Arabian Journal for Science and Engineering (2021) 46:1–15
https://doi.org/10.1007/s13369-020-05060-x

REVIEW–EARTH SCIENCES

Managed Aquifer Recharge in the Gulf Countries: A Review and Selection Criteria

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Received: 3 May 2020 / Accepted: 23 October 2020 / Published online: 6 November 2020

Abstract
The Gulf Cooperation Council (GCC) countries are arid with very limited availability of water resources. In recent years, these countries have started an intensive program to increase the storage of groundwater through various techniques of managed aquifer recharge (MAR). Water consisting of varying quantity and quality (derived from various sources) are used via MAR techniques to increase the groundwater storage and, if possible to enhance its quality, respectively. This paper presents a review of the MAR techniques practiced in GCC countries including the implementation strategies of the different structures. Generally, seven MAR techniques are utilized in GCC countries including dams, aquifer storage and recovery (ASR) technique, aquifer storage transfer and recovery (ASTR) technique, ponds, soil aquifer treatment (SAT) technique, rooftop rainwater harvesting, and Karez/Ain system. Results indicated that ASR using excess desalinated water or treated sewage effluent (TSE) is the most used MAR technique in GCC countries, followed by the use of ASTR, dams, and ponds. Based on this review, twelve different selection criteria have been developed for GCC countries for better MAR practice in the future.

Keywords Groundwater recharge · Recharge structures · Wastewater treatment · Ranking · Aquifer storage and recovery · Check dam

1 Introduction

The wealth of a country mainly depends on the availability of its natural resources. Gulf Cooperation Council (GCC) is an economic alliance of six Middle Eastern countries namely Kuwait, Saudi Arabia, Oman, Qatar, Bahrain, and the United Arab Emirates. These countries of the GCC are rich in oil and gas reserves and their economy depends on the export of oil. Almost 40% of the world's oil and gas market is exclusively covered by GCC countries. However, in contrast, the annual renewable water resources in these countries are only 500 m^3 per capita per year when compared with the global average of 6000 m^3 per capita per year. The average annual rainfall ranges from 70 to 130 mm except in mountain ranges of Western Saudi Arabia and Southern Oman where the rainfall is more than 500 mm [1]. While scanty rainfall is the main reason for less availability of water, significant and rapid population growth has accelerated depletion of water resources. The rate of increase in population during the period between 1970 and 2025 for the GCC countries are as follows: Kuwait (0.7 to 4.7 million), Saudi Arabia (5.7 to 40.9 million), Oman (0.7 to 4.9 million), Qatar (0.1 to 0.8 million), Bahrain (0.1 to 0.2 million), and the United Arab Emirates (0.2 to 4.5 million) [2]. These countries have made considerable progress in meeting the water demands of the exponentially increasing population. However, it appears that the scarcity of water resources has imposed restrictions on their development [3]. The water demand of the GCC countries is met by various conventional (rainfall recharge, falajes, springs, and flash floods) and non-conventional water resources (desalinated water, treated wastewater, and artificial water harvesting) [4]. Since rainfall is suboptimal, water supply from conventional sources is very meager. Therefore, the growing water demand among GCC countries is completely met by non-conventional water resources. Various desalination techniques are used in the Gulf region such as single and dual-purpose multistage flash, single-purpose and coproduction reverse osmosis, and single-purpose and coproduction vapor compression. The dual-purpose multi-

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stage flash technique is the most commonly used desalination technique due to its commercial viability and relatively low unit cost [3]. Ghaffour et al. [5] have suggested that desalination is no longer considered to be a nonconventional method, as 100% of water supply in big cities of GCC countries is met by desalinated water. However, desalination techniques are economically and technically viable only if they are operated at their full capacity. Besides, desalination plants have a limited life of 20 years and they are highly vulnerable to accidents and shutdowns. The primary energy source in GCC countries to run the desalination plants are the gas associated with oil production. Any reduction in oil production due to economic, political or market forces causes a shortfall in gas supplies used for power/distillation and industrial feedstock [5, 6]. Due to the Gulf war and the uncertainty of oil prices, the expansions in the construction of desalination plants were not economically feasible [7]. As per International Energy Agency 2020, due to the recent outbreak of the pandemic caused by the coronavirus COVID 19, the use of oil all over the world has dropped considerably and the price of a barrel has dropped down to US$ 3, and hence running gas-based desalination plants is very difficult. Another source of non-conventional water resources of GCC countries is the use of treated wastewater. Though there are many sewage and wastewater treatment plants in the Arab region, the use of treated wastewater does not appeal to people. Wastewater reuse must consider the socio-economic factors such as poverty, health, and lifestyle of any country [8]. This technology has got a very promising future for GCC countries due to its multiple and beneficial use [9, 10]. There are other suggested sources of water such as towed icebergs and cloud-seeding. However, they are unaffordable due to commercial and practical applicability [6]. Therefore, careful conservation and efficient use of groundwater resources using different managed aquifer recharge (MAR) methods are essential for GCC countries [11, 12]. Several research studies have been carried out to conserve the water resources in the arid Arab region. Since the agricultural sector is the biggest consumer of water (88%) in GCC countries, Abdo et al. [13] demonstrated the high potential for water conservation in this sector. To ensure minimum usage of water for agriculture, it is necessary to adopt advanced irrigation methods and enhanced farming technologies suitable for arid regions [9]. Kimrey [14] suggested that water spreading and well injection techniques are the best methods to replenish and manage aquifers in strategic locations like the Arab region. Abdulrazzak [15] indicated that the problems related to water resources in the GCC countries are not only due to physical aspects of intermittent or no surface runoff, depletion of deep fossil groundwater, overconsumption, saltwater intrusion, and pollution of shallow aquifers but also due to lack of measures to increase water use efficiency. Hajeeh [16]; Zaharani et al. [17]; Dawoud and Sallam [18]; Mahmoud and Abdallh [9] have emphasized that along with water conservation, strict law to control drilling of unplanned groundwater wells, regular monitoring of the implemented projects, reducing subsidies, economic analysis, policies and programs for groundwater development and further water literacy of the general public have to be implemented for better water management. To facilitate the implementation of these programs, strong political support and adequate capacity (human, institutional, and enabling environment) are essential [13]. The study carried out to review various MAR methods was conducted considering the above issues related to water resources. Other objectives of this study were to rank the methods based on multiple criteria and to suggest the most feasible methods for GCC countries.

