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A Review of Managed Aquifer Recharge Potential in the Middle East and North Africa Region with Examples from the Kingdom of Saudi Arabia and the United Arab Emirates

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Abstract: Groundwater extraction in most Middle East and North Africa (MENA) countries far exceeds its renewability, which ranges from 6% to 100%. Freshwater resources to support food production are very limited in this region. Future climate predictions include more consistent and longer wet periods with increasing surplus rainfall, which will enhance flood and flash flood occurrences in the MENA. Demand management of groundwater resources and managed aquifer recharge (MAR, also called groundwater replenishment, water banking, and artificial recharge, is the purposeful recharge of water to aquifers for subsequent recovery or environmental benefits) represent essential strategies to overcome the challenges associated with groundwater depletion and climate change impacts. Such strategies would enable the development of groundwater resources in the MENA region by minimizing the stress placed on these resources, as well as reducing deterioration in groundwater quality. Groundwater augmentation through recharge dams is a common practice in different countries around the globe. Most dams in the MENA region were built to enhance groundwater recharge, and even the few protection dams also act as recharge dams in one way or another. However, the operating systems of these dams are mostly dependent on the natural infiltration of the accumulated water in the reservoir area, with limited application of MAR. This review presents analyses of groundwater renewability and the effectiveness of recharge dams on groundwater recharge, as well as the potential of MAR technology. This study indicates that the recharge efficiency of dam's ranges between 15 to 47% and is clustered more around the lower limit. Efficiency is reduced by the clogging of the reservoir bed with fine materials. Therefore, there is a need to improve the operation of dams using MAR technology.

Keywords: managed aquifer recharge; groundwater renewability; MENA countries; dams; rainfall harvesting; climate change

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1. Introduction

Per capita annual water resource indicators show that water scarcity is very high in the Middle East and North Africa region (MENA). As of 2022, the MENA region has an estimated population of over 463 million (5.94% of the world's population), which is expected to reach approximately 700 million by 2050 [1]. The climate of the MENA region is generally hot and dry, although winters are mild to cold with variable rain. Annual precipitation in the MENA region ranges from 3 to 30 inches, depending on geography and topography. The Arabian peninsula, including the Gulf Cooperation Council (GCC) countries and Yemen, is in an arid region with lengthy periods of drought and low rates of annual precipitation. As a result, surface water sources are scarce and arable land is limited. Fresh groundwater and harvested rainwater represent the only conventional freshwater resources in the GCC countries, as well as in most of the other MENA countries (Figure 1).

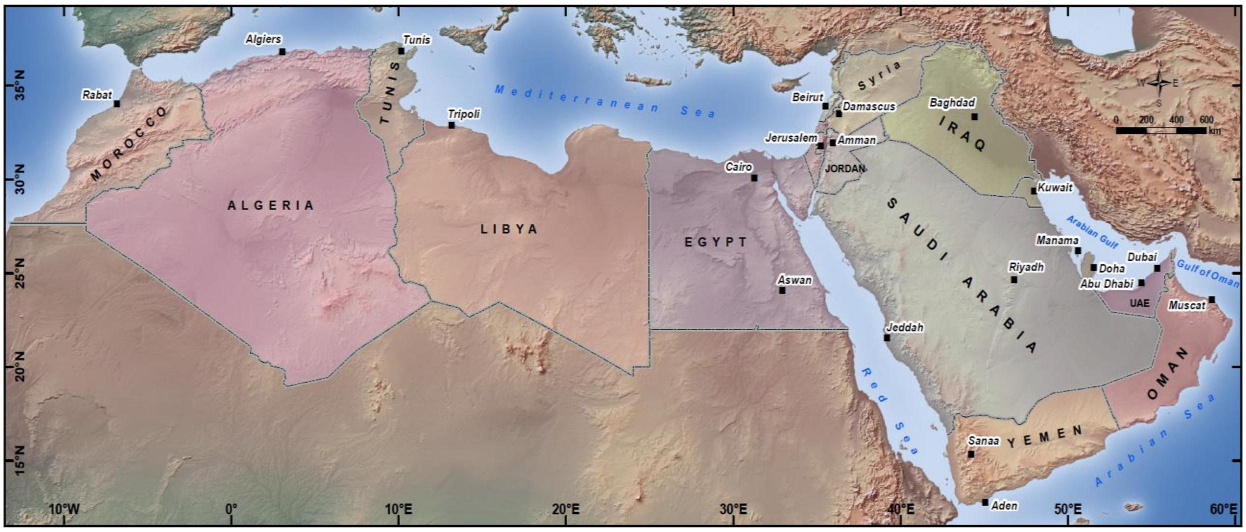


Figure 1. An overview of the study area in the MENA region.

The GCC countries rely heavily on nonconventional water resources for their domestic supply. For example, in the UAE, desalination plants supply more than 95 percent of the country's drinking water. The annual production of desalinated seawater in the UAE is estimated at 2.243 BCM (6.145 MCM/day), which contributes to about 39% of the total water budget of the country (5.646 BCM in 2018). Desalination plants are vulnerable to algal blooms and jellyfish accumulation that can lead to clogging of the fine membranes filtering the seawater. This can lead to a significant decrease in water production and an increase in operating costs. In 2008 and 2009, for instance, four major desalination plants in the UAE were temporarily closed due to red tides. In the summer of 2017, jellyfish affected the operations of the Al Zour Power and Desalination plant in Kuwait. Such events are occurring more frequently.

The exploitation of groundwater is growing at a rapid pace in all MENA countries and the use of groundwater is becoming unsustainable. Climate change has further aggravated the groundwater depletion problem [2]. Excessive runoff is enhanced by deforestation and the deterioration of soil health [3]. Addressing groundwater overdraft is among the most important environmental and economic challenges in the MENA region. In areas where suitable aquifers are present, MAR methods have potential to support agricultural water management [4,5]. In areas with mosaic irrigation, MAR has relatively low capital expenditure and thus might be attractive to most MENA countries, or for higher value agriculture that requires a high level of water security, as in the GCC countries. In arid and semi−arid areas, the MAR method has the largest influence on estimated cost, with the order of increasing cost for 1 Mm^3/y schemes as follows: infiltration basin, aquifer storage transfer and recovery (ASTR), aquifer storage and recovery (ASR), and seawater intrusion barrier. Infiltration methods typically have lower unit costs than well injection, and therefore are considered more viable for agricultural water supply. The seawater intrusion barrier has the highest cost due to the high capital and operating cost of deep−well injection targeting an aquifer that is used to supply drinking water, which requires the highest level of risk management to protect water quality [5]. Improving agricultural water management in the MENA region is an enduring necessity. Freshwater resources to support food production are very limited in this region [6,7]. Future climate predictions include more durable and longer wet durations with increasing surplus rainfall amounts, which will enhance flood and flash flood occurrences in the MENA [8–12]. Despite its efficiency, MAR is still an underutilized tool for groundwater management in this region. This might be due to the fact that MENA countries have suffered many droughts over the last three decades, and thus the amount or surplus of rainfall has not reached sufficient volumes to make this type of project viable.

In−depth investigations are being conducted by a multidisciplinary team from NASA and Oxford University to examine how long−term climate change influenced early humans and animals in the Arabian Peninsula [13]. In these research, 10,000 lakes were discovered 100 m below the surface in the Empty Quarter of the Arabian Desert, indicating an exceptionally wet climate between 10,000 and 23,000 years ago. There are two significant rivers on the Arabian Peninsula that may reopen, as well as two enormous lakes that may reopen as water reservoirs; this was extrapolated from the Giant Lake, which was initially 100 m (300 feet) deep, and Ptolemy's lake in Yemen, which is easily seen from Google Earth pictures [13–15]. Now, in the Arabian Peninsula, where it is beginning to rain again, camels can often be seen grazing on lawns and under Levey trees. In this review, narrative and integrative approaches were used to collect quantitative insights regarding the status and potentiality of aquifer recharge augmentation and MAR under climate change in the MENA region, which has not been discussed in previous reviews. The data were collected from different sources, as given in the reference list, as well as from the water authorities in the Kingdom of Saudi Arabia (KSA) and the United Arab Emirates (UAE). The main parameters influencing the augmentation of groundwater recharge through recharge dams and MAR are discussed with examples from the KSA and the UAE. In addition, this review focuses on filling the gap in analysis in all the previous MAR reviews, which is the feasibility of using MAR techniques for protection from flash flood hazards in countries in which climate change models predict high precipitation events with more intensity, arid countries in general, and MENA countries in particular.

2. Factors Affecting the Design and Implementation of MAR

2.1. Climate Change Impact on the Demand for Water and the Necessity for MAR

In the last two decades, droughts in the MENA region climate have lasted for longer periods and are becoming more frequent and more severe. Successive drought events, coupled with the groundwater depletion, are causing severe water shortages, influencing the social life, economy, and environment of several places in the MENA region. The MENA region has the highest expected economic losses from climate−related water scarcity. A business−as−usual scenario leads to a GDP decline of 14%, while a scenario encouraging water allocation to higher−value uses would lead to a GDP decline of 6% by 2050, [16].

When comparing the simulated precipitation scenarios of more than ten global climate models, the models only concur in high northern latitudes, where precipitation will increase, and the Mediterranean region, where precipitation will decrease. Less than 80% of the models in most other geographical areas predict an increase or decrease in yearly precipitation. Therefore, it is impossible to quantitatively predict how groundwater resources will alter in the future under climate change scenarios. However, these scenarios should be employed to illustrate the wide range of potential futures for groundwater resources [17–20].

Climate models are projecting a hotter, drier, and less predictable climate, resulting in a drop in surface water runoff by 20–30% in North African countries by 2050, mostly due to rising temperature and lower precipitation. Overall groundwater recharge is expected to reduce by 5% to 15% [18,21]. The long−term risk indicates that the groundwater recharge may decrease, and more inconsistency in rainfall could mean more common and extended periods of low discharge. Global warming and the associated rise in sea levels will lead to the acceleration of seawater intrusion, thereby affecting the quality of fresh groundwater resources in coastal aquifers. The author of [18] created a method for calculating general sensitivity and adaptive capacity, as well as the groundwater withdrawal−to−total withdrawals ratio, to use as indicators for groundwater supply dependence. His results showed that most MENA countries (e.g., Saudi Arabia, Jordan, Morocco, and Tunisia) have extremely high sensitivities. Fortunately, the four simulated climate scenarios indicated that groundwater recharge in these nations will not start to decline considerably before the 2050s.

Ref. [22] concluded that rainfall in the MENA region is predicted to be between 45% less to 22% more by the year 2100 compared to the levels during the period 1961–1990. This wide range of possible changes in rainfall by the year 2100 undermines the accuracy of models and poses significant challenges for decision−makers to properly develop mitigation and adaptation measures.

According to IPCC [23] projections, most mid−latitude land masses and wet tropical regions may experience high precipitation events with greater intensity. This change has been observed in the Arabian Peninsula since 2015. For example, in the UAE, except for the water year 2020–2021, there has been a general increase in the total annual precipitation, combined with major changes in precipitation patterns since 2016. The total annual precipitation in wet years such as the water years (e.g., 2019–2020 and 2021–2022) was more than double the average rainfall in all the northern and eastern parts of the UAE. The total rainfall in the water year 2019–2020 reached 500 mm in the area east of Al Ain city (Figure 2a), with a deviation from normal rainfall of 300 mm (Figure 2b).

In addition to the absence of agreement between the different climate models, the discussion above also indicates the inability of available climate models to predict possible changes of main climatic parameters in the short term at local or global levels. Thus, climate change challenges the management practices of the limited available water resources by adding uncertainties. In addition, the concept of integrated water resource management (IWRM) is unavoidable for water conservation and to meet water demands.

