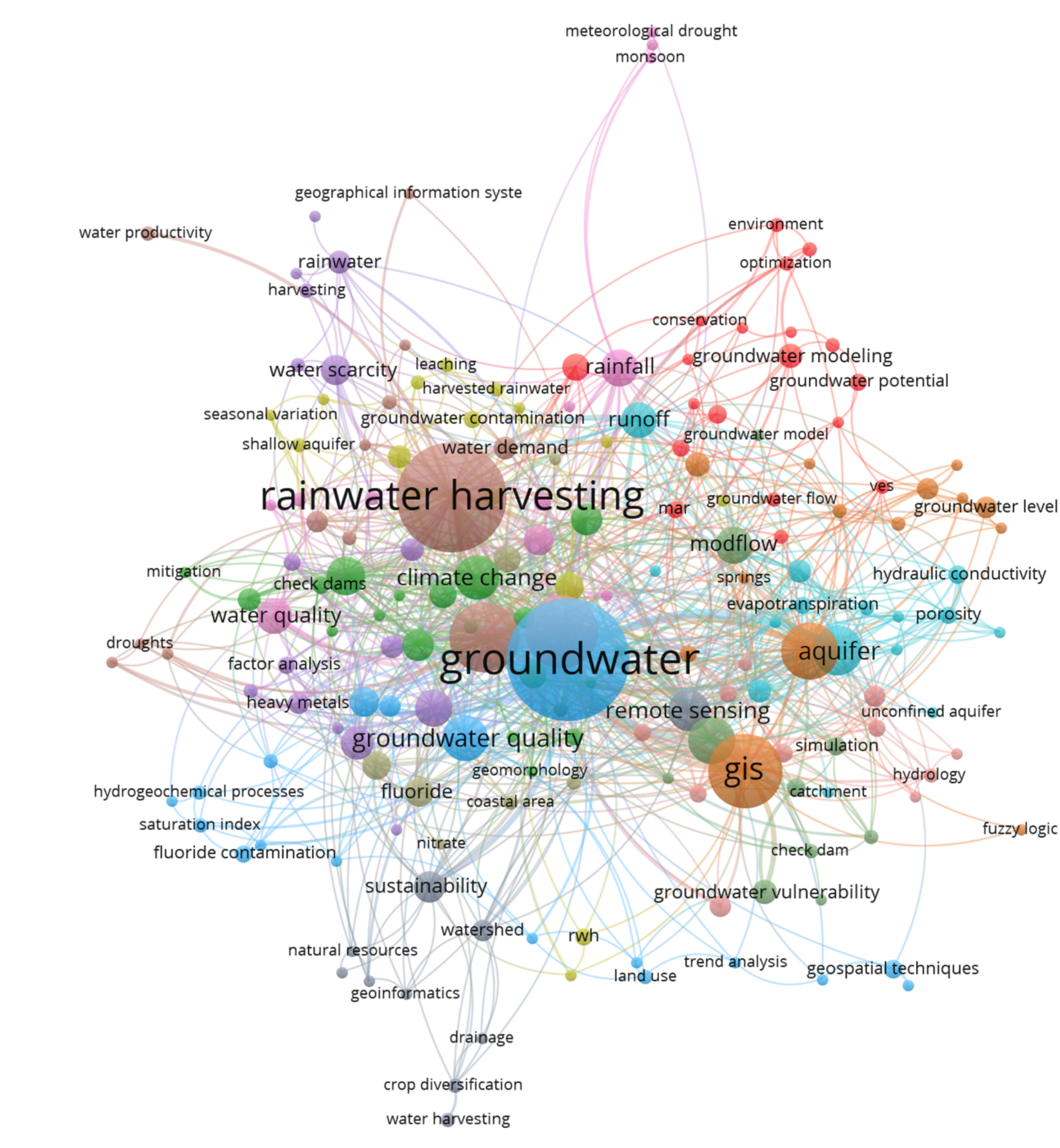

FIGURE 4. Representation of the keywords used across the paper considered for this review for the period 2017–2022.

(Patidar et al., 2023). This tool is an important contribution for site suitability mapping for artificial recharge structures.

