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Groundwater management in the face of climate change: enhancing groundwater storage in the alluvium aquifer of Wadi Araba, Jordan, through GIS-based managed aquifer recharge and groundwater MODFLOW

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ABSTRACT

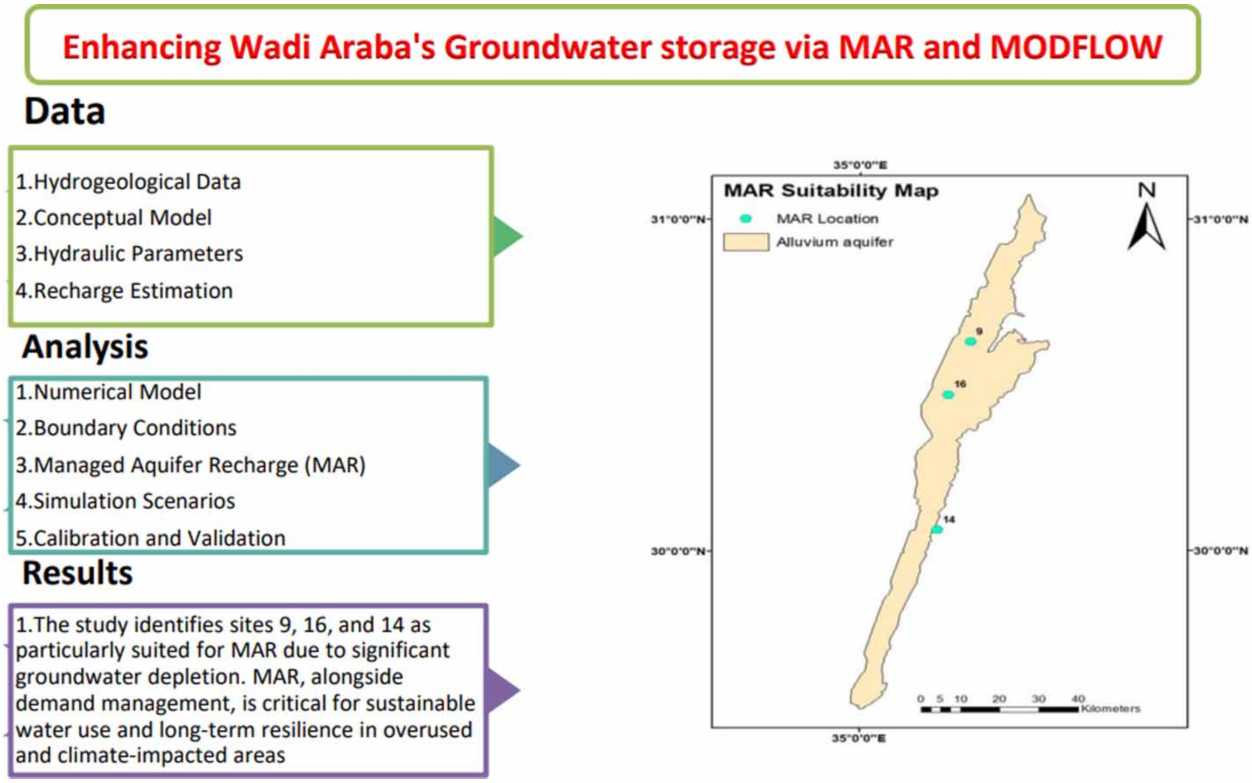
Groundwater is critical in countries such as Jordan, yet demand exceeds availability due to population expansion and arid conditions. The goal of this research is to address water scarcity and adapt to reduced rainfall by investigating the soil aquifer and evaluating the efficiency of managed aquifer recharge (MAR). The Wadi Araba Basin's alluvium aquifer is particularly important and contains a groundwater divide, with water flowing towards the Red Sea to the south and the Dead Sea to the north, as determined by rigorous modelling and scenario analysis. Precipitation infiltration is an important consideration in groundwater budget modelling. This study employs 12 monitoring wells to establish an acceptable relationship between estimated and observed water levels. Furthermore, the study creates a MAR suitability map, which evaluates eight potential MAR locations in the Wadi Araba region. According to forecasted scenarios, implementing MAR in conjunction with increased precipitation recharge has the potential to ameliorate the consequences of decreased rainfall in the model region. The plan aims to raise the water table in three areas by 1.96–3.12%, providing realistic solutions to enhance water availability and adapt to climate change.

Key words: climate change effect, GIS, groundwater, groundwater MODFLOW, managed aquifer recharge, Wadi Araba

HIGHLIGHTS

- Groundwater plays a crucial role in addressing water scarcity.
- Research in Wadi Araba Basin evaluating Managed Aquifer Recharge strategy to combat water scarcity.
- The potential to raise the water table by 1.16% in specific areas.
- Focusing on conductivity values to generate a calibration curve.
- The level chart of the basin revealed ground water divided in alluvium aquifer water flows in two directions.

GRAPHICAL ABSTRACT



Enhancing Wadi Araba's Groundwater storage via MAR and MODFLOW

Data

1. Hydrogeological Data
2. Conceptual Model
3. Hydraulic Parameters
4. Recharge Estimation

Analysis

1. Numerical Model
2. Boundary Conditions
3. Managed Aquifer Recharge (MAR)
4. Simulation Scenarios
5. Calibration and Validation

Results

1. The study identifies sites 9, 16, and 14 as particularly suited for MAR due to significant groundwater depletion. MAR, alongside demand management, is critical for sustainable water use and long-term resilience in overused and climate-impacted areas

1. INTRODUCTION

In the next decade, global water demand is projected to exceed 160% of the total global water volume, necessitating research into unconventional water resources as a solution to address water shortages and conflicts across various regions and sectors (Ricart *et al.* 2021). Climate change and the overexploitation of groundwater in semiarid and arid areas are exacerbating the already dire potable water shortages in the Middle East and North Africa (MENA; Whitman 2019; Benfetta & Ouadja 2020; Ouhamdouch *et al.* 2020).

Therefore, today, most countries around the world are attempting to manage water usage by many methods, including demand management and conjunctive usage strategies, which are essential components of sustainable groundwater management to address climate change. Both approaches help to reduce overexploitation of groundwater, maintain higher groundwater levels, and ensure the long-term availability of this vital resource. By incorporating these methods into water resource planning and policy, regions can enhance their resilience to climate-induced challenges and better manage groundwater storage (Khan *et al.* 2014), as described below:

- Demand management involves optimizing water use and minimizing waste through practices such as efficient irrigation techniques, distribution system leak repairs and water conservation efforts, ultimately leading to reduced groundwater extraction rates. This reduction in groundwater extraction helps to maintain higher groundwater levels, which are especially critical in arid and semiarid regions susceptible to climate-induced precipitation and recharge variations. Furthermore, demand management encourages the use of nonpotable water sources such as treated wastewater and harvested rainwater, minimizing reliance on groundwater for nonessential needs (Tortajada *et al.* 2019).
- Conjunctive usage: a method that involves the coordinated management of surface water and groundwater resources while acknowledging their interdependence. It incorporates the management of these sources, especially in light of climate change. Conjunctive usage involves measures such as managed aquifer recharge (MAR) to store excess water in aquifers during rainy seasons with surplus surface water due to higher precipitation. This is accomplished through techniques such as artificial recharge via infiltration basins, injection wells or spreading grounds. In contrast, when the surface

water supply diminishes during dry periods, stored groundwater can be used to meet water demands, minimizing dependency on surface water sources. Overall, conjunctive usage works as a buffer against excessive fluctuations in the surface water supply, aiding in the mitigation of the effects of climate variability (Foster *et al.* 2010).

