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ORIGINAL ARTICLE

Identifying Optimal Locations for Artificial Groundwater Recharge by Rainfall in the Kingdom of Bahrain

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Abstract

The Kingdom of Bahrain has extremely poor endowment of water resources. In the last four decades, the kingdom has experienced fast-paced socio-economic development and rapid population growth which has been associated with dramatic increase in water demands. To meet these water requirements, heavy reliance on groundwater was made, leading to its over-exploitation and resulting in a significant decline in groundwater levels and serious degradation in its quality due to saltwater intrusion. To rehabilitate groundwater, authorities need to pursue two management approaches: (1) lowering groundwater abstraction to its safe yield through implementing demand management and conservation policies; and (2) augmenting groundwater storage by managed aquifer recharge (MAR). In the latter case, recharge can be made during rainfall extreme events, where relatively large amounts of water become available in a relatively short time and accumulates at surface depressions. These waters can be stored in groundwater by enhancing their infiltration through gravity injection wells. In this research, the optimal locations for MAR in Bahrain are identified by employing a multi-criteria decision-making (MCDM) methodology using geographic information system (GIS). The weighted overlay method (WOA) was implemented to identify optimal MAR locations using eight parameters: geology, geomorphology, soil type, land use/land cover, slope, curvature, drainage density, and distance from lineaments. The highest scores (ranked excellent to very good), indicating the most suitable locations for both rainwater harvesting and MAR, were identified at a number of locations. Then, these locations were validated by actual MAR field projects conducted in Bahrain by the water authorities and the majority of these locations were found in agreement. As next steps, it is recommended to conduct an in-depth investigation at the identified locations using a higher-resolution satellite images with utilities infrastructure maps, and include the depth to groundwater as a criteria for the optimum selection of the sites, to be followed by MAR pilot field investigation, monitoring, and modeling for the highest potential locations.

Keywords Multi-criteria decision-making (MCDM) · Aquifer storage and recovery (ASR) · Managed aquifer recharge (MAR) · Weighted overlay analysis · Digital elevation model (DEM) · Integrated water resources management

1 Introduction

The Kingdom of Bahrain is located in an arid region with very limited renewable water resources. In the past four decades, the Kingdom has experienced sustained socio-economic development accompanied by accelerated population and urbanization, which has been associated with significant increase in water demands leading to groundwater withdrawal to exceed its natural recharge by more than two-fold (Zubari and Lori 2006). This over-exploitation has resulted in a considerable decline in groundwater levels, and serious degradation in groundwater quality due to saltwater intrusion rendering it unusable in many parts of the kingdom (Al-Zubari et al. 2018). In response, the water authorities in

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Bahrain have adopted major water supply augmentation programs starting from the 1980s. This was manifested in the developments of nonconventional water resources, namely expansion in desalination and reuse of treated municipal wastewater. These non-conventional sources aim at providing additional water supplies for the municipal and agricultural sectors, respectively, and also reducing pressures on groundwater resources (Zubari and Lori 2006).

In general, sustainable groundwater management strategies are divided into demand-side management interventions and supply-side engineering measures (Foster et al. 2003). The first strategy aims at constraining demand for groundwater abstraction by either applying demand management tools (technological, economic, and sociopolitical), or by supplementing groundwater resources with non-conventional water sources, as has been made by the water authorities in Bahrain. The second strategy aims at water harvesting and enhancing groundwater storage, which is being investigated in this study.

One of the well-known supply-side techniques for groundwater management in arid and semi-arid regions is managed aquifer recharge (MAR). MAR can be useful in re-pressurizing aquifers subject to declining yields and saltwater intrusion, such as the case in Bahrain. It should be regarded as part of the integrated water resources management strategy and it can play an important role as a part of a package of measures to restore groundwater balance (Gale 2005). Given increasing water demand and stresses on available water supplies, and the water imbalance between wet and dry seasons, MAR techniques are likely to become an important component of water projects in arid and semi-arid regions (Niazi et al. 2014).

Groundwater recharge could be made by diverting water to large spreading recharge basins that infiltrates into the aquifer, using injection wells, or by impounding water in a channel with an inflatable dam or a check dam or other approaches to increase infiltration (Maven 2019). One of the essential MAR techniques is the engineered system of Aquifer Storage and Recovery (ASR), whereby surface water is moved to aquifers via water harvesting or injection wells that serves to bolster the storage of groundwater resources. This technique was first applied in Green Bay, USA in 1957 to inject potable water into saline aquifers (Cederstrom 1957; Bahr et al. 2002). ASR projects are increasing in number nationwide, especially in areas with potential water shortages (EPA 2018).

