A review on implementing managed aquifer recharge in the Middle East and North Africa region: methods, progress and challenges

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ABSTRACT
The study critically reviews the application, management and challenges of managed aquifer recharge (MAR) in the Middle East and North Africa (MENA) region through a survey of 142 studies. The survey reveals the objectives and methods of MAR in the region. It also shows the technical and socioeconomic challenges that significantly cause MAR failure in MENA countries. The article concludes by presenting a framework to evaluate MAR feasibility and it provides recommendations and guidance for future studies and MAR designs in the MENA region, which is facing the impact of climate change.

Introduction
Sustainable management is essential for better utilization of water resources in the Middle East and North Africa (MENA) region. According to the World Bank, 19 countries are included in the MENA region (Figure 1). All (except Morocco) are some of the most water-stressed countries worldwide (United Nations, 2018). The climate is generally arid to semi-arid. The evaporation rate is high, while precipitation is low and usually intensive (Waha et al., 2017). As a result, surface water (e.g., rivers and lakes) is limited, and water demand depends heavily on groundwater. Also, the population rate is growing rapidly in the MENA countries. During the last two decades, the global population increased by 26%, whereas the population increased by 45% in the MENA countries (United Nations, 2019). More than 75% of MENA’s population resides in urban areas. This percentage is projected to amount to 90% in the Middle Eastern countries by 2050 (United Nations, 2019). The combined influence of these factors (climate change, population and urbanization) significantly exacerbates the stress on water resources.

The MENA countries secure their needs from water either by relying on aquifers, which leads to aquifer overexploitation and quality deterioration, or they use unconventional water resources such as treated wastewater, urban stormwater and desalinated...
seawater. The Gulf Cooperation Council GCC (Saudi Arabia, Oman, Kuwait, Bahrain, Qatar and the United Arab Emirates – UAE), and some Northern African countries (e.g., Algeria, Morocco and Tunisia) rely on groundwater for agriculture (Gleick, 2003; Madurga et al., 2008). More than half of Algeria’s and Morocco’s aquifers and one-quarter of Tunisia’s aquifers are overexploited (Fienen & Arshad, 2016). All GCC aquifers are heavily threatened by salinization, which causes quality deterioration and pollution from surface anthropogenic activities (Dawoud, 2008, 2011). Future projections show a larger scarcity in groundwater. The deficit in the water budget will reach, respectively, 190%, 90% and 45% in Yemen, Libya and Egypt in 2050, under plausible scenarios of climate change and socioeconomics (Mazzoni et al., 2018). The situation in the Arabian Peninsula is even worse. Mazzoni et al. (2018) expect that by the mid-21st century, fossil aquifers in the Arabian Peninsula will be drained of water, mainly due to anthropogenic stresses.

The use of managed aquifer recharge (MAR) has been widely increasing in arid and semi-arid areas since it is an economic, benign and resilient way to secure and manage water resources (Dillon et al., 2018; NRMMC-EPHC-NHMRC, 2009; Ross & Hasnain, 2018; Yaraghi et al., 2019). MAR, also called artificial recharge and water banking, is the
intentional augmentation of water resources for the purpose of water recovery and deriving other environmental benefits (Dillon, 2005). More specifically, MAR has five main objectives: (1) water system management, (2) water storage maximization, (3) physical aquifers management, (4) improving water quality and (5) achieving ecological benefits. Other benefits include improving soil conditions (Dillon, 2005; Gale et al., 2002) and preventing land subsidence (Dillon, 2005; Gale et al., 2002; Joel et al., 2016). There are five standard methods for implementing MAR: well, shaft and borehole, spreading, riverbank filtration, in-channel modification, and rainwater harvesting. All these techniques are used in the MENA region since they are a more economical way to supply water during drought and emergency periods. Different sources of water are being used to feed MAR projects, including surface water, harvested rainfall and treated sewage effluent (Dillon et al., 2009; Gale et al., 2002).

Though MAR is widely implemented in the MENA region, there has been very little research on MAR feasibility; thus, several projects have failed (see the fourth section). This paper presents an overview of MAR methods, progress and challenges in the MENA region. The unique impacts of environmental and socioeconomic challenges on MAR implementation are highlighted as well. The paper reviews 142 MAR studies in 18 MENA countries. Given the challenges associated with MAR implementation, one member state, Libya, is yet to conduct any MAR study. Figure 1 shows the number of reviewed studies in each country, including the used method. Studies were collected from online databases, the International Symposiums on Managed Aquifer Recharge (ISMAR) and the International Groundwater Resource Assessment Centre (IGRAC). The ISMAR was pioneered in 1988 by the American Society of Civil Engineers (ASCE). The last one, ISMAR10, was held in Madrid (Spain) in 2019. IGRAC is a web-based portal containing information about 1200 MAR schemes from 62 countries worldwide (Stefan & Ansems, 2017). To streamline the search query, we used a Boolean operator (OR) and a combination of keywords: managed aquifer recharge, artificial recharge and water banking. Particular attention was given to laboratory experiments and theoretical studies.

The review starts with a general introduction that includes the layout of the methodology. To make the background knowledge available, the second section describes different methods of MAR and their suitability, along with the pros and cons of each technique. The third section shows the progress in MAR in the MENA countries. The fourth section draws attention to the existing knowledge gap and outlines MAR challenges in the region, including socioeconomic considerations. The fifth section summarizes and restates the major findings and recommendations. Last, further research areas are suggested in the sixth section.

