EEET ECOLOGICAL ENGINEERING & ENVIRONMENTAL TECHNOLOGY

Ecological Engineering & Environmental Technology, 2026, 27(9), 341–360
https://doi.org/10.12912/27197050/226536
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Received: 2026.07.15
Accepted: 2026.08.03
Published: 2026.08.15

Traditional clay-based groundwater recharge systems for sustainable water management and the One Health concept: The Adrar model in Algeria

Naimi Oussama[1], Marianna Goroneskul[2,3], Bouderdara Nabila[1], Mohamed Mokhtari[4], Fidjah Abdelkader[5*], Olena Lyndiuk[6], Anatolii Hrynzovskyi[7], Oleksandr Hrynzovskyi[8]

[1] Applied Science Laboratory, National Higher School of Advanced Technologies (ENSTA), Algiers, Algeria
[2] Dmytro Motornyi Tavria State Agrotechnological University, Zaporizhzhia, Ukraine
[3] O.M. Beketov National University of Urban Economy in Kharkiv, Kharkiv, Ukraine
[4] LaRTFM Laboratory, Department of Mechanical Engineering, National Polytechnic Of Oran (MAURICE AUDIN), BP. 1523 El-M'Naouer 31000, Oran, Algeria
[5] Laboratory of Development in Mechanics and Materials (LDMM) - University of Djelfa, 17000, Algeria
[6] Department of Business, Administration and Law, Higer Educational Institution "University of Future Transformation", Chernihiv, Ukraine
[7] Department of Emergency and Tactical Medicine, Bohomolets National Medical University, Kyiv, Ukraine
[8] Department of Certification and Conformity Assessment, Institute for Conformity Assessment, Hygiene and Ecology of the O.O. Bogomolets National Medical University, Kyiv, Ukraine
* Corresponding author's e-mail: fidjah.abdelkader@gmail.com

ABSTRACT

The purpose of this review is to evaluate the potential of traditional clay-based groundwater recharge systems for improving groundwater sustainability in arid and semi-arid regions, with particular emphasis on the Adrar region of southern Algeria, while considering their contribution to sustainable water management and the One Health framework. The review also aims to identify the hydrogeological conditions, operational requirements, advantages, and limitations that determine the long-term performance of clay-lined recharge basins. The study adopts a comprehensive literature review and comparative analytical approach by synthesizing recent findings on groundwater depletion, managed aquifer recharge (MAR), hydrogeology, irrigation practices, and traditional clay-based recharge systems. Published hydrogeological data for the Adrar region, including groundwater chemistry, local geological conditions, and engineering characteristics of clay materials, are integrated with evidence from international studies to assess the applicability of this traditional technology under arid climatic conditions. The reviewed evidence indicates that clay-lined recharge basins can effectively increase groundwater recharge efficiency by extending water residence time, reducing evaporation losses, and promoting gradual infiltration where suitable hydrogeological conditions exist. The analysis further shows that the effectiveness of these systems depends on local soil properties, groundwater depth, sediment accumulation, maintenance practices, and irrigation management. Comparative evaluation with other MAR techniques suggests that clay-based recharge basins offer important advantages, including low construction cost, operational simplicity, and suitability for water-scarce regions, although their performance remains site-specific and requires continuous monitoring. The review is limited by the availability of published studies and the absence of long-term field validation under different hydrogeological settings. Future investigations should include quantitative monitoring, numerical modeling, and performance assessment under varying climatic conditions. The practical value of this review lies in providing guidance for selecting, designing, and maintaining clay-based recharge systems as low-cost groundwater management solutions. The originality of the study is the integration of hydrogeological, engineering, environmental, and One Health perspectives into a unified assessment of traditional clay-based groundwater recharge technology applicable to arid environments.

Keywords: clay basins, groundwater, resource sustainability, hydrological balance, water recharge.

INTRODUCTION

Groundwater represents a central naturally stored reserve of freshwater, made available through the extraction of water that seeps to the Earth's surface and accumulates in subsurface rock voids (Menon, 2007). This water is collected from subsurface geological formations of saturated rock and unconsolidated materials. The public water needs of many coastal cities and industrial areas depend on groundwater withdrawals. Recharge systems are the primary natural pathways for groundwater infiltration, including streams, lakes, stormwater infiltration, irrigation diversions, canals, and groundwater movement from adjacent aquifers (Yu et al., 2025). Groundwater remains a reliable global resource, and more than a third of the world's population depends on groundwater for their daily needs. Environmentally, groundwater discharge maintains the baseline flow of inland springs, lakes, and river systems in most parts of the world (Li and Elumalai, 2025). The supply of freshwater available for human consumption continues to dwindle worldwide. In addition, rapid urbanization and climate-related thermal stress increasingly affect regional environmental conditions, reinforcing the need for integrated approaches to sustainable water resource management (Ejaz et al., 2026). Many are turning to water reuse, which can be a practical option, mainly when groundwater systems can be recharged with reused water (Tortajada et al., 2025). While water reuse is sometimes considered a temporary solution, it can also be an effective means of increasing tap water supplies and restoring hydrological integrity. Groundwater constitutes the most significant portion of the world's freshwater supply, yet most people remain poorly aware of it and often misunderstand it. Protecting groundwater quality is a significant challenge because contamination is often invisible and requires various tests to detect it. Cleanup can also be challenging due to the difficulty in locating contamination and the high costs associated with it (Mester et al., 2025). Many important groundwater basins are suffering from severe depletion due to pumping rates that are much faster than natural recharge rates, which are occurring globally (Jakeman et al., 2016). A study by Amin et al. revealed that clay layers insulate aquifers, highlighting the role of clay in protecting groundwater (Amin et al., 2025). Algeria, like many other countries, is experiencing a decline in its groundwater reserves. Arid and semi-arid regions worldwide are more vulnerable to climate change and human activities, exposing local socioeconomic environments to major crises. Recent ecological studies have also emphasized that environmental heterogeneity and landscape characteristics influence ecosystem resilience and should be considered when developing sustainable natural resource management strategies (Vambol and Borowski, 2026). Recent environmental studies have further demonstrated that improvements in environmental quality are closely associated with enhanced ecosystem functioning and public health, supporting the interdisciplinary principles underlying the One Health concept (Ali et al., 2024). Since the 1970s, the Algerian government has implemented programs to provide water for agricultural development and population growth in southern Algeria. The northern regions of Algeria suffer from groundwater pollution. A study by Ardjane et al. examined drinking water pollution in several areas (Boumerdes, Tiaret) containing high levels of magnesium, nitrate, sodium, and calcium in the groundwater, exceeding World Health Organization standards. The researchers concluded that 81.25% of the water was of poor quality (Ardjane et al., 2025). Meanwhile, the southern regions are more abundant and less polluted, making them more susceptible to exploitation. A study by Kendouci et al. examined the overexploitation of groundwater in the city of Bechar in southern Algeria. Intensive pumping caused the groundwater level to drop from 3 to 12 meters, leading to the drying up of the Moghel spring. The study confirmed that overexploitation of groundwater in this region is leading to serious environmental consequences, including the drying up of the spring (Kendouci et al., 2023). Despite the growing body of research on groundwater depletion, artificial recharge, and sustainable water management in arid regions, the available literature remains fragmented. Most published studies have focused on hydrogeological processes, groundwater quality, or engineering aspects of managed aquifer recharge independently. Comparatively little attention has been paid to traditional clay-based recharge structures as nature-based solutions that integrate groundwater conservation with broader environmental sustainability and ecosystem resilience (Zhang and Kanyerere, 2020; Standen et al., 2020; Kebede et al., 2024). In particular, there is a lack of comprehensive reviews evaluating the potential of traditional clay aquifer technologies under the environmental and socio-economic conditions of the Algerian Sahara, while also considering their broader implications for sustainable water management and the One Health perspective linking human, animal, and ecosystem health.

Therefore, the purpose of this review is to critically analyze the current state of knowledge regarding the use of traditional clay-based groundwater recharge systems for groundwater conservation in arid regions, with particular emphasis on southern Algeria. The review identifies existing knowledge gaps, synthesizes available hydrogeological and environmental evidence, evaluates the potential advantages and limitations of clay-based recharge systems, and examines their contribution to sustainable groundwater management and the One Health framework. It is hypothesized that integrating traditional clay recharge practices with contemporary groundwater management strategies may provide a cost-effective and environmentally sustainable approach to improving groundwater resilience under increasing climatic and anthropogenic pressures. This hypothesis is examined through a critical synthesis of the available scientific literature, with particular emphasis on hydrogeological evidence, engineering performance, environmental sustainability, and groundwater management practices reported for arid regions. Ultimately, this review seeks to bridge traditional knowledge with contemporary scientific understanding and to identify future research directions for the wider implementation of clay-based groundwater recharge systems under arid environmental conditions.