1.1 Managed Aquifer Recharge (MAR)

MAR is a purposeful recharge of water into aquifers for subsequent recovery. Advantages of MAR include secured water supply, improved water quality, mitigation of seawater intrusion, reduction in evaporation rate, and mitigation of flood damage [19]. Different methods of MAR techniques that are in practice include aquifer storage and recovery (ASR), aquifer storage transfer and recovery (ASTR), soil aquifer treatment (SAT), percolation pond, infiltration galleries, check dam, river bank filtration (RBF), and rain water harvesting (RWH), dry wells, dune filtration, underground dams, sand dams [19]. The criteria for adopting a particular method of MAR depend on the land use, geological conditions (topography, drainage, type of formation, rocks), aquifer types (confined, unconfined and semi-confined), and water quality [20–22]. Water from different sources (stormwater, reclaimed water, mains water, desalinated seawater, rainwater, and groundwater from other aquifers) of different quality can be used for MAR with appropriate pretreatment before recharge. However, the quality of water used for MAR should be within the standards suggested. Among the various MAR techniques, a few techniques are practiced in GCC countries to augment the groundwater recharge. A complete review of these MAR methods practiced in GCC countries has helped to understand the efficiency of these methods in coping with the water resources problem of the arid region.

2 Study Area

The study area comprises of the six GCC countries. GCC countries cover an area of about 2,557,470 km^2 and 85% (Al-Rashed and Sherif [7]) of the land belongs to Saudi Arabia (Fig. 1).

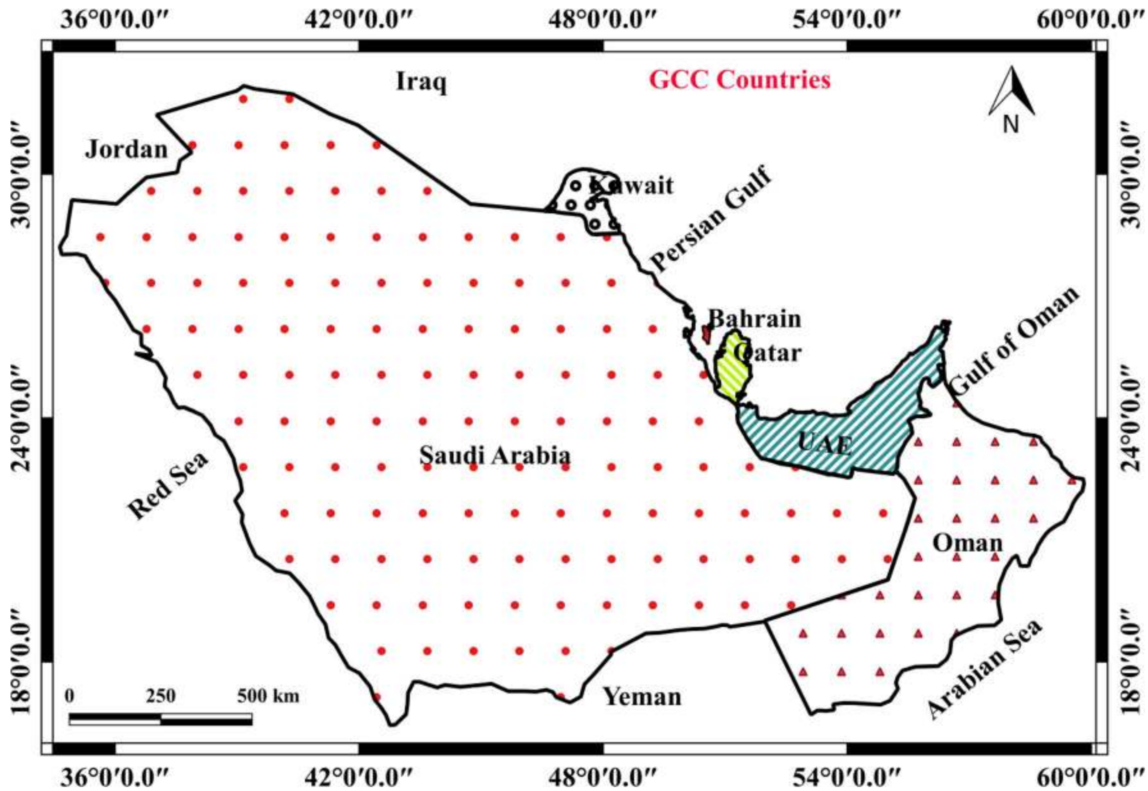

Fig. 1 Location of GCC countries

The main aquifer system consists of Ummer Radhuma formation which is overlain by the younger formation of Rus, Dammam, and Neogene of similar gradients aquifer [6]. By geomorphological means, GCC countries are mostly covered by deserts. The main topographical features include Al Hajar and Asir Mountain in Oman and Saudi Arabia, respectively. The western part of Saudi Arabia is composed of igneous and metamorphic rock, whereas the Eastern part of Saudi Arabia, as well as United Arab Emirates, Qatar, Bahrain, Kuwait is composed of a stable shelf. Oman is covered by Tethyan Geosyncline [7]. The scanty rainfall pattern resulted in the absence of perennial lakes and rivers in these countries. Sometimes rainfall occurs with high intensity in short duration which causes flash floods [23, 24].

Renewable groundwater occurs in the shallow aquifers which are recharged by the rainfall and runoff. The groundwater sources for agriculture activities are mostly drawn from non-renewable fossil water from the deep aquifer. Similarly, over-exploitation of groundwater for various developmental activities along the coastal region has led to seawater intrusion. Hydro-geochemically, the groundwater is dominated by sodium and chloride or sulfate. The groundwater in the Sabkhah region which is a flat area lying between the desert and coastal area is strongly influenced by evaporates [6].