In a study by [24], groundwater stress was defined as the ratio between groundwater abstraction and adjusted groundwater recharge, including the recharge fraction that should be reserved to meet environmental flows. Currently, groundwater abstraction from shallow and deep aquifers in the region, which is mainly for agricultural purposes, is radically greater than groundwater renewability [25–27]. In Saudi Arabia, more than 80% of extracted water from the Umm er Radhuma aquifer is used for irrigation applications; the remaining portion is used for municipalities, industry, and livestock [28]. Similarly, the intense groundwater abstraction from the Nubian Sandstone Aquifer in Libya and Egypt represents extraction from non−renewable groundwater reserves [29]. Current groundwater extraction from the surficial quaternary aquifer in the UAE is almost threefold its renewability from all recharge sources [27]. Global warming and the associated climate change will further harm groundwater availability in the region. The growth in population and the corresponding increase in water demand will lead to much higher groundwater consumption. Available rainfall harvesting systems may increase the groundwater recharge by a percentage ranging from 4 to 40% by using rainwater accumulated behind the recharge dams [30–33]. This wide variation in the increase in recharge from existing recharge dams suggests that MAR in this region could play an important role through the following factors:

1. Overexploitation of groundwater resources in the MENA region (Table 1) promotes aquifer exhaustion. In addition, climate change has a negative impact on certain areas, leading to depletion of aquifers and deterioration of groundwater quality due to saltwater intrusion in coastal areas and upward coning of saline water from deep aquifers in inland areas [27,34]. Declining irrigation water quantity and quality is causing several socio−economic problems, including lower revenue for farmers, a hike in joblessness, poverty, and decreased food security. It is estimated that even

under baseline growth projections, policies and reform would be required to cope with water scarcity induced by climate change [16,22].
2. Increase in water demand due to population growth, especially in urban areas, could lead to further unregulated exploitation of groundwater resources. Increased temperatures due to climate change will lead to increased water requirements for agriculture. There will also be other climate effects, including, importantly, sea−level rise and more extreme rainfall events [35]. Therefore, there is a need to raise the recharge efficiency of the existing recharge dams.
3. With the expected increase in the precipitation events with more intensity in the region, feasible MAR methods, if applied properly within the framework of existing rainfall−harvesting infrastructure, could alleviate these problems.
4. In addition, managed aquifer recharge has become unavoidable for targeted integrated water management in MENA countries [36]. This involves good water supply management from periods of availability to need, which is considered as a tactic to alleviate climate change. Although these interventions will not reverse climate change, they can control direct negative effects on the water supply.

2.2. Location of Recharge Schemes and Water Availability

Dams and engineering structures have a long history in the MENA region (Figure 3). The oldest irrigation system began in Egypt around 6000 BC, transferring water from the Nile River to arable land with dams and canals [37]. Marduk Dam on the Tigris near Samarra was built in Iraq (1500 BC), the Marib dam was built in Wadi Dhana in Yemen (750 BC), and the Falaj (qanat) system spread across the Arabian peninsula, Persia and Egypt (1300–300 BC) [38–40]. Recharge dams in the MENA region (Figure 3) can be categorized into four types, namely, concrete, earth fill, rockfill, and underground dams. According to the International Commission on Large Dams (ICOLD), a dam is designated as a large dam if its height is greater than 15 m, or if it is between 10 and 15 m and meets at least one of the following criteria: (1) a crest length of 500 m or more; (2) a spillway discharge of at least 2000 m^3/s; (3) a reservoir volume of 15 MCM or more [41–43]. The recharge dams in the MENA region vary in height (5–125 m), length (100–9000 m), reservoir surface area (0.1–41.1 km^2), storage capacity (0.04–450 MCM), and purpose (mainly recharge augmentation with/without one or more of the other purposes including irrigation, protection, and drinking water supply) [44–46]. Out of the existing 2017 dams in the MENA region, 1311 dams are exclusively for recharge augmentation.

Most of the dams are located at the wadi outlet to increase the percentage of natural rainwater percolation (indirect/non−intentional recharge) from surface water runoff annually accumulated behind these dams. Most climate models project frequent high precipitation events with more intensity, resulting in an increase in surface water runoff in middle latitudes. This will also increase water availability for MAR, especially in the reservoir areas behind recharge dams. Moreover, due to siltation problems and the high evaporation rate in the MENA region, the recharge augmentation percentage rarely reaches more than 20% of the water accumulated behind the dam [31], and there is a crucial need for MAR (direct recharge). The operation procedures of most of the dams can be changed/modified to enable intentional/direct groundwater recharge from the water behind the dam. Stormwater and harvested rainwater have been successfully used for groundwater recharge over the last sixty years [37]. In some of the GCC countries, excess desalinated water is commonly used for aquifer storage and recovery (ASR) in water security projects. The water balance shown in Table 1 indicates that most MENA countries are facing severe groundwater depletion. In all the GCC countries except Oman, groundwater abstraction is far greater than its renewability. With the present dramatic change in the precipitation patterns and intensity, MAR techniques could play an important role in alleviating the impacts of groundwater depletion.

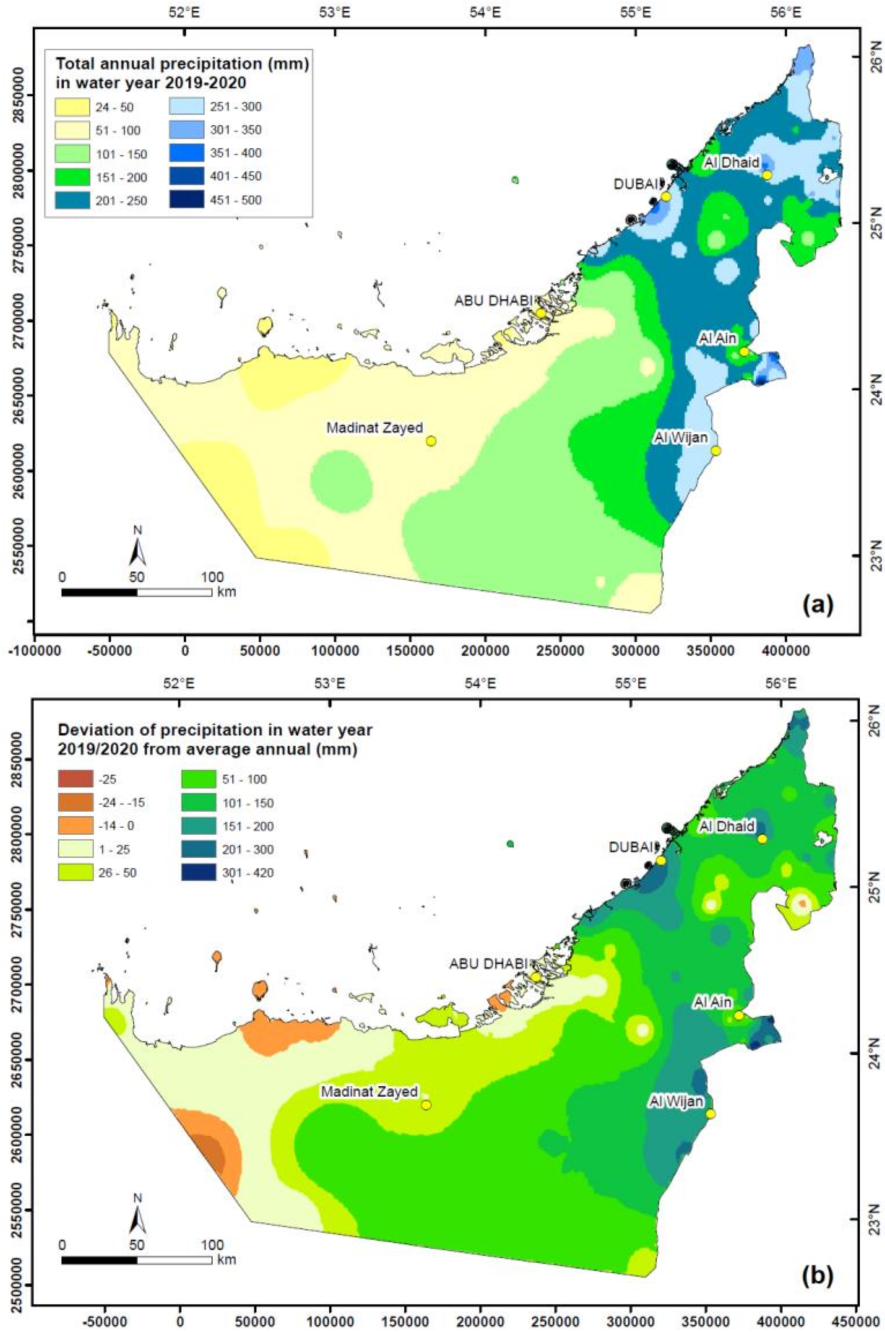


Figure 2. (**a**) Annual average precipitation (mm) in the UAE in the water year 2019–2020 and (**b**) deviation of annual average precipitation (mm) in the UAE in the water year 2019–2020 from average annual precipitation in the period 1979–2015.

Table 1. Water balance in MENA region countries and calculated water use/freshwater availability (%).

	Demand (MCM)			**Supply (MCM)**									
Country	**Water Use (Domestic, Industrial, and Commercial)**	**Agricultural Abstraction**	**Total Demand (MCM)**	**Surface Water**	**Groundwater Abstraction**	**Desalination**	**Reused Water**	**Renewable Water from Rain**	**Total Renewable Water**	**Total Water Supply (MCM)**	**Water Use/Freshwater Availability (%)**	**Average Precipitation (mm/yr.)**	**Total Annual Precipitation (MCM)**
KSA [46,47]	4792	21,200	25,990	175	19,460	2300	230	4000	7180	25,990	0.04	70	192,795
UAE [27,48]	2233	2854	5087	25	2200	2138	549	200	628	5087	0.13	90	5540
OMAN [46,47,49]	330	2242	2572	102	800	326	46	1400	1736	2572	0.02	125	38,687
KUWAIT [46,47,50]	768	858	1626	nil	838	717	144	20	149	1626	0.56	121	2156
QATAR	654	250	904	nil	190	540	114	60	96	904	0.08	74	850
BAHRAIN	271	153	424	nil	58	243	41	82	118	424	0.37	83	62
Yemen [51]	850	3060	3910	1000	560	30	100	1500	2500	3910	ND	232	88,200
Jordan [52]	400	1054	1454	288	619	ND	147	275	275	1329	ND	120	8191
Syria [53]	4662	15,337	19,999	16,000	ND	ND	299	1500	16,000	17,799	ND	300	46,000
Lebanon [54]	841	1000	1841	1300	2500	ND	ND	5000	6000	1841	ND	705	6900
Iraq [55]	5255	37,815	43,070	30,000	11,810	60	ND	1200	31,200	43,070	ND	250	94,000
Egypt [56,57]	15,400	64,550	79,950	55,500	2100	350	13,500	500	8000	79,950	ND	30	18,100
Libya [58]	1020	4980	6000	150	3650	90	165	625	3000	4980	ND	56	98,500
Tunisia [59]	841	2700	3541	1268	1991	73	260	1595	4595	3592	ND	158	34,000
Algeria [60]	522	3314	3836	11,400	1342	535	1200	7600	19,000	3836	ND	86	212,000
Morocco [61,62]	1900	14,000	15,900	10,400	3170	150	245	1519	2500	15,900	ND	302	155,000
IPT [1] [63]	1122	1550	2672	170	ND	705	468	1780	ND		2672	290	10,000

[1] Israel and Palestinian Territories.

2.3. Aquifer Suitability for MAR

Aquifers in the MENA region can be classified into two main types (Figure 3).

(a) Surficial aquifers:

Unconsolidated superficial deposits vary in age from the Pleistocene to the recent past, with varying occurrence and thickness over the MENA region. Three major classifications can be made of these lithological units: (1) alluvial or fluvial, (2) Eolian, and (3) Sabkha deposits. Distinctive current landform features are mainly due to these three units. These units have a major impact on the hydrological regime of the area (Figure 3).

(b) Mega transboundary aquifers:

These aquifers constitute a significant portion of the sedimentary column of the Lower Cretaceous to the Neogene periods [24,64]. These transboundary aquifers are responsible for a major part of the surface and groundwater resources in the Middle East and North Africa (Figure 3). The blend of rising scarceness and mounting climate−related dangers is likely to motivate competition in the development of these waters. Every country in the MENA region shares at least one aquifer with a neighbor (Figure 3). The main hydrogeological system in the countries of the MENA region is formed by some common mega aquifers such as the Umm er Radhuma formation (mainly karstified limestones) and the overlying Rus (mainly gypsum and anhydrite), Dammam (mainly carbonates) and Nubian Sandstone (Figure 3). The Umm Er Radhuma aquifer is dropping moderately towards the east by about 0.1° and is constrained by the Euphrates River [26]. It has a thickness of 250 m in Saudi Arabia and shrinks in the north part of the Western Desert of Iraq (up to 50 m). The thickness in the south part of the Western Desert of Iraq is 500 m. In Kuwait its thickness is 650 m, in Qatar it is 370 m, in the UAE it is 370 m, and in Oman it is up to 650 m [65]. The rocks are largely continental sediments of the Cambrian to Late Cretaceous period dispersed over an area of almost 630,000 km^2 and penetrating up to 3.5 km below the surface. The estimated groundwater reserve in this part of the Nubian Sandstone Aquifer System (NSAS) is approximately 28,000 km^3 [29].