**Types of MAR**

This section briefly describes the main methods of MAR, along with its suitability, merits and demerits in different types of environments. Figure 2 depicts a schematic view of these methods.

‘Well, shaft and borehole’ is a primary MAR method used to infiltrate water, especially in low permeable surfaces (Hannappel et al., 2014). Once the water has been infiltrated, there are two types of recovery: aquifer storage and recovery and aquifer storage, transfer and recovery. In the aquifer storage and recovery, the same well is used for injection and
recovery, whereas different wells are used in aquifer storage, transfer and recovery. In spreading methods, water with impaired quality, such as urban runoff or treated sewage effluent, is diverted into basins or channels that allow water infiltrates to unconfined aquifers. The riverbank filtration primarily refers to groundwater abstraction near rivers banks or lakes that will induce infiltration from the surface water. In-channel modification aims to intercept stream water by building dams in rivers beds or wadis. The water is then temporarily stored to infiltrate into aquifers. Pumping wells are later used for extraction during drought months. The rainwater harvesting method refers to gathering rainfall from building rooftops and surfaces. The water is infiltrated into aquifers using barriers, bunds and trenches. For additional information about MAR methods, see Dillon et al. (2018) and Joel et al. (2016). Table 1 summarizes the main characteristics, and merits and demerits of each MAR method.

Progress in MAR in the MENA region

The MENA region has a long tradition of water harvesting (Abdo & Eldaw, 2006; AQUASTAT-FAO, 2018; Prinz, 1996). Table 2 shows the number of dams that have been constructed, until 2013, in 14 MENA countries to intercept river waters and harvest rainfall. No dams had been constructed in Palestine, Israel, Bahrain, Qatar or Kuwait. According to the AQUASTAT-FAO (2018), the first two dams were built in Egypt (i.e., Rosetta) and Algeria (i.e., Meurad) in 1840 and 1854, respectively. Dams’ construction has increased rapidly in the MENA region during the last two decades. Even though rainfall is minimal and surface water is very scarce in Saudi Arabia, for example, the number of constructed dams has increased from 230 in 2006 to 482 in 2014 (Saudi Ministry of Environment Water and Agriculture, 2020). Very few surface dams have been built in karst aquifers in Lebanon (two dams) and Jordan (10 dams), because they are prone to failure. An example of this was a well-constructed 20 m dam in the Kurdistan region (Iraq) that failed in 2005 (Stevanović, 2015).
### Table 1. Managed aquifer recharge (MAR) types, characteristics, main merits and demerits.

| Main MAR type                     | Specific MAR type            | Energy (pumping and discharge) costs | Surfaces footprint | Evaporation losses | Confined or impermeable surfaces | Unconfined | Karst or fracture | Other merits                                                                 | Other demerits                                                                 |
|----------------------------------|-----------------------------|-------------------------------------|-------------------|-------------------|---------------------|------------|------------------|--------------------------------------------------------------------------------|--------------------------------------------------------------------------------|
| Well, shaft and borehole recharge| Aquifer storage and recovery Aquifer storage, transfer and recovery | High                               | High               | Small             | No                  | High       | Low              | Hard to estimate the recharge capacity of the aquifer due to the strong hydraulic heterogeneity | Since water availability varies seasonally in arid and semi-arid regions, the method can be effective during drought/emergency periods |
|                                  |                             |                                     |                   |                   |                     |            |                  | • Old/dry wells can be used                                                     | • Limited in brackish or saline aquifers since it mixes with ambient water, producing low-quality water and reduces recovery volume (Ward et al., 2009) |
|                                  |                             |                                     |                   |                   |                     |            |                  | • When considering economics, aquifer storage and recovery is preferred. However, aquifer storage, transfer and recovery outweighs aquifer storage and recovery if the main objective is water quality management because of the longer infiltration period in the aquifer storage, transfer and recovery method (Maliva & Missimer, 2010). | • Pretreatment may be required to avoid clogging |
|                                  |                             |                                     |                   |                   |                     |            |                  | • However important, it is hard to adjust the distance between aquifer storage, transfer and recovery wells (Gastélum et al., 2009; Herrmann, 2005). Pavelic et al. (2004) noted that observation wells are critical for demonstrating the viability of the aquifer storage, transfer and recovery method. | • Losses occur by lateral flow |