Mondal and Singh (2004) introduced a technique that employs cross-correlation between the increase in water levels following the monsoon and precipitation to identify suitable locations for aquifer recharge in hard rock terrain with unconfined aquifers. Dinesh Kumar et al. (2008) adopted environmental isotopes (^{3}H and ^{18}O) in combination with water level and hydrogeological methods to demarcate the appropriate regions for aquifer recharge in the urban area of Delhi. A small watershed in a granitic terrain in Peninsular India was examined and the area was found to have experienced significant exploitation. The study concluded that defunct dug wells are the most suitable structures for recharge purposes in the area, despite their deep-water level, due to their technical feasibility and cost-effectiveness (Sreedevi et al., 2013). The study conducted by Narjary et al. (2014) examined the phenomenon of decreasing water levels and emphasised the significance of groundwater recharge in Haryana. A rise in water level ranging from 2.3 to 3.16 m was reported in the Karnal district during 2009–2010 due to anthropogenic activities. Further, Islam and Talukdar (2016) suggested integrating groundwater recharge and rainwater harvesting could be implemented in urban water supply systems.

Several other approaches have also been used to assess the site suitability such as Samadder et al.

(2011) identified the paleochannels in the West Ganga and used the Tritium Tagging technique to ascertain the natural recharge of groundwater in paleochannel regions, which was found to be between 19–29% of annual precipitation. In contrast, the floodplain area exhibited a recharge rate of only 6–9%. Comparable isotopic and hydrochemical methods were employed to identify appropriate locations for artificial recharge interventions in hard rock regions that are characterised by diminishing groundwater resources. In a study conducted by Saha et al. (2014), various methods, such as electrical conductivity, chloride, heavy oxygen isotopes and deuterium, were employed to determine the paths of aquifer recharge. These methods were combined with hydrogeological sections to identify lineaments where sufficient groundwater can be collected by artificial recharge in granitic aquifers in urban areas of Ranchi, Jharkhand. A three-dimensional mathematical model was formulated to simulate transitory groundwater flow in a multi-aquifer system. The system included a lower constricted aquifer that was replenished through the implementation of rooftop runoff management systems. Subsequently, the model was used to evaluate the operational effectiveness of the artificial recharge systems across varying recharge and extraction capacities (Islam & Talukdar, 2016).

2.2. Water quality issues for artificial recharge

The general opinion among scholars is that the implementation of artificial recharge positively impacts groundwater quality. However, there are also documented instances in which the interaction between percolating water and rock formations compromises the chemical quality of aquifers. Attention has been drawn towards the qualitative aspect of water being recharged and the degree of enhancement of its quality as it traverses the unsaturated layer before its integration with the water table.

In India, various guidelines on water quality for irrigation and drinking purposes are available. These include the Bureau of Indian Standards (BIS) guidelines for drinking water (IS 10500, 1993) and guidelines on quality for irrigation water (IS 11624, 2019). In addition to its other functions, the Central Pollution Control Board (CPCB) has established standards for monitoring protocol for water quality (CPCB, 2007) and the safeguarding of wellheads during the construction of wells for drinking water. To date, there has been a lack of established guidelines on the qualitative aspect of the water being recharged or the susceptibility of the aquifer concerning recharge. However, the CGWB has formulated and disseminated specific standards for source water quality and issued relevant advisories (CGWB, 2007; Singh et al., 2019). Dillon et al. (2014) have introduced a methodology known as the "viability assessment" to address water quality concerns in MAR. This approach comprises four distinct stages: (a) planned utilisation of water resources, (b) the origin of water supply and entitlement to its use, (c) hydrogeological attributes of the area, and (d) capacity for water retention and purification. According to their results, doing a sanitary study before beginning any construction activities is critical to detect possible risks and hazardous occurrences within the catchment's boundaries. Therefore, an aquifer assessment that encompasses developing and implementing a secure recharge facility is imperative. Additionally, they suggested implementing preventative measures, adopting corrective actions and formulating a proposed plan for water safety.