Finding new water sources for irrigation and other uses underscores the importance of balancing the need for new sources of groundwater for irrigation with the necessity of preserving the sustainability of available groundwater resources by providing guidance regarding responsible groundwater management practices in the context of irrigation to mitigate potential overuse. Suggestions related to water use efficiency, regulatory measures and aquifer recharge practices to ensure sustainable irrigation practices will be useful in such cases. In addition, we suggest the establishment of groundwater monitoring networks, the implementation of pumping limits and the role of regulatory agencies mainly in overseeing groundwater extraction for irrigation purposes (Schaible & Aillery 2012).

Climate change, which is resulting in higher temperatures and reduced average precipitation, directly impacts aquifer recharge and, subsequently, groundwater availability (Abdulaziz & Faid 2015; Nassery & Salami 2016; Al-Maktoumi *et al.* 2018; Alkhatib *et al.* 2019). Jordan ranks fourth among the most water-stressed countries globally. Over the years, its per capita annual water resources have drastically decreased, falling below the acute water shortage threshold of 500 m^3 (Hadadin *et al.* 2010; JAEC & WorleyParsons 2011; MWI 2016; MEMR, 2017). The country's groundwater resources are divided into 12 basins, each with distinct aquifer systems. Approximately 60% of Jordan's total water supply comes from groundwater, serving domestic, agricultural and industrial needs (MWI 2016; Salameh *et al.* 2018). Groundwater quality plays a crucial role in determining its suitability for various applications; however, excessive pumping, continuous abstraction and insufficient recharge rates may lead to groundwater depletion and degradation over time (Magesh & Chandrasekar 2011; Abbasnia *et al.* 2018).

Throughout the Middle East, MAR has become an essential component of integrated water management methods (El Arabi 2012). By developing water resources during times of abundance and utilizing them during periods of scarcity, MAR helps mitigate water supply issues and immediate water scarcity impacts (Alelaimat *et al.* 2022). In their research, Alelaimat and colleagues created a MAR suitability map for the alluvium aquifer in Wadi Araba, considering precipitation, soil, geology, slope, land use and water table depth. Their findings revealed that eight out of nine MAR-eligible sites are located within the Wadi Araba alluvium aquifer.

Particularly in arid and semiarid locations, addressing the possible effects of climate change on groundwater recharge presents problems due to high degrees of uncertainty (Pulido-Velazquez *et al.* 2015). We know relatively little about the consequences of climate change on groundwater, even though many studies have looked at its effects on surface water (Green *et al.* 1997; Holman 2006; Woldeamlak *et al.* 2007; Bates *et al.* 2008; Nyenje & Batelaan 2009). Groundwater is essential for human use, but it also helps keep ecosystems in balance and is thus of great importance.

There are several major challenges faced by MAR implementation that need to be carefully considered. The hydrogeological heterogeneity of aquifers adds complexity that makes site selection and system design difficult. This is just one of the challenges. Potential environmental effects, such as changes to the local hydrology and ecosystems, also need to be carefully considered and mitigated. All of these difficulties highlight the complexity of putting MAR into practice.

MAR offers many benefits, and it is a flexible and sustainable solution. It addresses long-term water needs by improving storage and reducing overextraction, which makes a substantial contribution to sustainable groundwater management. MAR serves as an adaptive measure in the face of climate change, helping areas cope with changing patterns of precipitation and the increasing threat of water scarcity. Moreover, the economic benefits of MAR compared to other water supply methods are apparent and include increased agricultural productivity, the creation of jobs and more affordable infrastructure.

MAR has been used in many previous case studies as follows:

- Hossain *et al.* (2021), in their study, focused on the Barind tract in Bangladesh, a drought-prone area heavily reliant on groundwater due to limited rainfall and surface water. This research examines the feasibility of MAR in the region. Data from various sources, including bore logs, rainfall and information about water bodies, were analyzed. The study identifies opportunities for MAR, such as re-excavated canals, check dams, ponds and beels, which can store stormwater for irrigation. Challenges include high turbidity in stormwater, unsuitable clay layers for direct recharge and limited knowledge of MAR techniques. Addressing these issues is essential to harness MAR's potential for sustainable groundwater use.
- Henao Casas *et al.* (2022) assessed the social and environmental concerns that MAR systems solve and their qualities that reduce the projected climate change impacts in the study area. MAR in the Los Arenales groundwater body has increased

groundwater levels, reduced groundwater pumping energy and costs and CO_2 emissions, restored a surface water body, improved rural population indices, and improved groundwater demand control and CC adaptive capacity among irrigation communities. Despite declining streamflow, the Los Arenales MAR systems can be controlled to cope with CC, offer surface storage capacity to mitigate flooding, and reduce droughts and water scarcity. This study shows that MAR is a water management technique that can address many demands in the present and future, which is important for adapting to adaptation gaps in underdeveloped countries, rural areas or places without climate data.

- Kourakos *et al.* (2023) studied the San Joaquin Valley in California, USA, and illustrated the difficulties in choosing appropriate MAR sites in an area with complex hydrogeological conditions, such as differences in aquifer characteristics and subsurface heterogeneity.
- Sherif *et al.* (2023) reported that groundwater extraction in the MENA region frequently exceeds the natural renewal capacity by 6–100%. The lack of freshwater for agriculture is a major issue. Climate projections indicate that wet periods will be longer and more persistent, leading to greater floods across the MENA. Strategies such as demand management and MAR are critical in combating groundwater depletion and climatic consequences. These measures can help to relieve stress on MENA's groundwater resources and prevent water quality degradation. While several countries use recharge dams, their efficacy varies, often ranging from 15 to 47%. Integrating MAR technology into dam operations is critical to increasing efficiency, especially given the problems caused by small particulates clogging reservoir beds.

The primary objective of this study is to employ the groundwater model MODFLOW to enhance understanding and assess the alluvium aquifer in Wadi Araba with respect to MAR. The research relies on available geological, hydrogeological and data from abstraction and monitoring wells spanning the past four decades within the alluvium aquifer.

2. METHODS

2.1. Study area

Wadi Araba's alluvium aquifer is situated in the southern part of the Jordan Valley, between the Gulf of Aqaba and the Dead Sea, as shown in Figure 1. The alluvial aquifer rises gradually from the Gulf of Aqaba and peaks at approximately 200 m above mean sea level (amsl) in Jabal Al Risha on the central west edge of the Wadi Araba basin. To the north, the terrain dips to 400 m below the sea level to the Dead Sea. The northern alluvium aquifer surface drainage flows towards the Dead Sea, whereas the southern alluvium aquifer surface drainage flows towards the Red Sea.

The alluvium aquifer, also known as the shallow aquifer, runs parallel to the Wadi Araba Valley and is composed primarily of interbedded sand, gravel and clay deposits at an average depth of approximately 70 m. During the summer, temperatures in the southern sections of Jordan may reach well above 40 °C, while during the winter, they can dip to well below 0 °C, especially at night. The relative humidity seldom rises above 50% in the winter and rarely rises above 15% in the summer. Humidity is low for most of the year, making the summer heat more bearable and the winter cold more severe. There is an uptick in precipitation from October through January and February, a dip until May, and then zero precipitation from June through September. Most precipitation falls between the months of December and March.