3 Methodology

The optimum way to conserve rainfall in the arid and semi-arid region is through groundwater recharge. Hence, a detailed review of the literature was carried out to identify the recharge efficiency of different MAR methods practiced in GCC countries. Though there were many MAR structures adopted for GCC countries, the implementation of the most efficient structure can be helpful to increase the groundwater potential. Hence, these reviews led to identify the different selection criteria to rank the best MAR structure to be adopted in GCC countries. Twelve selection criteria were carefully identified by this study. The selection procedure includes the use of a rating scale from 1 to 8 based on the effectiveness and feasibility of the chosen criteria. Finally, the hierarchy of the structures was identified based on the total scales allotted to each recharge structures.

4 Results and discussion

Seven types of MAR methods were practiced in GCC countries to augment groundwater resources. These include dams, aquifer storage, and recovery (ASR), aquifer storage transfer and recovery (ASTR), pond, soil aquifer treatment (SAT), rooftop rainwater harvesting, and Karez/Ain system.

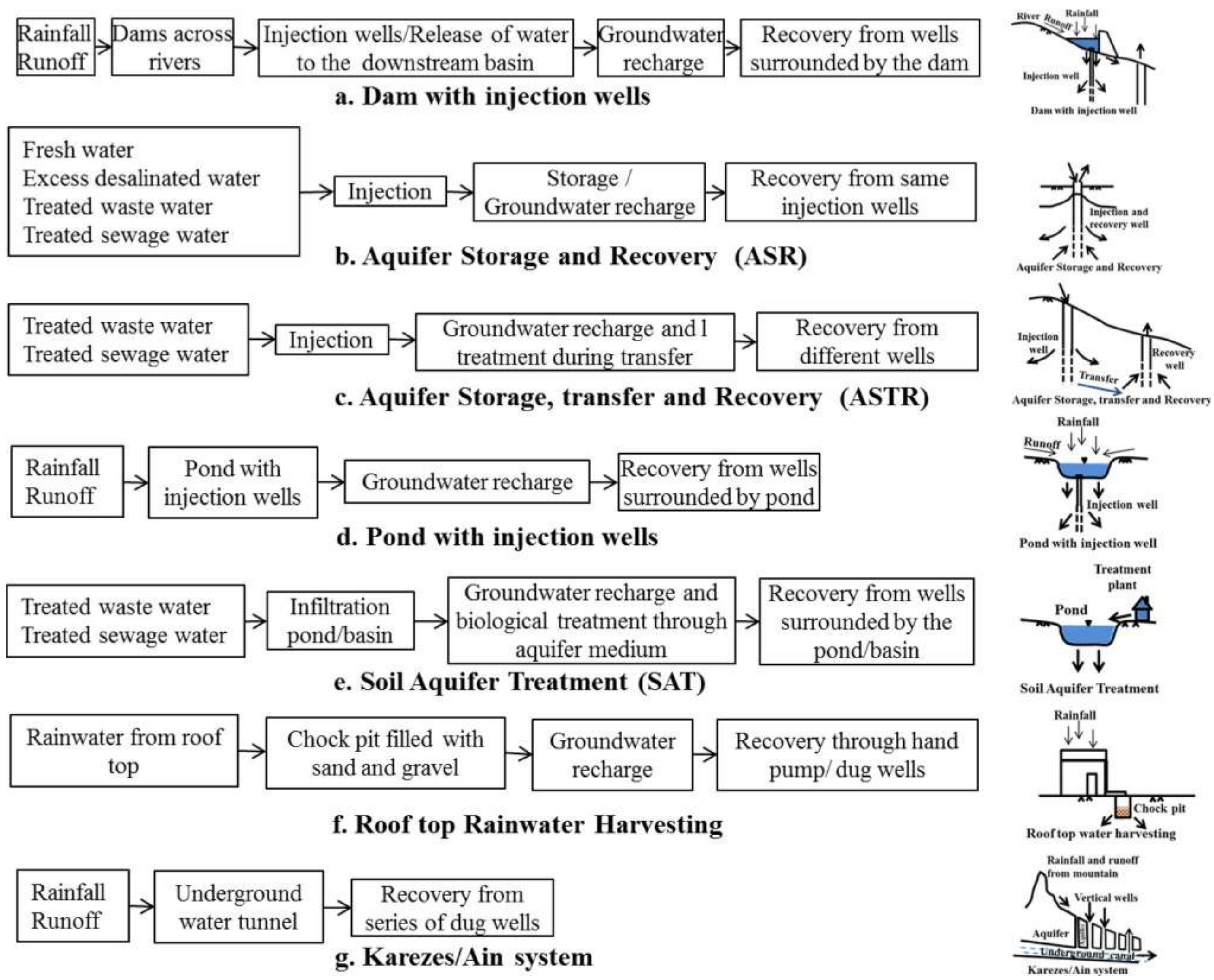

Fig. 2 Schematic representation of different MAR structures adopted in GCC countries

The sources of recharge water and recharge techniques are schematically represented in Fig. 2. The efficiency of these structures in improving the groundwater potential and selection of the best MAR structures are discussed in the following sections.

4.1 Dam

Dams are the most common methods of MAR structure found in all GCC countries. Dams are constructed perpendicular to the river. The length of the dam depends on the width of the river bed and the height depends on the purpose and available runoff into the river. Water stored in the dam is allowed to recharge groundwater or diverted through channels for irrigation purposes. Adequate research on technical aspects has been carried out to assess the impact of the dam to improve groundwater potential in GCC countries. These studies include assessment of the impact of a dam on groundwater recharge without and with injection wells, impact on groundwater quality, and control on seawater intrusion. Apart from an impact assessment, a few studies focused on the management of water, harvested by the dam. Assessment of efficiency of the dam without injections wells by Chowdhury and Al-Zahrani [25] indicated that 302 dams in Saudi Arabia were built with the total storage capacity of about 1.4 billion cubic meters of surface runoff annually. Among these 302 dams, 275 dams are efficient in recharging about 992.7 m^3 of water per year. Recharge assessment based on isotopic signatures indicated that 20 to 40% of water stored by the Wurrayah, Tawyeen Dams in UAE was successfully recharged into the aquifer [26].