WATER RESOURCES

Groundwater has become the cornerstone of global water security because it provides the largest accessible reserve of freshwater for drinking water supply, irrigation, industrial production, and ecosystem maintenance, particularly in regions where surface water resources are limited or highly variable (Menon, 2007). Approximately 22 million km³ of groundwater accounts for nearly 99% of the planet's readily available freshwater resources, whereas surface waters constitute only a minor fraction (UNESCO, 2022; Gleeson et al., 2016; Taylor et al., 2013). Owing to its substantial storage capacity, relatively stable physicochemical characteristics, and resilience to short-term climatic variability, groundwater is increasingly recognized as a strategic resource for ensuring long-term water security under conditions of population growth, agricultural expansion, and climate change (Fryar and Mukherjee, 2020; Ortega Guerrero, 2024).Beyond serving as a water supply, groundwater performs multiple ecological and hydrogeochemical functions that are fundamental to environmental sustainability. It maintains river baseflow during dry periods, supports wetlands and groundwater-dependent ecosystems, and regulates hydrogeochemical processes that influence water quality (UNESCO, 2022). However, increasing groundwater abstraction, climate change, urbanization, and agricultural intensification have progressively disrupted the natural balance between recharge and discharge in aquifer systems worldwide (Taylor et al., 2013; Gleeson et al., 2020; UNESCO, 2022). In addition, hydrogeochemical alterations associated with anthropogenic activities represent an additional threat to groundwater sustainability, emphasizing that sustainable groundwater management must simultaneously address both quantitative depletion and water-quality deterioration (Chinemerem et al., 2026). Consequently, contemporary groundwater management has shifted from maximizing water extraction toward integrated strategies that combine aquifer protection, groundwater recharge, and long-term ecosystem sustainability. Although groundwater generally benefits from natural filtration processes and longer residence times than surface water, these characteristics do not eliminate its vulnerability to anthropogenic and geogenic contamination (Jain, 2023; Mukherjee et al., 2024). Once contaminants enter aquifer systems, their persistence, slow transport, and limited groundwater circulation often make remediation technically complex and economically expensive (Lapworth et al., 2022). Therefore, protecting groundwater quality requires not only sustainable recharge strategies but also continuous environmental monitoring using modern analytical technologies (Oladosu et al., 2026). From the One Health perspective, maintaining groundwater quality is essential because groundwater contamination directly threatens human health through drinking-water exposure, affects livestock water supplies, and alters the functioning of groundwater-dependent ecosystems (Xie et al., 2023; WHO, 2022). This relationship is particularly important in arid and semi-arid regions, where deterioration of groundwater quality is associated with an increased burden of waterborne diseases, including diarrhoeal diseases, cholera, typhoid fever, and viral hepatitis, further emphasizing the importance of sustainable groundwater management within the One Health framework (El Morabet et al., 2023). The Adrar region illustrates these challenges. The chemical composition of local groundwater (Table 1) indicates relatively elevated salinity and nitrate concentrations, which may reflect natural hydrogeological conditions together with increasing anthropogenic pressures. These hydrochemical parameters indicate progressive groundwater mineralization and reflect the combined influence of prolonged residence time, water–rock interactions, hydrogeological conditions, and anthropogenic inputs. Such processes may gradually reduce groundwater quality, particularly in arid regions where natural recharge rates are limited and groundwater renewal is slow (Appelo and Postma, 2005; Güler et al., 2002). Therefore, sustainable groundwater management should focus not only on maintaining water availability but also on preserving chemical quality. Elevated salinity and nitrate concentrations are of particular concern because they may affect drinking-water suitability and pose potential health risks for populations and livestock dependent on groundwater resources (WHO, 2022; Xie et al., 2023).

Instead of evaluating each parameter individually, the overall hydrochemical characteristics indicate that groundwater in Adrar remains generally suitable for use but exhibits signs of increasing salinity and nitrate enrichment. Elevated electrical conductivity (2080 µS/cm), total dissolved solids (1310 mg/L), and nitrate concentration (64 mg/L) exceed commonly recommended guideline values, suggesting that long-term groundwater exploitation without adequate recharge may gradually reduce water quality. These observations are consistent with broader trends reported for many arid regions, where declining groundwater levels are frequently accompanied by increasing mineralization and deterioration of hydrochemical conditions.

Table 1. Chemical composition of groundwater in Adrar (Sekkoum et al., 2012)

Parameter	Value	Unit
pH	7.28	-
Electrical conductivity	2080	µS/cm
Total dissolved solids (TDS)	1310	mg/L
Calcium ion (Ca^{2+})	111	mg/L
Magnesium ion (Mg^{2+})	101	mg/L
Sodium ion (Na^{+})	160	mg/L
Potassium ion (K^{+})	6	mg/L
Chloride ion (Cl^{-})	245	mg/L
Sulfate ion (SO_4^{2-})	380	mg/L
Bicarbonate ion (HCO_3^{-})	311	mg/L
Nitrate ion (NO_3^{-}	64	mg/L

Groundwater recharge sources

Groundwater recharge is a fundamental process controlling aquifer sustainability. Under natural conditions, recharge occurs through direct infiltration of precipitation, seepage from rivers, lakes, and ephemeral streams, and subsurface inflow from adjacent aquifers. Additional contributions may originate from irrigation return flows, infiltration from urban drainage systems, leakage from water supply networks, and managed aquifer recharge projects.

In arid environments, natural recharge is typically limited by low precipitation, high evapotranspiration rates, and the episodic nature of rainfall events. Consequently, groundwater abstraction often exceeds natural replenishment, resulting in progressive depletion of groundwater reserves. Numerous studies have therefore highlighted the growing importance of managed aquifer recharge using infiltration basins, recharge ponds, check dams, rainwater harvesting systems, and other nature-based solutions to restore groundwater balance.

In southern Algeria, including the Adrar region, groundwater recharge depends primarily on infrequent rainfall events and localized infiltration processes. Because natural recharge rates remain substantially lower than groundwater withdrawals, improving infiltration efficiency has become a key challenge for sustainable groundwater management. Traditional clay-based recharge structures represent one of several nature-based approaches that may enhance groundwater replenishment while minimizing evaporation losses under hyper-arid climatic conditions. Besides increasing groundwater availability, such nature-based recharge systems may contribute to safer water supplies by reducing the vulnerability of groundwater resources to quality deterioration, thereby supporting the interconnected health of humans, animals, and ecosystems.

GROUNDWATER DEPLETION

Drivers and global trends of groundwater depletion

Groundwater depletion has become one of the most critical challenges for global water security, particularly in arid and semi-arid regions where groundwater often represents the principal or only reliable freshwater resource. Rapid population growth, agricultural expansion, industrial development, and climate change have substantially increased groundwater abstraction, while natural recharge rates have remained limited or even declined in many regions. As a result, groundwater extraction exceeds natural replenishment in numerous aquifer systems worldwide, leading to progressive depletion of groundwater reserves.

Approximately one-third of the world's irrigated agricultural land depends on groundwater, and observations from many countries indicate a continuous decline in groundwater levels in intensively exploited aquifers. Although groundwater has traditionally been regarded as a resilient resource because of its large storage capacity, growing evidence demonstrates that excessive abstraction can exceed the adaptive capacity of aquifer systems and compromise their long-term sustainability (Gage, 2019).

Groundwater depletion is no longer considered solely a hydrogeological issue. It is increasingly recognized as an environmental, socio-economic, and public health challenge because groundwater quantity and quality directly influence drinking water security, agricultural productivity, ecosystem functioning, and climate resilience. Consequently, sustainable groundwater management requires integrated approaches that simultaneously address water availability, water quality, ecosystem conservation, and human well-being.

Despite considerable advances in hydrogeological research, important knowledge gaps remain regarding long-term groundwater resilience, the effectiveness of nature-based recharge strategies, and the integration of traditional groundwater conservation practices into modern water resource management. These limitations highlight the need for comprehensive evaluations of sustainable recharge technologies capable of improving both groundwater quantity and quality under changing climatic conditions.

Consequences of groundwater depletion

Groundwater depletion produces a cascade of interconnected environmental, economic, and social consequences that extend far beyond declining groundwater levels. Excessive groundwater abstraction reduces future water availability, increases pumping depths and energy consumption, accelerates land subsidence, promotes salinization, and decreases river baseflow, thereby affecting both groundwater-dependent ecosystems and surface water resources. Because groundwater systems respond slowly to natural and anthropogenic disturbances, recovery of depleted aquifers often requires decades or even centuries (Perez-Quesada et al., 2024).

From the perspective of One Health, groundwater depletion simultaneously affects human health, animal health, and ecosystem integrity. Declining groundwater availability and deteriorating water quality reduce access to safe drinking water, increase dependence on lower-quality water sources, and may elevate exposure to chemical and microbiological contaminants. Livestock production is similarly affected through reduced availability of reliable water resources, while groundwater-dependent habitats, wetlands, and oasis ecosystems experience progressive ecological degradation.