Several regions in India have been reported to enhance water quality by implementing artificial recharge methods. According to Stiefel et al. (2009), significant enhancements in sulphate concentration and electrical conductivity were observed during the post-artificial recharge construction period in arid regions of Rajasthan. Kumar et al. (2009) investigated a basaltic aquifer in Maharashtra using isotopes such as $\delta^{18}O$, ^{3}H and δD. According to the researchers, the chemical nature of the groundwater inside the watershed changed favourably. Saharawat et al. (2011) investigated the recharging mechanism and ensuing revival of an alluvial aquifer holding salty groundwater in northwestern India's semi-arid area. According to their report, the salinity of pumped-out water was found to be lower after recharge. The increase in potassium and borate concentrations can be attributed to their liberation from clay minerals, which persist in the adsorbed state. The occurrence described by Brindha et al. (2016) has been documented in Nalgonda, Telangana, the Pombar River, and the Vaniyar River basin of Tamil Nadu. As per their assertions, the hydrogeological aspects must be considered before implementing AR in a region affected by fluoride. Additionally, continuous surveillance of fluoride levels in groundwater is recommended.

According to Gowrisankar et al. (2017), constructing a check dam in the Krishnagiri area of

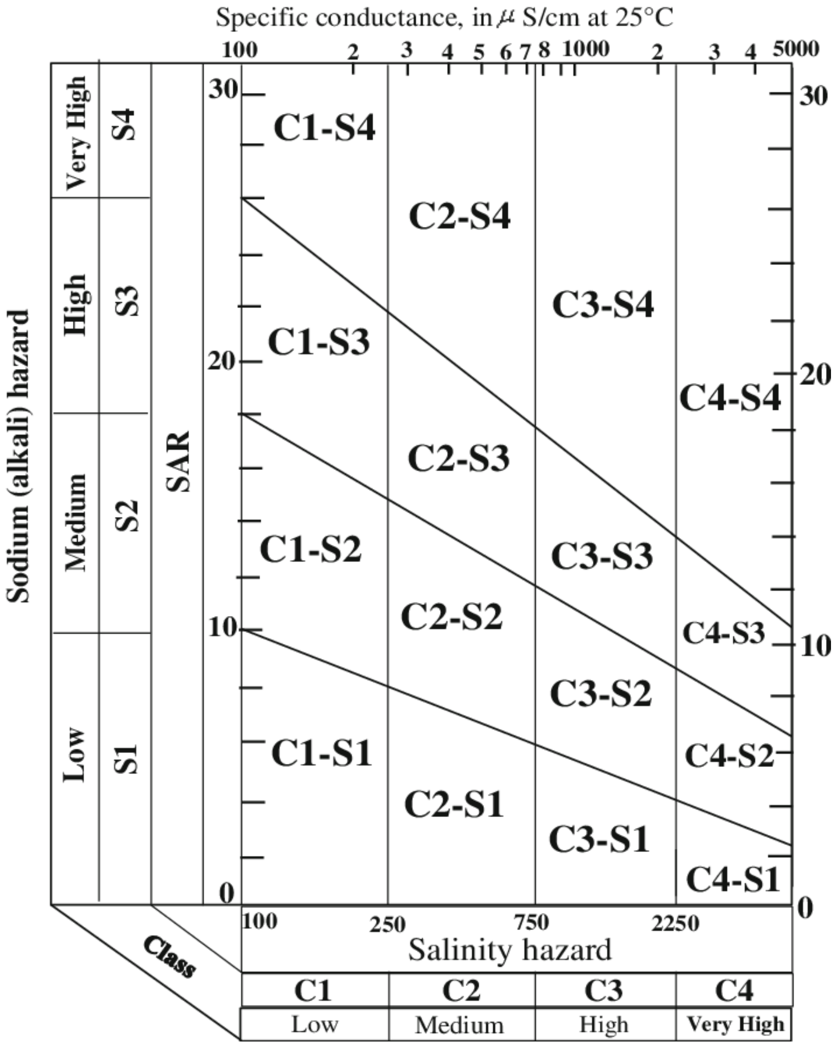

FIGURE 5. United States Salinity Laboratory classification of irrigation waters (USSL, 1954).