To enhance the groundwater recharge from the dam, injection wells are installed upstream of the dam. Al-Othman [27] attempted to identify the recharge efficiency of the dam with and without considering the injection wells using groundwater modeling. After the construction of injection wells in the upstream of the dam, the infiltration has increased from 2.1 to 2.33 million m^3. Apart from recharge enhancement the injection wells also reduce 48% of evaporation from Hautat Bani Tamim Dam, Saudi Arabia [27]. Alrehaili and Hussein [28] found that with the injection wells in the dam, 80% and 86% of the water recharged during 2005 and 2007, respectively, at Alilb Dam in Diriyah, Riyadh, Saudi Arabia. The application of the injection wells et al. Ghat Dam, situated in Riyadh, Saudi Arabia has resulted in speeding the recharge to groundwater in the area downstream of the dam. The water level has raised by 11.6 m in one of the downstream wells 14 days after the beginning of the artificial recharge process and the total dissolved salts have decreased from 2752 to 1536 ppm [29].The increase in recharge by injection wells depends on the number and space between them. If the injection wells are located closer to each other, the intersection of the radius of influences of the wells reduces the recharge capacity [27–30]. Mohamed [31] investigated the optimum spacing between the injection wells and the number of wells to be constructed to achieve maximum recharge. The study concluded that the construction of three wells in a row gives more recharge than that of three wells at the vertices of the triangle. Another combination such as five wells at the vertices and center of the square gives a slight increase in the recharge rate than four wells only at the corners. Groundwater modeling by Missimer et al. [32] indicated that the width of the Wadi channel and the spacing between injection wells significantly impact the potential recharge rate. The results suggested that more wells at closer distances reduce the recharging capacity. Hence, care should be taken while using multi-well systems except where the channel is very wide or the downstream spacing of the wells is greater than about 2 km.

MAR structures have mainly focused to improve the groundwater level rather than groundwater quality. Only a few studies have focused on the quality of recharged water and its impact on reducing seawater intrusion in GCC countries. Sen et al. [29] have confirmed the improvement of groundwater quality due to the construction of MAR in Saudi Arabia. Bajjali [33] has assessed that continuous seepage of fresh water into shallow aquifers dilutes groundwater salinity which results in mitigation of seawater intrusion. After the construction of dams in Ma'awil, Samail, and Sahalnawat watersheds, approximately 57%, 19%, and 31% of the area were showing noticeable improvement in groundwater quality [33]. The construction of the dam at AlKhod, Oman region has reduced the salinity and improved the groundwater level near the coastal regions [34].

Though MAR structures are used to harvest rainwater, only the efficient management of harvested water helps to obtain maximum benefit from these structures. The recharge efficiency of the dam mainly depends on the geology of the reservoir, the thickness of the alluvial aquifer within and upstream of the reservoir, the design of the dam, and the ability of the reservoir to transmit water into the adjacent aquifer [32]. If the structures are constructed without hydrogeological investigations, the water infiltrated from the dam will not reach the demand area. In such conditions, Al-Turbak [35] has suggested that releasing the water into the Wadi is better for suitable water management. Contrary to the established belief that this method of releasing water is poor, Al-Turbak [35] and Al-Muttair et al. [36] have proved that 82% to 94.5% of recharge was absorbed by the soil in Saudi Arabia. Five alternative plans were applied by Al-Muttair et al. [36] to assess the recharge efficiency of the dams. These include not releasing the water from the dam, the release of reservoir water to the downstream channel, release to a downstream basin, removal of silt from the reservoir bed, and scratching of the reservoir bed. Among these methods, removal of silt from the reservoir bed (if silt deposits are not too deep), scratching of the reservoir bed was considered to be the best alternative to increase the efficiency of the recharge from the dam [36]. Based on the infiltration tests in Wadi Ahin dam, Oman, Haimerl [37]; Haimerl et al. [38] have identified that the efficiency of groundwater recharge from dam depends upon the moisture content of the soil, water level of the surface flow, and the time of infiltration. When the water level is very high, the release of reservoir water to the downstream channel would be considered as the best management plan. A large number of abandoned wells are replenished through this method of recharge in the alluvial area [32]. Sendil et al. [39] have indicated that maximum efficiency from the dam cannot be achieved with a particular water management scheme due to the high rate of evaporation and variable geological conditions in the arid region. Summary of studies carried out to assess the efficiency of the dam as recharge structures are given in Table 1.

Many recharge studies were carried out in Saudi Arabia followed by UAE and Oman. There were many dams constructed in the GCC countries among which the dams in Saudi Arabia were prioritized by Jaafar [40] as high, low, and not feasible. The high, low, and not feasible prioritization was based on the reliability for domestic and irrigation purpose, yield, and cost. High priority dams were feasible for less than 4% of the total number (about 394) of dams, low priority dams amounted to 23% feasible of the total number, and remaining were found to be not feasible.

4.2 Aquifer Storage and Recovery (ASR)

ASR is a technology that serves primarily to store water in an aquifer through injection wells during periods of abundance and withdraw it during times of need from the same well. Water treatment is not a primary goal of ASR. Water supply from the desalination plant in GCC countries serves domestic, industrial, and agricultural needs. Water require-

Table 1 The efficiency of the dam as a recharge structure

Authors	Location	Structure	Findings
Al-Turbak and Al-Muttair [77]	Saudi Arabia	80 dams	82% and 94.5% of water stored in the two reservoirs was taken into the soil but more time is taken to reach the water table
Al-Turbak [35]	Riyadh, Saudi Arabia	Al-Amalih	Releasing the water from the dam is the best water management when wells are located away from the dam
Al- Muttair et al. [36]	Saudi Arabia	Malham and AI-Amalih recharge dam	Removal of silt from the reservoir bed and scratching of the reservoir bed will increase the efficiency
Ekaabi [26]	UAE	Wurrayah, Tawyeen Dams	20 to 40% of recharge due to dams
Al-Othman [27]	Saudi Arabia	HautatBaniTamim Dam	After the construction of recharge wells in the upstream of the dam the infiltration is increased by 11% and evaporation is reduced by 48.3%
Chowdhury and Al-Zahrani [25]	Saudi Arabia	275dams	275 dams recharge about 992.7 MCM/year
Alrehaili and Hussein [28]	Saudi Arabia	Alilb Dam with injection wells	80% and 86% of the rainwater was found to be available for artificial recharge
Bajjali [33]	Oman	Ma'awil, Al Kabir Dams, Tanuf Dam, Sur Dam	19% to 57% of the watershed area improved by freshwater (TDS < 1000)
Abdalla and Al-Rawahi [34]	Oman	AlKhod dam	40–60% of the annual well's abstraction in the area is contributed from MAR which also reduced the salinity
Mohamed [31]	Saudi Arabia	El-Ghat dam, Saudi Arabia	Solution for water shortage and flooding problem in urban area
Missimer et al. [32]	Saudi Arabia	Murwani Dam	The recharge rate could be 400,000 m^3/day using 100 wells. Restores the abandoned wells and maintain the viability of the alluvial aquifer systems
Jaafar [40]	Saudi Arabia	Dam	High priority dams were feasible less than 4% of the total number of dams, and fewer priority dams amounted to 23% feasible, with the remaining found to be not feasible