The socio-economic consequences are equally significant. Declining groundwater levels increase the costs of pumping, irrigation, and water supply infrastructure, disproportionately affecting rural communities and small-scale farmers. Reduced groundwater availability may decrease agricultural productivity, threaten food security, intensify competition among water users, and increase regional vulnerability to drought and climate change. In many arid regions, these pressures contribute to social instability and further accelerate unsustainable groundwater exploitation.

These multidimensional consequences demonstrate that groundwater depletion should be addressed not only through increasing water supply but also through protecting groundwater quality, enhancing natural recharge, and implementing sustainable, nature-based groundwater management strategies capable of supporting long-term environmental sustainability and public health.

In the context of this review, the One Health framework is applied not merely as a conceptual background but as an analytical perspective linking groundwater recharge technologies with three interconnected dimensions: environmental sustainability (aquifer restoration and ecosystem resilience), animal health (water availability for livestock and wildlife), and human health (safe water supply, food security, and reduced exposure to water scarcity). The following sections critically evaluate the reviewed evidence within these three dimensions.

INCREASING DEMAND FOR GROUNDWATER

Groundwater demand has increased dramatically over the past several decades and continues to rise in response to population growth, agricultural intensification, urban expansion, industrial development, and climate change. Unlike many surface water resources, groundwater provides a relatively stable and accessible supply during prolonged droughts, making it an increasingly strategic resource for water security in both developed and developing countries. Consequently, dependence on groundwater has expanded well beyond traditional domestic use and now underpins food production, industrial activities, and regional economic development (Vinh et al., 2024).

This growing reliance on groundwater has fundamentally changed the balance between water abstraction and natural recharge. In many regions, groundwater extraction has become largely demand-driven rather than resource-driven, resulting in persistent overexploitation of aquifers. Although groundwater is a renewable resource, its capacity for replenishment is constrained by local hydrogeological conditions, recharge rates, and climatic variability. Therefore, the sustainability of groundwater use depends not only on the volume of available groundwater but also on maintaining a long-term equilibrium between withdrawal and recharge.

Increasing demand has also intensified concerns regarding groundwater quality. Expanding agricultural production, urbanization, industrial activities, and mining contribute to the accumulation of nutrients, salts, heavy metals, and other contaminants within aquifer systems. Because groundwater circulation is generally slow, pollutants may persist for decades, making groundwater restoration technically difficult and economically costly. Consequently, groundwater quantity and quality should be considered inseparable components of sustainable water resource management rather than independent management objectives.

Algeria reflects many of these global challenges. More than half of the country's population depends on groundwater for domestic water supply, while agriculture remains the largest consumer through extensive irrigation systems (Houari et al., 2024). In southern Algeria, where surface water resources are extremely limited, groundwater constitutes the principal foundation for food production, regional development, and socio-economic stability. However, the increasing dependence on groundwater has intensified pressure on aquifer systems, raising concerns regarding long-term water availability and progressive deterioration of groundwater quality.

From the One Health perspective, increasing groundwater demand extends beyond water resource management. Reliable access to high-quality groundwater is essential for protecting human health through safe drinking water, sustaining livestock production, maintaining agricultural productivity, and preserving groundwater-dependent ecosystems. Water security therefore represents not only a resource management issue but also a public health priority, particularly in regions where groundwater serves as the primary source of drinking water (El Morabet et al., 2023). These interconnected challenges emphasize that future groundwater management should integrate hydrogeological, environmental, ecological, and public health considerations to ensure sustainable and resilient water systems under changing climatic conditions.

GROUNDWATER REPLENISHMENT

Groundwater replenishment is an important component of sustainable water management. A variety of methods are available to increase groundwater supplies. However, improving groundwater availability alone is insufficient unless groundwater quality is also preserved, since effective water purification and treatment remain essential for protecting human health and ensuring the long-term sustainability of water resources (Zahorodniuk et al., 2019)

Artificial recharge using surface diffusion methods has been widely adopted in many countries. Artificial recharge techniques have been found to modify the natural flow of water through various urban structures, including infiltration tanks, check dams, nala barriers, and gulley plugs, among others (Xu et al., 2022).

Efforts to increase renewable groundwater resources through rainwater harvesting and artificial recharge have gained renewed priority. These efforts complement a groundwater management strategy that includes regulating overdevelopment. Regulating groundwater development in critical areas is an important strategy for sustainable groundwater management. Overdevelopment of groundwater resources is increasingly recognized as a significant problem. The rapid spread of enhanced pumping technologies, resource characteristics, demographic shifts, and government policies drives the trend toward overdevelopment of groundwater resources.

The key challenge is to prioritize the proper allocation of water resources without impacting groundwater levels and agricultural productivity. Any sustainable strategy should be based on an assessment of the actual amount of water allocated for domestic and agricultural use, as well as maintaining a balance in the ecosystem. It should focus on cost-effective analysis of water use, improving water productivity, irrigation efficiency, and post-harvest treatment. Practical approaches include encouraging groundwater users not affected by climate change to switch from exploiting high-quality aquifers to lower-quality groundwater sources, restricting withdrawal rights for industries that lack water-efficient technologies, and supporting improvements in irrigation efficiency.

Natural recharge processes

The main natural processes that enrich atmospheric and surface-derived water sources are infiltration and recharge through soil-rock-water interactions. During these processes, flowing water undergoes kinetic, hydrolytic, and oxidation-reduction reactions. Water must be in contact with rocks; therefore, infiltration is a necessary condition for this process. However, direct recharge of aquifers will only occur after the downward movement of water passes through a vadose zone, where intense water-rock interactions occur. Greater exposure to water leads to more extensive chemical reactions, as rapidly soluble components, such as carbonate minerals, calcium, and magnesium, dissolve into solution. The formation of these components begins in the soil zone and continues through subsequent stages of infiltration and recharge. These water-rock interactions produce groundwater with diverse properties under different climatic and hydrogeological conditions (Döll and Fiedler, 2007). Climate variability and changing precipitation regimes continue to increase uncertainty in groundwater recharge, particularly in arid environments (Odiana and Yusuf, 2026).

Figure 1 illustrates the natural water cycle. This process is a natural cycle that demonstrates the continuous change of water between its levels on the Earth's surface and within the atmosphere. The cycle begins with the conversion of solar energy from liquid water in seas, lakes, and soil into water vapor that rises into the atmosphere. This vapor condenses as the temperature drops, forming ice grains or crystals in clouds. As these grains or crystals grow

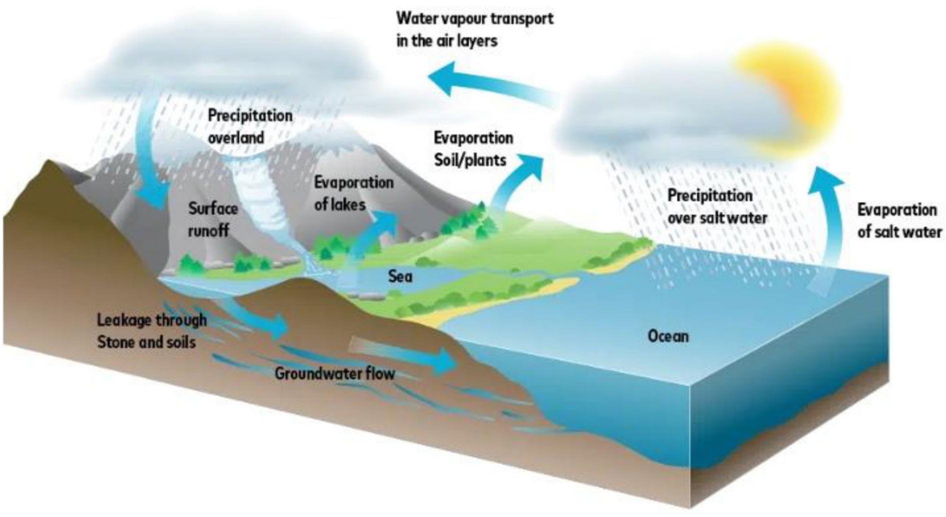

Figure 1. Water cycle in nature (Apure, 2023)

and heat up, the water falls to the ground as rain or snow. Some of the precipitation returns as surface runoff to replenish streams and lakes, while the rest infiltrates soil and rocks to recharge groundwater. The cycle involves interconnected physical and chemical processes that ensure the recharge of water resources and the balance between surface and groundwater stores(Kuang et al., 2024).

The water cycle moderates climate change by regulating global temperatures and humidity, and supports ecosystems by providing fresh water for plant growth and sustaining nutrient cycles. It can be a primary source of water for drinking and water systems, and supports hydropower generation by managing water flow. The varying rainfall characteristics and their global and spatial distribution support horticulture and human activities. Furthermore, rain is stored and seeps into the soil, replenishing groundwater reserves and improving resistance to drought and desertification. This cycle also contributes to reducing water pollution by reducing the concentration and spread of toxins within the ecosystem, thus improving water quality. Understanding and monitoring the water cycle is fundamental to economic planning in the face of climate change and population growth (Zhang et al., 2017).