Tamil Nadu led to a significant reduction in groundwater fluoride concentration in downstream regions due to the dilution of freshwater recharge. Similarly, Satheeshkumar et al. (2017) observed a comparable improvement in the Vaniyar sub-basin in Tamil Nadu. Thangamani et al. (2017) conducted a study to assess the effects of a check dam on the Amaravathi basin. The study found that the water quality had improved with reference to the U.S. Salinity Laboratory (USSL) classes (Figure 5), which are based on salinity and sodium hazards. Specifically, this study observed an improvement from C2S2 to C2S1 classes. The sodium hazards classification (C) and SAR classification (S) are shown in Table 2. Kalpana et al. (2019) studied the Pamber River basin and identified two distinct impacts. The first impact was observed at a shallow depth less than 20 m below the ground, where fluoride concentration was diluted and reduced. The second impact was observed at a greater depth, up to 90 m (bgl), where the fluoride concentration increased. This increase was attributed to the flushing of fluoride-rich salt, which accumulated in the vadose zone during the recharge process.

Artificial recharge has also been identified as a viable solution for addressing seawater intrusion in coastal aquifers that results from freshwater pumping. In a study by Hollingham (2002), Hubli and Dharwad city in Karnataka was examined, revealing an estimated leakage of 20.5 gigaliters per year (Gl/year) and a 15–24 Gl/year recharge. The seepage has contributed to an elevation in the water table and enhanced the aqueous composition. Nair et al. (2013) examined the chlorine and bromine ratio in the subsurface water of the coastline aquifer in Chennai's northern area. This investigation discovered salty water incursion up to 10 km inland. Installing a check dam resulted in an additional 37% recharge, proving its effectiveness in preventing salty water permeation. As

TABLE 2. Classification system for Salinity Hazards and Sodium Hazards (Rashidi, 2012; USDA).

Salinity hazard class	Range (µS/ cm)	Quality remark	Sodium hazard class	Range (meq/L)	Quality remark
C1	<250	Low	S1	0–10	Excellent (little or no hazard)
C2	250–750	Medium	S2	10–18	Good (appreciable hazard but can be used with appropriate management)
C3	750–2250	High	S3	18–26	Doubtful (unsatisfactory for most crops)
C4	>2250	Very high	S4	>26	Unsuitable (unsatisfactory for all crops)

previously stated, using treated wastewater for agricultural reuse is currently not feasible. The study conducted by Nijhawan et al. (2013) pertained to the opinions of professionals in some areas of Central India regarding the utilisation of treated municipal wastewater for agricultural purposes. This study focused on the efficacy of soil water treatment (SWT) in enhancing water quality. Approximately 64% of those surveyed agreed favourably using processed wastewater for agricultural irrigation, whereas 28% held an opposing viewpoint. Despite undergoing secondary treatment, half of the respondents expressed reservations regarding the quality of the source water (wastewater) before its introduction into the aquifer. In numerous urban areas, unintended recharge is prevalent owing to water supply pipeline leakage. According to the research conducted by Saha et al. (2018), leakage from domestic pipes has neutralised groundwater abstraction and maintained the groundwater level within the shallow, unconfined aquifer of Patna, Bihar.

2.3. Operational problems and challenges

Recharge structures have a connection with a variety of operational issues and challenges that frequently impede their long-term operation. These issues frequently result in the conceptual failure of artificial recharge systems' applicability in certain scenarios. Clogging is one of the most serious issues with artificial recharge structures. There are four forms of clogging: physical clogging, chemical clogging, biological clogging and mechanical clogging.

Physical clogging is the most common kind of congestion and it is produced by the deposition of aquifer sediments as well as organic and inorganic suspended particles in source water (Du Xinqiang et al., 2009; Youngs et al., 2009). In general, it is believed that the smaller the pore size of the permeating soil, the higher the quantity of suspended solids, and the larger the size of suspended solids, the easier the clogging occurs. Whereas the higher the infiltration rate, the smaller the size of suspended solids and the thicker the clogging layer (Skolasińska, 2006; Shan et al., 2013). An aquifer is a symbiotic habitat made up of physical, chemical and biological factors that serve as an antagonist to the chemical composition of groundwater. The recharged water surges dramatically into the aquifer, altering the initial balance of water-rock interaction. As a result, dissolution, precipitation and other reaction mechanisms may cause alterations to water quality as well as aquifer permeability, complicating chemical clogging as it depends on various factors (Zhang et al., 2020). Biological clogging appears to be the second most important mechanism that clogs wells (Oberdorfer & Peterson, 1985). Microbial communities, including bacteria and algae, typically make up the majority of the biological species found in source water and under ambient conditions and these microorganisms can proliferate quickly throughout the recharge process (Zhang et al., 2020). Mechanical clogging, also known as gas bubbles, is created by the flow of water inside the recharge well casing or by air entering the recharge pipe network under negative pressure. This entrapped air raises the oxidation-reduction potential (ORP) and encourages microbial activity and geochemical processes, which leads to additional blockage (Beckwith & Baird, 2001; Heilweil et al., 2004).