ment from desalinated water is not uniform throughout the year, it varies season to season, but production from the desalination plant is almost uniform in a year. Khezri [41] has evaluated the efficiency of the ASR system in the Liwa area, UAE under various operational schemes. High efficiency was observed with a long time of storage with multiple cycles of operation or additional recharge storage or combination of both [42–44]. A report by Menche [45] has indicated that the ASR pilot project at Liwa could meet the water supply of Abu Dhabi for up to three months at 40 million imperial gallons per day (181,800 m^3/d). On the other hand, most GCC countries can utilize the ground reserves for 24 h except in Saudi Arabia and Kuwait where the ground reserves can be utilized for three to four days. A case study in Abu Dhabi by Schlumberger water services [46] on ASR revealed that 88% of water was efficiently recovered with a storage capacity of four billion imperial gallons (18,184,360 m^3). Also, 100% recovery was possible with groundwater quality (total dissolved solids of 250 ppm to 580 ppm) meeting the recommended limits of international drinking water standards. A pilot ASR test at the Nizwa unconfined aquifer found that aquifers in UAE were highly suitable to bear 400 million imperial gallons (1,818,436 m^3) [47]. According to Kimrey [48], ASR is one of the feasible methods of alternative water supply to irrigation in the Ummer Radhuma aquifer, Qatar. Supply from ASR was considered as standby for irrigation with stabilization or retardation of deterioration in the quality of groundwater. Missimer et al. [49] have considered that ASR systems are feasible only to meet peak day demands and short-term operational needs. In such conditions, Missimer et al. [49] and Almulla et al. [50] have suggested that the strategic ASR systems must be developed to substantially reduce the water security risk and provide a higher degree of safety.

The other non-conventional source of water supply in GCC countries is the reuse of wastewater after certain treatments. ASR technique is also used to replenish the depleted aquifer using treated wastewater. The treated wastewater is being injected and recovered from the alluvial aquifer of western Wadi Qidayd, Saudi Arabia. Quality of recovered wastewater from the aquifer is based on the on quality of ambient groundwater, quality of the contaminant present in the effluent, and its level of treatment and dilution and aquifer through flow [18]. AlRukaibi and McKinney [51] indicated that the efficiency of the ASR increases with a decrease in time between the stopping of injection and the start of a recovery operation. ASR operation at the Kabd area in Kuwait involved 9 months injection followed by 3 months of recovery. The total daily recovery was 100,000 m^3/day from 8 ASR wells with a 77.42% recovery efficiency [52]. ASR may not be feasible in all locations; their efficiency varies based on the type of aquifer. Mukhopadhyay et al. [53] have assessed the technical feasibility of ASR using untreated wastewater in the carbonate Dammam formation and the clastic Kuwait group aquifers. In the absence of any pretreatment of injection water, the experiment suggested that the problem of clogging was more severe for the clastic Kuwait group due to low hydraulic conductivity and low dispersivity. This study has revealed that Dammam formation is more suitable for ASR.

Missimer et al. [54] have made a cost comparison of water supplied from wastewater treatment and desalinated water. The cost per cubic meter of water supplied from wastewater treatment by ASR/MAR and desalinated water was US$0–0.50/$m^3$ and US$2–5/$m^3$, respectively. Though the water supplied from the wastewater treatment plant is cheaper than desalinated water, the feasibility of these two technically viable options depends upon both costs and social acceptance. The use of wastewater for domestic purposes still has restrictions on the user's mind and hence broad awareness needs to be created among the user. Hutchinson [55] has suggested the procedure to be followed while injecting desalinated water for ASR, which includes the location of ASR site along the desalination pipe, capacity of the aquifer to accept 1000 m^3/d of water, quality of native groundwater (fresh or slightly brackish and TDS less than 2000 mg/L), infrastructure for continuous monitoring of water-level and water-quality in observation wells and recovery wells. A summary of studies carried out using the ASR method of MAR is given in Table 2.

4.3 Aquifer Storage Transfer and Recovery (ASTR)/Aquifer Recharge and Recovery (ARR)

The use of shallow aquifer to treat and store impaired-quality of influent water is termed as ASTR/ARR. The purpose of the study carried out by Missimer et al. [56] is to demonstrate the feasibility of using wadis for ARR with the explicit goals of treating and restoring wastewater supplies in the Kingdom of Saudi Arabia. A major advantage of using Wadi aquifers for ARR is that the natural biological treatment processes occur with a very low expenditure of energy and a low carbon footprint (in aquifer natural processes and gravity flow). The use of reclaimed water by the ASTR method would reduce demands on fresh groundwater resources and other alternative water supplies, such as expensive and energy-intensive seawater desalination systems. However, Wadi aquifers present some design challenges. This system must be designed according to natural processes acting within the Wadi to allow reuse of resources [57–59]. Lopez et al. [60] have attempted to use water stored in dams as a source of water for ASTR in the dune fields of Western Saudi Arabia. The study has suggested the concept of linking a Wadi dam with a downstream recovery system. This concept is particularly applicable to systems in which the rock bounding reservoir has poor permeability which does not allow significant horizontal recharge. In Oman, the effluent from Salalah central sewage treatment plant was recharged through several tube wells located parallel to the coast. This design has helped to reduce the seawater intrusion from 3.4 to 2.7 km and also increased the groundwater level in the vicinity of the injection wells [61].