Figure 2 represents the distribution of elevations and geographical regions in Algeria. It is noted that the southwestern regions are lower in elevation than the northern regions. The green color represents the lowlands, while the red color represents the highlands. From an analysis of Figure 2, it is noted that the highest elevation is 2,866 meters, and the lowest is -51 meters below sea level. The natural depressions may be suitable for water collection or the creation of artificial reservoirs. Adrar is a desert region located in southeastern Algeria. It is characterized by a traditional irrigation system based on the Foggara system, which consists of a series of wells connected by underground canals. This system transports groundwater between oases along a natural slope without mechanical intervention.

This technique is similar to the irrigation system used in the Persian qanats in Iran (UNESCO), (Mokhtarnia et al., 2022).

Combining Figures 1 and 2, we can conclude that the study area of Adrar, southern Algeria, is a low-lying region characterized by vast groundwater resources. However, over the years, this water has experienced a significant decline, resulting in a fluctuation in its level. This leads to increased economic costs for the government and the population.

THE ECONOMIC COST OF GROUNDWATER DECLINE

Declining water tables and increased energy use for pumping water

Declining groundwater tables affect crop yields through two main factors: groundwater depth and land-use changes. When the groundwater table

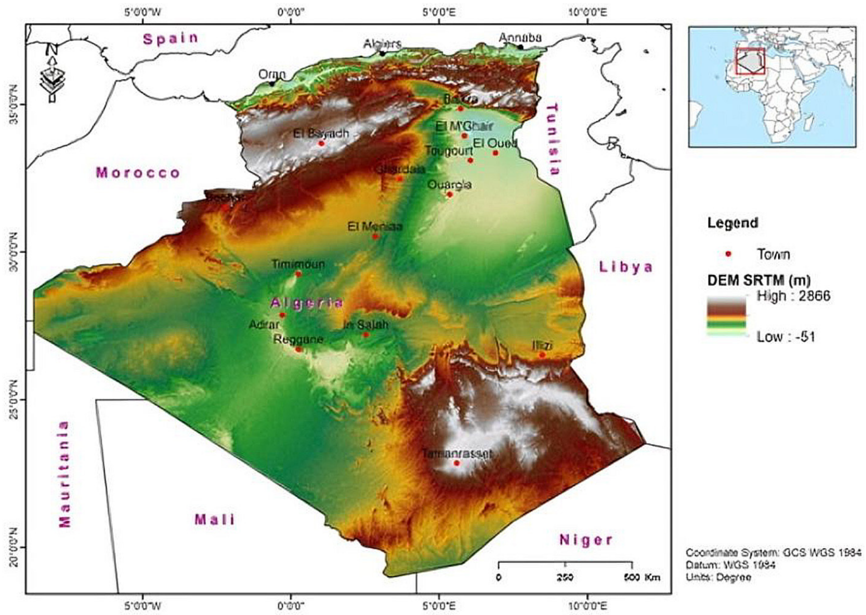

Figure 2. Distribution of elevations and geographical regions of Algeria (Hamlat et al., 2025)

recedes, farmers are forced to pump water from greater depths, requiring more energy and incurring higher costs. At certain depths, pumping becomes prohibitively expensive, prompting farmers to reduce irrigation and switch to less water-intensive crops, thus reducing overall water demand. The cost of pumping is also affected by groundwater quality: as high-quality surface water is replaced by saline groundwater, the decline in water quality also reduces water demand. Finally, higher groundwater prices, caused by declining groundwater levels and deteriorating quality, can lead to reduced demand for irrigation water.

As the depth of the water increases, the height increases, and consequently, the power increases. According to Bernoulli's law of fluid mechanics, shown in Equation 1:

$$P_1 + \frac{1}{2}\rho v_1^2 + \rho g h_1 = P_2 + \frac{1}{2}\rho v_2^2 + + \rho g h_2 + \Delta P_{12} + \frac{W}{q_v} \quad (1)$$

where: p is the total pressure (in N/m²), ρ is the density of the fluid (kg/m³), v is the velocity of the fluid at the point (m/s), g is the acceleration due to gravity, which is 9.81 m/s², h is the reference height of the fluid (m).

Note that the higher the height, the more energy is required to move the fluid from point 1 to point 2.

When the water flow and pump efficiency are constant, the electrical power required is directly related to the height to be pumped, according to Equation 2:

$$W = \frac{\rho g Q}{\eta} h \quad (2)$$

where: ρ – the density of water (≈1000 kg/m³), g – the acceleration due to gravity (≈9.81 m/s²), Q – the volumetric flow (m³/s), η – the efficiency pump (relative, between 0 and 1), h – vertical height (m), W – electrical power (W).

Figure 3 shows a practical example of increasing electrical power as the groundwater level decreases.

When the water level is h3, the pump exerts more electrical power to draw water than when the water level is h2 h1.

Declining agricultural yields

Groundwater has become an essential input for agricultural production. Its availability at reasonable prices and in sufficient quantities makes it a reliable source of irrigation. Those with access to groundwater have access to a wide range of crop, agricultural, and production options, which increases their productivity and reduces risks. Thus, groundwater mitigates the adverse effects of drought. In agriculture, crops with higher net value per hectare require more irrigation than food crops. Therefore, any constraints on groundwater availability may affect the area and productivity of these crops. Consequently, crop production may be affected by reduced irrigation due to higher irrigation costs (Zhang et al., 2010).

Groundwater supports more than 40% of global crop production, making its depletion a serious threat to agriculture and food security. Declining groundwater levels result in reduced surface soil moisture and increased irrigation water pumping costs, ultimately reducing crop productivity. The primary concern is that while groundwater provides a buffer against rainfall variability and supports agriculture despite arid climate conditions, over-pumping and climate-related changes in groundwater recharge are causing global groundwater reserves to shrink.

The damage caused by the over-extraction of groundwater primarily arises from groundwater decline. Under current conditions, rising temperatures and declining rainfall are leading to a decline in groundwater recharge, which is exacerbated by increased groundwater irrigation due to increased water demand for crop irrigation.

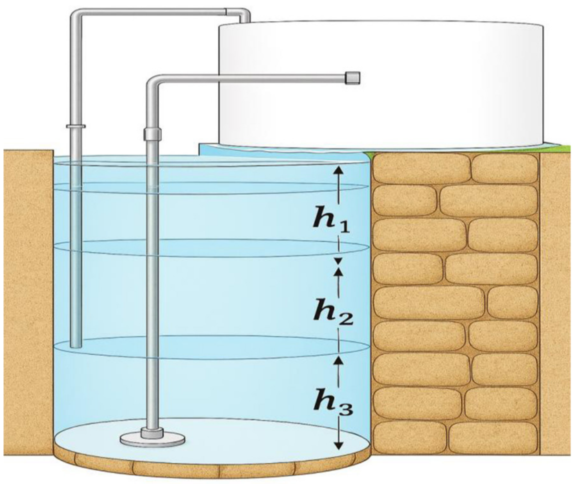

Figure 3. Declining groundwater level

Groundwater decline directly affects crop productivity through increased pumping costs. In most irrigated areas around the world, drought-related water shortages are compensated for by increased groundwater pumping. This study aims to provide estimates of how these other increased demands affect well pumping depths and how increased pumping depths increase the value of water for crop production. The links between groundwater decline and crop productivity arise primarily from hydrological and economic mechanisms. The hydrological mechanism links groundwater decline to productivity through fluctuations in groundwater levels. The economic mechanism is associated with two different costs: the cost of irrigation and the capital cost borne by the farmer.

The hydrological mechanism arises from the fact that the groundwater table acts as a natural water source. Water that holds back the groundwater table flows upward, reducing the amount of water lost by the irrigated crop through evaporation. Therefore, a shallow groundwater table mitigates drought stress, thereby increasing yield. It does this by directly supplying water to the crop's roots. The groundwater table also indirectly affects yield by influencing the amount of irrigation water used by farmers. When the groundwater table declines, the amount of water lost by plants through evaporation increases, creating drought stress for the plants. This naturally reduces yield. As the groundwater table declines, yield may increase, decrease, or remain the same depending on the resulting change in irrigation water and the relative costs of water acquisition through groundwater and surface water irrigation.

The economic mechanism operates by changing the cost of water acquisition and irrigation. Irrigation and capital costs account for a significant portion of the total crop production costs. Irrigation costs are closely linked to groundwater levels, as lower groundwater levels are associated with higher pumping costs. Capital costs arise as a result of lower groundwater levels, which necessitate an increase in the capacity of existing pumps.