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**Table 1. (Continued.)**

| Main MAR type          | Specific MAR type                      | Clogging potential | Energy (pumping and discharge) costs | Surfaces footprint | Evaporation losses | Confined or impermeable surfaces | Unconfined | Karst or fracture | Other merits                                                                 | Other demerits                                                                 |
|------------------------|----------------------------------------|--------------------|-------------------------------------|--------------------|-------------------|-----------------------------|-------------|------------------|--------------------------------------------------------------------------------|--------------------------------------------------------------------------------|
| Spreading methods      | Infiltration ponds and basins           | Low                | Low                                 | Large              | High                      | Low                         | High         | Low              | ● Basins are valuable to avoid flooding during extreme rainfall, and take advantage of rainfall, the primary natural source of freshwater in arid areas (Knapton et al., 2017) | • Aquifers’ physical, hydraulic, geochemical and microbiological processes should be known to mitigate water loss (Gale et al., 2002) |
|                        |                                        |                    |                                     |                    |                               |                             |             |                  | ● Reduces soil erosion and soil removal (Gale et al., 2002)                        | • Identifying suitable sites to ensure the MAR process’s effectiveness is highly recommended (Ajur & Mogheir, 2020b; Rahman et al., 2013) |
|                        |                                        |                    |                                     |                    |                               |                             |             |                  | ● Can treat water during aquifer passage                                        | • Needs a perennial stream                                                      |
|                        |                                        |                    |                                     |                    |                               |                             |             |                  | ● Recharged water is of high quality unless the quality of surface water is poor, then, subsequently, clogging occurs (Dillon et al., 2018; Ghodeif et al., 2016; Shamrukh & Abdel-Wahab, 2008) | • Long travel time, which should be considered before implementation (Gale et al., 2002) |
|                       | River/lake/dune filtration             | High               | Low                                 | Small              | No                              | High                         |              |                  | ● Suitable in karst and fractured aquifers (Khadra & Stuyfzand, 2019)           |                                                                                 |
| In-channel modification| Dams and channels                      | Low                | Low                                 | Large              | High                      | Low                         | High         | Low              | ● Helps prevent flooding and takes advantage of rainfall                         | • Dams may be partially impermeable (Stevanovic, 2015)                          |
|                        |                                        |                    |                                     |                    |                               |                             |             |                  | ● Low construction cost, especially in sand dams                                  | • Proper design and integrated modeling, based on geological and hydrogeological investigations, are difficult but required (Ringleb et al., 2016; Salameh et al., 2019) |

(Continued)
Table 1. (Continued).

| Main MAR type               | Specific MAR type | Clogging potential | Energy (pumping and discharge) costs | Surfaces footprint | Evaporation losses | Confined or impermeable surfaces | Unconfined Karst or fracture | Other merits                                                                 | Other demerits                                      |
|-----------------------------|-------------------|---------------------|--------------------------------------|--------------------|-------------------|----------------------------------|-------------------------------|--------------------------------------------------------------------------------|---------------------------------------------------|
| Rainwater harvesting        |                   | Low                 | Low                                  | Small              | Low                | High                             |                               | • Economic option and easy to apply at smaller scales                          | • Harvested water could be contaminated by air, animals and birds, which cause water quality degradation, especially in the case of low rainfall (Boisson et al., 2014; Niazi et al., 2014) |
|                             |                   |                     |                                      |                    |                   |                                  |                               | • Reduces flood risk (surface run-off (Gale et al., 2002; Nachshon et al., 2016)) |
|                             |                   |                     |                                      |                    |                   |                                  |                               | • Can be used in cooperation with living/green walls in urban areas to improve water quality through the filtering process |
|                             |                   |                     |                                      |                    |                   |                                  |                               | • Helps mitigate the heat island effect and, consequently, modifies urban microclimate conditions (Hamel et al., 2012) |
|                             |                   |                     |                                      |                    |                   |                                  |                               | • Old/dry wells can be used                                                   |
Table 2. Number of dams constructed in the Middle East and North Africa (MENA) region before 2013 (still in operation).

| Country     | Year the first dam was built | Construction period | | | | | References |
|-------------|------------------------------|---------------------|---|---|---|---|---|
| Iran        | 1957                         | before 1970, 1970s, 1980s, 1990s, 2000s, 2010s, unknown | 689 | AQUASTAT-FAO (2018); Iran Water Resources Management (2020) |
| Saudi Arabia| 1970                         | 0, 8, 52, 3, 167, 252, 0 | 482 | AQUASTAT-FAO (2018); Saudi Ministry of Environment Water and Agriculture (2020) |
| Syria       | 1960                         | 10, 13, 32, 18, 5, 0 | 141 | AQUASTAT-FAO (2018); Wikipedia (2020a) |
| Morocco     | 1929                         | 19, 8, 38, 34, 30, 7 | 136 | AQUASTAT-FAO (2018) |
| UAE         | 1982                         | 0, 0, 5, 5, 104, 0 | 114 | Al-Nuaimi and Murad (2008); AQUASTAT-FAO (2018) |
| Algeria     | 1854                         | 18, 3, 22, 5, 20, 4 | 72 | AQUASTAT-FAO (2018) |
| Tunisia     | 1925                         | 18, 2, 14, 1, 2, 5 | 61 | AQUASTAT-FAO (2018) |
| Yemen       | 1985                         | 0, 0, 3, 6, 30, 0 | 46 | AQUASTAT-FAO (2018) |
| Oman        | 1985                         | 0, 0, 9, 11, 9 | 43 | AQUASTAT-FAO (2018) |
| Iraq        | 1951                         | 5, 1, 5, 0, 0, 0, 20 | 31 | AQUASTAT-FAO (2018); Wikipedia (2020b) |
| Libya       | 1972                         | 0, 0, 7, 4, 0, 7 | 18 | AQUASTAT-FAO (2018); Brika (2018) |
| Egypt       | 1840                         | 6, 1, 0, 1, 0, 8 | 16 | AQUASTAT-FAO (2018) |
| Jordan      | 1967                         | 2, 0, 2, 2, 4, 0 | 10 | AQUASTAT-FAO (2018) |
| Lebanon     | 1961                         | 1, 0, 0, 0, 1, 0 | 2 | AQUASTAT-FAO (2018) |