The recent alluvial aquifer in the Wadi Araba Valley is composed of several sediment types, including Holocene alluvium, wadi sediments, lacustrine sediments, alluvial sediments and fluviatile sediments. This aquifer, also known as the shallow aquifer, is composed mostly of interbedded sand, gravel and clay deposits and has an average groundwater level depth of approximately 70 m. The Ministry of Water and Irrigation and Federal Institute for Geosciences and Natural Resources (MWI & BGR 2019) report that it is refilled by baseflow, wadi flood infiltration and precipitation infiltration. According to Radulovic *et al.* (2020), the thickness of the alluvium aquifer within the modelled region can reach up to 400 m.

Its natural flow direction is from the groundwater divide towards both the Gulf of Aqaba (Red Sea) and the Dead Sea. In specific regions of Wadi Araba, groundwater can also seep into the deep sandstone aquifer, as reported by MWI (2017).

2.2. GIS-based managed aquifer recharge and groundwater MODFLOW

2.2.1. MAR method

In the current investigation, GIS-based tools are used to find the best sites for MAR projects in the Wadi Araba region and to efficiently design the projects themselves. These tools analyze multiple data layers that include characteristics such as soil composition, patterns of precipitation, land use and topographical features. This makes it easier to identify the best MAR sites while accounting for factors such as groundwater recharge potential and proximity to water-demand areas. Making

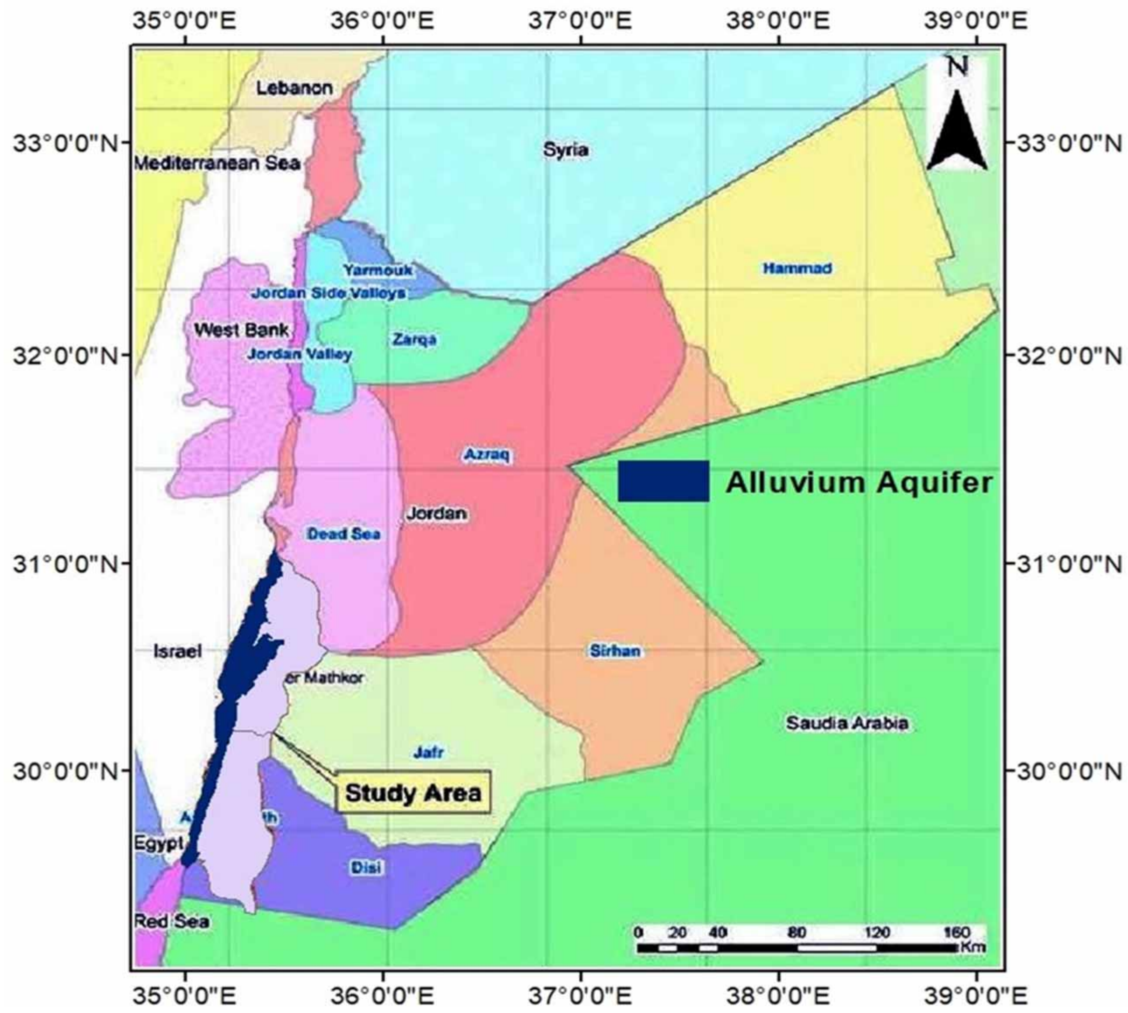


Figure 1 | Alluvium aquifer location.

use of these data helps decision-makers choose the best locations for MAR projects. Moreover, the same set of tools plays a crucial role in the creation of MAR project designs, allowing for the identification of the best practices, such as the installation of injection wells or recharge basins, and the calculation of the necessary infrastructure to meet predetermined groundwater storage targets. Furthermore, an evaluation of the MAR projects' operational efficacy is conducted by means of the MODFLOW computer model, which is utilized to replicate groundwater flow patterns. To confirm that the intended project outcomes are achieved, a comparison is made between the data from monitoring wells and these simulations. In addition, the use of predictive modelling is made to anticipate how these efforts might lessen the effects of reduced rainfall as a result of climate change in the local area.

Employing GIS-based MAR and MODFLOW can support other water management goals, such as enhancing water quality and minimizing saltwater intrusion.

- Water quality enhancement: groundwater quality can be improved using GIS-based MAR in conjunction with MODFLOW modelling. As recharged water percolates into the ground, MAR projects operate as natural filtration systems, efficiently eliminating impurities and increasing water quality. This strategy has been successfully adopted in a number of places and has the potential to greatly improve water quality (Zhang *et al.* 2019).
- Minimizing saltwater intrusion: GIS-based technologies can be used to control and minimize saltwater intrusion in coastal locations where it is a major threat. These technologies, which incorporate MODFLOW modelling, aid in understanding

the dynamics of saltwater intrusion and devising control solutions. Case studies from regions dealing with saltwater intrusion issues indicate the efficacy of these measures in maintaining freshwater resources (Roy & Datta 2020).

- Integration with multiple water management goals: MAR and MODFLOW are GIS-based tools that can be integrated with a variety of water management goals. They assist aims such as water quality enhancement, saltwater intrusion mitigation, and sustainable resource management in addition to groundwater storage. This holistic viewpoint acknowledges the linked nature of water management objectives and emphasizes the potential for complete solutions (Lyra *et al.* 2021).