Figure 4 shows a drought-stricken orchard in the Adrar region of southern Algeria. This is due to the lower groundwater levels and low rainfall.

It is evident from the figure that farmers are unable to plant due to soil salinity.

Destruction of ecosystems

Groundwater is found beneath the Earth's surface in the pores of soil and within cracks in rock formations. It forms an important reservoir for maintaining stream flows, especially in arid regions with little flow, and can also maintain water levels in lakes and wetlands. Water enters the groundwater reservoir through recharge, which occurs when rainfall or surface water penetrates the soil and seeps into the groundwater table. Date palms are the most important trees found in the Adrar oases. Declining groundwater levels cause them to dry out and die, thus reducing vegetation cover in the area and increasing temperatures.

Groundwater plays a fundamental role in maintaining ecosystem functions. Water, in general, is a fundamental component of ecosystem composition and dynamics. The constant movement, circulation, and recycling of water support

Figure 4. Agricultural lands suffering from drought

the growth and health of ecosystems. Living organisms, in general, require water to survive, and their distribution and abundance are directly related to the availability of water. Water availability also determines the properties of the associated soil, and soil composition depends on the chemical quality of groundwater. Soil solutions are the primary source of nutrients that plants need. Water circulation and movement generally influence global nutrient cycles and regulate the thermal energy at the Earth's surface. Consequently, a decline in the water table has devastating effects on ecosystems, resulting in reduced water availability (Saito et al., 2021)

Figure 5 is a comparison between Tourfine Fouggara 2008 and 2024.

USE OF CLAY AQUIFERS

Groundwater recharge processes

Groundwater recharge is the process by which water moves vertically through the soil surface to replenish the aquifer. The primary recharge mechanism is rainfall, when water seeps down through the unsaturated zone. Areas with high infiltration rates tend to exhibit relatively higher recharge rates; however, other factors, such as soil type, vegetation cover, and slope, also influence recharge by affecting infiltration and runoff rates. Soil physical properties influence not only groundwater recharge but also microbial activity and ecosystem functioning, which are important components of sustainable environmental management (Patah and Othman, 2024). Local topography, geology, and hydrogeological conditions also exert strong controls. Despite these advantages, the performance of clay-based recharge systems remains highly site-specific, being governed by local hydrogeological conditions, recharge water quality, and operational management. Progressive deposition of fine sediments and suspended solids, together with biofilm development and other clogging processes, can substantially reduce infiltration capacity and, consequently, long-term recharge efficiency (Lippera et al., 2023; Sinshaw et al., 2026). In addition, prolonged operation without periodic maintenance can promote sediment accumulation and clogging, leading to a progressive decline in hydraulic conductivity, reduced infiltration performance, and increasing maintenance requirements (Sufyan et al., 2024; Meles et al., 2024; Seidl et al., 2024). The long-term performance of recharge basins therefore depends not only on their initial design but also on regular monitoring, sediment removal, and adaptive management practices. Furthermore, variations in rainfall patterns, aquifer properties, and groundwater levels introduce uncertainty into recharge performance, indicating that successful implementation requires site-specific assessment rather than direct transfer of recharge designs between different hydrogeological settings. An impermeable clay-rich layer or a thick, unsaturated zone below the water table acts as a barrier to vertical flow, limiting groundwater recharge. Rainfall over the soil's infiltration capacity causes surface runoff, which either flows downslope or seeps into the water table, exposing the aquifer and groundwater system to lateral recharge from streams and water bodies (Condon and Maxwell, 2019). The Adrar region is characterized by low rainfall. In arid and semi-arid regions, water basins are vital centers for artificial groundwater recharge (Mohamed Haroon, 2004).

Figure 5. Drying up of natural springs

Well-selected and managed basins – often located within cultivated lands that intercept surface water flow from hillsides – provide a regular supply of infiltration water. This enhanced resource contributes to the stability of groundwater-dependent irrigation systems during periods of aridity. Coordinating surface and groundwater reservoir operations with recharge controls helps optimize the simultaneous use of both resources. Surface runoff and infiltration characteristics in watersheds vary greatly depending on soil texture and vegetation cover. Water retention in watersheds stimulates evaporation, transpiration, and associated losses. Facultative cover with shrubs or grasses creates local subsurface flow systems and maintains enhanced recharge beneath vegetated margins. Thus, water retained in watersheds supplements the amount reaching streams, rivers, and riparian areas.

Watersheds offer the opportunity to enhance recharge. Once water enters the basin, evaporation begins to remove it, along with infiltration or recharge. Both the quantity and the period over which infiltration occurs affect the importance of a recharge basin in enhancing recharge. Recharge basins that hold a large amount of water for a short period will produce less recharge than basins that hold a smaller amount of water for a longer period. Recharge basins containing sediments will enhance recharge, as sediments prevent evaporation from the basin water. When using natural or artificial recharge from a basin, basin construction is important; A water basin constructed without a substantial soil layer may leak, but the amount of water lost in this way is unlikely to be a factor in a recharge program unless the basin is vast. Basins, which are typically held for some time and contain water at any given time, are a source of recharge. In arid regions where water quantities are relatively small, the quantity of water in the basin is often unimportant; what matters most is the duration of water retention. In these conditions, sediment may settle in these basins, reducing their effectiveness as recharge structures. Figure 6 illustrates a traditional clay basin used for collecting water for irrigation.

It collects water and humidifies the air. Heat-tolerant trees, such as olives and citrus, are planted nearby.

Design and construction of water basins

In arid regions where scarce rainfall limits groundwater recharge, the efficient design and construction of water basins is critical to enhancing infiltration and storing sufficient water for agricultural and municipal use. Water basin construction begins with identifying suitable locations based on slope, soil type, land cover, and land use, all of which affect the efficiency of surface water diffusion and infiltration. Basins are typically excavated by removing soil to depths exceeding one meter, facilitating deep infiltration through sandy and gravelly soils. In the Adrar region, basins are rectangular, measuring 4 × 8 meters and 20 to 50 cm high, and are constructed of clay.

The low-permeability, compressible clay layers, rich in clay mineral deposits, result from the development of sedimentary basins and various geological processes, forming local aquifers that

Figure 6. Traditional clay water basin

contribute to the natural replenishment of groundwater supplies. These clay basins retain water by forming low-permeability layers that prevent surface water from flowing downward, thus naturally preserving and supporting groundwater reserves (Merriman, 2005). Local farmers compact the clay well within the basin to allow water to collect. The clay from the Adrar region exhibits the characteristics listed in Table 2.

Analyzing Table 2, we conclude the following: 9% sand, 54% silt, and 37% clay, indicating a soil rich in fine particles (silt and clay) at 91%, making it highly water-retaining when compressed.

- Liquidity limit (WL) = 81%
- Plasticity limit (WP) = 34%
- Plasticity index (IP) = 47%

It can be noted that the contraction and swelling capacity is high, classifying it as a highly plastic clay (CH) according to the United States Classification System (USCS). - The high silica and alumina content enhances the internal cohesion strength after compaction.

- The presence of calcium carbonate reduces the acidity of the medium and reduces the potential for chemical corrosion.

This highly plastic clay (CH) has a high water-holding capacity when compacted and is effective at preventing water seepage. Farmers compact the clay in layers 20–30 cm thick using heavy equipment and limited amounts of water to ensure uniformity of density. Clay basins offer a suitable environment for groundwater replenishment in hot regions, as evaporation is significantly reduced, and transpiration only occurs when a dry cover forms after a drought. Therefore, these cover effects must be taken into account in this type of application. Increased water availability from shallow groundwater sources has the potential to significantly increase evaporation, thereby impacting the hydrological cycle in water-constrained areas (Soylu, 2011).

The significantly reduced soil evaporation from the clay cover is an important factor in how the soil-water balance is affected when the dry cover develops in an upwelling situation, either due to capillary action or seepage upstream. In a previous study, groundwater dynamics and exchange flows under water-saving irrigation were recently investigated to understand the implications for sustainable water management in the Tarim River Basin, western China (Zhang et al., 2014).

Scattered clay covers are naturally formed on the surface through particle separation during infiltration or upwelling, playing a crucial role in water management in hot regions. These clay covers may extend across the entire basin during the dry season, severely reducing evaporation.

Comparison of clay-based recharge basins with other managed aquifer recharge techniques

Although clay-based recharge basins represent an effective and sustainable solution for groundwater replenishment in arid and semi-arid environments, they constitute only one of several managed aquifer recharge (MAR) techniques currently applied worldwide. Each recharge method differs in terms of recharge mechanism, hydrogeological suitability, operational complexity, maintenance requirements, and economic considerations. Therefore, selecting an appropriate recharge technique requires evaluation of local environmental conditions together with long-term management objectives. A comparison of the principal characteristics of commonly used recharge techniques is presented in Table 3.