Both the surficial and outcropping fractured deep rock aquifer systems are under unsteady state conditions, where the groundwater recharge is much smaller than the extraction rate. A major part of the groundwater abstraction from these two aquifer systems goes to irrigation. According to the suitability criteria outlined by [37,66], these depleted or partially depleted aquifers have the capacity to store more water due to their thick unsaturated zones that were originally saturated with freshwater, their high transmissivity, high storage capacity, and fresh to slightly fresh native groundwater [66,67].

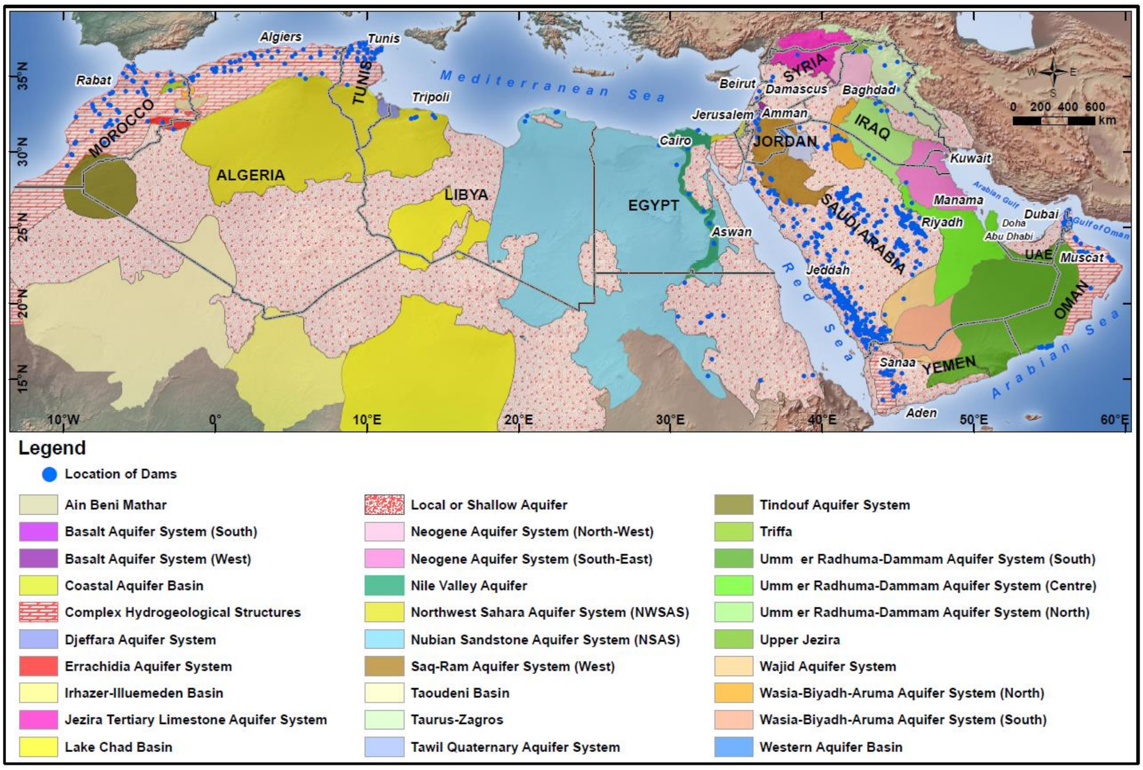


Figure 3. Simplified hydrogeological map of the MENA region. Locations of major dams are shown (data source: [68]).

Karstified limestone aquifers in the MENA region need additional aquifer characterization to determine the fate of infiltrated water in karst environments due to its major impact on the uptake process in these countries. The quantity and quality of groundwater should be monitored around MAR project areas [25].

2.4. Management of Reservoir Clogging and Dam Efficiency

To ensure high sustainable recharge dam efficiency, the hydraulic conductivity of the aquifer must be efficiently managed to prevent aquifer siltation. Two factors are used to quantify the overall efficiency of recharge dams: (1) recharge efficiency, defined as the ratio of annual recharge through the structure to annual accumulated water; (2) runoff collection efficiency, defined as the dam storage capacity divided by the annual captured runoff volume [69]. The extent of the clogging problem depends on the nature of the generated sediments and the aquifer's lithological composition. For example, injection of water into inert aquifers (e.g., sands and sandstone) requires more rigorous anti−clogging procedures than in limestone aquifers, where hydraulic conductivity is sustained by carbonate dissolution of organic matter [37].

3. Recharge Methods and Water Quality Protection

All water is derived from precipitation, a small portion of which infiltrates into the vadose zone and percolates deep to reach the water table, thereby forming the component of natural groundwater recharge. Groundwater recharge is generally defined as the downward movement of water that crosses the vadose zone (unsaturated zone) and enters the saturated zone. Low precipitation coupled with high temperatures and high evaporation rates leads to the near absence of surface water resources in arid regions and overdependence on groundwater to meet agricultural, domestic, and industrial water demands [70–72].

Groundwater recharge depends on several geological and climatic factors such as the infiltration capacity of the soil, the porosity and permeability of the water−bearing geological formations; the spatio−temporal distribution of the rainfall, temperature, and wind conditions prevailing in the area; and the types of vegetation. Recharge rates show high spatio−temporal variability. The volume of precipitation is the most important factor governing groundwater recharge [73]. However, there are many uncertainties associated with its exact quantification, especially in arid regions, due to the large spatio−temporal variability associated with runoff and high evapotranspiration and deep groundwater levels [74]. Natural groundwater recharge can be either diffuse or localized. In case of diffuse recharge, the volume of water infiltrating the vadose zone and reaching the groundwater table covers a large area through precipitation. The climate of the MENA region plays an important role in groundwater recharge; for example, occasional rainfall events in the arid regions result in wadi flows through which diffuse recharge takes place in the unsaturated zones, finally replenishing the aquifers [75]. In the case of localized recharge, as the name suggests, the groundwater recharge is localized and the volume of infiltrated water recharging the aquifers is not uniform. In general, natural groundwater recharge includes diffuse as well as localized recharge. The significance of each type of recharge varies with the climatic conditions. The groundwater recharge rates in arid regions can vary between 0.2 to 35 mm/year, which is about 0.1 to 5% of the mean annual precipitation [67,76]. On the other hand, relatively higher recharge rates are observed where irrigated agriculture is practiced.

Groundwater depletion and the deterioration of groundwater quality in MENA countries has resulted from the lack of natural recharge, rampant and rigorous abstraction for agricultural needs, and seawater intrusion caused by groundwater depletion. Groundwater is overexploited because its recharge rate from rainwater is far less than the exploitation rate. In such a case, a feasible solution to enhance the hydrodynamic and physicochemical conditions of the groundwater is to directly recharge water−table aquifers from rainwater accumulated behind dams [77,78].

Artificial groundwater recharge involves the alteration of the hydrologic cycle by decreasing the components of evaporation and surface runoff and increasing infiltration under human influence. Artificial groundwater can be classified as unintentional groundwater recharge, unmanaged aquifer recharge, and managed aquifer recharge [79]. Managed aquifer recharge (MAR) refers to a group of techniques that have been used to manage groundwater systems under stress [37,78,80–82]. MAR plays a significant role in the management of water resources by promoting the conjunctive use of groundwater and surface water [37] and providing a buffer in times of climate extremes and drought [37]. MAR is being considered as a necessary and fundamental technique for meeting water demands under increasing population and climate change [83,84]. MAR has gained significance in the last 50 years and there have been enormous developments to intensify groundwater recharge rates, including flood relief drainage wells and the use of septic tanks to dispose of sewage water. There are several types of MAR techniques available, and the selection of a given technique depends on site−specific conditions, mainly the availability of surplus recharge water, geology, depth to groundwater table, and groundwater quality. The surplus recharge water available for MAR can be from the treated wastewater, surplus desalinated water (as in the case of Middle Eastern countries), and rainfall runoff. Special emphasis is given to the quality of recharge water so that aquifer water quality is not adversely affected. MAR has become a necessity, especially in the MENA region, where several MAR techniques are employed. The efficiency of MAR systems is largely determined by local hydrogeological conditions that may or may not be favorable for the type of MAR systems in question [85]. Despite its shortcomings, which may include losses in evaporation, huge land area obligations, sediment deposition, the hazard of structural disaster, and high pollution vulnerability, water storage in surface reservoirs as a means of recharge augmentation is common in the MENA region. Therefore, there is a need to manage aquifer recharge in these water structures using intentional recharge methods [86–88]. During the last fifty years, there has been enormous development in MAR to improve the groundwater renewability ratio, including recharge and drainage wells for flood relief and the use of treated sewage water as a water source for aquifer recharge. Intentional recharge, also called artificial recharge, is increasingly being used in urban areas of the MENA region as a water management tool (Figure 4).

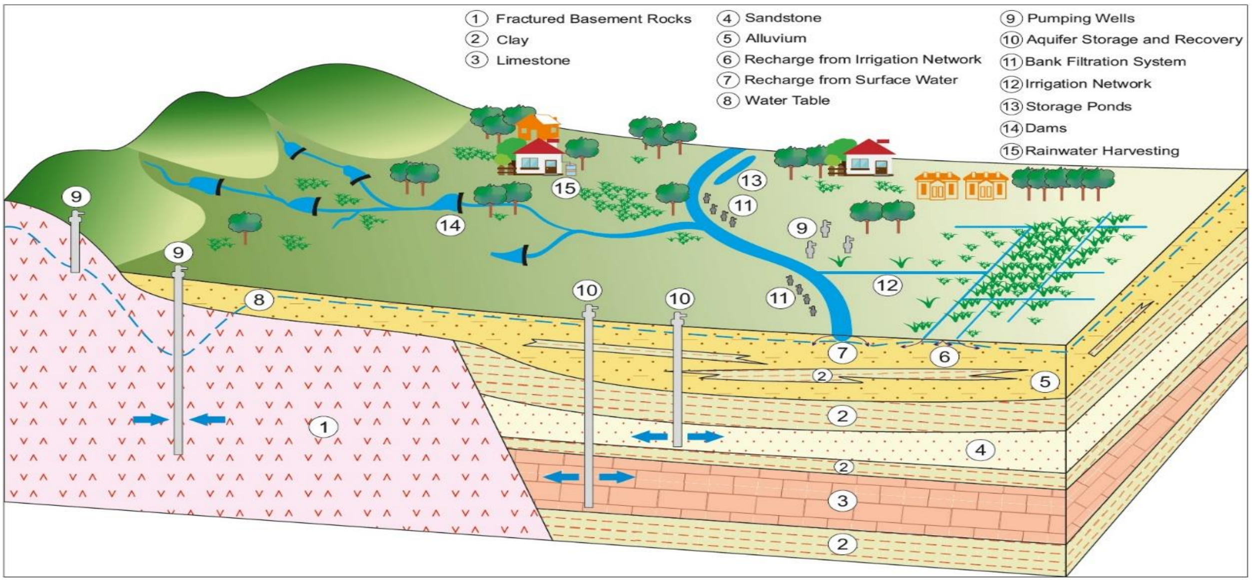


Figure 4. Recharge methods and water sources commonly used in aquifer storage and recovery projects for a variety of uses in the MENA region (source: [37]).

4. Results

4.1. Water Resources Renewability

The MENA region has very low per capita renewable water resources and its available resources have continued to decrease since 1992 (Figure 5). The 2020 renewable freshwater resources per capita are 50 m^3a^{-1} in the KSA, less than 30 m^3a^{-1} in the UAE, Kuwait, Qatar, Bahrain, and 1000 m^3a^{-1} in Iraq. All the MENA countries depend on groundwater abstraction from the shallow and upper mega aquifer system to meet agricultural demand.