During the last few decades, there has been an increased development of MAR in MENA countries. Table 3 classifies MAR projects based on their type, objective, influent source and final use. It can be seen that the two most common objectives in MENA countries were to maximize storage (39%) and manage physical aquifers (29%). Achieving ecological benefits was not found to be one of the objectives of MENA countries (except in Iran). There are three main methods of MAR being used: (1) in-channel modification (37%); (2) well, shaft and boreholes (21%); and (3) rainwater harvesting (18%). Globally, well, shaft and boreholes, and spreading are the most commonly applied methods (Stefan & Ansems, 2016), whereas in-channel modification is the most common in the MENA region. In the MENA region, the highest priority is given to aquifer recovery and management. In MENA countries, different water input sources are used for MAR. Stormwater was most used at 41%. After that, treated sewage effluent and surface water were used at 25%, and 22%, respectively. Only the Gaza Strip uses brackish water as an input source for MAR projects. Irrigation is the primary use of recovered water (67%), while 29% of MENA countries use MAR for domestic purposes.

Most of the studies in the MENA region have indicated that the use of MAR has successfully increased groundwater storage, and improved groundwater quality (including countering seawater intrusion). For instance, MAR had a substantial impact on river flow in the Kamal Abad river basin (southern Iran) and the increase in recharge volume reached 33% of aquifer storability (Yaraghi et al., 2019). In north-
Table 3. Managed aquifer recharge (MAR) objectives, types, influent sources and final uses in the Middle East and North Africa (MENA) region.

| Country     | MAR main objective | MAR main type | MAR influent source | MAR final use | References                                                                                                                                 |
|-------------|--------------------|---------------|---------------------|---------------|-------------------------------------------------------------------------------------------------------------------------------------------|
| Morocco     |                    |               |                     |               | (AQUASTAT-FAO, 2018; Bermani et al., 1992; Bouchaou, 2012; Bouri & Dhia, 2010; Yones & Housene, 2019)                                      |
| Algeria     |                    |               |                     |               | (AQUASTAT-FAO, 2018; Stevanović, 2015)                                                                                                   |
| Tunisia     |                    |               |                     |               | (AQUASTAT-FAO, 2018; Claieb, 2014; Chekibane et al., 2019; Conie & Bachouli, 2019; Farsd et al., 2014; Mhamdi & Heilweil, 2007; Nasri et al., 2009; Zammouri & Feki, 2005) |
| Libya       |                    |               |                     |               | (AQUASTAT-FAO, 2018)                                                                                                                      |
| Egypt       |                    |               |                     |               | (Abd-Elhamid et al., 2019; AQUASTAT-FAO, 2018; Dillon et al., 2018; El-Arabi & Daroul, 2012; Elewa, 2005; Ghodeif et al., 2016; Ismail et al., 2006; Shamsul & Abdel-Wahab, 2006; Van Ginkel et al., 2009) |
| Palestine   |                    |               |                     |               | (Adbul-Hamid, 2008; Ajjur & Mogheir, 2020a; Al-Batih et al., 2019; Al-Kharib et al., 2019; Alim et al., 2020; Rahman et al., 2013)          |
| Israel      |                    |               |                     |               | (Abbo & Gev, 2008; Aherbach & Sellenger, 1967; Aharony et al., 2019; Ben Moshe et al., 2020; Dalin, 1984; Goren, 2009; Gutman et al., 2017; Negev et al., 2020) |
| Jordan      |                    |               |                     |               | (Al-Raggad & Jasem, 2016; AQUASTAT-FAO, 2018; Ghaida & Elias, 2019; Salameh et al., 2019; Taloo, 2007; Wolf et al., 2007; Xanke et al., 2015; Xanke et al., 2017) |
| Saudi Arabia|                    |               |                     |               | (Abderrahman, 2005; AI-Othman, 2011; AI - Muttair et al., 1994; AQUASTAT-FAO, 2018; Missimer et al., 2014; Othmanb, 2016)               |