4.4 Pond with Injection Wells

Ponds are surface water bodies either natural or excavated artificially without any major investment. The rainwater stored by the pond is infiltrated into the aquifer, thereby improving groundwater level and quality. The major disadvantages of the pond as a recharge structure in GCC countries are high evaporation rates and siltation. Ghazaw [62] has focused on the optimal design of facilities for controlling, storing, and reusing flood water in Buraydah pond, Qassim, Saudi Arabia. This study suggested that the ponds must be constructed along with the technically designed injection wells with a suitable filter and silt removal. Research carried out on the efficiencies of the pond in Qassim, Saudi Arabia indicated that the pond with the capacity of 280,000 m^3 with one injection well was able to recharge 200,000 m^3 of water per year after evaporation and seepage losses [62]. Sherif et al. [63] have assessed the groundwater recharge in Wadi Tawiyean, UAE by groundwater modeling. Initially, the model was simulated without the pond and the estimated recharge was 1,247,716 m^3, whereas the model simulated with the pond (pond area 0.169 km^2 with 8 m water level) indicated a recharge of 4,216,428 m^3 in Wadi Tawiyean. The review on the pond as a recharge structure indicated that the percolation ponds should be constructed on permeable terrain with the injection wells to get the maximum benefit from this structure.

Table 2 The efficiency of ASR as a recharge structure

Authors	Location	Findings
AlRukaibi and McKinney [51]	Kuwait	TDS of recovered water is 1500 ppm and evaporation of surface water is reduced
AlRukaibi and McKinney [52]	Kuwait	The total daily recovery was 100,000 m^3/d from 8 ASR wells with a 77.42% recovery efficiency
Missimer et al. [54]	Saudi Arabia	Cost of ASR water is \$0–0.50/m^3 less than desalinated water (\$2–5/m^3)
Khezri [41]	Liwa, UAE	High recovery efficiency during multiple cycle operation or additional recharge storage
SEWA [47]	Nizwa, UAE	400 MIG of water could be stored
Dawoud et al. [78]	Abu Dhabi, UAE	Factors affecting quality of recovered water during ASR
Lopez et al. [60]	Western Saudi Arabia	Concept of linking a Wadi dam with downstream ASR system is capable of storing 1 Mm^3 of stormwater
Missimer et al. [32]	GCC	The requirement of strategic ASR systems
Menche [45]	Liwa, UAE	With 100% recover, the water quality is within the drinking standards
Almulla et al. [50]	Sharjah, UAE	ASR of 280 MIGs in Sharja can cover up for a minimum of 25% of any major crisis that might occur
Schlumberger water services [46]	Abu Dhabi, UAE	88% of water was efficiently recovered with a storage capacity of four billion imperial gallons
Kimrey [48]	Qatar	Stabilized quality of groundwater for irrigation
Mukhopadhyay et al. [53]	Kuwait	ASR is best suitable in Dammam aquifer and it is moderately feasible in Kuwait group due to low hydraulic conductivity and low dispersivity

4.5 Soil Aquifer Treatment (SAT)

SAT is a method of MAR in which the primary treated wastewater or tertiary treated sewage effluent (TSE) is allowed to infiltrate from a pond. During the passage through an unsaturated aquifer medium, the microorganism present in the wastewater is substantially removed. Changes in geochemistry and the quality of recovered water depend upon the types of geological materials and distance of the pumping well from the pond [64]. This type of treatment is uncommon in GCC countries, only very limited attempts have been carried out to assess the efficiency of the SAT. It is estimated that a total of 16,790 m^3 of tertiary treated wastewater was released to the basins of Sulaibiya, Kuwait and only about 8000 m^3 out of 16,790 m^3 has reached the groundwater table. It is also found that the quality of the water after the SAT has improved except for nitrate content [65]. MAR using TSE represented a promising and potential option in the management of water resources in the Kingdom of Bahrain. It increased the groundwater level and reduced the salinity [66, 67]. However, Ahmed et al. [66] have suggested that before implementing this method of MAR proper attention must be given to health, environmental, ecological, aesthetics, financial, economic, political, and social losses.

4.6 Rooftop Rainwater Harvesting

Rainwater falling on the rooftop is diverted through pipes into a sump or soak pit filled with sand and gravel. The diverted water recharges the groundwater level and results in the improvement of both quality and quantity. Rooftop harvesting is considered to be the best urban water management scheme which compensates for some quantity of potable water demand of the city. Studies on climatic change in GCC countries indicated the increase in annual rainfall with high intensity in the future [68, 69]. Rooftop rainwater harvesting may cause more damage to buildings in the cities and urban centers since they were designed mostly based on dry weather in Saudi Arabia and other GCC countries. Hence, rainwater harvesting was considered to be one of the reasonable solutions for water shortage and flooding problems in urban areas [69, 70].Rainwater management was considered as the best adaptation strategy to combat extreme climate variability in the Saudi region [71]. Guizani [72] has estimated that 7.3 m^3 per 100 m^2 of rainwater can be harvested in several cities of Saudi Arabia.

4.7 Karezes/Ain System

The Karez/Ain system is described as the series of vertically dug wells linked by an underground water canal to receive rainwater from nearby mountains and catchment. The importance of revitalization of Karezes/Ain recharge structures was described by Hussain et al. [73]. As the water loss through evaporation is less from Karezes, water is available throughout the year, irrespective of the season. Karezes system of recharge is a traditional method of MAR structure, which is not practiced in the present scenario as it requires regular

Table 3 The efficiency of the pond, rooftop rainwater harvesting, SAT, Karezes/Ain system

Authors	Location	Findings
Pond		
Sherif et al. [63]	WadiTawiyean, UAE	Increased the groundwater recharge by 70%
Rooftop rainwater harvesting		
Amin et al. [71]	Saudi Arabia	Flood control in urban regions
Guizani [72]	Saudi Arabia	7.3 m^3 per 100 m^2 of rainwater can be harvested
Soil Aquifer Treatment (SAT)		
Al-Otaibi and Al-Senafy [65]	Kuwait	Quality of water improved except nitrate
Ahmed et al. [66]	Bahrain	Increase in groundwater head and reduced salinity
Shammas [61]	Oman	Reduced saline intrusion from 3.4 km to 2.7 km
Karezes/Ain system		
Hussain et al. [73]	Saudi Arabia	Supplied over 40,000 m^3 of water per day

maintenance and skilled labor. Ain Zubaida Karezes system in Saudi Arabia supplied over 40,000 m^3 of water per day and remained functional until 1974. This type of structure is named as "Aflaj system" in Al-Ain, UAE which could discharge 17 l/s of water [74].