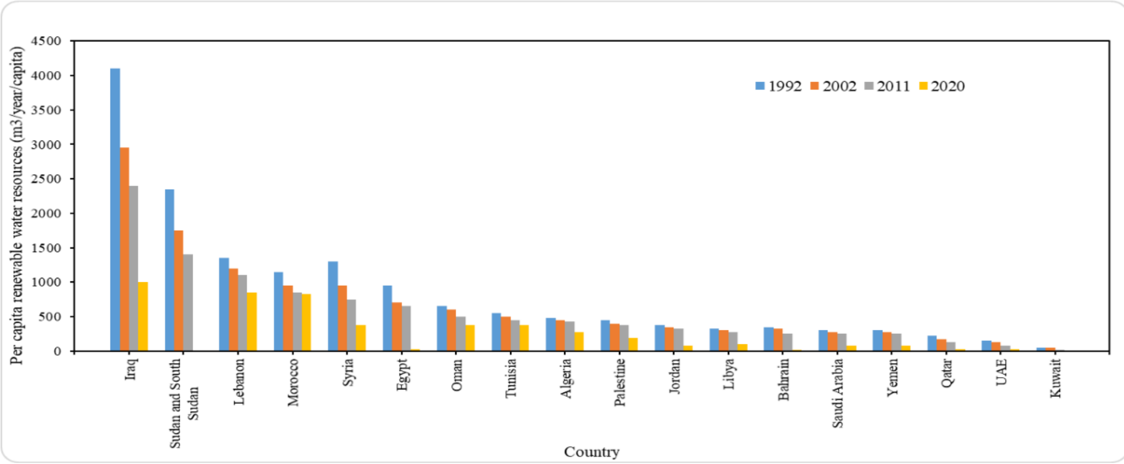


Figure 5. Per capita renewable water resources in the MENA region for the years 1992, 2002, 2011, and 2020 (source: [89,90]).

The governments of all MENA countries (including countries with perennial streams and rivers) have invested in building hundreds of dams to enhance rainfall harvesting and, consequently, increase groundwater recharge. Recharge augmentation by reservoirs and recharge dams is considered an effective tool to supplement the water resources by harvesting floodwater, which is usually drained to the sea and the desert. The MENA region has among the highest water scarcities in the world (Figures 5 and 6).

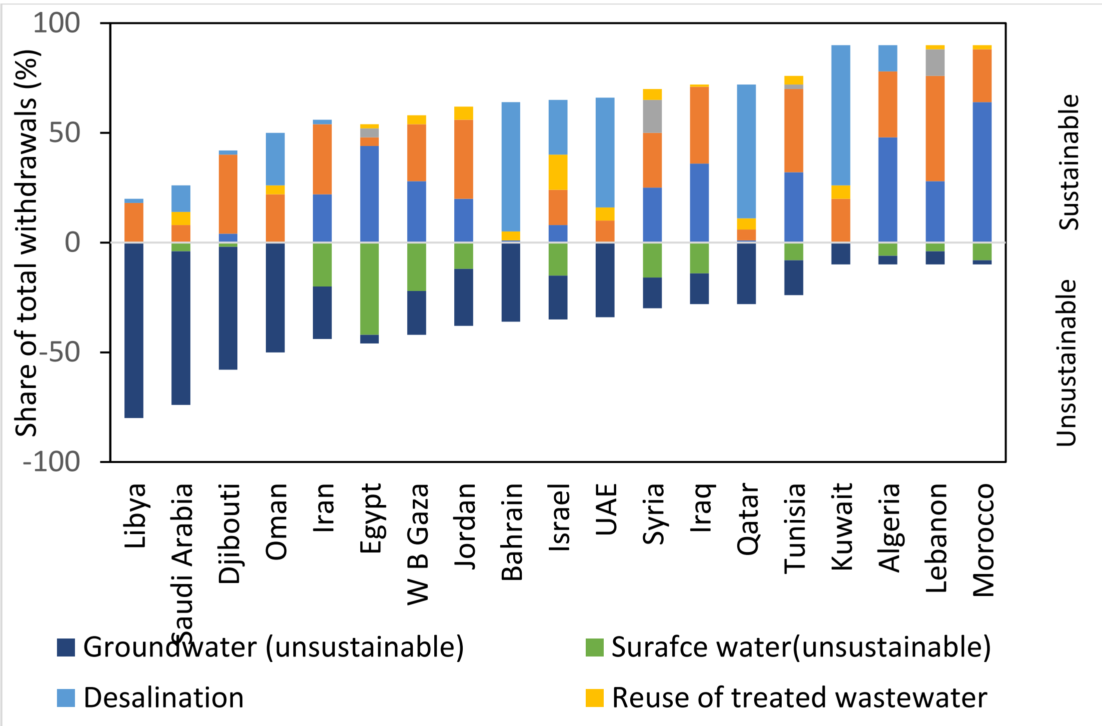


Figure 6. Sustainable and unsustainable water use in the MENA region in percentage (source: [24]).

The environmental flow requirement is defined as the surface flow quantity that is needed to keep aquatic ecosystems healthy. Surface water withdrawal exceeds the environmental flow requirement in the majority of the MENA region, as shown in Figure 6 [24]. For example, in the Nile region, about 10% of surface water consumption is sustained at the expense of environmental flows. Groundwater abstraction in the Arabian Peninsula, Libya, and northwestern African countries (Tunisia, Algeria, and Morocco) far exceeds the renewal rate (Figure 6).

Most aquifers in the MENA region used for irrigation are at least partially depleted. Therefore, the thickness of the unsaturated zone is increasing and there is significant room for water in these aquifers. Despite the intensive groundwater depletion and the increased number of recharge dams, the MAR percentage of total groundwater use ranges from 0.06 to 30% of recharge dams (Table 2). Based on the available data, it is not clear if the reported 30% for Qatar is groundwater recharge or includes the volume of subsurface storage. Among the GCC countries, Oman has the second−highest MAR percentage of the total groundwater use. This may be due to the good practices used in Oman to manage siltation and clogging of dams. In addition, Oman has the highest groundwater renewability in the GCC countries (76%) from natural recharge and augmented recharge.

The Nile aquifer system in Egypt is continuously recharged by return flow and through seepage from surface water bodies; hence, groundwater is considered as the second source of water after the Nile River [91]. In the Nile Delta area, this aquifer has an overall groundwater reserve capacity of 500 BCM [92–95]. Flux from the Nubian Sandstone Aquifer contributes 35% of the total recharge to the Nile Aquifer System [92]. In 2010, the groundwater abstraction from the Nile Aquifer System (NAS) was estimated at 6200 MCM, which is lower than the safe yield (8400 MCM) [92–95]. However, abstraction in the Nile Delta area already exceeds the safe yield [91]. In some places in the Nile Delta, there has been a considerable decrease in groundwater recharge, resulting in seawater intrusion at a distance of more than 100 km from the shoreline [56,92–96]. The second major aquifer in Egypt is the Nubian Sandstone Aquifer System (NSAS). Groundwater resources below the Egyptian Western Desert are estimated to be around 28,000 BCM, and its natural recharge rate is about 120 MCM (i.e., less than 0.03% of the present extraction rate, which is 4000 MCM/year) [29].

Unlike most other extractable resources, drinkable groundwater is a significant element of the entire water resource and is renewable [97]. In addition, lasting groundwater resource development is a favorable social outcome wherever it is conceivable. One of the main misinterpretations of the sustainability of groundwater development is to consider that withdrawal from a basin should not exceed groundwater renewability [97]. According to this interpretation, groundwater development is mostly unsustainable in the entire MENA region. For example, it is neither economic nor feasible to abstract only 120 MCM (recharge rate/safe yield) from the NSAS in Egypt. A more practical alternative is to manage aquifer recharge by using all possible recharge augmentation techniques. Other means also include inducing infiltration from neighboring surface water sources and capturing water that would have been naturally discharged. If the extraction is balanced by these sources, a dynamic steady−state equilibrium, referred to as "sustained yield", can be achieved [98].

4.2. Recharge Dams and MAR Development

According to [37], the worldwide surface water storage capacity is around 12,900 BCM, usually with a few years of residence time (average <3.3 years), and the global modern groundwater (for groundwater aged 25–100 years) reserve is projected to be 800–1900 BCM. There was a decrease in the number of new large dams from 1970 to 1990, which created environmental concerns such as reservoir clogging [3].

There has been an increase in the total number of dams worldwide in the last century, reaching 45,000 large dams in the year 2000 [41]. The increase in the number of large dams has continued over the last two decades worldwide, with a total of 58,713 dams at present [42]. These dams are of various types and purposes. Earth dams predominate and account for 65% of all registered dams (Table 2). With the present aggregate storage of about 7714 BCM, dams contribute to the efficient management of finite water resources [42].

Recharge dams as a means of augmenting groundwater recharge are common in the MENA region [99]. Hundreds of recharge dams with capacities ranging from less than 0.5 to 10 MCM have been constructed across the arid landscapes of the Arabian peninsula, especially in Saudi Arabia, Oman, and the UAE. At present, there are more than 2015 dams in MENA countries, with a total design capacity of 194,800 MCM (Table 3). The groundwater recharge efficacy of these dams depends on several parameters such as the climate, geology, and hydrogeology of the dam site and the amount of sediment load [100]. Sediment deposited on the reservoir bed transported by wadi flows during rainfall events represents a common problem in arid regions [101–104]. A reduction in dam storage capacity and recharge efficiency are among the adverse consequences of sediment deposition in reservoirs.

The number of dams and the total volume used in Managed Aquifer Recharge (MAR) is different from one country to another in the MENA region, depending on the area, climate, economic situation, and population (Table 3). With 563 dams, Saudi Arabia has the greatest number of dams, while Egypt has the least [105]. Groundwater renewability in the MENA region ranges from less than 6% to 100% in a few countries, depending on the total groundwater abstraction, climate, hydrogeological setting, and water infrastructure. The universal need for water for human existence and development makes a future lack of availability concerning. There are three main types of dams: recharge, protection, and irrigation and drinking dams. For example, there are 155 dams in Oman [106,107] for flood protection (3 dams), recharge augmentation (46 dams), and surface water storage (106 dams).

Table 2. Worldwide dam types and numbers (source: [41]).

Type	Number of Dams	Type	Number of Dams
Earth fill dams	37,984	Barrages	300
Rock fill dams	7745	Arch dams	2358
Gravity dams	8323	Multiple arch dams	129
Buttress dams	473	Others	1401

The annual rainwater volume that falls in Oman is estimated to be 15.841 BCM, with 12.553 BCM lost to initial absorption and evaporation [106]. Recharge from rainfall is about 2.397 BCM annually and represents 88% of the inflow in Oman [39,41]. The total storage capacity of dams in Oman has increased from 87.6 in 2007 to 323 MCM in 2018 [89]. As of 2021, there are 43 recharge dams in Oman with a combined storage capacity of 93.5 MCM/year [49]. Most of these recharge dams are aligned along the coast to serve the dual purpose of groundwater recharge and prevention of saline water intrusion [108].

The first dam in the western area of the Kingdom of Saudi Arabia (KSA), the "Ikrimah" dam, was built in 1956; it is 11 m in height, 290 m in length, and has a total storage capacity of 500 MCM. It has been used for underground water recharge. Since then, many other dams have been constructed in the KSA in the last sixty years, reaching 563 dams covering all the regions of the KSA, 117 of which have heights of more than 15 m [38]. The total storage capacity of the existing dams in the KSA is 2590 MCM [44,106]. Based on their purpose, these dams can be classified into recharge dams (339), protection dams (235), potable water dams (40), and irrigation water dams (6). Although most dams in the KSA are constructed for groundwater recharge, the largest capacities are associated with dams for potable water.

Likewise, there are currently over 120 recharge and storage dams in the UAE, intercepting an estimated volume of 150 MCM/year of surface water runoff from 15 main catchment areas. The total dam capacity in the UAE increased from 18 MCM in 1983 to 98 MCM in 2015 [31,32]. Nine major recharge dams have a capacity of 47 MCM/year [21,107–113]. More than 98% of all dams in the UAE are built to augment aquifer recharge. Despite the important role of dams in groundwater recharge augmentation, these dams face several challenges, as will be discussed below.

In Qatar, there are two major aquifers. The Rus aquifer is situated in the northern area of Qatar and comprises chalky limestone, whereas the Abu Samra aquifer lies in the southwestern region and consists of granular limestone rocks. The annual natural recharge is about 25 MCM/year (43% of the total annual recharge, which is 58 MCM/year), mainly derived from rainfall and inflow from the KSA (through the Abu Samra aquifer) and return flow from irrigation [105]. Aquifer replenishment through MAR in Qatar is about 33 MCM/year (57% of total annual recharge), which comes from the injection of treated sewage effluents (TSE). The total annual recharge accounts for less than 30% of the available water in Qatar [105].