(Continued)
| Country  | Source 1                                                                 | Source 2                                                                 |
|---------|--------------------------------------------------------------------------|--------------------------------------------------------------------------|
| Syria   | (AQUASTAT-FAO, 2018; Kattan et al., 2009; Tröger & Wannous, 2016; Wannous et al., 2016; Wannous & Natour, 2009) |                                                                           |
| Lebanon | (AQUASTAT-FAO, 2018; Ibrahim et al., 2019; Khabra & Storffzand, 2019; Klingbeil, 2012; Masclioppo, 2013) |                                                                           |
| Iraq    | (Abdulla et al., 2002; AQUASTAT-FAO, 2018; Stevanovic, 2015; Stevanovic & Turkiewicz, 2008; Wannous & Natour, 2009) |                                                                           |
| Iran    | (Abbasi et al., 2019; Ahmadi et al., 2010; AQUASTAT-FAO, 2018; Arrani, 2010; H. Hashemi et al., 2013; Hossein Hashemi et al., 2014; Kalantari & Goli, 2005; Kalantari & Ranganz, 2000; Salajegheh & Keshtkar, 2005; Salih, 2006; Vardanjani & Farjadian, 2012; Varaghi et al., 2019) |                                                                           |
| Yemen   | (AQUASTAT-FAO, 2018; Wahib Saif, 2009)                                   |                                                                           |
| Oman    | (Abdalla & Al-Rawahi, 2013; Al-Shukaili & Kacimov, 2019; AQUASTAT-FAO, 2018; Dillon et al., 2018; A. Kacimov et al., 2012; Anvar Kacimov et al., 2019; Klingbeil, 2012; Lutson et al., 1991) |                                                                           |
| Kuwait  | (Al-Senafl & Sherif, 2005; Klingbeil, 2012; A Makropadhyay et al., 2013; A Makropadhyay & Fadhelmawia, 2009; Ambrasha Makropadhyay et al., 1994) |                                                                           |
| Bahrain | (Klingbeil, 2012; Naik et al., 2017)                                      |                                                                           |
| Qatar   | (Al-Murahl & Shamakh, 2017; Qatar Planning and Statistics Authority, 2018) |                                                                           |
| UAE     | (H. Al-Neimi & Murad, 2007; AQUASTAT-FAO, 2018; Rashid & Almulla, 2005; Stuyfzand et al., 2017) |                                                                           |
east Tunisia, MAR increased the aquifer storage by 51%, raising the water table by 7.5 m over a decade (Zammouri & Feki, 2005). A subsurface dam (Gali Basera) was constructed in northern Iraq and MAR wells around the dam were able to meet water needs during summer periods without deteriorating the quality of the aquifer (Stevanovic & Iurkiewicz, 2008). MAR has also improved the groundwater quality in Tunisia (Bouri & Dhia, 2010), Morocco (Bennani et al., 1992) and Egypt (Khodeif et al., 2016; Shamrukh & Abdel-Wahab, 2008), and reduced seawater intrusion in Sebaou Basin (Algeria) (Kadri et al., 2011) and Korba coastal aquifer in Tunisia (Comte & Bachtouli, 2019).

**MAR challenges in the MENA region**

Many challenges can hinder MAR implementation and maintenance and, hence, lead to failure. This section discusses several MAR failures that occurred in 10 MENA countries: Palestine (Adbul-Hamid, 2008; Ajjur & Mogheir, 2020b; Al-Khatib et al., 2019; Anabbawi, 2018), Yemen (Al-Qubatee, 2009), Jordan (Salameh et al., 2019; Xanke et al., 2017), Egypt (Dillon et al., 2018; Khodeif et al., 2016), Iraq (Stevanović, 2015), Israel (Guttman et al., 2017; Idelovitch & Michail, 1985), Lebanon (Daher et al., 2011), Syria (Tröger & Wannous, 2016) and the UAE (Dawoud, 2008), and Tunisia (Comte & Bachtouli, 2019). MAR challenges in the MENA region can be categorized into three primary concerns: technical issues, health-risk issues and socioeconomic aspects.

**Technical issues**

The main technical issues that challenged MAR projects in the MENA region are shown in Table 4. These issues can be categorized into three main points: site feasibility, recharged water pollution, and design and management issues. Table 4 also suggests possible learned lessons that will guide researchers in the MENA region.

Several aquifers in the MENA countries are karst with high heterogeneity. These include Umm Al-Radhuma, Western Mountain Basin and Jezira Tertiary Limestone Aquifer System (UN-ESCWA and BGR, 2013). Heterogeneity in karst aquifer characteristics causes significant clogging and influence dispersion, and, hence, reduces the recovery rate (Daher et al., 2011; Van Ginkel et al., 2009). Our analysis shows failures in most MAR systems in karst aquifers. Examples from Kuwait include Parson’s experiment in 1964, another experiment in 1973 where for 27 days desalinated water was injected into two wells, and injecting approximately 16,000 m³ of water for 30 days into the Dammam Formation in Sulabiya in the mid-1990s. All these attempts failed due to low rates of recharge and uptake (Dawoud, 2008). Another study from Lebanon concluded the non-feasibility of MAR, via infiltration ponds or injection wells, to the main Damour aquifer (Daher et al., 2011). Further, an aquifer storage and recovery project was implemented in the 2000s in the Hadith karst aquifer in Lebanon. The project is working six months per year, with an injection capacity of 500 m³ per hour for each well. The source water comes from the Beirut River. Daher et al. (2011) reported the non-feasibility of such an injection in the area due to technical and economic factors. Also, Idelovitch and Michail (1985) documented low infiltration rates in spreading basins in the Dan project in Israel due to high heterogeneity in geological layers. Conversely, in Damascus,
### Table 4. Managed aquifer recharge (MAR) challenges in the Middle East and North Africa (MENA) region.