However, there are many constraints on the use of GIS for both MAR and MODFLOW:

- The quality of geological, hydrological and climatic data critically affects the accuracy and dependability of GIS-based analyses, especially when used in conjunction with MAR and MODFLOW modelling (Ntona *et al.* 2022).
- Data errors can produce untrustworthy outcomes, underscoring how important it is to have accurate information (Pavlis *et al.* 2010).
- Both spatial and temporal resolutions impose constraints on GIS. The former may result in MAR and MODFLOW model inaccuracies because small-scale hydrogeological variations are not adequately captured, while the latter may impair the accuracy of modelling transient groundwater flow and recharge processes, particularly in situations where the necessary temporal data resolution is not easily accessible (Yuan 1996).
- The currency and availability of GIS data vary over time and require frequent updates to keep the model accurate. Because different sources have different formats, projections and scales, data integration can be challenging (Russo *et al.* 2015).

The implementation cost of MAR and groundwater MODFLOW modelling can vary significantly depending on several factors, including the scale of the project, the location, the complexity of the hydrogeological conditions and the specific goals of the groundwater management effort (Ross & Hasnain 2018):

- Infrastructure costs: the cost will depend on the type and size of the facility, as well as local construction costs. The construction of MAR facilities, such as infiltration basins, injection wells or spreading grounds involves significant infrastructure costs.
- Site preparation: preparing the site for MAR implementation, including land acquisition, clearing and grading can add to the overall cost.
- Water source costs: the source of water for MAR, whether it is stormwater, treated wastewater or other sources can impart costs.
- Operational and maintenance costs: monitoring, water treatment (if required) and facility upkeep must be budgeted for.
- Monitoring and data collection: regular monitoring of groundwater levels, water quality and system performance is essential for MAR.

2.2.2. MODFLOW model of the alluvium aquifer

In this study, a MODFLOW model was developed to analyze the flow behaviour of the alluvium aquifer in the Wadi Araba Basin, covering an area of 2,518 km^2. To represent the region, a grid with a cell size of 100×100 m was employed, resulting in a total of 840 rows and 300 columns, creating a one-layer model with a total of 252,000 cells.

Due to the complexity of the actual conditions, a perfect replication by the conceptual hydrogeological model was not possible, although the model boundary conditions came as near as possible. Inactive cells with a no-flow border were classified as those that were either in the basement complex or beyond the flow boundary. Both the Dead Sea and the Red Sea were modelled as constant head boundaries, with the Dead Sea's headset at 400 m below sea level and the Red Sea's headset at 0 m above sea level. Both the head-dependent flow boundary and the specified flow boundary methods were used in the transient model to successfully capture the hydrogeological dynamics of the alluvium aquifer. In the recharge zones of the aquifer, where precipitation serves as the primary source of replenishment, the most productive cells were identified (see Figure 2).

To mimic the replenishment of groundwater by infiltration and evaporation, the recharge package and evapotranspiration were used. Recharge and abstraction wells were defined as flow boundaries in the model to appropriately represent their impacts. Using precipitation mean data from nine monitoring stations between 1979 and 2020, recharge and evaporation zones were calculated (DOM 2020). The temporal distribution of the recharge rate was incorporated into the transient model for each zone, resulting in a thorough understanding of the aquifer's behaviour throughout time.

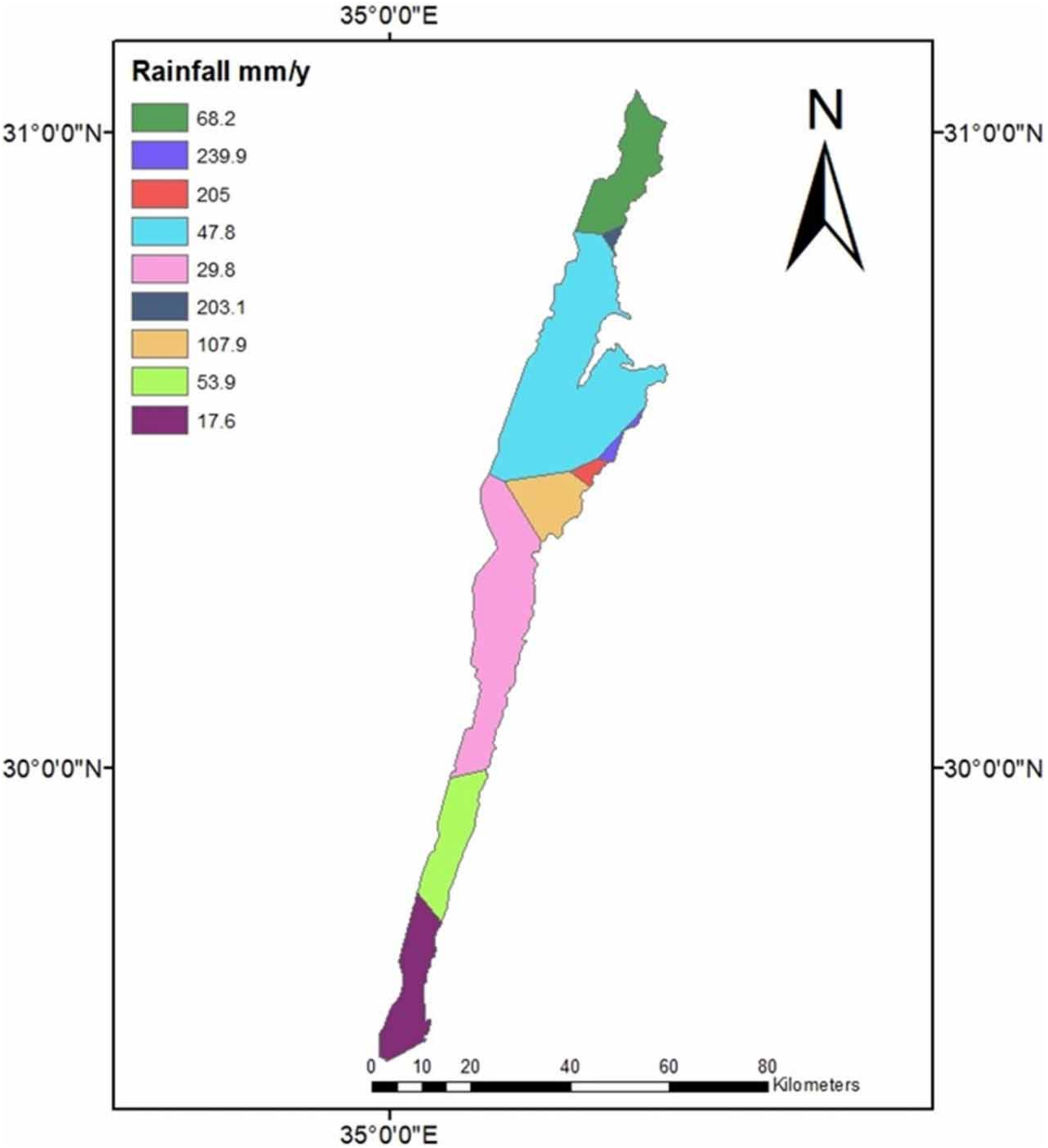


Figure 2 | Alluvium aquifer rainfall distribution.

The MODFLOW WEL Package simulates wells that withdraw water from or add water to the aquifer at a constant rate during a stress period. The user must define, for each stress period, the row, column and layer number of the cell in which the well is located and its extracted/recharge flow rate (Q). Q is expressed as a fluid volume per unit time [L^3/T].