There are 347 dams in Yemen with storage capacity varying from less than 0.2 MCM to more than 0.5 MCM [49,51]. In Jordan, there are 42 dams including the desert dams, with a total dam capacity estimated at 350 MCM [114,115]. In Syria, there are 166 dams with a total capacity of 18,000 MCM [53]. There are 20 main dams with a total capacity of 888 MCM in Lebanon [54], and 13 dams with a total capacity of 26,762 MCM in Iraq [116]. The total dam capacity in Libya rose from 10 MCM in 1970 to 390 MCM in 2015 [58,117,118]. As of 2017, there were 230 large dams with an overall storage volume of 23,000 MCM in the northwestern African countries (Morocco, Algeria, and Tunisia) [119,120]. Morocco developed a dam policy beginning in 1967. The policy aimed for the design and construction of two to three dams each year to secure irrigation water and drinking water supply, mitigate flood risk, and produce hydropower [121]. In Morocco, there are 245 dams (145 large and 100 small) with a total capacity exceeding 18,000 MCM, and 13 hydraulic water transfer structures with a total length of 1100 km and an annual volume of 2500 MCM [121]. In Tunisia, there are 39 dams (total capacity is 2690 MCM), 230 hill dams, and 950 hill lakes [121]. The overall dam storage volume in Tunisia rose from 680 MCM in 1975 to 2690 MCM in 2017, developing at an average yearly rate of 9.41% [122]. The total dam capacity in Algeria increased from 1810 MCM in 1970 to 8300 MCM in 2015, growing at an average annual rate of 10.19% [60,123,124].

Table 3. Number of dams, storage capacity, MAR volume, and groundwater renewability percentage in the MENA region.

Country	Total Number of Dams	Total Storage Capacity (MCM)	Max. Measured Total Accumulated Water (MCM)	Natural Recharge (MCM)	Augmented Recharge by MAR (MCM)	MAR Percentage of Total Groundwater Use	Percentage of Reported Global MAR Capacity	Dam Purposes	Groundwater Reserve (MCM)	Groundwater Renewability Percentage (%)
KSA [11,12,45]	563	2590	ND	2400–4526	333.5	2	3.06	Drinking, irrigation, recharge, protection	248,000–761,000	27
Oman [1,21,22,28,75]	155	323	ND	1397–2000	109	3.5	1	Drinking, irrigation, recharge, protection	42,000 (Freshwater type)	63
UAE [11,12,31,34,111, 112,124,125]	117	98	40	187–220	15	0.5	0.13	Recharge, recreation, protection	30,000–300,000 (Fresh and brackish water)	6
Kuwait [11,12,50]	0	0	0	20	0	0	0	–	881–1543	22
Qatar [11,12,126]	ND	ND	ND	25	60	30	0.3	ND	2038–2500	40
Yemen [11,12,36,51]	397	462	ND	1000–2100	5	0.21	0.045	Drinking, irrigation, recharge, protection	13,500–64,383	44

Table 3. *Cont.*

Country	Total Number of Dams	Total Storage Capacity (MCM)	Max. Measured Total Accumulated Water (MCM)	Natural Recharge (MCM)	Augmented Recharge by MAR (MCM)	MAR Percentage of Total Groundwater Use	Percentage of Reported Global MAR Capacity	Dam Purposes	Groundwater Reserve (MCM)	Groundwater Renewability Percentage (%)
Jordan [1,11,12,114,115]	42	350	ND	231–326	9	1.44	0.08	Irrigation, recharge	11,618	22
Syria [11,12,53,127]	166	18,000	ND	6000	ND	ND	ND	Drinking, irrigation, recharge	38,872	88
Lebanon [11,12,54]	20	888	ND	4728–7263	ND	ND		Drinking, irrigation, recharge	2929	70–100
Iraq [11,12,114]	13	26,762	ND	1200	ND	ND	ND	Recharge	50,963	29
Egypt [11,12,29,34,56, 91,92,94,95,112]	7	132,000	ND	6600	22	0.3	0.20	Drinking, irrigation, recharge	500,000 (NAS) 90,000,000 (NSAS)	100% (NAS) 0.03% for the NSAS
Libya [11,12,58,118]	18	390	ND	650–700	ND	ND	ND	Recharge, irrigation	249,469–100,000,000	10
Tunisia [11,12,120,127, 128]	269	2546	ND	1595	6.1	0.26	0.0559	Irrigation, recharge, protection	18,944	69
Algeria [60,120,123,129, 130]	80	8600	ND	1517	1.7	0.06	0.0155	Irrigation, recharge	361,327–91,900,000	52
Morocco [11,12,62,131]	245	18,000	ND	3400	100	2.4	0.91	Irrigation, drinking, recharge, protection	64,279–7400,000	60
IPT [11,12,37,132]	ND	ND	ND	1780	138	11.5	1.3	ND	7134	ND

Ref. [133] provides a global inventory of MAR schemes where 1200 case studies from 62 countries were analyzed. The study highlights the wide acceptance of MAR as a valuable tool for augmenting groundwater resources. MAR is in operation in 23 European countries at 224 sites to provide a sustainable source of drinking water. Most of the major MAR sites in the region rely on surface spreading techniques to enhance infiltration. MAR represents an important source of drinking water [134].

Three types of MAR techniques are practiced in Qatar [135]. The first technique involves the enhancement of natural groundwater recharge through the drilling of shallow injection wells in natural depressions, injection of fresh recycled water through the drilling of deep recharge wells in Doha, and recharge of urban stormwater through deep boreholes in Doha, where most of the population is concentrated. There are 313 shallow recharge wells, also referred to as passive recharge wells, with water entering the aquifer under the influence of gravity in shallow depressions, drilled by the Ministry of Environment in Qatar in 2009 [136]. Modeling studies indicated that 161 of these recharge wells result in a recharge of 10.7 MCM/year of water, which is about 14.26% of the total natural recharge. MAR, through enhancement of rainfall infiltration and recharge through treated wastewater, has been suggested as an option for sustainable development of water resources in Qatar.

Artificial groundwater recharge from the injection of treated wastewater, recharge wells, and irrigation return flows accounts for 54.6% of the total recharge in the country [137].

Early primitive trials of single well artificial recharge started in Kuwait in the late 1970s [138]. Aquifer storage and recovery as a means of sustainably enhancing groundwater resources in Kuwait has been investigated in great detail by different researchers [139–141]. The available studies report that the success of an ASR project depends on the topography of the location, hydrogeological characteristics, and compatibility between the recharged water and the aquifer groundwater and lithology. The success of ASR is reflected in the recovery efficiency of the injected water. Instead of a single injection and recovery phase, multi−cycle phases of injection and recovery are recommended. Through numerical modeling, the best possible scenario for maximum recovery of injected water can be determined. Advanced treated wastewater was injected into an aquifer at an ASR pilot project site in the Al Kabd area of Kuwait. Modeling scenarios suggested that 9 months of injection followed by 3 months of recovery using eight wells showed 77.42% recovery efficiency [142].

Yemen has been facing problems related to the overutilization of groundwater resources during the last few decades. Efforts are being made to mitigate the impacts of declining groundwater levels by inducing recharge through the construction of earth embankments and dams [143]. The use of basins as an alternative to the construction of recharge dams was investigated by [144] in the Sana'a basin of Yemen. A decline in infiltration rates was observed in the basins over two decades. This decline was mainly attributed to sediment accumulation and a decrease in hydraulic conductivity at the bottom of these infiltration basins.

In response to the declining groundwater levels and quality, the government of Bahrain has focused on various alternative sources such as the use of surplus treated wastewater to recharge the Dammam aquifer [145–147]. The recharge of the Dammam aquifer with treated wastewater can be carried out along the eastern coasts to prevent saline water intrusion. To manage the groundwater supply, MAR using water collected during extreme rainfall events has been suggested. Ref. [148] used a multi−criteria decision−making approach to identify suitable sites for artificial groundwater recharge from surface runoff in Bahrain.

Even though rainfall harvesting techniques in the MENA region are a traditional practice, the quantitative aspects of MAR in these countries have not been studied in detail. However, several studies [62,100,129,131,132,149,150] have indicated that only around 25% of the accumulated water in the ponding areas of dams reaches the target aquifers. This is attributed to reservoir sedimentation. For arid and semi−arid regions, underground water storage is more viable than surface storage. Underground storage has no evaporation losses, is not vulnerable to pollution, and is more economic [36,100,117,131,132,149].

The current storage capacity of dams in the MENA region ranges from 98 to 132,000 MCM (Table 3). The small increase in groundwater storage through MAR plays an important role in reducing groundwater stress on the local scale.

4.3. Sediment Control and Recharge Effectiveness

Of the different types of available MAR techniques, groundwater recharge through recharge dams is a commonly used method in Middle Eastern countries, especially Saudi Arabia, the UAE, and Oman [31,108,113,151]. The major challenges affecting the efficiency of recharge dams are (1) the reduction in storage capacity of reservoirs due to sedimentation and (2) the reduction in infiltration rates, which are adversely affected by the sediment deposits on reservoir beds, as shown in Figure 7 [99,152,153]. Sparse vegetation, high topographic gradient, and short but intense rainfall events are the main reasons for sediment accumulation on reservoir beds in arid regions. Gully erosion plays an important role compared to soil erosion in sediment production in arid regions [152]. Dam siltation problems are a widely investigated topic [154–159]. Storm events lead to the compaction of earlier deposited sediments, resulting in a significant reduction in the permeability of the reservoir beds [160–163]. Sedimentation in reservoirs not only leads to a decrease in groundwater recharge, but also results in the loss of water by evaporation as the residence time of the water in the dam increases [164]. Several solutions to deal with the sedimentation problem have been proposed [165]; however, they are site−specific, depending on the dam catchment area, climate topography, and geology [166]. Information related to the volume of sediment transport and management strategies should be a prerequisite for the construction of recharge dams to ensure proper functioning [163].

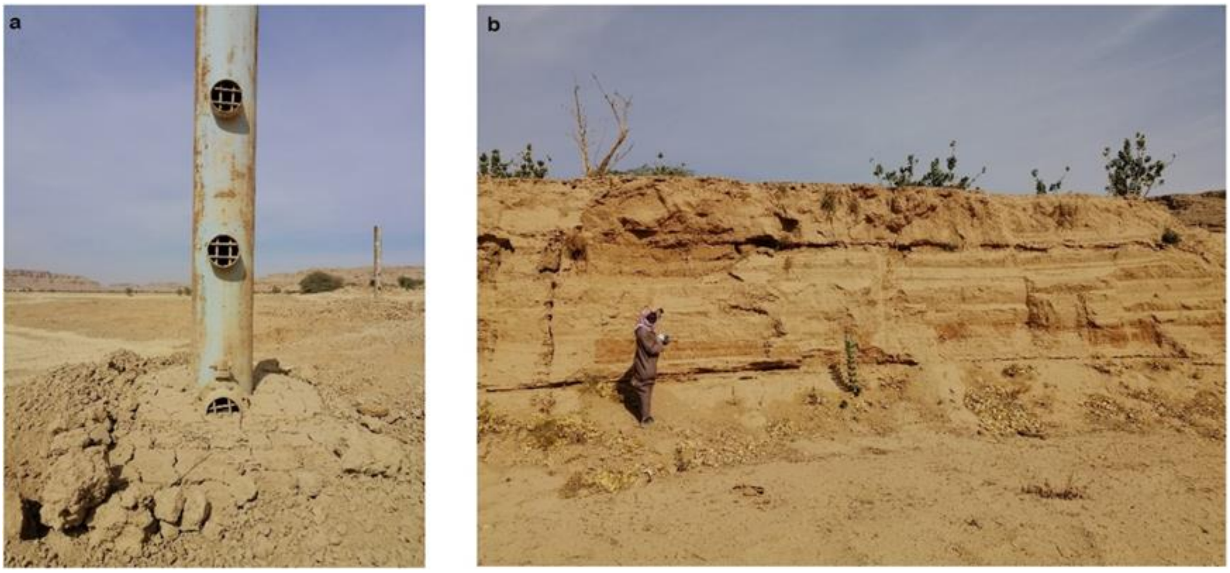


Figure 7. (**a**) Sediment blocking water entry in recharge wells drilled in dam reservoir and (**b**) sediment deposition in a reservoir bed in a recharge dam in central Saudi Arabia.