| Country   | Site                          | MAR challenge                                                                 | Lessons learned                                                                 | References                  |
|-----------|-------------------------------|-------------------------------------------------------------------------------|---------------------------------------------------------------------------------|-----------------------------|
| **Challenge 1: Site feasibility** |                               |                                                                               |                                                                                 |                             |
| Palestine | Spreading basins in the Gaza  | Analysis of seven rainwater and treated sewage effluent-harvesting structures revealed that MAR is not feasible at two sites. These sites were allocated based on slope criterion. Other criteria such as aquifer characteristics, hydraulic conductivity, soil and land use did not support the selection of these two sites. As a result, the infiltration process was ineffective and clogging occurred. | Several factors should be considered before the selection of MAR sites. These factors include:<br> - Hydrogeological settings (aquifer characteristics, land use/cover, rainfall characteristics, evapotranspiration, aridity index, soil, runoff data, etc.)<br> - Socioeconomic factors (demography and future population projections, implementation cost, operation and maintenance costs) | Ajur and Mogheir (2020b) |
| Saudi Arabia | Assir region (south-west Saudi Arabia) | A total of 80 proposed dams in the Assir region were evaluated according to their priorities. The analysis gave a priority rank for each dam, considering several demographics along with physical and structural characteristics. Results indicated that 73% of dams were not feasible. Only 4% of the total dams were at a high priority, while the remaining were found to be less-priority dams | Planning and political aspects | Jaafar (2014) |
| Jordan | Wadi Rajil and Wadi Mugheir | Two in-channel modification structures were found to be ineffective. In Wadi Rajil, a dam was constructed to harvest and recharge water; however, low permeability was found in the dam lakebed. In Wadi Mugheir, three weirs were unnecessary because flood water could naturally infiltrate in the area | | Salameh et al. (2019) |
| Egypt | Nile River | Several riverbank filtration sites along the river failed to deliver the expected amount of water after a short period of operation due to clogging in the canal bed. These sites were implemented without adequate knowledge of the hydrogeological characteristics of the area. A proper well design was also absent | | Ghodeif et al. (2016) |
| Yemen | Sana’a Basin | Two large dams, Mekhtan and Musaibeeh, were constructed to recharge the aquifer and fulfil water demand. In both dams, efficiency was low and did not meet expectations; the evaporation rate was high, the water table was low, soil permeability was very low and the catchment area was small. Also, improper locations of these dams led to conflicts between residents | | Al-Qubatee (2009) |

(Continued)
| Country | Site | Challenge 2: Pollution or deterioration in recharged water | Lessons learned | References |
|---------|-----|--------------------------------------------------------|-----------------|------------|
| Palestine | Kobar and Abu Shekheidim villages (West Bank) | The analysis of harvested rainwater samples did not meet the World Health Organization (WHO) or local Palestinian quality standards. The analysis showed total and faecal coliforms in all and 86% of the tested samples, respectively. Debris from poorly managed rooftops and leakage from the nearest water tanks were the reasons behind this contamination. | The rainwater harvesting systems should be appropriately managed. Local authorities should monitor the quality of harvested water and disinfect cisterns to avoid pollution. | Abdul-Hamid (2008) |
| | Yatta, Hebron (West Bank) | A total of 47 samples from harvested rainwater were collected and analysed in 2016. The study showed a high potential of locals developing cancer due to high concentrations of heavy metals in the collected water. The percentages of potassium and aluminium metals found in the water were above the WHO and local Palestinian quality standards. | | Al-Khatib et al. (2019); Anabtawi (2018) |
| Egypt | River Nile, Luxor | Several issues hampered the bank filtration process, including pollution from oil spills, high turbidity and low levels of water in the river. | Pollutants should be prevented and abstraction wells should be allocated within a short distance from the riverbank. | Dillon et al. (2018) |
| Tunisia | Korba aquifer, east of Cap Bon | Infiltrated treated sewage effluent at spreading sites was of poor quality and contaminated by wastewater. Water samples located around spreading basins showed boron isotopic composition similar to the wastewater signature. | It is necessary to treat source water before the recharge process to prevent groundwater contamination. The target of this treatment depends on the required effluent quality and aquifer characteristics. | Cary et al. (2013); Comte and Bachtouli (2019) |
| Jordan | Wala karst reservoir | Recharged water was polluted from livestock farming, arable agriculture and human occupation along the wadi. | It is necessary to properly manage the system by protecting the wellfield and the reservoir. Frequent monitoring is required as well. | Xanke et al. (2017) |
| Syria | Damascus Plain | The Figeh spring is the main water supply in the region. While 7.5 m³/s of water is enough to supply the region, runoff reaches 50 m³/s in heavy rain seasons. The problem is that the aquifer is recharged rapidly, causing floods in tunnels. | Paying attention to climate and weather forecasting is essential for successful MAR implementation. Also, a new method for recharging extra water must be implemented. | Tröger and Wannous (2016) |
| UAE | Eastern region near Al-Ain city | In 1998, desalinated water was injected at a rate of 832 m³/day for about seven months. The project was stopped due to the high cost of desalination and limited available freshwater. | MAR systems should be designed considering treatment cost and water availability. Poor economic analysis leads to substantial losses of water and expenses. | Dawoud (2008) |
| Iraq | Chaq-Chaq Dam in northern Iraq | Material design and foundation depth were inadequate, causing the dam to be destroyed after heavy floods in 2005/06. | Properly designing a system that considers climate extremes should be done before an implementation process. | Stevanović (2015) |
Syria, karst settings were found to be favourable when suitable wells were located adjacent to Figeh Spring. The discharge exceeds 280 \( \text{Mm}^3 \) in good rainy seasons (Wannous et al., 2016).