Based on structural data and hydraulic parameter evaluations, the alluvial aquifer was divided into six zones, as reported in the studies by MWI-WIS (2019); Radulovic *et al.* (2020). As shown in Figure 3, these zones were divided based on tectonic blocks, where each block corresponds to a distinct hydrogeological zone.

The hydraulic conductivity and porosity of each delineated zone are shown in Table 1.

The transmissivity values were obtained by pumping tests in the alluvium aquifer wells. To assist with the calibration of the transient model, historical water level data from monitoring wells were gathered from the study by MWI-WIS (2019). The data are from continuous groundwater level readings by 23 piezometers from 1980 to 2020 in the alluvium aquifer.

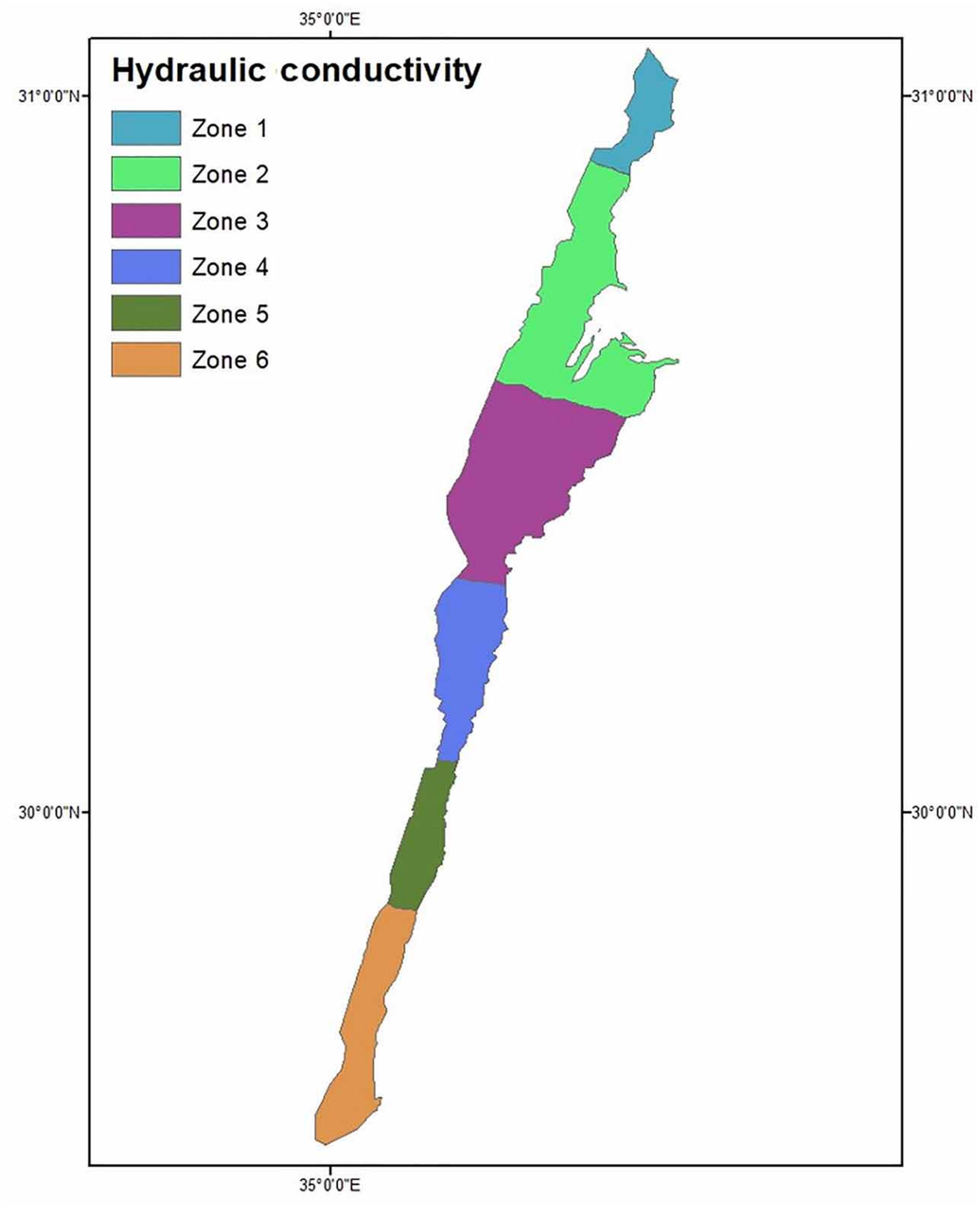


Figure 3 | Delineated zones of hydraulic parameters.

2.2.3. Steady-state model

The conceptual hydrogeological model served as the foundation for the steady-state flow condition. The steady-state simulation's output heads served as the baseline for the transient flow model's beginning head condition.

The geometry of the steady-state model and the model boundary conditions were meticulously defined to provide realistic simulation of the boundary conditions according to the conceptual hydrogeological model. This offered a robust framework for the transient flow simulation and allowed for a thorough description of the aquifer system's dynamics.

Table 1 | Hydraulic parameters of the alluvium aquifer

Zone	Aquifer/aquitard	Hydraulic conductivity (m/s)	Porosity	Specific storage	Specific yield
Zone 1	Alluvium aquifer	2.8×10^{-5}	0.2	4.00×10^{-4}	6.78×10^{-2}
Zone 2	Alluvium aquifer	3×10^{-5}	0.2	1.82×10^{-7}	3.06×10^{-5}
Zone 3	Alluvium aquifer	4×10^{-6}	0.2	4.00×10^{-4}	6.80×10^{-2}
Zone 4	Alluvium aquifer	1×10^{-4}	0.2	1.55×10^{-5}	2.60×10^{-3}
Zone 5	Alluvium aquifer	6×10^{-5}	0.2	8.90×10^{-4}	1.49×10^{-1}
Zone 6	Alluvium aquifer	9×10^{-5}	0.2	9.00×10^{-4}	1.51×10^{-1}

2.3. Transient state model

The 40 annual time periods from 1980 to 2020 represent the model's discretized time. Table 1 presents the data for specific yield and storage for the defined zones. Groundwater abstraction in the Wadi Araba Basin was tracked from 2003 to 2020. Except for data from Energoprojekt (1989, 1990), which undertook the rehabilitation of existing wells as well as a program of drilling new wells to be able to abstract an annual total of 8.8 million cubic meters from 1990 to 2003, there are no statistics on groundwater abstraction available prior to 2003. According to calculations, groundwater removal was almost 50% lower before 1990 than between 1990 and 2003. The wells along the border have been continuously drained since the Peace Treaty between Jordan and Israel in 1994, and their current estimated yearly production is 8 MCM. The observed abstraction rates for all the producing wells have been entered into the transient model's prescribed cells for wells across the appropriate time periods (MWI-WIS 2019). The reduction in the Dead Sea level (EcoWatch 2016; ISRAMAR 2022) was modelled as a variable head constant in the transient model (Table 2).

Calibration of the transient state model was performed using measurements of the groundwater level within the alluvium aquifer recorded in 12 monitoring wells that had readings for the period 1980–2020. These wells were located in promising locations that met the MAR criteria, within the good and very good categories, based on the Wadi Araba MAR suitability map created by Alelaimat *et al.* (2022), and the data were used to model the vulnerability of the water table to the effects of climate change on groundwater in the alluvium aquifer. The time discretization of the model involves dividing it into 40 yearly stress periods, representing the years 1980–2020. Each of these stress periods is further subdivided into 10 time steps, providing a detailed temporal resolution for the simulation.