2.4. Governance of artificial recharge

Water resources management and environment protection authorities need to be aware of the advantages and disadvantages of MAR in order to guarantee that it continues to produce the intended benefits and prevent excessive piezometric pressures or waterlogging, failure during drought, and contamination of aquifers (Dillon et al., 2019). The best method to control this is to establish well-founded regulations and procedures that guarantee MAR is carried out in a manner that safeguards groundwater conditions and the needs of its receptors, including the surrounding ecosystem. The Indian government has produced a handbook on artificial recharge (CGWB, 2007), which outlines the procedures for designing, planning, monitoring water quality and levels, and assessing the financial viability of augmenting recharge through streambed recharge structures and urban rainwater collection. Based on the UN Water Safety Planning approach, a water quality guide for natural water sources in India was created, and it can be used based on trained villagers' visual observations (Dillon et al., 2014). In order to guarantee efficient operations and to produce the data necessary to support future adoption of MAR, including research and governance, it is essential to monitor current operations and keep up a public repository of site information, reports and statistics.

2.5. Impact assessment of recharge structures

A pertinent demand in examining the influence of artificial recharge pertains to the appropriate level to evaluate its impact on groundwater resources. The use of remote sensing data is a prevalent technique employed for impact assessment. This tool has the potential to facilitate the examination of the expansion of crop acreage and irrigation coverage as well as enhancements in soil moisture. Using the tritium tagging method, Israil et al. (2006) established a correlation between recharge and the resistivity of the upper unsaturated layer of the Himalayan foothills. The researchers concluded that this particular correlation could serve as a means to evaluate the pace of replenishment in comparable regions. For sustainable development of groundwater resources, Becker (2006) explored the use of diverse remote sensing methodologies to evaluate the influence of different recharge structures such as check dams, recharge shafts and recharge borewells on groundwater recharge and suggested that artificial recharge is a viable solution. Chinnasamy et al. (2015) utilised GRACE Tellus satellite datasets to evaluate the recharge potential of Rajasthan and determined that the state exhibits significant potential for recharge. Further comprehensive investigations are required to determine the appropriate recharge methods and their optimal design and to identify precise locations. According to Thiyagarajan et al. (2020), the water storage and recharge potential of RWH structures can be evaluated using satellite data. The utilisation of this method is not limited to small-scale applications because it possesses the benefit of high temporal resolution, rendering it suitable for large-scale areas.

Water level increase is recognised as an essential indicator for measuring the effects of recharge. Rainwater harvesting with runoff preserving barriers (gully plugs, rockfill dams, check dams and bench trenching) is primarily intended to slow or hold back flowing water (subsurface dams and contour trenching) and penetrate (percolation tank) into the subterranean (Raju et al., 2006). The performance of ten recharge wells, each 24 to 30 m deep, built in a previously operating village pond in the Ramganga basin was investigated. During their three-year study, they discovered that volumes ranging from 26,000 to 62,000 m^3 were restored annually over a period of 62 to 85 days. Average recharge rates ranged from 164 to 295 mm/day, with a total recharge rate of 221 mm/day (Alam et al., 2020).