The comparison presented in Table 3 was compiled from the literature discussed throughout this review and highlights the principal characteristics of the most widely applied groundwater recharge techniques. Although the reviewed studies consistently report the practical advantages of clay-based

Table 2. Clay properties

Geotechnicals properties							
Sand (> 0.02 mm)	Silt (0.02–0.002 mm	Clay (<0.002 mm)	Liquid limit WL	Plastic limit WP	Plastic index IP	VB	Specific density γs
9%	54%	37%	81%	34%	47%	8	2.6 g/cm^3
Chemical composition							
$SO4^{-2}$	$CaCO_3$	Cl-	SiO_2	Al_2O_3	Fe_2O_3	MgO	Other
0.41%	3.6%	0.14%	0.63	0.16	0.07	2.4%	7.46%

recharge basins, the overall level of evidence remains limited. Most available publications are site-specific case studies with relatively short monitoring periods, whereas comparative long-term evaluations against other MAR techniques remain scarce. Consequently, it is still unclear whether the reported advantages primarily reflect the intrinsic performance of clay-based systems or favorable local hydrogeological and climatic conditions. This limitation should be considered when extrapolating these findings to other arid regions.

As shown in Table 3, clay-based recharge basins differ from engineered MAR techniques primarily in their operational simplicity, low construction costs, and reliance on natural infiltration processes. These characteristics make them particularly suitable for arid and semi-arid regions where financial resources and technical infrastructure may be limited. Unlike recharge wells and aquifer storage and recovery (ASR) systems, which require substantial engineering infrastructure and water pretreatment, clay-based basins rely primarily on gravity-driven surface infiltration and can often be constructed using locally available materials. Compared with recharge ponds, clay basins are particularly adapted to traditional oasis agriculture, where episodic floodwater can be retained and gradually infiltrated to replenish shallow aquifers. However, their performance remains highly dependent on local hydrogeological conditions, sediment characteristics, and maintenance practices, whereas engineered MAR systems generally provide greater operational control but at considerably higher construction and operational costs. Consequently, the selection of an appropriate recharge technique should be based on site-specific hydrogeological conditions, water availability, economic feasibility, and long-term management objectives rather than on a single technological approach.

From a One Health perspective, the reviewed recharge techniques should not be evaluated solely on hydraulic performance. Their comparative value also depends on their capacity to simultaneously enhance groundwater security, sustain ecosystem services, and reduce risks to human and animal health. However, only a limited number of the reviewed studies explicitly assessed these broader outcomes, indicating an important gap in the current literature.

Water retention, irrigation, and salinity effects

The effectiveness of clay-based recharge systems depends on the interactions among irrigation

Table 3. Comparison of clay-based recharge basins with commonly used managed aquifer recharge (MAR) techniques

Recharge technique	Main recharge mechanism	Suitable hydrogeological conditions	Main advantages	Main limitations	Typical applications
Clay-based recharge basins	Surface infiltration through prepared clay basins	Arid and semi-arid regions with permeable subsurface	Low construction cost; simple operation; utilizes floodwater; environmentally compatible	Sediment accumulation; clogging; site-specific infiltration rates	Traditional groundwater recharge in oasis agriculture
Recharge ponds	Surface infiltration	Permeable soils with shallow unsaturated zones	Large recharge capacity; simple construction	Evaporation losses; clogging; land requirement	Artificial recharge of alluvial aquifers
Infiltration trenches	Lateral infiltration	Localized recharge in permeable soils	Efficient stormwater infiltration; relatively small land footprint	Limited recharge volume; maintenance required	Urban stormwater management
Recharge wells	Direct injection into aquifers	Confined or deep aquifers	Minimal land requirement; rapid recharge	High construction cost; clogging risk; water pretreatment required	Municipal water supply; aquifer restoration
ASR (Aquifer Storage and Recovery)	Injection and later recovery	Suitable confined aquifers	Water storage with subsequent recovery	High operational complexity; strict water-quality requirements	Strategic water storage
MAR (integrated approaches)	Various recharge methods	Site dependent	Flexible design; improves groundwater sustainability	Requires detailed hydrogeological assessment	Regional groundwater management

Note: Compiled by the authors based on the literature cited in this review.

practices, soil properties, groundwater conditions, and water quality. These factors collectively influence infiltration rates, groundwater recharge efficiency, and the development of soil salinity, particularly in arid and semi-arid environments.

Drip irrigation alters groundwater flow dynamics and can mitigate the secondary salinization commonly associated with traditional irrigation methods. However, when brackish groundwater is used without adequate leaching, salts may progressively accumulate within the root zone, adversely affecting soil quality and agricultural productivity. Consequently, irrigation water quality represents an important factor in the long-term sustainability of groundwater recharge systems.

Soil characteristics strongly influence infiltration and recharge processes. Coarse-textured soils generally facilitate faster infiltration, whereas finer-particle soils result in slower recharge and longer water retention. Hydraulic conductivity is one of the principal factors controlling recharge rates and volumetric flow. Groundwater depth also plays an important role, as recharge rates decrease when the wetting front approaches the groundwater table. In addition, the spacing between recharge points affects recharge efficiency through hydraulic interactions among adjacent infiltration zones.

Traditional clay-lined water basins provide favorable conditions for temporary water storage and gradual infiltration. Their gently sloping floors retain water for several days, thereby enhancing infiltration while reducing rapid runoff losses. Under local climatic conditions, evaporation losses from these basins may be lower than those from equivalent free-water surfaces, allowing a greater proportion of stored water to contribute to groundwater recharge.

Representative examples of the influence of irrigation water quality on agricultural conditions are shown in Figures 7 and 8. Figure 7 illustrates an orchard containing a traditional clay-lined water basin. No visible signs of surface salinization are observed, and the vegetation exhibits healthy growth. In contrast, Figure 8 presents a neighboring orchard located approximately 10 m away, where irrigation relies on groundwater extracted from a 15 m deep well. Visible salt accumulation on the soil surface indicates the adverse effects of saline irrigation water on soil quality and agricultural productivity. These observations emphasize the importance of appropriate recharge and irrigation practices for maintaining soil health and supporting sustainable agricultural development in arid environments.

Water basin management and maintenance

Effective maintenance of recharge basins is essential for the long-term sustainability and performance of artificial groundwater recharge projects. Proper operation and regular maintenance preserve the infiltration capacity of recharge basins, extend their service life, and ensure the continued effectiveness of groundwater recharge under arid environmental conditions.

Maintenance procedures include the removal of suspended sediments, mobile colloids, aquatic plants, terrestrial vegetation, and accumulated waste that may reduce infiltration efficiency. Encroachment by aquatic and terrestrial plants must be controlled to maintain the hydraulic capacity and operational performance of the basin. In some cases, excessive sediment accumulation or mechanical failure of operating equipment necessitates periodic partial or complete rehabilitation

Figure 7. Traditional clay-lined water basin in an orchard

Figure 8. Impact of saline irrigation water on agricultural land

of the recharge facility. Design features that allow safe and rapid drainage facilitate the scheduling and implementation of routine maintenance. During these operations, upstream storage and conveyance facilities on tributaries should be temporarily closed to prevent re-entry of water and sediments.

Artificial groundwater recharge is widely recognized as an effective approach for storing excess water underground during periods of surplus for subsequent use during drought. Recharge can be achieved using several methods, including water spreading, borehole recharge, pump-assisted recharge wells, and natural recharge wells. Among these, water spreading remains one of the most commonly applied techniques, involving the controlled application of surface water to permeable land surfaces through recharge basins, stream channels, ditches, furrow flooding, and irrigation systems.

In arid regions, where annual rainfall is typically less than 500 mm and evaporation rates are high, most precipitation occurs as short-duration, high-intensity storms that generate episodic runoff in ephemeral streams (wadis). Under these conditions, infiltration through streambeds and recharge structures plays a major role in replenishing groundwater resources. Consequently, successful artificial recharge projects require not only appropriate engineering design but also continuous maintenance and integrated groundwater management based on careful resource assessment and suitable technologies.

Artificial recharge projects provide an effective means of conserving both surface water and groundwater resources in arid regions. They can mitigate groundwater depletion, declining groundwater levels, saltwater intrusion, and land subsidence. In addition, reclaimed wastewater treated to the tertiary level can be used for aquifer recharge, providing underground storage while undergoing further natural purification before subsequent reuse. An important inconsistency identified in the reviewed literature concerns the balance between maximizing infiltration and minimizing clogging. While several studies recommend fine sediments or clay linings to improve water retention, others identify sediment accumulation as one of the principal causes of declining recharge efficiency over time. This apparent contradiction indicates that long-term basin performance depends not only on the construction material itself but also on maintenance frequency, sediment management, and local hydrogeological conditions.