The model duration has been extended for the prediction scenarios by another 30 years, up to the year 2050. This new window of time allows researchers to investigate and analyze the aquifer system's behaviour in greater depth, taking into account both past and future changes and trends.

Table 2 | Dead Sea surface level

Year	Water level (amsl)	Source
1980	−400	
1992	−407	
1997	−411	
2004	−417	
2010	−423	
2016	−430.5	https://www.ecowatch.com/
2017	−431.2	https://www.isramar.ocean.org.il/isramar2009/Deadsea/LongTerm.aspx
2018	−432.2	
2019	−432.9	
2020	−433.6	

2.4. Predictive scenarios

The Intergovernmental Panel on Climate Change's report on global warming predicts that temperatures will continue to rise through 2019 from their 1850–1900 average (IPCC, 2018). The MENA, which include both arid and semiarid regions, is expected to experience worsening water scarcity as a result of changes in quality as well as quantity. Changes in temperature, rainfall patterns, and temporal and spatial variability caused by climate change will have substantial effects on groundwater replenishment.

Several recent studies in Jordan have documented the effects of climate change, demonstrating its urgency as a threat to the region's water resources and hydrogeological systems (Bani-Domi 2005; Freiwan & Kadioğlu 2008; Hamdi *et al.* 2009; Shakhatreh 2011; Matouq & colleagues 2013; Sada & colleagues 2015). To create efficient water management plans and long-term solutions, our results highlight the need to research and understand the possible consequences of climate change on groundwater supplies. Previous research has shown that in the southern area of Jordan, where the alluvium aquifer region is located, precipitation has decreased, and mean minimum and maximum temperatures have increased. Additional model scenarios were generated for the years 2020–2050 to investigate the possible effects of these climatic changes on the aquifer system. Current abstraction rates and all obtainable data were used in these situations.

The period 2020–2050, a span of 30 years, was further divided into periods represented by the years 2030, 2040 and 2050. The model simulated the probable consequences of climate change by considering 10 and 30% declines in rainfall for each scenario. In addition, a scenario was developed to evaluate the efficiency of MAR in preventing groundwater levels from falling. Over the next 30 years, this model predicted a 10% increase in recharge from precipitation. The purpose of the study was to investigate the viability of MAR as a technique to mitigate the consequences of diminishing rainfall on groundwater levels by modelling these various scenarios and learning more about the aquifer's reaction to changing climate conditions.

3. MODELLING RESULTS

The calibration phase of the model entailed manually changing parameters via trial and error until the simulation results matched the observed data within an acceptable range. The conductivity values were adjusted to generate the calibration curve. Figure 4 is a scatter plot comparing computed and observed water levels in observation wells, and it reveals that the majority of the wells exhibited high agreement between the calculated and observed water levels. The precision of the model's predictions was much enhanced once this calibration was applied. A groundwater level chart reveals a groundwater divide in the alluvium aquifer in the center of the Wadi Araba Basin, with water flowing in opposite directions. Groundwater

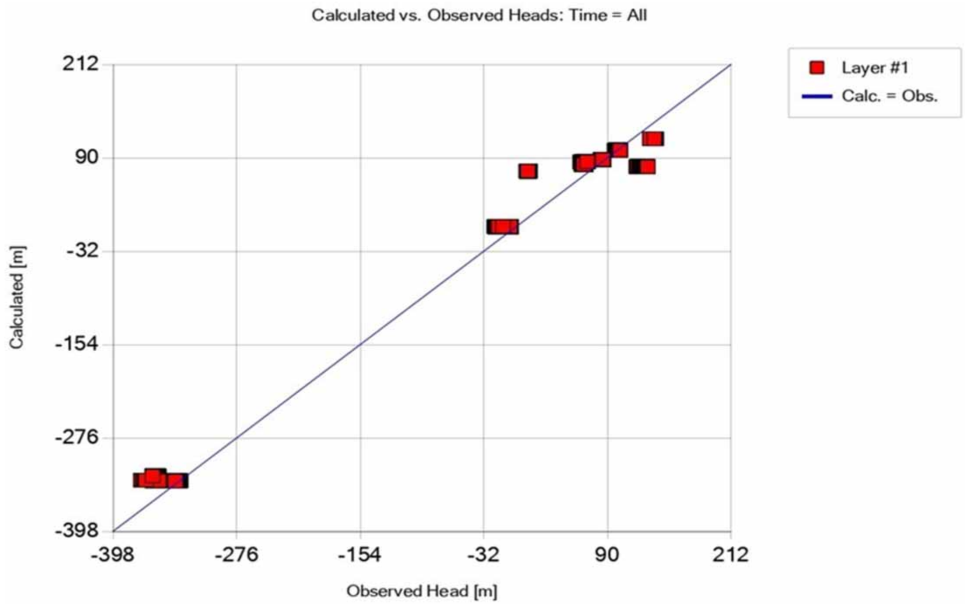


Figure 4 | Calculated vs. observed head.

in the northern half of the valley flows north–northeast towards the Dead Sea. On the other hand, groundwater in the southern half of the valley flows south–southwest towards the Red Sea.

The model simulation groundwater budget indicates that precipitation infiltration is the primary source of water inflow into the system. This discovery prompted us to examine the implications of climate change on the rainfall needed for aquifer recharge using future scenario analysis. In Table 3, we see the results of the model projections for the monitoring wells that would be placed in the proposed MAR locations. These projections are helpful for understanding how groundwater levels may shift in the future under various climatic scenarios, which in turn might inform the design of future controlled aquifer recharge initiatives.

According to the data presented in the table, the maximum drawdowns of −15.4, −17.8 and −17% occur at sites 9, 16 and 14, respectively, located in the middle part of the aquifer. Reduced precipitation as a result of climate change has an enormous effect on aquifer recharge and is the main cause of this depletion. According to the MAR suitability map and field research, these areas are excellent candidates for MAR method implementation.

In general, the alluvial aquifer drawdown stabilizes over the duration of the model predictions in all scenarios, most likely caused by the constant head boundary along the Red Sea and Dead Sea. The predictive simulations present the effects of climate change in the study area due to the drawdown shown in the observation wells.

The results based on the scenario of increasing recharge from precipitation by 10% indicate that the water table rises at sites 16, 14 and 9 by 2.3, 3.12 and 1.96%, respectively. However, the water table levels at the other sites remain relatively stable. These findings suggest that sites 16, 14 and 9 are particularly sensitive to the effects of climate change, as they experience significant water table increases in response to increased recharge. As a result, these locations are among those most vulnerable to the consequences of global warming. In addition, they exhibit a strong response to the application of MAR techniques, making them potential candidates for implementing MAR interventions. Figure 5 illustrates the variations in water table levels at these specific sites, highlighting their significance in terms of climate change effects and MAR responsiveness.

4. DISCUSSION

Climate change poses a global challenge that significantly impacts water resources, particularly in arid and semiarid regions. With an emphasis on MAR and the modelling of the alluvium aquifer in Wadi Araba, this comparison tried to evaluate the impact of climate change on groundwater supplies. The findings from various studies conducted worldwide and in Jordan support the understanding that climate change directly affects groundwater dynamics, necessitating sustainable water management practices.