Summary of studies carried out on the efficiency of the pond, rooftop rainwater harvesting, SAT and Karezes/Ain systems are given in Table 3.

Recharges using these structures are not commonly practiced in all GCC countries. Rainfall higher than normal rainfall in GCC causes flooding due to urbanization. In such situation rooftop rainwater harvesting is considered to be the best option to conserve all the water falling on the roof. Rainwater harvesting system does not require more space, pretreatment, and sophisticated technologies for its construction and maintenance. A major loss due to evaporation in GCC countries can also be avoided by the rainwater harvesting system. Rainwater harvesting system in new and old buildings and stormwater collection systems along the sides of the roads would substantially improve groundwater recharge. Such a scheme is in practice in several states of India by making rainwater harvesting mandatory for all the buildings, both public and private through legislations [75]. Pond and SAT techniques require space and periodical maintenance; hence these types of structures can be adopted based on suitable geological conditions. Karezes/Ain recharge systems are a very old method of recharge technique that is suitable near the mountain to capture more runoff.

5 Ranking of Feasible MAR Structure for GCC Countries

Seven different MAR methods and their efficiency in improving groundwater potential were reviewed. However, the implementation of MAR has led to significant improvement in groundwater potential within GCC countries. Irrespective of the geological conditions, traditional dams with injection wells are widely chosen as the most common method of MAR in GCC countries to harvest direct rainfall and runoff in the river. Secondly, ponds are used as shallow recharge structures to collect direct rainfall and runoff from the catchment. Water harvested by the dams and ponds is subjected to evaporation loss. Rooftop water harvesting is restricted to urban areas and only less amount of rainwater is harvested using this structure because of less intensity of rainfall in GCC countries. Karezes/Ain system requires a stable aquifer system so that the underground tunnel can be constructed with dug wells. It requires continuous maintenance to avoid collapse during severe flooding. Rainwater is the only source for the dam, pond, RWH, and Karezes/Ain system, whereas ASR, ASTR/ARR, and SAT can use desalinated water, treated wastewater, treated seawater as a source of recharge. TSE can be treated more conveniently by the SAT method. The efficiency of the biological treatment of wastewater depends on the geological medium present near the pond or basin. ASR and ASTR methods of recharge are being widely practiced in GCC countries to recharge excess desalinated water and treated wastewater. The selection of the best recharge structure among all these methods would enable planners to improve the groundwater potential in GCC countries. Twelve site-specific selection criteria such as cost of construction, area occupied by recharge structure, geology, operation and maintenance, type and quantity of source water, quality, proximity, availability of water throughout the year, water loss, recovery efficiency, use of recovered water, social acceptance were considered to rank these MAR methods. The important criteria and rating scales and reason for ratings are given in Table 4.

The higher ranking was assigned to the most important selection criteria. Similarly, equal rankings were assigned if the expected outcomes/benefits are the same from the structures. The hierarchy of MAR methods was identified based on the highest score as represented in Table 5. Even though many methods of MAR was adopted in GCC countries, ASR with desalinated water is considered to be the most feasi-

Table 4 Important criteria and rating scales to rank best MAR structure for GCC countries

Criteria	Scale	Reason for scaling
Cost of construction	1	High technology desalinated plant, geophysical, drilling, and logging, ASR injection/abstraction wells
	2	Collection system, wastewater treatment, transport, ASR injection/abstraction wells
	3	Collection system, sewage treatment plant, transport, pond/basin construction, recovery wells
	4	Collection system, wastewater treatment, transport, ASTR injection, and abstraction wells
	5	Construction of masonry dams and injection wells
	6	Construction of tunnel and dug wells
	7	Pipelines and soak pit
	8	Earth removal, stabilizing and injection wells
The area occupied by recharge structure	1	Very large area required for underground tunnels and dug wells
	2	Large area required to store more volume of runoff
	2	Large area required it varies based on the treatment quantity
	3	Constructed within the river
	4	Less area for soak pit construction
	5	Very less area required only for injection/abstraction wells
Geology	1	Construction of tunnel requires stable geological medium
	2	Geological medium very important to remove biological load
	3	Aquifer should have the ability to transmit to have a small treatment capacity
	4	Suitable Geological profile is very important
	5	The only small quantity of water in GCC country mostly this can be infiltrated using soak pit
	6	Almost suitable in all areas due to its shallow depth
	7	Suitable geological conditions mostly available within river stretch
Operation and maintenance	1	A very highly skilled person required
	2	Highly skills required to work in the tunnel and remove sediments
	3	Responsibility for individual skills
	4	The moderately skilled person required to remove the clogging layer due to microbiological clogging
	5	Skills required to identify the leakage, freshwater flushing, inject and recovery
	6	Substantial skills required to identify the leakage, inject and recovery
	7	Less skilled to stable the bund to scrap the bottom to remove clogging
	8	Very less skilled person to scrap the river bed
Type and quantity of source water	1	Rainwater, quantity depends on the location of the construction site
	2	Rainwater, quantity deepens on intensity and area of the building
	3	Rainwater, direct rainfall and runoff in catchment
	4	Treated sewage water, available with a reasonable quantity
	5	Rainwater, direct rainfall and river runoff
	6	Treated wastewater available reasonable quantity
	7	Excess desalinated water available in large quantity
Quality	1	Moderately treated sewage water
	2	Good quality treated wastewater
	3	Good quality rainwater and runoff water
	4	Very good quality rainwater only
	5	Very good quality treated quality
Proximity	1	Runoff from the mountain region