CONCLUSIONS

The synthesis of the available literature provides substantial support for the proposed hypothesis, although further long-term field validation remains necessary. Nevertheless, the literature demonstrates that the environmental benefits of clay-based recharge basins have been investigated far more extensively than their direct implications for human and animal health. Future One Health-oriented research should therefore integrate hydrogeological monitoring with ecological and public health indicators to provide a more comprehensive assessment of the societal value of managed aquifer recharge systems. However, the strength of the current evidence should be interpreted cautiously because most available studies are observational, geographically limited, and methodologically heterogeneous. Future research should prioritize standardized performance indicators and direct comparative field studies between clay-based recharge basins and alternative MAR technologies. The evidence reviewed consistently supports the premise that clay-based recharge systems constitute an effective and environmentally sustainable approach for enhancing groundwater recharge when appropriate hydrogeological, climatic, and operational conditions are considered.

A major contribution of this review is the integration of dispersed information on the hydrological, environmental, and engineering aspects of clay-based recharge systems into a unified framework. Unlike previous studies that primarily examined individual recharge techniques or local case studies, this review highlights the interactions among soil characteristics, recharge processes, irrigation practices, salinity management, basin maintenance, and groundwater sustainability within the context of the One Health concept. This integrated perspective provides a broader understanding of the factors governing the long-term performance of traditional clay-based recharge systems.

The review also addresses an important knowledge gap by consolidating current evidence on the role of clay-lined recharge basins as a low-cost and sustainable groundwater management strategy suitable for water-scarce regions. The comparative assessment of recharge approaches further demonstrates that the selection of recharge techniques should be based on site-specific hydrogeological conditions, water availability, economic feasibility, and long-term operational requirements rather than on a single universal solution.

From a practical perspective, the findings emphasize that the long-term success of recharge basins depends not only on their initial design but also on appropriate irrigation management, sediment control, regular maintenance, and continuous monitoring of groundwater quantity and quality. Integrating these technical and environmental considerations contributes to improving groundwater resilience, protecting ecosystem functions, and supporting sustainable agricultural production.

Although the reviewed studies demonstrate the considerable potential of clay-based recharge basins for enhancing groundwater resources in arid and semi-arid regions, important uncertainties remain regarding their long-term performance under different hydrogeological and climatic conditions. The available evidence also indicates that recharge efficiency is influenced by multiple interacting factors, including soil properties, groundwater conditions, irrigation practices, basin maintenance, and water quality. Consequently, the sustainable application of clay-based recharge systems requires an integrated approach that considers these factors collectively rather than individually within the broader framework of sustainable groundwater management and One Health.

REFERENCES

1. Amin, M. M., Rahman, A., Akter, M. S., Rana, M. M., Shariot-Ullah, M. (2025). Hydrogeochemical response of aquifers to intensive groundwater pumping for rice-rice rotation. *Groundwater for Sustainable Development*, 101485. https://doi.org/10.1016/j.gsd.2024.101485
2. Apure. (2023, October 13). Why is the water cycle important? - Apure. Apure. https://apureinstrument.com/blogs/why-is-the-water-cycle-important
3. Ardjane, T. A., Meddah, B., Bekkoussa, B. S., Zemour, K., Mairif, M. (2025). Groundwater quality assessment using water quality index coupled with multivariate statistical analysis in the alluvial plains of El-Abd and El-That, Tiaret Region, Northwestern Algeria. *Acque Sotterranee-Italian Journal of Groundwater*, *14*(2). https://doi.org/10.7343/as-2025-852
4. Ali, N., Kausar, A., Vambol, S., Kozub, P., Kozub, S. (2024). Environmental retrieval during COVID-19 lockdown in the megacity Karachi, Pakistan. *Ecological Questions, 35*(3), 1–16.
5. El Morabet, R., Khan, R. A., Alsubih, M., Khan, N. A., Yusuf, M., Khan, P.,..., Lutsak, O. (2023). Epidemiology study of diarrhoea, cholera, typhoid, Hepatitis A and Hepatitis E in middle east and north Africa Region. *Ecological Questions, 34*(4), 1–21.
6. Condon, L. E., Maxwell, R. M. (2019). Simulating the sensitivity of evapotranspiration and streamflow to large-scale groundwater depletion. *Science advances*, *5*(6), eaav4574. https://doi.org/10.1126/sciadv.aav4574
7. Döll, P., Fiedler, K. (2007). Global-scale modeling of groundwater recharge. *Hydrology and Earth System Sciences Discussions*, *4*(6), 4069–4124. https://doi.org/10.5194/hess-12-863-2008
8. Gage, A. (2019). *Defining and Addressing Interconnected Goals in Groundwater Management Planning Across the USA* (Doctoral dissertation, University of Massachusetts Libraries).
9. Hamlat, A., Hadidi, A., Kadri, C. B. (2025). A GIS-google earth based approach to identifying regions affected by rising groundwater levels in Algeria. *Environmental Claims Journal*, 1–30.

10. Houari, I. M., Bouselsal, B., Lakhdari, A. S. (2024). Evaluating groundwater potability and health risks from nitrates in the semi-arid region of Algeria. *Ecological Engineering & Environmental Technology*, *25*.
11. Jakeman, A. J., Barreteau, O., Hunt, R. J., Rinaudo, J. D., Ross, A., Arshad, M., Hamilton, S. (2016). Integrated groundwater management: an overview of concepts and challenges. *Integrated groundwater management: Concepts, approaches and challenges*, 3–20.
12. Kendouci, M. A., Mebarki, S., Kharroubi, B. (2023). Investigation of overexploitation groundwater in arid areas: case of the lower Jurassic aquifer, Bechar province Southwest of Algeria. *Applied Water Science*, *13*(4), 102.
13. Khezzani, B., Bouchemal, S. (2018). Variations in groundwater levels and quality due to agricultural over-exploitation in an arid environment: the phreatic aquifer of the Souf oasis (Algerian Sahara). *Environmental earth sciences*, *77*(4), 142.
14. Kuang, X., Liu, J., Scanlon, B. R., Jiao, J. J., Jasechko, S., Lancia, M.,..., Zheng, C. (2024). The changing nature of groundwater in the global water cycle. *Science*, *383*(6686), eadf0630. https://doi.org/10.1126/science.adf0630
15. Li, P., Elumalai, V. (2025). Hydrogeology and the Global Significance of Groundwater. In *Sustainable Groundwater and Environment: Challenges and Solutions* (pp. 1–20). Cham: Springer Nature Switzerland.
16. Menon, S. V. (2007). Ground water management: need for sustainable approach.
17. Merriman, R. J. (2005). Clay minerals and sedimentary basin history. *European Journal of Mineralogy*, *17*(1), 7–20.
18. Mester, T., Szabó, G., Kiss, E., Balla, D. (2025). Towards environmental sustainability: Wastewater management and sewer networks for protecting groundwater in rural settlements. *Urban Science*, *9*(3), 80.
19. Mohamed Haroon, K. O. (2004). *Assessment of surface water runoff and groundwater recharge using mathematical models.* Electronic Theses and Dissertations, UAEU Dissertations.
20. Mokhtarnia, K., Talebian, M. H., Eshrati, P. (2022). Developing a theoretical framework of heritage value for the Persian qanat. *Journal of Iranian Architecture Studies*, *11*(21), 205–223.
21. Perez-Quesada, G., Hendricks, N. P., Steward, D. R. (2024). The economic cost of groundwater depletion in the high plains aquifer. *Journal of the Association of Environmental and Resource Economists*, *11*(2), 253–285. https://doi.org/10.1086/723938
22. Saito, L., Christian, B., Diffley, J., Richter, H., Rohde, M. M., Morrison, S. A. (2021). Managing groundwater to ensure ecosystem function. *Groundwater*, *59*(3), 322–333. https://doi.org/10.1111/gwat.13094
23. Sekkoum, K., Talhi, M. F., Cheriti, A., Bourmita, Y., Belboukhari, N., Boulenouar, N., Taleb, S. (2012). Water in Algerian Sahara: environmental and health impact. *Advancing desalination*, 197–216.
24. Soylu, M. E. (2011). *Quantifying evapotranspiration and water table interactions in regions of shallow groundwater: Sensitivity to soil properties, vegetation, and climate variability*. The University of Nebraska-Lincoln.
25. Tortajada, C., Radcliffe, J. C., van Rensburg, P., González-Gómez, F. (2025). Sustainable water reuse for water security. *Environmental Research Letters*, *20*(2), 021003. https://doi.org/10.1088/1748-9326/ad1c8e
26. UNESCO World Heritage Centre. (n.d.). The Persian Qanat. https://whc.unesco.org/en/list/1506/
27. Vinh, D. H., Tran, D. D., Cham, D. D., Hang, P. T. T., Man, D. B., Mon, D.,..., Tuyen, D. T. N. (2024). Integrated exploitation of rainwater and groundwater: A strategy for water self-sufficiency in Ca Mau Province of the Mekong Delta. *Hydrology*, *11*(4), 55.
28. Xu, C., Sun, Y., Shi, B., Wang, X., Li, R., Li, M.,..., Feng, C. (2022). Study on the processes influencing and importance of ecological water replenishment for groundwater resources: A case study in Yongding River. *Water*, *14*(5), 828. https://doi.org/10.3390/w14050828
29. Yu, S., Wang, T., Bai, X., Chen, G., Wan, P., Chen, S.,..., Deng, F. (2025). Hydrochemical characteristics and formation mechanisms of groundwater in the Nanmiao emergency groundwater source area, Yichun, Western Jiangxi, China. *Water*, *17*(14), 2063. https://doi.org/10.3390/w17142063
30. Zhang, L., Wang, J., Huang, J., Huang, Q., Rozelle, S. (2010). Access to groundwater and agricultural production in China. *Agricultural Water Management*, *97*(10), 1609–1616. https://doi.org/10.1016/j.agwat.2010.05.005
31. Zhang, S., Fan, W., Yi, Y., Zhao, Y., Liu, J. (2017). Evaluation method for regional water cycle health based on nature-society water cycle theory. *Journal of Hydrology*, *551*, 352–364. https://doi.org/10.1016/j.jhydrol.2017.06.030
32. Zhang, Z., Hu, H., Tian, F., Yao, X., Sivapalan, M. (2014). Groundwater dynamics under water-saving irrigation and implications for sustainable water management in an oasis: Tarim River basin of western China. *Hydrology and Earth System Sciences*, *18*(10), 3951–3967. https://doi.org/10.5194/hess-18-3951-2014
33. Vambol, V., Borowski, G. (2026). Studying the heterogeneity of woody biomass: An experimental