Due to the complexity of groundwater systems and residence periods ranging from days to tens of thousands of years, it is challenging to predict the precise reactions of groundwater to climate fluctuation and change (Gurdak *et al.* 2009; Aizebeokhai 2011; Kumar 2016; Wang *et al.* 2016). Because of the possible decline in recharge capacity and greater reliance on groundwater to augment surface water supplies due to unpredictable precipitation patterns, groundwater recharge in arid and semiarid regions is uncertain (Panigrahy *et al.* 2015; Pulido-Velazquez *et al.* 2015).

Several reports have examined how climate change would affect Jordan's underground water resources. Over a 20-year period in three Jordanian cities, Hamdi *et al.* (2009) noticed a rise in the average high temperature and a drop in the amount of rain, which shows that the climate is changing. From 1964 to 1999, Bani-Domi (2005) observed an increase in the mean lowest temperature and a decrease in the mean annual precipitation at most sites in Jordan. By using the Water Evaluation and Planning (WEAP) tool, Ta'any *et al.* (2014) showed that growing water demand negatively impacts Azraq Basin groundwater supplies as a result of rising temperatures and decreased precipitation. Understanding and mitigating climate change's influence on water resources is crucial, as Tahboub (2015) pointed out, citing the significant consequences of global warming on Jordan's groundwater supplies.

This research supports these global and regional findings by focusing on MAR and providing new insights from modelling the alluvium aquifer in Wadi Araba. The results of this study show that MAR adoption is an effective method for adapting to the negative impacts of climate change on water availability in arid and semiarid regions. Sustainable urban water management relies heavily on natural groundwater recharge rates, which MAR helps to improve.

Similar global research emphasizes the need to learn how climate change affects groundwater supplies and how MAR may be used to manage water in a sustainable way. The Olifants River Basin is under greater water stress because of the effects of

Table 3 | Groundwater level changes (2020–2050) in the monitoring wells according to the predictive scenarios

MAR sites	Observation well	Present condition water level (amsl) (calibrated model)	WL (amsl)											
			Scenario 1 (rainfall − 10%)						Scenario 2 (rainfall − 30%)					
			2030	%	2040	%	2050	%	2030	%	2040	%	2050	%
Site 10	DA1011	−336.02	−341.33	−1.58	−345.47	−2.81	−350.25	−4.23	−344.41	−2.5	−349.8	−4.11	−352.63	−4.94
	DA1012	−358.21	−362.03	−1.06	−365.64	−2.07	−367.38	−2.56	−367.44	−2.58	−372.2	−3.89	−380.31	−6.17
	DA1013	−352.84	−363.04	−2.89	−366.27	−3.81	−369.09	−4.61	−368.7	−4.49	−371.9	−5.39	−379.21	−7.47
	DA1019	−365.09	−371.02	−1.62	−375.41	−2.83	−382.22	−4.69	−376.68	−3.17	−381.6	−4.52	−390.71	−7.02
Site 12	DA1032	−358.68	−361.58	−0.8	−366.16	−2.09	−369.4	−2.99	−368.67	−2.79	−373.4	−4.11	−380.55	−6.1
Site 9	DA3028	−80.31	−83.18	−3.57	−86.5	−7.71	−89.11	−11	−85.03	−5.88	−88.74	−10.5	−92.68	−15.4
Site 16	DF1003	72.44	74.96	−3.47	77.42	−6.87	80.86	−11.6	77.53	−7.03	80.41	−11	85.35	−17.8
Site 19	DA3005	183.7	185.22	−0.82	187.19	−1.9	190.15	−3.51	188.46	−2.59	192.3	−4.68	195.67	−6.52
Site 8	EA1011	136.22	139.68	−2.54	143.85	−5.6	146.46	−7.52	142.55	−4.65	146.08	−7.24	149.34	−9.63
Site 14	EA1026	85.38	88.96	−4.19	92.65	−8.51	95.08	−11.4	89.47	−4.79	94.36	−10.5	99.89	−17
Site 5	EA3004	66.72	67.92	−1.79	68.84	−3.18	70.24	−5.28	68.35	−2.44	70.16	−5.16	73.2	−9.71
	EA1015	129.9	130.69	−0.6	132.15	−1.73	133.69	−2.92	132.21	−1.78	133.96	−3.13	135.16	−4.05

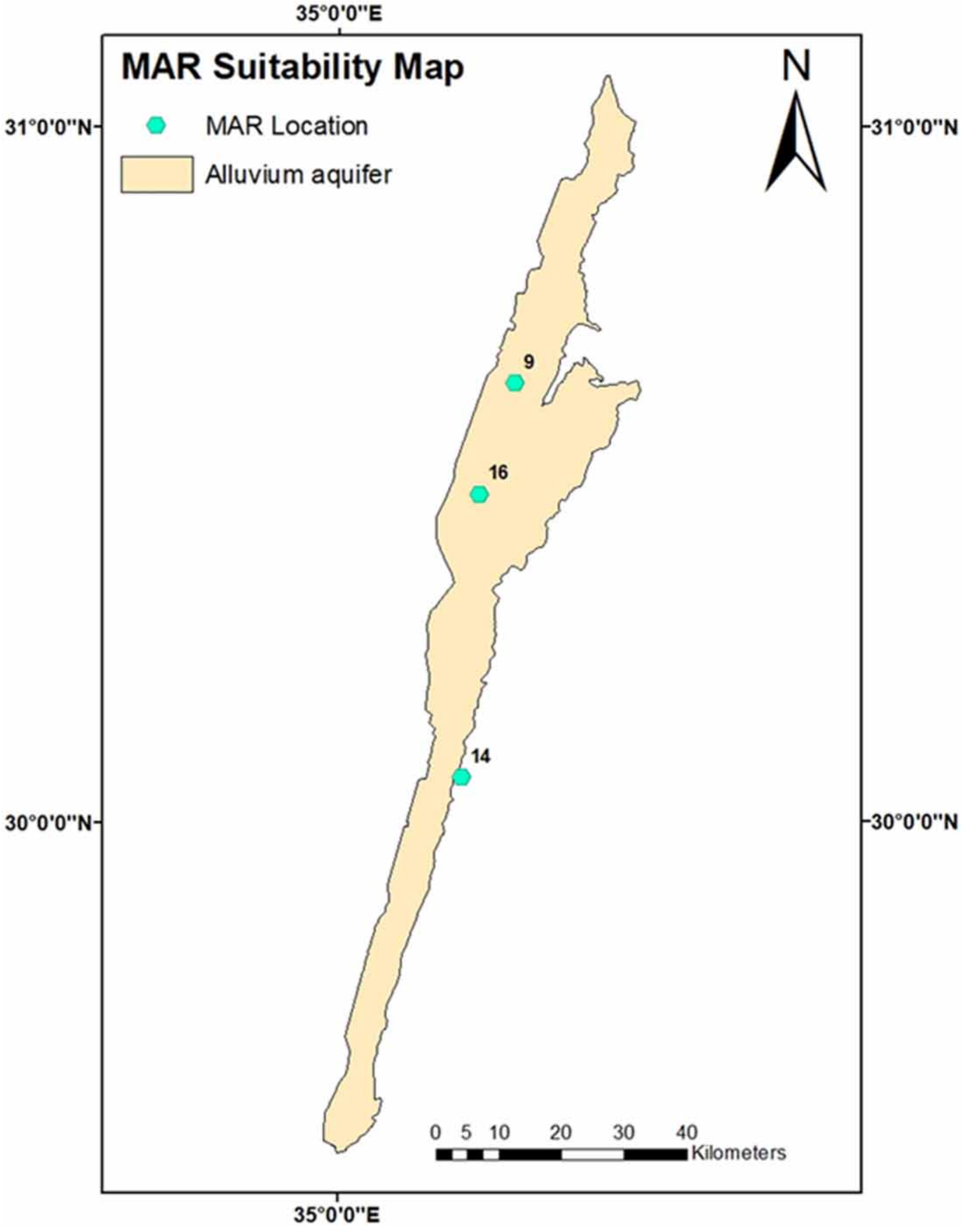


Figure 5 | MAR suitable locations based on groundwater modelling.