Conventional dredging or scratching of the reservoir bed during dry periods and pressure flushing are some of the commonly used techniques, but are not the most effective or feasible for mitigating sedimentation problems in dam reservoirs [167]. Removal of silt and scratching of the reservoir beds to improve the infiltration rates and, therefore, the efficiency of recharge dams have been suggested as a dam management option based on the study of two sites in Saudi Arabia [163]. The release of the stored water downstream to enter existing abandoned wells through gravity flow was demonstrated as an effective technique for mitigating the impact of sediment deposition on the reservoir bed and improving groundwater recharge [103]. Suction dredging has been proposed by many researchers for the removal of sediment from reservoirs [163]. However, it may not be a feasible technique in arid regions due to the high−water requirements of the process. Ref. [162] demonstrated a hydro−ecoengineering technique for improving infiltration rates in dams affected by sedimentation problems. In their study on the Al−Khoud dam reservoir in Oman, they demonstrated that planting of Christ's thorn trees enhanced infiltration rates in the sediment by 1.9 to 5.9 times, and by 1.7 to 3.3 times in bare soils (not affected by sediment deposition). Since the dam sidewalls are not affected by the sedimentation process, lateral infiltration of the water may take place through these sidewalls. Ref. [163] suggests the excavation of pits inside the dam reservoir to allow for lateral infiltration in order to overcome the reduction in groundwater recharge due to sediment deposition.

To overcome the problem of decreasing infiltration rates due to silt deposition on reservoir beds, the use of gravity−driven recharge wells has been demonstrated as an effective technique at several dam sites in central Saudi Arabia [163,164]. A study conducted at the Al Alb dam reservoir [163] showed that the construction of recharge wells in reservoirs increased recharge efficiency by 44% and decreased evaporation rates by 86%. Ref. [163] concluded that the construction of six recharge wells a Hauatat Bani Tami dam in central

Riyadh resulted in an increase in recharge rates by 11.48% and a decrease in evaporation by 48.3%. Ref. [99], a study on the recharge effectiveness of Sahalanowt Dam in Salalah, Oman, found that recharge rates were reduced from 16 cm/hour to 0.18 cm/hour due to sediment deposition in the reservoir. They suggested the removal of the sediment from the reservoir bed, as well as the improvement of the hydraulic conductivity of the underlying rocks by raking or ripping to improve the overall recharge efficiency. Ref. [163] mentions that, globally, the loss of reservoir storage capacity due to sedimentation has exceeded the volume of storage added since the mid−1990s. The effect on hydraulic conductivity due to clogging from sediment deposition at the MAR site in Morocco was investigated by [168].

4.4. Local and Regional Impacts

Dams typically serve key functions such as recharge, flood control, and electricity production. Ref. [169] indicates that almost 33% of dams are used for two or more key purposes, and the number of multi−purpose dams has increased in recent years. The social impacts of dams have not been well documented in the literature. It is very complex to conceptualize the social impacts of infrastructure development with a variety of social impacts in the spatial and temporal domains. The frameworks utilized are usually not explicit to dams and, therefore, neglect crucial impacts related to them. A novel framework (matrix framework) for scholarly and practical analysis is suggested by [33,170] for dams' social impacts, with time, space, and value as vital elements, including infrastructure, community, and livelihood. Dams are commonly used to (a) recharge groundwater; (b) protect communities from floodwater, torrents, and related risks; (c) provide drinking water for the areas near the dam; (d) support agricultural and farming activities, (e) artificial recharge of depleted coastal aquifers and remedial measures for mitigating seawater intrusion; and (f) hydropower generation [44].

In addition to large dams, several small dams and reservoirs exist with the primary objective of flood control, groundwater recharge, or the supply of water to local communities for domestic uses, irrigation, and livestock watering [58,60,117,119,120,122,123,171]. However, there is a wide variety of social impacts in many large−scale dam projects [172]. These include (a) migration and displacement of people; (b) unequal benefits and cost−sharing among different groups; (c) effects on the local people and their cultures; (d) effects on housing and infrastructure; and (e) impacts on community health.

The International Association for Impact Assessment (IAIA) has developed a set of Social Impact Assessment (SIA) principles that are valid for large development projects. These principles comprise, among additional aspects, attention to the preventive principle, inter−generational equity, the conservation of cultural and social multiplicity, and the internalization of the costs of a planned intervention [173]. Ref. [16] reported that Organization for Economic Co−operation and Development (OECD) countries have utilized 70% of their economically viable dam potential, while developing states are merely utilizing 30% of their potential. The construction of large dams worldwide in the future is principally subject to the pace of development activities in these countries [174–176].

A few adverse impacts have also been reported. As many as 300 million people have been displaced globally by ongoing and completed dam projects during the last 20 years. With the displacement caused by development projects, those associated with the construction of large dams are the best studied, mainly due to the magnitude of dams' impact. The impacts on internally displaced people (IDPs) are severe, ranging from loss of land, income, cultural identity, community and access to housing, health, and education. Women, children, the elderly, indigenous people, and members of ethnic minority groups are especially vulnerable and invariably pay the highest price of development [177].

A study by [120] revealed that there was a substantial decrease in sediment fluxes in the coastal Mediterranean waters of the Maghreb mainly due to dam construction. The Aswan Dam in Egypt stopped sediment flux to the Mediterranean Sea along the Nile Delta shoreline, causing annual damages to the shoreline in Alexandria City due to erosion and intense saltwater intrusion, which reached a distance of 150 km south of the shoreline [58,116,127]. In this area, the soil became salinized and the concentration of pesticide residuals and heavy metals dramatically exceeded WHO limits, threatening public health.

Farmland and related terrestrial ecosystems are generally submerged in ponding areas of dams, causing adverse effects on the local ecology [173]. Dams modify the geological conditions of reservoir areas and, thus, the risk of landslides and earthquakes is amplified [176]. It was also reported that the construction and operation of the Grand Ethiopian Renaissance Dam (GERD) will reduce the flow in the Nile River and in the irrigation network of the Nile Delta, as well as trigger seawater intrusion from the Mediterranean Sea during the filling stage of the reservoir [178].

4.5. Dam Management Practices/Evolution of Governance

In the MENA region, both renewable and fossil aquifers are encountered. The MENA countries possess the lowest annual renewable water resources in the world (1274 m^3 per capita). This makes it the most water−stressed region globally [117]. For example, the ratio of annual groundwater renewability is 0.03% in Egypt (for the Nubian Sandstone Aquifer), about 10% in Libya, and 27% in the KSA (Table 3). During the period 2003–2009, GRACE data [98] indicated that the north−central Middle East lost a volume of 143,600 MCM of groundwater. Some North African countries such as Algeria, Tunisia, and Morocco mainly depend on groundwater for their agriculture use. The percentages of groundwater reliance in these countries are 88%, 64%, and 42%, respectively. It is also pertinent that more than 50% of the aquifers in Algeria and Morocco and about 25% of the aquifers in Tunisia are overexploited [117].

Recharge dams are generally constructed perpendicular to wadis to impound the surface water runoff in a particular wadi at the location where it is desired to recharge the aquifer. Adequate research on technical aspects has been carried out to assess the impact of dams to improve groundwater potentiality in MENA countries. These studies include an assessment of the impact of managed and unmanaged recharge on groundwater quantity and quality. In addition to the impact assessment studies, a few studies focused on the management of water harvested by the dams. An assessment of the efficiency of dams without injection wells indicated that 302 dams in Saudi Arabia were built with a total storage capacity of 1.4 billion cubic meters of surface runoff annually. Among those, 275 dams recharge about 992.7 m^3 of water per year [179]. Recharge assessment based on isotopic signatures indicated that 40% of water stored by the Wurrayah Dam in the UAE was successfully recharged into the aquifer [31,125]. The effectiveness of recharge of groundwater by a check dam was assessed [167] in Saudi Arabia. Infiltration from reservoirs increased sharply just after a flood event and then dropped due to sedimentation. Sedimentation reduced the efficiency of the check dam. The study suggested that the release of water from the check dam to the downstream channel provides a feasible alternative to increase the groundwater recharge if the precipitation is higher than average. Groundwater recharge methods are primarily classified into two categories:

(1) Unmanaged recharge methods refer to methods in which water is discharged into soil or aquifers without consideration of the impacts on groundwater quality and resource value [37].

(2) Managed aquifer recharge is the deliberate release of water to aquifers with the intention of human health and environment protection, with resulting reclamation or environmental benefits [3]. Elevated rates of water recovery are usually considered the main goal of all recharge practices in MAR approaches. The realization of high rates of artificial recharge is dependent to various aspects such as the chemical, physical, and biological characteristics of the recharged water, soil, and the receiving aquifer [180].

The operational practices of most of the dams in the MENA region indicate that as floodwater is detained, sediment settles, leading to clogging of the pore spaces in the upper layers of aquifer systems and deposition of silts and sediments on the bed of the ponds.

In several countries, it has been estimated that fifty to more than seventy percent of stored water directly evaporates into the air [151]. As such, the current operational practices of most dams need to be reviewed and improved. According to [120,180], the average capacity loss in 230 dams in North Africa was projected to be 0.54% per year. The catchment areas (both upstream and downstream) and reservoirs both face many serious issues owing to the silting of dams [58]. Various methods for managing aquifer recharge are currently used in the MENA region and can be classified into eleven broad categories (details are reported in [70,100,181]):

1. Streambed channel modifications: This represents the oldest form of recharge enhancement.
2. Bank filtration (BF): This is a controlled interaction process between surface water and groundwater where surface water infiltration is forced to flow to pumping wells installed on the banks of rivers and lakes to remove particles and pathogens and prevent overexploitation of aquifers. BF is also used to overcome surface−water abstraction problems caused by low seasonal river water levels and recurrent oil spills and other pollutants [37].
3. Spreading of water: Also known as spate irrigation, this works by spreading surplus water on the surface to enhance soil moisture and food production on relatively dry lands. It is widely practiced in semi−arid countries [78] and unintentionally causes groundwater recharge [133].
4. Recharge dams: Dams are a well−known MAR method. The geometrical design (length, width, and height) of dams is usually governed by the width of the river/wadi bed, geological and geomorphological setting, volume of runoff into the river/wadi, and the purpose of the dam. Usually, water stored behind the dam is allocated to recharge the aquifer or diverted for domestic and irrigation purposes [100].
5. Recharge wells: Recharge or injection wells are used to directly discharge water into an aquifer [72,78,182].
6. Percolation pond with or without injection wells: Whether existing naturally or excavated artificially, the stored in these ponds is partially recharged into aquifers, thereby enhancing groundwater level and quality. Due to the high evaporation rate in the MENA region, a high percentage of accumulated water in ponds evaporates, leading to decreased recharge efficiency. Therefore, percolation ponds should be built on permeable land with injection wells to achieve the optimum advantages from these structures [128,149,183].
7. Aquifer storage and recovery (ASR): This technology works by storing excess water in an aquifer system through infiltration ponds or by using injection wells during periods of high inflow, then extracting the water when needed. The ASR method is commonly used in GCC countries to meet emergency water demands.
8. Aquifer storage, transfer, and recovery (ASTR)/aquifer recharge and recovery (ARR): ASTR/ARR is a common technique in the MENA region. It facilitates the occurrence of natural biological treatment processes with low carbon footprint and energy requirements and. Furthermore, ASTR strives to reduce the burden on fresh groundwater resources by utilizing reclaimed water [100].
9. Soil aquifer treatment (SAT): Infiltration ponds are used to infiltrate the treated sewage effluent (TSE). Through this process, microorganisms in wastewater are removed as they pass through the unsaturated zone of the aquifer.
10. Rooftop rainwater harvesting: Rooftop rainwater is directed through pipes towards a sand−filled soak pit or sump that can subsequently recharge the underlying aquifer. With appropriate building designs, it represents a potential method for adaptation to predicted climate change impacts in the MENA region.
11. Aflaj/Karezes/Ain System: Aflaj (singular: Falaj) are old−fashioned surface/underground artificial channels used to collect and divert groundwater, surface water, or spring water towards demand areas using gravity. Oasis settlements typically used these systems to secure freshwater.

In the MENA region, documents on policies and guidelines related to health and environmental protection in MAR operations are limited and, in some cases, not available. Such documents might exist at the national level for a few developed countries in the region and can be used with sensor networks and data acquisition and control systems to facilitate decision support and risk analysis in the MENA region [76].

4.6. Applicability to Arid/MENA Regions

Water resources in the MENA region are scarce, but indispensable for sustainable growth and development. Several researchers (e.g., [174,184]) have testified that dams can be efficiently exploited for artificial recharge of groundwater in the MENA region. These dams store surface water runoff from storms to effectively recharge shallow groundwater wells, thereby protecting the livelihood of local communities. The MENA region has seen a sizeable increase in the number of new dams, even though the area does not receive a large amount of annual rainfall. For instance, in Saudi Arabia, the number of dams has doubled in the last 10 years, reaching 563 in 2020 (Table 3). Investment choices in projects related to water harvesting are based on several factors that must be examined and appraised both individually and in relation to each other. Many challenges and complexities are involved in conducting feasibility studies of the dams. A framework to assess the feasibility of MAR under uncertainty was developed by [185], shown simplified in Figure 8. In the proposed framework, integration occurs on two levels: level one in which many variables from the hydrologic, hydrogeologic, and financial studies are analyzed using a single model, and level two, in which the uncertainty in the cost–benefit analysis is explored by the identification of crossover points.