**Health-risk issues**

Table 3 shows that eight MENA countries use treated sewage effluent as a water source in MAR projects, and 13 MENA countries use rainfall. The treated sewage effluent and harvested rain could carry health-risk challenges if recharged water were of bad quality. In a spreading project in the Korba aquifer (Tunisia), the infiltrated poor-quality-treated sewage effluent caused deterioration in the recharged water. The analysis showed a boron isotopic composition similar to the wastewater signature in several samples located around spreading basins (Cary et al., 2013; Comte & Bachtouli, 2019). In the West Bank (Palestine), an analysis showed significant percentages of total and faecal coliforms in the harvested rainwater samples. Debris from poorly managed rooftops and leakage from the nearest water tanks were the reasons behind this contamination (Adbul-Hamid, 2008). Other studies in the West Bank area (Al-Khatib et al., 2019; Anabtawi, 2018) linked some locals diseases such as cancer with high heavy metals percentages in collected rainwater. In some other MAR projects in Jordan, farming activities and human occupation along MAR sites have polluted recharged water (Xanke et al., 2017). Therefore, MENA countries should consider using a good-quality source of water that meets the WHO quality standards. They should also manage MAR systems properly and monitor the quality of recharged water to prevent health-risk implications.

**Socioeconomic challenges**

Public–private partnerships are crucial to the success of community projects such as MARs. MAR projects should be all-inclusive and participatory, from the planning stages to implementation. As part of corporate social responsibility, private entities should provide governments and stakeholders with monetary and technical support. Attention should especially be paid to farmers, the highest consumers of water in the MENA area. During the last several decades, farmers’ rejections have hampered several MAR projects in the MENA region. Niazi et al. (2014) detailed that the best sustainable scenario for MAR in the Sirik region (Iran) was the most socially acceptable one, despite it not being economical. Instead of shutting down farmers’ wells, it would allow farmers to improve their wells at no cost and water to flow by gravity into boreholes in the farming lands. In a Muscat (Oman) aquifer, the economic analysis showed that injecting treated sewage effluent was appealing, but local users did not accept mixing treated sewage effluent with current water resources. Their constraint was related mainly to the treated sewage effluent use in injection. In Tunisia, consumers refused to buy olives and citrus from orchards irrigated with low-quality treated wastewater (Hussain et al., 2019). Also, farmers in Qatar, West Bank (Palestine) and Tunisia viewed injecting treated sewage effluent for agriculture as unsafe, even after local monitoring (Dare & Mohtar, 2018). As the aforementioned studies reveal, gaining social acceptance was unachievable in several MAR projects in the MENA region.
Figure 3. Proposed framework to evaluate managed aquifer recharge (MAR) implementation.
The economic analysis of MAR is scarce in MENA countries. Economic analysis requires identifying the level of sophistication of the right MAR technology, which is highly dependent on the hydrogeological situation and land and water values (Dillon & Arshad, 2016; Shah, 2014). This information is not easily available in several MENA countries. Therefore, it is essential to document capital and operational costs, which can serve as a reference for future studies and MAR implementation guides. Further, in many MENA countries, farm incomes are variable due to regional market fluctuations, which discourages farmers from investing in MAR projects. Due to high risks and the non-immediate rewards from MAR investment, cost–benefit analyses are of utmost importance.

Examples from other arid regions demonstrate that MAR costs vary substantially based on the selected method, size of the project, location and hydrogeological conditions. The economic data for 21 MAR sites in arid areas in the United States and Australia were analysed, showing the cost-effectiveness of the spreading method (US$0.156/m³) when compared with aquifer storage and recovery/aquifer storage, transfer and recovery (US$2.67/m³) (Ross & Hasnain, 2018). In 2008, aquifer storage and recovery/aquifer storage, transfer and recovery projects contributed 52 Mm³ of water per year in some parts in Australia (Dillon et al., 2009). The average levelized cost (i.e., the required annual revenue that will recover all associated capital, operational and maintenance costs during the project life divided by the supply volume) was also computed. The study concluded that large projects are more economical than small ones. The estimated average levelized costs were US$3/m³ for small projects, whereas they were US$1.21/m³ for large projects (Dillon et al., 2009). The annual recovery capacities of small and large projects are 15,000–75,000 and 75,000–2,000,000 m³, respectively.

**MAR feasibility**

MAR feasibility requires recovering stored water when needed but also avoiding adverse impacts on aquifers and the environment. To address such feasibility, MAR objectives, influent water sources, and proper sites and methods should be identified. In the MENA region, the fundamental purposes of MAR projects are long-term aquifer conservation, aquifer recovery and the need for emergency storage. The last purpose is intended for countries that depend heavily on desalination as a primary source of water, such as the GCC. A good example is constructing 315 aquifer storage and recovery wells in the Liwa desert in the UAE. The project aims at recovering 170,000 m³ of water daily for three months to meet water requirements during emergency periods. The Shuweihat S1 Power and Desalination Plant is the source of injected water at a rate of 26,500 m³/day. Also, in terms of MAR feasibility, the relationship between recharge and uptake should be studied. This requires conducting laboratory experiments and field investigations. Laboratory experiments imply the installation of equipment along with allocating time and skilled labour to monitor physical models. Because of this, conducting laboratory experiments might be challenging in many MENA countries. It is also hard to imitate practical site conditions and represent heterogeneous aquifers in the laboratory. Field tests are generally more trustworthy, particularly if specific (limited) areas are being considered. After a laboratory experiment or field test has been conducted, it is advisable...
to implement a pilot MAR scheme before full-scale operation systems. Social and economic analyses have to demonstrate the feasibility of a MAR project as well.