Table 4 continued

Criteria	Scale	Reason for scaling
	2	Direct fall of rain, runoff from the catchment
	3	Direct fall of rain, runoff from the watershed
	4	Collection, transport to the treatment plant, transport to ASR location
	5	Direct rainfall on the rooftop, transport to soak pit
	6	The desalinated plant is located very near to the sea, most of the ASR also near to the this plant
Availability of water throughout the year	1	Based on monsoon season and runoff from the mountain region
	2	Based on the intensity of rainfall
	3	Based on the seasonal rainfall and runoff
	4	Varied based on the season and quality of treated sewage water
	5	Varied based on the season, less in the winter season
	6	Available all season
Water loss	1	Very high evaporation loss due to the large surface area
	2	High evaporation loss
	3	High loss due to evaporation and clogging of layers due to treated sewage water
	4	Low loss due during leakage and clogging
	5	Loss is less as water is in the underground tunnel
	6	Low loss during the transmitting
	7	Very low loss due to leakage and transport
Recovery efficiency	1	35% as an only small quantity of water available for recharge
	2	40% (mainly deepens on the runoff water)
	3	40 to 50% (as clogging is more recovery is less)
	4	50% (surface evaporation is high)
	5	50 to 60% large surface are water loss due to evaporation
	6	90% efficient with multiple ASR
	7	95% efficient with multiple ASR
Use of recovered water	1	Domestic, irrigation and industrial (excluding drinking)
	2	Domestic, irrigation and industrial
	3	Irrigation and industrial use
Social acceptance	1	Highly objectionable
	2	Moderately acceptable
	3	Acceptable
	4	Highly accepted

ble MAR method for GCC countries followed by ASR with treated wastewater, ARR/ASTR, dam, pond, RWH, SAT, and Karezes/Ain system. A study carried out in Kuwait has also highly ranked the desalination method [76]. If large quantity of water is available with reasonable quality, then ASR and ASTR can be used. On the other hand, if the quantity of water is less and the quality is poor, SAT may be a viable option. However, if the quantity of water is less and the quality is good, rainwater harvesting technique may be more suitable. Dams and ponds are considered to be efficient recharge structures when water is to be harvested directly from the catchment.

6 Conclusion

Water demands of GCC countries are not uniform. It varies based on the size of the population, type of irrigation practice, number and nature of industries. Another potential problem is that aquifers in GCC countries are interlinked hydrogeologically and pumping in one country may affect the groundwater potential of another country. Hence, each country should manage its water demand for various purposes by using the conventional and non-conventional method of water supply. A non-conventional method requires high cost, more energy and it is not always reliable, whereas conventional methods of water conservation require low cost and promote the prosperity of the country. Hence, the present

Table 5 Ranking of best structure based on the score scale

Criteria ↓	MAR structure →	ASR DW	ASR WW	ARR/ASTR	Dam	Pond	RTWH	SAT	Karezes/Ain
1	Cost of construction	1	2	4	5	8	7	3	6
2	The area occupied by recharge structure	5	5	5	3	3	4	2	1
3	Geology	4	4	3	7	6	5	2	1
4	Operation and maintenance	1	6	5	8	7	3	4	2
5	Type and quantity of source water	7	6	6	5	3	2	4	1
6	Quality of source water	5	2	2	3	4	4	1	3
7	Proximity of source water	6	4	4	3	2	5	4	1
8	Availability of water throughout the year	6	5	5	3	3	2	4	1
9	Water loss	7	7	6	1	2	4	3	5
10	Recovery efficiency	7	7	6	5	4	1	3	2
11	Use of recovered water	2	2	2	3	3	3	1	3
12	Social acceptance	3	2	2	4	4	4	1	4
	Total score	54	52	50	50	49	44	32	30
	Priority of structure	1	2	3	3	4	5	6	7

study was carried out to assess the efficacy of the different MAR methods. This review reveals the implementation of seven methods of MAR: dams, ASR, ASTR, ponds, SAT, rooftop rainwater harvesting, and Karez/Ain system. Among all different methods of MAR, recharging with ponds and dams was the most commonly implemented method followed by ASR with desalinated water. Higher evaporation losses were identified, when ponds and dams are used as recharge structure. To reduce the evaporation rate, various management techniques were followed by many types of research which include the introduction of injection wells, removal of silt and scratching of reservoir bed, and other management options such as the release of water into the downstream side of the dam, diversion of water to demand area. ASR is a recently adopted technology in a GCC country to recharge excess desalinated water and treated wastewater. The review on ASR methods revealed that they help to recover almost 80 to 95% of recharged water. However, two major constraints were highlighted while implementing ASR. It requires a suitable geological medium to store injected water and good quality ambient groundwater. ASTR and SAT methods of MAR are implemented only in a few countries of GCC as they use partially treated wastewater as a source of recharge. Though they use the impaired quality of water, research on ASTR and SAT methods show possible improvement in recovered groundwater quality. The ASTR and SAT technique of recharge has also proved to reduce seawater intrusion when implemented near the coastal regions. Rooftop harvesting and Karezes/Ain system are having good potential to harvest rainwater. Even then, the review of these studies shows that these methods are not commonly adopted in all GCC countries. It was found that the efficiency of these structures in improving the groundwater potential was based on several criteria. Prioritization of the best recharge structure among all these methods would enable planners to improve the groundwater potential in GCC countries. Even though any method of MAR can be adopted in GCC countries (as it receives rainfall of irregular pattern), based on the twelve selection criteria, ASR with desalinated water is considered to be the most feasible MAR method for GCC countries followed by ASR with treated wastewater, ARR/ASTR, dam, pond, RWH, SAT and Karezes/Ain system. Before adopting these methods, a thorough field study should be carried out to collect detailed information about the geology, size of the structure required, the arrangement of the structure, external contamination into the site, the amount of rainfall-runoff, quality of water to be recharged. Different types of research carried out to identify the efficiency of the MAR methods, have revealed wide gaps in this specific area of research. There was no integrated research to assess the effect of MAR in terms of water level, water quality by using various hydrological assessment tools. When treated wastewater is used for groundwater recharge through ASR, ASTR, and SAT, there should be socio-economic studies to understand the opinion of people on the use of the treatment of wastewater to recharge. Many studies have been carried out only to assess the effect of dams and ASR when compared with the other recharge structures. It is understood from the review that the efficiency of other recharge structures also needs to be explored in detail.

Acknowledgement I would like to thank Vellore Institute of Technology (VIT), Vellore, India, in supporting me to complete my Post-Doctoral Research review work carried out in United Arab Emirates University, UAE.

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