Raju et al. (2006) investigated sub-surface dams built over the Swarnamukhi River. The investigation concluded that the average post-monsoon rise was 1.44 m, and the pre-monsoon rise was 1.80 m. The construction of these underground dams in the Swarnamukhi River watershed enhanced groundwater storage, increasing land productivity. In their study, Parimalarenganayaki and Elango (2015) highlighted that a check dam is an effective MAR method for improving groundwater recharge. They found that the water stored in the check dams increased groundwater level from 1 to 3.5 m until about 2 km. Abraham and Mohan (2019) reported a 4.7 m increase in the water table during the operational period of check dams in Tamil Nadu, compared to an average 1.5 m rise in the water table over the rainy season. The results show that the investigated check dams effectively and efficiently recharge the local aquifer. Dashora et al. (2018) recently investigated the recharge performance of four check dams in the Dharta watershed of the Aravali Hills in the Udaipur region of Rajasthan from 2014 to 2015. The average annual recharge volume was calculated to be 0.7 million m^3, which supported 16% of agricultural production from the neighbouring communities during the rabi season. In 2014 and 2015, total recharge was 37% and 70%

of combined runoff, respectively. Further, Dashora et al. (2019) monitored the recharge estimation of four check dams by daily water balance method for three years (2014–2016) and found the mean annual recharge to be 779,000 m^3.

Massuel et al. (2014) used a comprehensive method integrating water accounting, geochemistry and hydrodynamic modelling to investigate the ability of a conventional percolation tank to replenish the aquifer. Over the course of two years, the tank's percolation efficiency varied from 57% to 63%. Abraham and Mohan (2015) investigated the efficiency of recharge structures such as check dams and percolation ponds with percolation wells in improving the recharge process in a Tamil Nadu watershed. They discovered an average increase in water level of 2 to 3 m in locations around individual recharge infrastructure. In contrast, after two years of artificial recharge, the groundwater level increased by roughly 5 m in the region encompassing the combined recharge structures. Yadav et al. (2022) observed that shallow infiltration ponds known as Chaukas may recharge groundwater while boosting soil moisture in Rajasthan. They developed a model using HYDRUS-1D to assess prospective groundwater recharge, and it was discovered that 5% of the precipitation depth had recharged directly into the groundwater. Besides the recharge, the study revealed that the greater soil moisture allowed naturally occurring grass cover to grow, which the locals could utilise as pastureland.

Artificial recharge structures should be planned and conducted on a watershed or sub-basin scale, and their effects should be evaluated. Most artificial recharge structures built in a small region are standalone or, at best, few in number, and local-scale hydrological effects are the main focus of impact analyses. Such impact evaluations do not account for trade-offs between upstream and downstream stakeholders in the watershed or sub-basin (Sharda et al., 2006). Duraiswami et al. (2016) stressed the importance of impact analyses considering hydrogeology, hydrology and ecology. Such studies are challenging because of the regional variability of many characteristics and the need for long-term data generation.

Sakthivadivel and Scott (2005) studied the conflict between upstream and downstream water users. The study found that the construction of numerous recharge structures in the upstream portion of the catchment significantly impacted the reservoir that supplies water to Rajkot Town in Gujarat. Pathak et al. (2013) found a similar impact in an eastern Rajasthan watershed, where increasing water availability boosted the average irrigation area per dug well from 0.5 to 1.4 hectares during the Rabi season. Kumari et al. (2014) evaluated the effects of ten structures on the Parasai-Sind catchment in Uttar Pradesh's Buldelkhand region, which covers 1246 hectares. Following implementation, it was observed that the net recharge experienced a notable increase of 71.8%, and there was also a significant improvement in the well yield. The provision of recharged water ensured irrigation for the Rabi season across the entirety of the treated area within the watershed. Chatterjee et al. (2018) drew attention to the significant depletion of groundwater resources in the Baswa-Bandikui watershed in Rajasthan. The authors emphasised the need for immediate action to prevent further degradation of this vital resource.

The evaluation of the effects of artificial recharge necessitates meticulous consideration of climate change variables. Implementing artificial recharge in the Arvari River basin of Rajasthan has increased the flow. Glendenning and Vervoort (2011) discussed the potential influence of increased rainfall during this period on the observed increase in flow. Using digital remote sensing data on a GIS platform for modelling a watershed presents a more cost-effective and expeditious alternative to estimating the hydrological impact at a watershed scale through field monitoring. The utilisation of this approach is of significant value in the evaluation of the influence of artificial recharge on streamflow and the amount of runoff that can be accumulated by rainwater harvesting. This approach is more appropriate for assessing the impact of surface water than groundwater, especially in the case of anisotropic hard rock aquifers. The Gaiwel watershed of Andhra Pradesh was studied by Perrin et al. (2012) using the Soil Water Assessment Tool (SWAT) model. This study aims to calibrate runoff volumes and storage in 29 percolation tanks. Their observations show tanks contributed 23% of the total annual recharge during a typical monsoon year. Additionally, it was observed that implementing additional construction of structures was deemed impractical because of the potential impact of diminished runoff on the surrounding downstream regions.