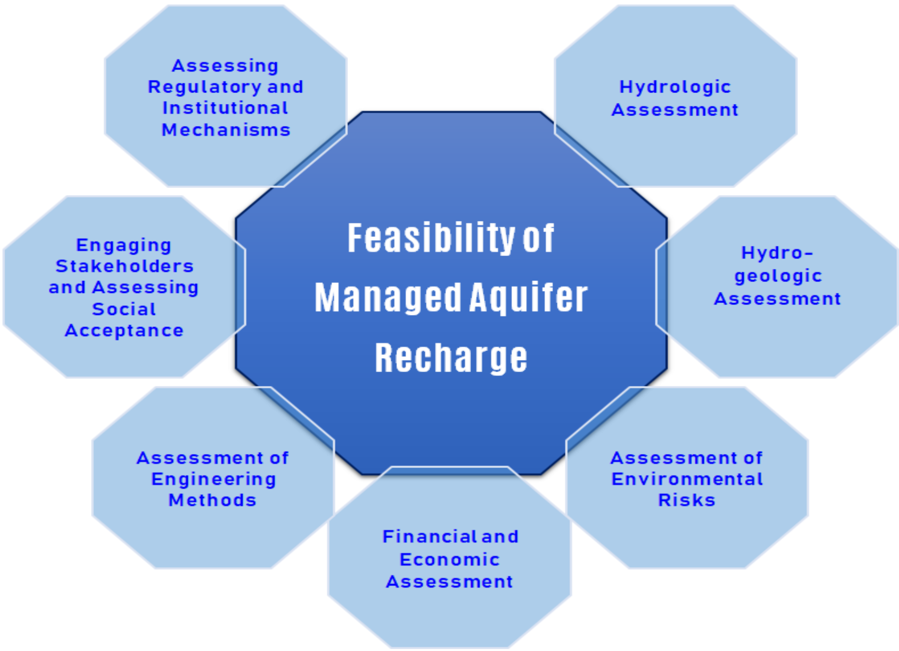


Figure 8. Framework for evaluating the feasibility of managed aquifer recharge (source: [185]).

An approach for feasibility analysis of groundwater recharge dams was developed by [174]. The developed methodology was applied to more than 80 dams in the Asir province in Saudi Arabia. The methodology is based on formulating several standards and criteria, including three major elements that need to be evaluated when developing the approach for the feasibility and prioritization process; these elements are (1) political−administrative, (2) socio−economic, and (3) physical−environmental. The study indicated that an evaluation of the reliability of the annual cost and yield is critical before any decision for investment. Irrigation requirements are the chief constraint on yield and trustworthiness of recharge dams. The reliability of dams, which is linked to their size and net inflows, increases with escalating yield [174].

4.7. Research Gap and Limitation of MAR

To evaluate the use of MAR for integrated groundwater resource management, several other researchers (e.g., [66,76,186–189]) have reviewed MAR development, implementation, and limitations over the past six decades. This included surveying and analyzing various case studies that applied flow and transport models. Large cities in the United States, Europe, and Australia employ infiltration basins specifically to manage stormwater by collecting surface runoff waters. The seven MAR techniques used in GCC countries—ponds, soil aquifer treatment (SAT), rooftop rainwater harvesting, recharge dams, aquifer storage and recovery (ASR), aquifer storage transfer and recovery (ASTR), and Karez/Ain systems—along with their implementation methods, were presented in a review article by [190]. Ref. [67] is the first known attempt to estimate the volume of MAR on a global scale, to demonstrate the development of all the major forms of MAR, and to link these developments to breakthroughs in both research and regulatory frameworks. To sustain, enhance, and secure stressed groundwater systems, as well as to safeguard and increase water quality, MAR is an increasingly significant water management technique, alongside demand management. However, to the best of our knowledge, only [67,190] from the above−mentioned references included cases from MENA region. The primary objective of this review is to fill the primary analysis gap in previous MAR reviews, which is the viability of using MAR techniques for the prevention of flash flood hazards in the nations where climate change models predict high precipitation events with greater intensity, that is, arid countries generally and MENA countries specifically. The main limitations of MAR in the MENA region are as follows:

- The availability of water for MAR is the main difficulty, because all MENA region countries are in semi−arid and arid regions. Increased usage of treated sewage water and harvested rainwater should be the focus of the initiatives;
- Recharge dams, which lack intentional recharge mechanisms, make up most of the rainfall harvesting methods in the MENA region;
- Extreme precipitation events are expected to become more intense, causing flash flood peaks to rise. The accumulated water behind dams might be more than their total capacity and water may flow to the sea or evaporate;
- Most of the aquifers in the MENA region are inert aquifers (such as sands and sandstones), where siltation and aquifer clogging problems are severe and necessitate strict clogging preventative measures.

5. Recharge Dams and MAR Examples in the KSA and the UAE

Construction of dams for recharge and flood control has been practiced in Saudi Arabia for a long time, and information about more than two dozen ancient dams in the Hijaz region of Saudi Arabia, especially around Taif and Khaybar, has been presented by [191]. Details about the Wadi Al−Khanaq dam, 15 km to the east of Madina, which was constructed during the period 661–679 AD, can be found in [192]. In modern times, the Ikrimah dam in Taif, built in 1956 with a capacity of 0.5 MCM, was the first dam to be constructed in Saudi Arabia. Based on an overview of the different groundwater recharge studies undertaken in Saudi Arabia (e.g., [102,135,193,194]), there has been a steady increase in dam construction in the kingdom over the last 70 years. For example, in 2006, the total number of dams increased to 230, with the height of the dams ranging from 3 m to 106 m [40]; by 2014, the number of completed dams had doubled and stood at 482, ranging across various provinces of the kingdom with a combined storage capacity of 2.08 BCM.

Currently, there are 563 dams in Saudi Arabia with a combined storage capacity of 2.59 BCM (Figure 9).

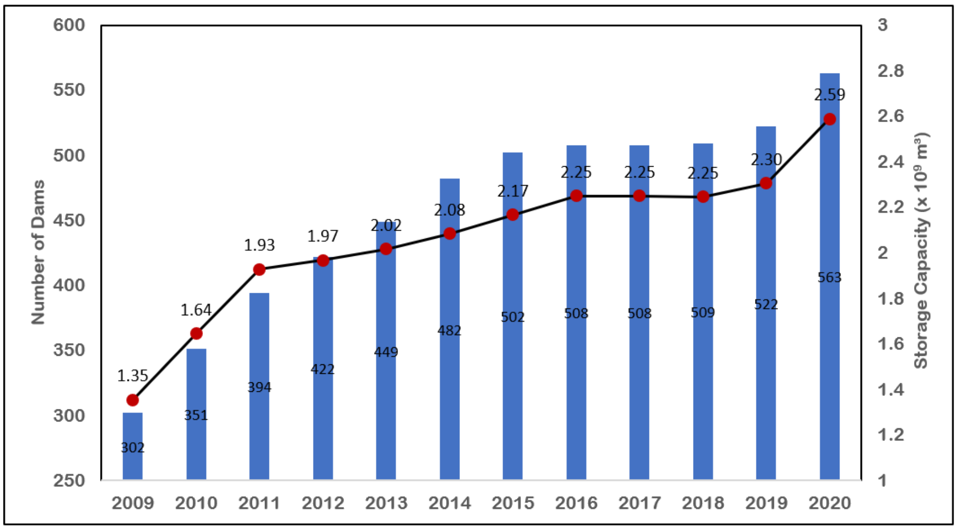
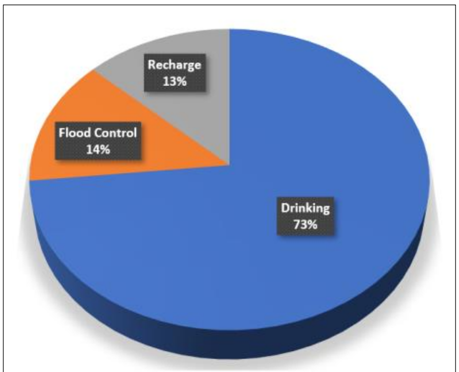


Figure 9. Existing dams in Saudi Arabia and their total capacity.

One hundred and seventeen of these dams are categorized as large dams (more than 15 m in height) per the International Commission on Large Dams (ICOLD) classification [114,195]. Figure 10 shows dam storage volume according to use. Though most dams in the kingdom were built with the purpose of groundwater recharge, dams built for drinking water supply have the maximum storage capacity. These dams are located within the Arabian Shield in western Saudi Arabia. The relatively high rainfall in this region, coupled with the rugged topography and presence of crystalline rocks, makes it ideal for the construction of large dams for potable water use. Figure 11 shows the distribution of the dams within the kingdom.



Purpose of Dam	Capacity (BCM)
Drinking	1.90
Flood Control	0.35
Recharge	0.34
Total Capacity of Dams	2.59

Figure 10. Types of dams in Saudi Arabia and their storage capacities.

Dams are built for different purposes such as flood control, drinking water supply, and groundwater recharge. Recharge dams are the sites for most of the MAR projects in Saudi Arabia [101,102,196]. Al-Turbak [150] showed that groundwater recharge could be enhanced by almost 35% by using artificial schemes. Feasibility studies of MAR projects have been carried out by several researchers. Lopez et al. (2015) investigated the potential of dune aquifers for MAR in western Saudi Arabia. They estimated the hydraulic conductivity of dunes with different empirical equations. However, significant deviations were found between predicted and measured hydraulic conductivities.

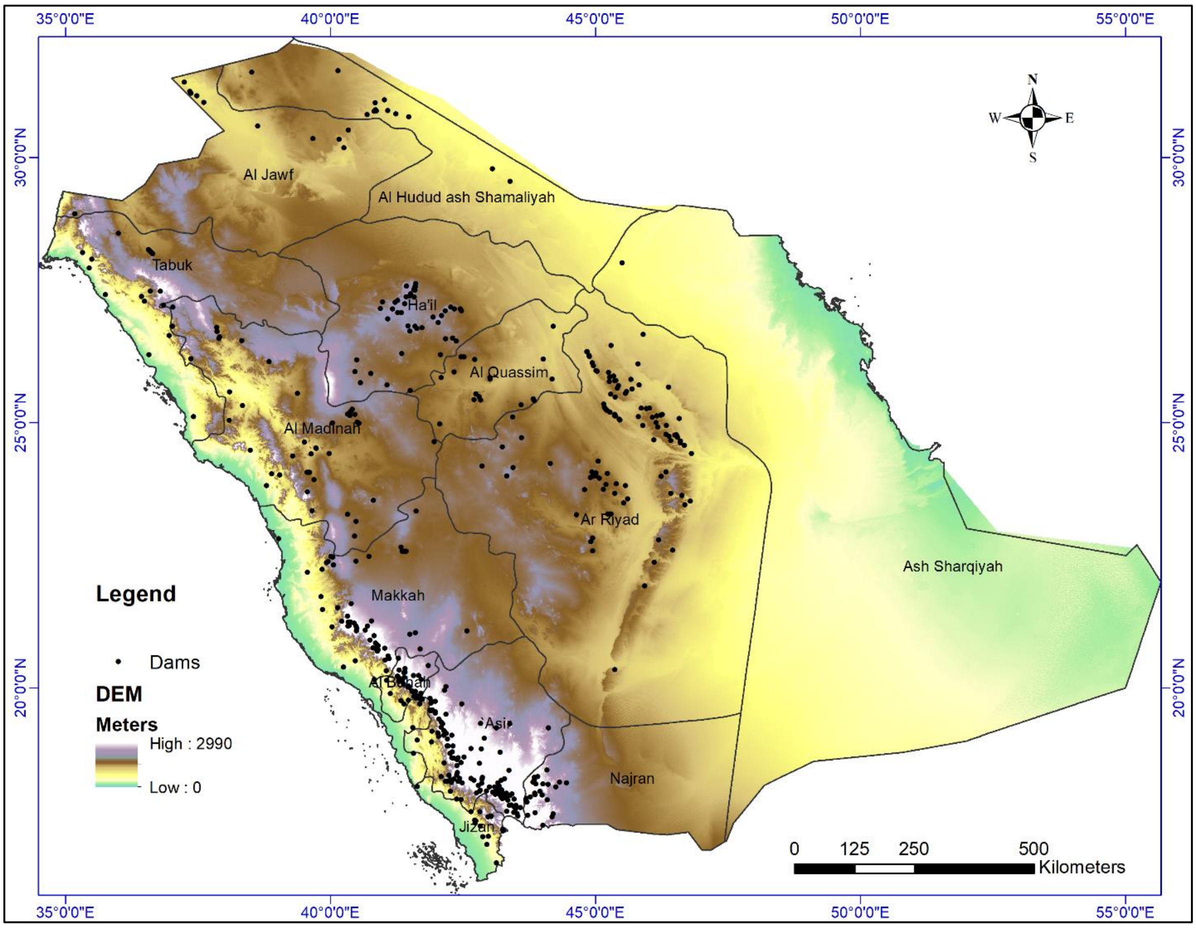


Figure 11. DEM and existing dams in Saudi Arabia.