and statistical approach. *Journal of Ecological Engineering, 27*(1), 434–444.

34. Oladosu, M. A., Abah, M. A., Odimgbe, E. I., Adewale, F. E., Arthur, C., Ajayi, A. S.,..., Ohanele, E. C. (2026). Smart electrochemical sensors and IoT for monitoring heavy metals in Nigerian water: review of advances and deployment challenges. *Trends in Ecological and Indoor Environmental Engineering, 4*(1), 79–89. https://doi.org/10.62622/TEIEE.026.4.1.79-89
35. Zahorodniuk, K., Voitsekhovsky, V., Korobochka, A., Hrynzovskyi, A., Averyanov, V. (2019). Development of modernized paper filtering materials for water purification, assessment of their properties. *Eastern-European Journal of Enterprise Technologies, 1*(10), 6–13.
36. Chinemerem, N. A., Ovie, I. E., Christian, I. C., Oladosu, M. A., Abah, M. A., Amadi, C. S.,..., Odimgbe, E. I. (2026). Petroleum-driven hydrogeochemical alteration and groundwater contamination in an offshore Niger Delta Depobelt: An integrated multivariate statistical, water quality index, and geospatial engineering assessment. *Trends in Ecological and Indoor Environmental Engineering*. In press.
37. Patah, S. F. A., Othman, N. M. I. (2024). Influence of soil temperature on root development and microbial diversity in paddy fields: A comprehensive review. *Trends in Ecological and Indoor Environmental Engineering, 2*(4), 1–9. https://doi.org/10.62622/TEIEE.024.2.4.01-09
38. Odiana, S., Yusuf, D. D. (2026). Time series modelling and forecasting of temperature and rainfall in Nigeria using ARIMA models. *Trends in Ecological and Indoor Environmental Engineering, 4*(3), 17–27. https://doi.org/10.62622/TEIEE.026.4.3.17-27
39. Zhang, H., Xu, Y., Kanyerere, T. (2020). A review of the managed aquifer recharge: Historical development, current situation and perspectives. *Physics and Chemistry of the Earth, Parts A/B/C, 118*, 102887.
40. Standen, K., Costa, L. R., Monteiro, J. P. (2020). In-channel managed aquifer recharge: a review of current development worldwide and future potential in Europe. *Water, 12*(11), 3099. https://doi.org/10.3390/w12113099
41. Kebede, M. M., Kumar, M., Mekonnen, M. M., Clement, T. P. (2024). Enhancing groundwater recharge through nature-based solutions: benefits and barriers. *Hydrology, 11*(11), 195. https://doi.org/10.3390/hydrology11110195
42. Gleeson, T., Wada, Y., Bierkens, M. F., Van Beek, L. P. (2012). Water balance of global aquifers revealed by groundwater footprint. *Nature, 488*(7410), 197–200.
43. Taylor, R. G., Scanlon, B., Döll, P., Rodell, M., Van Beek, R., Wada, Y.,..., Treidel, H. (2013). Ground water and climate change. *Nature climate change, 3*(4), 322–329. https://doi.org/10.1038/nclimate1744
44. UNESCO. (2022). *The United Nations world water development report 2022: Groundwater: Making the invisible visible.* UNESCO.
45. Fryar, A. E., Mukherjee, A. (2020). Groundwater hydrogeology. In *Encyclopedia of Geology* (2nd ed., Vol. 6, pp. 399–407). Elsevier. https://doi.org/10.1016/B978-0-12-409548-9.12115-3
46. Ortega Guerrero, M. A. (2024). Groundwater flow and transport in fractured geologic media: A review. *Revista Mexicana de Ciencias Geológicas, 41*(1), 103–129. https://doi.org/10.22201/cgeo.20072902e.2024.1.1772
47. Gleeson, T., Cuthbert, M., Ferguson, G., Perrone, D. (2020). Global groundwater sustainability, resources, and systems in the Anthropocene. *Annual review of earth and planetary sciences, 48*(1), 431–463. https://doi.org/10.1146/annurev-earth-071719-055251
48. Jain, H. (2023). Groundwater vulnerability and risk mitigation: A comprehensive review of the techniques and applications. *Groundwater for Sustainable Development, 22*, 100968. https://doi.org/10.1016/j.gsd.2023.100968
49. Mukherjee, A., Coomar, P., Sarkar, S., Johannesson, K. H., Fryar, A. E., Schreiber, M. E.,..., Vengosh, A. (2024). Arsenic and other geogenic contaminants in global groundwater. *Nature Reviews Earth & Environment, 5*(4), 312–328. https://doi.org/10.1038/s43017-024-00519-z
50. Lapworth, D. J., Baran, N., Stuart, M. E., Ward, R. S. (2012). Emerging organic contaminants in groundwater: a review of sources, fate and occurrence. *Environmental pollution, 163*, 287–303. https://doi.org/10.1016/j.envpol.2011.12.034
51. Xie, X., Shi, J., Pi, K., Deng, Y., Yan, B., Tong, L.,..., Jiang, G. (2023). Groundwater quality and public health. *Annual Review of Environment and Resources, 48*(1), 395–418. https://doi.org/10.1146/annurev-environ-112321-114701
52. World Health Organization (2022). *State of the world's drinking water: An urgent call to action to accelerate progress on ensuring safe drinking water for all.*
53. Güler, C., Thyne, G. D., McCray, J. E., Turner, K. A. (2002). Evaluation of graphical and multivariate statistical methods for classification of water chemistry data. *Hydrogeology journal, 10*(4), 455–474. https://doi.org/10.1007/s10040-002-0196-6
54. Appelo, C. A. J., Postma, D. (2004). Geochemistry, groundwater and pollution. *CRC press.* https://doi.org/10.1201/9781439833544
55. Lippera, M.C., Werban, U., Vienken, T. (2023). Application of physical clogging models to Managed

Aquifer Recharge: A review of modelling approaches from engineering fields. *Acque Sotterranee – Italian Journal of Groundwater, 12*(3), 9–20.

56. Sinshaw, B. G., Dahlke, H. E., Viers, J. H., Safeeq, M. (2026). Global advances in managed aquifer recharge: a systematic synthesis. *Environmental Reviews, 34*, 1–18.
57. Sufyan, M., Martelli, G., Teatini, P., Cherubini, C., Goi, D. (2024). Managed aquifer recharge for sustainable groundwater management: new developments, challenges, and future prospects. *Water, 16*(22), 3216.
58. Meles, M. B., Bradford, S., Casillas-Trasvina, A., Chen, L., Osterman, G., Hatch, T.,..., Kisekka, I. (2024). Uncovering the gaps in managed aquifer recharge for sustainable groundwater management: a focus on hillslopes and mountains. *Journal of Hydrology, 639*, 131615. https://doi.org/10.1016/j.jhydrol.2024.131615.
59. Seidl, C., Wheeler, S. A., Page, D. (2024). Understanding the global success criteria for managed aquifer recharge schemes. *Journal of Hydrology, 628*, 130469. https://doi.org/10.1016/j.jhydrol.2023.130469
60. Ejaz, F., Kausar, A., Ulfat, I., Vambol, S., Vambol, V., Lyndiuk, O. (2026). Geospatial assessment of urban environmental and mitigation strategies for thermal stress in Lahore, Karachi, and Islamabad. *Applied Geomatics, 18*(3), 110.