3. FUTURE SCOPE IN THE DIRECTION OF AQUIFER RECHARGE

Much progress has been observed in the design, operation, and maintenance of artificial recharge strategies. However, further scope for improvement should be explored for large-scale adaptation and improving resiliency considering climate change. In the context of groundwater recharge, it is significant to understand the sensitivity of hydrological processes to climate variability in the region (Kumar et al., 2020). Future studies can build upon using more advanced modelling techniques and machine learning to improve the understanding of complex hydrological processes governing groundwater recharge. Sahu et al. (2022) suggested that identifying potential groundwater recharge sites can be combined with socio-economic data to assess the feasibility and sustainability of the recommended recharge structures. Yadav et al. (2022) recommended combining the Chauka system with other RWH techniques to maximise groundwater recharge and increase the availability of water resources in water-scarce regions. They also suggested investigating the economic and social benefits of the artificial recharge structure on the local communities. Laskar (2022) recommended integrating traditional RWH with modern RWH, such as injection wells, storage reservoirs and subsurface barriers, to increase artificial recharge's contribution to a sustainable environment for agricultural production. The International Groundwater Resources Assessment Center's (IGRAC) current efforts to create a global inventory of MAR assist in locating MAR locations that are both typologically and geographically close together (Stefan & Ansems, 2018). These initiatives should be supported as they are leaders in the field of big data analytics applied to artificial recharge. It is also anticipated that management based on artificial intelligence would be included in the artificial recharge process as a whole. According to Zhang et al. (2020), there is a need to encourage the use of artificial intelligence and big data analytics techniques in order to produce outcomes that are supported by evidence and can be used with confidence in artificial recharge planning and execution.

Most publications have evaluated the effects on a local scale, specifically the influence of an independent structure. Most of the research works considered in this study employed specific parameters to evaluate the situation, including the increase in water level, the extent of the area that received benefits, quantification of recharge volume, and determination of the proportion of this volume accessible for subsequent irrigation purposes. Nonetheless, there is a paucity of research data on the effects of multiple and dispersed structures at a watershed or sub-basin scale. To conduct a comprehensive evaluation of a watershed or sub-basin, researchers must conduct long-term observations of various factors such as land use and land cover, climatic conditions, depth to water level, variations in groundwater quality, groundwater flow patterns and hydraulic properties of the aquifer, among other variables.

4. CONCLUSION

The increasing reliance on groundwater has resulted in an increase in aquifer strain. The present worldwide groundwater footprint is projected to be 3.5 times greater than the aquifers' physical area. Furthermore, around 1.7 billion people live in areas where groundwater resources are depleted and/or groundwater-dependent ecosystems are threatened. A similar impact on groundwater supplies has been reported in northwest India. Numerous research has indicated that aquifers within the nation are rapidly diminishing, particularly in regions characterised by dry climates. Artificial recharge is widely recognised as the primary measure for augmenting groundwater resources. However, it is worth considering whether such interventions to increase the groundwater supply are sufficient to promote sustainable resource utilisation. The arid and semi-arid areas face limitations in terms of artificial recharge and rainwater harvesting because of the scarcity of water for recharge. This review highlights the various trends, challenges and the future scope of artificial recharge in the Indian context. A brief survey of the literature reveals that the deployment of artificial recharge schemes has several significant challenges, including site suitability, land availability, and water quality concerns. In addition to these two, it is noted that operational and governance concerns impede the appropriate operation of artificial recharge structures. Maintaining an open repository for current operational structures, site data and the establishment of efficient, evidence-based governance are essential to overcoming these obstacles. New insights on artificial recharge must also be disseminated, and further study on the topic, its application, and overcoming operational obstacles are all encouraged.

DATA AVAILABILITY STATEMENT

Data will be provided by the corresponding author upon request.

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