The modified Beyers equation has low prediction error and was found to be suitable for estimating the K values of dune aquifers over large areas, thereby reducing the costs involved in the successful implementation of MAR projects. The use of treated wastewater in MAR as an option for meeting the groundwater demands of small rural communities in wadis was found to be economically viable compared to supplying desalinated water to these communities [103]. The coupling of recharge dams with aquifer storage and recovery wells on the downstream side was found to be effective in enhancing groundwater recharge [197].

Overall groundwater recharge is expected to be reduced by 5% to 15% (low confidence). In the long term, groundwater recharge may shrink, and inconsistent rainfall could trigger more recurrent and extended periods of low water levels. Considering a minimum recharge reduction of 5% and a maximum of 15%, the annual decrease in the groundwater recharge in the UAE may vary between 6.6 MCM and 20 MCM [125]. Due to the acceleration of seawater intrusion, the quality of fresh groundwater resources in coastal aquifers could also be affected.

The entire UAE remains typically dry throughout the year, with surface water runoff generated during rainy months only (Figure 12). Runoff generation fluctuates from one wadi to another depending on topography, hydrogeology, and headwater catchments [111]. Some climate models suggest the dry climate will continue, at least in some parts of the country, but some models predict a wetter climate in some regions, with higher rainfall that may be heavier, but less frequent [27]. UAE dams are mostly located in the mountainous area (Figure 13), where considerable runoff accumulation occurs. In 2015, the number of completed dams in the UAE was 115, with heights ranging from 2 to 33 m with an average of 8 m; lengths ranging from 22 to 2800 m with an average of 213 m; and total capacity ranging from 0.0019 to 18.5 MCM with an average of 0.5761 MCM. Historical records of the total accumulated water (Figure 14) indicate that the total accumulated water volume has ranged from 0.9 in the water year 1984–1985 to 32.6 MCM in the water year 2019/2020 [30,111]. Table 3 indicates that the augmentation of groundwater recharge due to the construction of more than 140 dams in the last forty years is in the range of 8–15 MCM/year [32,198–200]. In all UAE dams except for two, there are no MAR operation systems and recharge occurs only through rainwater percolation. As such, the implementation of MAR in the UAE would be of significant benefit for groundwater storage and sustainability.

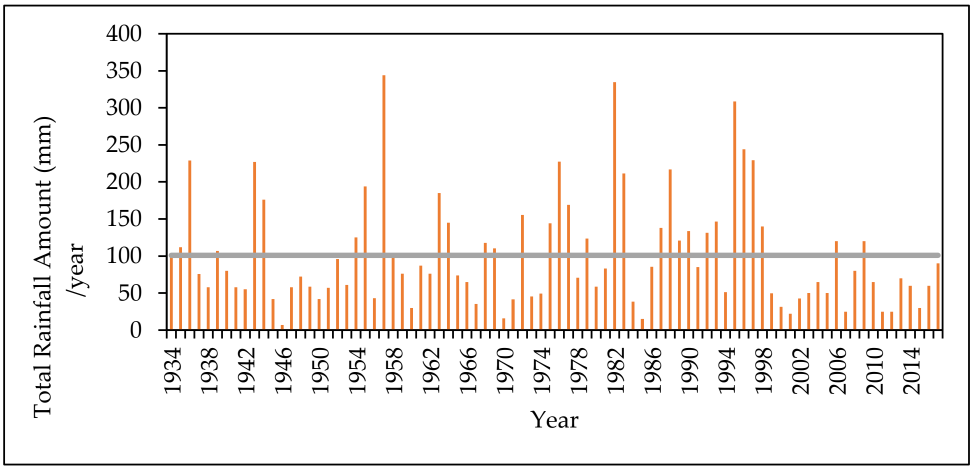


Figure 12. Total and average annual rainfall (mm).

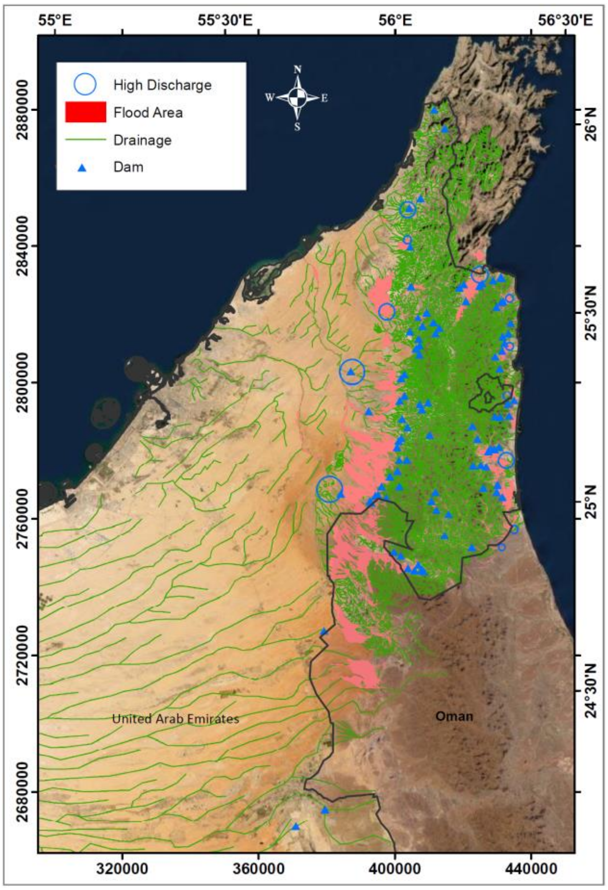


Figure 13. Drainage map and existing dams in the UAE.

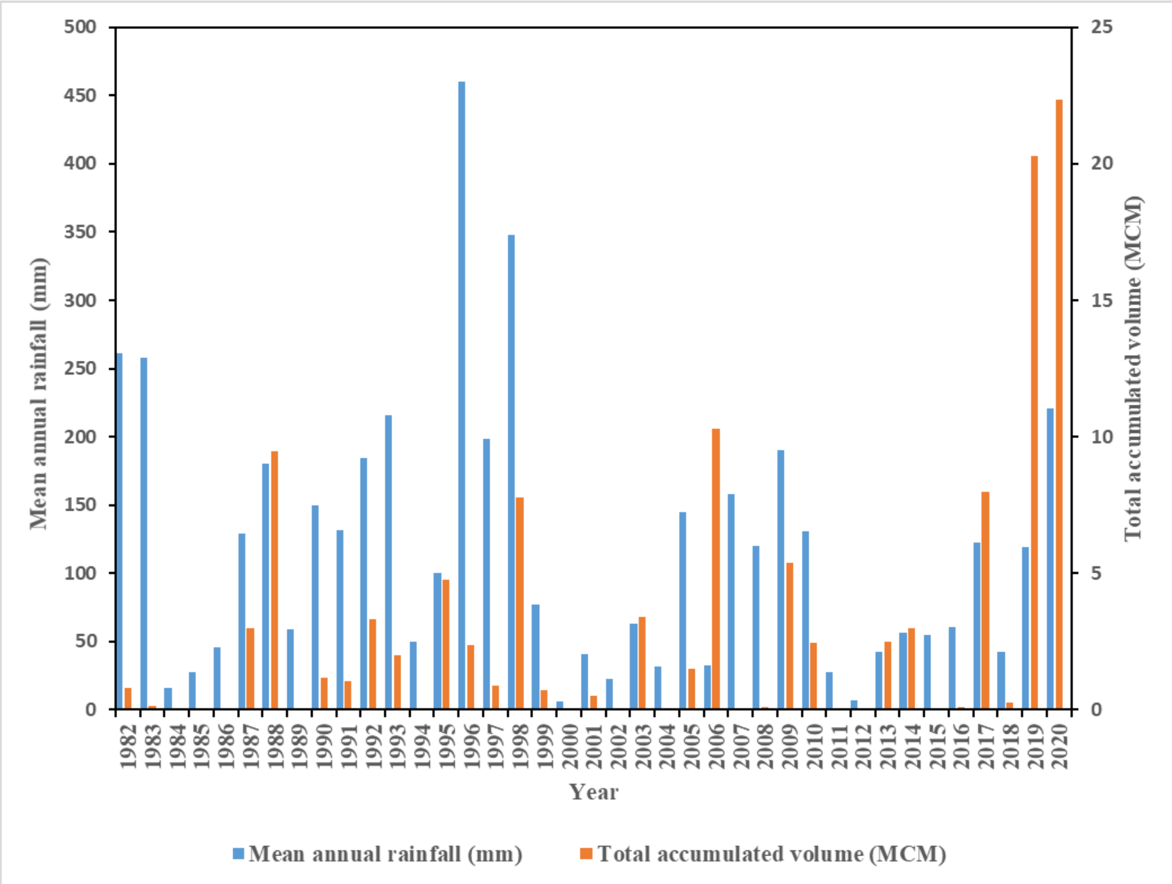


Figure 14. Total annual rainwater accumulated behind dams in the period 1982–2020.

6. Conclusions

Groundwater renewability in the region is less than 50% of extraction, and this problem is becoming more severe under the impacts of climate change. Several aquifers are transboundary; hence, the overexploitation of such aquifers will have a regional impact. Seawater intrusion in coastal aquifers is becoming commonplace in the region. Water demand in MENA countries varies based on population, living standards, cultivated lands and types of crops, irrigation practices, and the nature of industrial activities. With the predicted rising intensity of extreme precipitation events, which will lead to higher peaks of flash floods, depleted groundwater aquifers in the MENA region represent potential targets for MAR, especially in areas where suitable infrastructure, such as recharge dams, exists.

This analysis of the collected data indicates that, despite the considerable expenditure on dams, their contribution to global MAR capacity is limited (around 7%). In the MENA region, MAR is not yet considered a main groundwater management strategy. Proper plans for groundwater management with sufficient investment for implementing new MAR facilities and monitoring are needed.

More than 65% of the dams in the MENA region are installed in the main wadis for groundwater recharge. Water stored in dam reservoirs results in natural (indirect/non−intentional recharge) groundwater recharge. The storage capacity of the existing dams in the MENA region ranges from 98 to 132 BCM. This storage capacity is relatively small to have a significant impact on groundwater sustainability through MAR. However, up to 70% or more of the water accumulated in such dams can be used for groundwater recharge with MAR. An increase in MAR projects, coupled with water demand management, could be a feasible solution for groundwater restoration, particularly with the predicted increase in precipitation.

Sediment accumulation in dams reduces infiltration rates as well as the storage capacity of reservoirs. High evaporation rates lead to the loss of almost 70% of the accumulated water. Except for aquifer storage and recovery (ASR), direct recharge is not common in the region. Therefore, dam operation and management systems should be modified to incorporate proper MAR techniques to increase recharge efficiency and improve groundwater renewability. In MENA countries, MAR can be taken into account in reservoir design in order to limit losses by evaporation.

Major cities in the region are situated in coastal areas, and the main infrastructure is in low−lying lands. An increase in seawater temperature due to climate change and the rising frequency of extreme weather events will lead to higher peaks of flash floods and storm surges, and a greater risk of coastal disasters. The predicted extreme rainfall events in the region may cause flooding due to urbanization. In such situations, rainwater harvesting, and MAR represent feasible options to mitigate floods and conserve surface water. MAR and rainwater harvesting systems would substantially improve groundwater recharge. MAR is frequently used in large cities in Europe (Berlin, Paris suburbs, Lyon, Dunkirk, Geneva) to regulate stormwater by capturing surface runoff in infiltration basins.

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Data Availability Statement: The data used in this study is not publicly available and therefore can not be share on some repositories. However, some part of the data can be acquired upon reasonable request from the corresponding author.

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