Figure 3 depicts a framework for all the aspects needed to evaluate MAR feasibility. Before applying this framework, the characteristics of each MAR method and its merits and demerits (Table 1) should be used as a baseline for choosing an appropriate method. For example, if the topsoil layers are permeable, then spreading, in-channel modification, and rainwater harvesting methods could be used with low construction and maintenance costs. Aquifer storage and recovery and aquifer storage, transfer and recovery methods are not appealing due to their high treatment cost and low infiltration rate compared with rainwater harvesting methods. In deep, unconfined aquifers, surface spreading can be applied. If the land cost is high, injection wells are good choices (Yuan et al., 2016). Direct injection in unconfined aquifers is not feasible economically. Conversely, aquifer storage and recovery and aquifer storage, transfer and recovery methods are required in underlying confined or shallow, unconfined aquifers (≤ 100 m) if the topsoil layers are impermeable (Yuan et al., 2016). Confined aquifers can better protect injected water from lateral flow losses.

Conclusions and recommendations

Most MAR projects in the MENA countries demonstrated that MAR is a promising solution for water resources scarcity. This review gives some examples of MAR developments in the MENA countries, documenting the success or failure of each project. Several successful project examples in five MENA countries (Algeria, the UAE, Iraq, Palestine, and Lebanon) have contributed to the growth of the global IGRAC-MAR inventory. Extra MAR sites in other countries are also documented. Conversely, failed projects illustrate valuable lessons to take into consideration when implementing new facilities.

MAR is gaining recognition in the MENA region, and water organizations have added it to national water strategies; however, this review shows that MAR systems are limited to a few incomplete projects or unsuccessful trials in countries such as Libya, Algeria, Lebanon, Iraq, Qatar, Kuwait, Saudi Arabia, Yemen, and Bahrain. The rapid increase in MENA’s population, unsustainable abstraction, technical and social constraints, and weak regulations have hindered MAR in many countries. Another reason for MAR’s lack of success is the large deficit in data regarding aquifer characterizations, hydrogeological conditions and economic analyses. Data scarcity obscures MAR feasibility in the MENA region. Gaining social acceptance of the MAR process and ensuring its cost-effectiveness has also been challenging in the MENA region. The effectiveness of MAR can only be achieved by creating an integrated knowledge base that includes all these factors. This knowledge will encourage making informed and timely decisions on MAR implementation processes.

It is critical to rethink the feasibility of MAR before making the practice common in all groundwater management plans. No specific method is effective in all areas. Using an evaluation framework, as proposed in the fifth section, helps identify the optimum performance and feasibility of MAR. To this end, health-risk and socioeconomic analyses should be performed. After ensuring MAR feasibility, there should not be a lag in the time it takes to implement the process. For example, Massaad (2000) proposed reducing seawater intrusion in the Hadith aquifer by feeding aquifer storage and recovery wells
from the Beirut River in the 1960s. The first test was conducted in the 1970s and the project was implemented in the 2000s. Projects should move on a much faster timeline.

Special attention should be drawn to karst regions such as in Lebanon, Jordan, Egypt, Palestine, Israel, Syria, Iraq and the GCC countries. Our survey shows that little has been done to reveal the fate of infiltrated water in karst environments, which has negatively affected the uptake process in several MENA countries. The water levels, water quality and soil moisture of karst environments should be monitored around MAR projects. Developing countries can use inexpensive tracers (e.g., dyes and chloride) to monitor the fate of recharged water, whereas radon and stable isotopes of water are good choices in developed countries. Periodic monitoring of MAR projects in karst environments helps quantify both water losses from evapotranspiration and lateral flow and water deterioration by ambient groundwater. After that, it is advisable to consider the uncertainty of the recovery process.

**Future research**

This review shows that several MENA countries have not drawn adequate attention to the MAR; they did not consider it as a main part of water management policies and strategies in light of increasing demands and limited and deteriorating water resources. Since implementing MAR is necessary for reducing water problems, MENA countries should approve measures for establishing scientifically based criteria and procedures for implementing new MAR facilities and monitoring existing ones. These measures will ensure the effectiveness of MAR projects and protect public health and the environment. WHO guidelines for water protection, data from local studies, public participation and economic efficiency studies are good places to start to create these measures. Our research also showed that providing guidance to MAR owners and local authorities, especially rainwater harvesting users, to aid them in conducting regular monitoring and maintenance has not yet been explored. Such monitoring and maintenance help ensure a good-quality water supply for users. Otherwise, pollution is expected in recharged water, which creates significant risks for human health, as illustrated by MAR failures in Palestine, Egypt, Tunisia and Jordan (Table 4).

The MENA region is highly vulnerable to climatic changes, according to the Intergovernmental Panel on Climate Change (IPCC) (2014). The MENA region is projected to have warmer temperatures, less but extreme precipitation, and (more common) heatwaves. Although MAR can increase water storage and alleviate the climate impact on water availability, further research is needed to reveal the response MAR projects can have to future changes in climatic parameters and how to include these changes within design processes.

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The findings reported herein are solely those of the authors. The authors declare no conflict of interest.
Authors contributions

Conceptualization, Salah Ajjur and Husam Baalousha; Data collation, Methodology, Analysis and Writing – first draft preparation, Salah Ajjur; Review and editing, Salah Ajjur and Husam Baalousha; Fund acquisition, Husam Baalousha.

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