climate change, as shown in the study by Nkhonjera & Dinka (2017). Toure *et al.* (2016) detected a progressive reduction in groundwater levels over time in the Klela Basin, Mali, affected by climate change dynamics. Future and historical declines in groundwater levels in Bangladesh have been forecasted by Kirby *et al.* (2016) as a result of increased agricultural water demand.

Moreover, Pulido-Velazquez *et al.* (2015) predicted a decrease in mean annual recharge in the Serral-Salinas aquifer, Spain, under different climate change scenarios. Ertürk *et al.* (2014) projected water scarcity as a future challenge in a small Mediterranean watershed in Turkey due to climate change impacts on groundwater resources.

In addition, studies focusing on the application of MAR in specific regions have shown promising outcomes. Sida *et al.* (2022) successfully implemented a large-scale MAR scheme in the Beijing Plain, China, leading to a significant increase in nearby groundwater levels. Holländer *et al.* (2009) proposed a novel MAR approach to enhance the water supply in coastal plains by utilizing excess monsoon season runoff. Ebrahim *et al.* (2016) demonstrated the potential for MAR in Oman's

Samail Lower Catchment. Guyennon *et al.* (2017) explored adaptation measures using MAR to enhance water supply system resiliency in a semiarid region in southern Italy.

Our research is in line with these international initiatives because it highlights why it is so important to learn about the effect that climate change has on groundwater supplies in arid and semiarid areas. Preventative methods in water management are further supported by the responses of the alluvium aquifer in Wadi Araba to fluctuating precipitation and evaporation rates. For the problem of groundwater overabstraction, MAR shows promise, especially when combined with efficient demand control measures.

GIS-based MAR and MODFLOW modelling can be utilized to optimize groundwater storage to account for climate change according to the following:

- Identifying suitable recharge sites: GIS can be used to analyze geographical and geological data to identify suitable locations for MAR facilities. Factors such as soil types, aquifer characteristics, land use and proximity to water sources (e.g., rivers or treated wastewater facilities) can all be considered.
- Climate change projections: GIS can be used to access and visualize climate change projections for the studied region. The data include temperature, precipitation patterns and other variables.
- Hydrogeological modelling can be employed to create groundwater flow models that simulate the movement of water within aquifers. These models can incorporate climate change scenarios to predict future groundwater levels and assess the impacts of different MAR strategies.
- Monitoring and adaptive management: continual monitoring of groundwater levels, water quality and climate conditions is essential. By using GIS, spatial databases can be created for monitoring sites, and MODFLOW models can periodically be updated with new data. This allows for adaptive management, where MAR strategies can be adjusted in response to changing climate conditions and their effects on groundwater storage.

In summary, combining MAR with GIS and MODFLOW modelling can have significant social and economic implications.

1 - Social implications:
  - Improved water availability: more efficient groundwater management can result from infrastructure costs: combining MAR with GIS and MODFLOW modelling. By guaranteeing a more dependable and sustainable supply of drinking water for communities, lowering water scarcity and lowering the possibility of drought-induced water shortages, this might have a good social impact.
  - Environmental conservation: using MAR, GIS and MODFLOW can help to protect and restore natural ecosystems that rely on groundwater, such as wetlands and rivers. This contributes to environmental sustainability and can enhance biodiversity.
  - Increasing water quality: effective groundwater management using GIS and MODFLOW can lead to improved water quality, reducing health risks associated with contaminated groundwater sources. Access to safe and clean drinking water is a fundamental social benefit.

2 - Economic implications:
  - Cost savings: costs can be reduced because sustainable groundwater practices can reduce the need for costly alternative water sources such as desalination or importing water.
  - Agricultural productivity: better management of groundwater resources can lead to increased agricultural productivity, which has positive economic implications in terms of food security and the livelihoods of farmers.
  - Job creation: MAR projects often require construction and maintenance activities, which can create job opportunities in the local economy. In addition, the expertise needed for GIS and MODFLOW modelling can lead to employment opportunities in the water resource management sector.
  - Economic resilience: sustainable groundwater management can improve economic resilience by lowering susceptibility to water scarcity, which can cause disruptions in business, tourism and industrial operations.

In conclusion, this study and others like it have shown that there is an immediate need for sustainable and all-encompassing water management strategies to address the effects of climate change on groundwater supplies. Especially in arid and semiarid countries, MAR is an efficient method for reducing the negative impacts of climate change on water availability. Combating the effects of climate change on water supply requires proactive measures, such as groundwater resource management, to maintain long-term sustainability and balance between water needs and available resources. The integration of GIS-based MAR planning and MODFLOW modelling allows for a comprehensive approach to optimize groundwater storage in the face of climate change.

5. CONCLUSION

Based on the findings, it seems appropriate to examine the feasibility of (MAR) as an adaptation strategy to counteract the detrimental impacts of climate change on water availability in the arid and semiarid region of Wadi Araba, where MAR has the ability to increase natural groundwater recharge rates, by providing a vital water supply locations where groundwater overabstraction and decreasing rainfall rates have caused a drop in the water table.

Furthermore, these regions were extremely susceptible to MAR techniques, making them attractive candidates for MAR-based applications. According to a study on the alluvium aquifer, the groundwater in the northern and southern portions of the valley flows in opposite directions, indicating the separation of the Wadi Araba Basin.

This study evaluated the effect of MAR on current and future groundwater levels using scenario-based examinations utilizing VISUAL MODFLOW FLEX software. The results highlighted the significant effect of climatic variability and change on decreasing groundwater levels by revealing the importance of precipitation infiltration as the principal input source to the aquifer system. Therefore, it is crucial to address the effects of climate change on groundwater supplies, especially in areas where this resource is intensively used.

Groundwater overexploitation in certain sections of the alluvium aquifer is rising as a result of rising water demand rates and climate change pressures, but MAR offers a possible alternative. However, to effectively address groundwater overabstraction, it is essential to employ both MAR and effective demand management techniques. Long-term sustainability and keeping water demands in check with existing resources require ongoing groundwater resource management activities. This research sheds light on how MAR could mitigate climate change's detrimental effects on water supplies in Wadi Araba. Water resource managers have the potential to create efficient plans to guarantee long-term sustainability and resilience in the face of changing climatic circumstances by focusing on the areas that are most vulnerable to climate change and most responsive to MAR interventions.

CONSENT FOR PUBLICATION

All authors reviewed the results, approved the final version of the manuscript and agreed to publish it.

DATA AVAILABILITY STATEMENT

All relevant data are included in the paper or its Supplementary Information.

CONFLICT OF INTEREST

The authors declare there is no conflict.

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