Scientific literature indicates many studies were conducted to identify and locate the optimal locations for MAR and water harvesting (WH) implementation in arid and semi-arid regions. Due to the spatial nature of the investigation and the involvement of many controlling parameters for WH and MAR, these studies typically employ geographic information system (GIS) and the general methodology of multi-criteria decision-making (MCDM) methodology, where optimal locations are identified based on some set criteria on the values of these parameters. Within the methodological approach of the MCDM, various techniques and methods are employed, the most widely used are the Weighted Overlay Analysis (WOA) (Senanayake et al. 2016; Samson and Elangovan 2015; Kaliraj et al. 2014; Riad et al. 2011), Fuzzy Logic Model (FLM) (Ghayoumian et al. 2007; Mahdavi et al. 2013), Fuzzy C-means Model (FCM) (Mahdavi et al. 2013; Dashtpagerd and Vagharfard 2014), and Boolean Logic Model (BLM) (Ghayoumian et al. 2007; Riad et al. 2011; Al-Adamat 2012; Vaqharfard and Dashtpagerdi 2014; Al-Shabeeb 2015). Within the WOA, the weights of the parameters are being assigned based on two techniques: the Analytical Hierarchy Process (AHP) (Sabokbar et al. 2012; Mehrabi et al. 2013; Kaliraj et al. 2014; Al-Shabeeb 2015) and the Multi-influencing Factor (MIF) (Samson and Elangovan 2015; Ramireddy et al. 2015).

The most widely used parameters in the literature in identifying the optimal locations for WH and MAR in arid regions are, in this order: slope, soil characteristics (soil infiltration rate), land use/land cover, lineaments (fractures/joints), geomorphology, aquifer characteristic and depth to groundwater. In the case of relatively large areas, rainfall spatial distribution is included. Typically, the output of these studies is in the form of ordinal maps showing the degree of suitability for WH and MAR. The effectiveness and accuracy of the adopted MCDM methodology and its various techniques in identifying the optimal locations are validated by ground-truthing. This is basically achieved by comparing the obtained optimum locations for WH and MAR with actual groundwater levels as an indication of groundwater natural recharge in these locations (e.g., Samson and Elangovan 2015), and in other cases, the obtained locations are validated by conducting pilot projects at the optimal sites (e.g., Al-Shabeeb 2015).

As groundwater continues to be an important water source in supplementing Bahrain's increasing water requirements, as well as to serve as strategic reserve in emergency cases, MAR by rainfall represents one of the main potential strategies to augment groundwater storage, an option that has not been explored yet in Bahrain. If practiced effectively and in appropriate sites, it could help in increasing groundwater storage and improve its quality, as well as protecting the aquifer from the seawater intrusion. This research aims at contributing to the effective and sustainable management of groundwater resources in the kingdom of Bahrain by identifying potential surface locations for groundwater artificial recharge by rainfall using the MCDM methodology and GIS techniques.

2 Study Area

The Kingdom of Bahrain consists of an archipelago of over forty islands and shoals located in the western part of the Arabian Gulf between Saudi Arabia and Qatar (Fig. 1). The total land area of the Kingdom is about 780 km^2 with an estimated population of about 1.5 million in 2018. As most of the Arabian Peninsula, Bahrain is situated in an arid region with extremely poor endowment of freshwater resources, and when its population is taken into account, is considered as one of the most water-stressed regions of the world. Its climate is characterized by high average temperatures (Fig. 2), erratic and limited rainfall averaging about 80 mm/year (Fig. 3), and high evapotranspiration rates averaging 1800 mm/year (Zubari 1999). The combination of these conditions results in high deficit in the country's natural water budget, and therefore creating unfavorable conditions for a perennial surface water system to exist (Zubari and Lori 2006). However, it should be noted that in some cases, most of the annual rainfall is received in few days with high intensity, which if utilized properly through WH and/or MAR techniques can become beneficial in enhancing groundwater storage.

The Dammam aquifer system represents the only natural, renewable relatively freshwater source available for Bahrain. The system is developed in the Dammam Formation rocks (Fig. 4), which consists of two groundwater zones, the Alat zone (termed 'A' aquifer), and the Khobar zone (termed 'B' aquifer). The 'B' aquifer zone is developed in highly fractured limestones and dolomites and is the principal aquifer in Bahrain, where it provides most of groundwater abstraction. The best quality of water produced from Khobar is at about 2500 mg/L. The 'A' aquifer zone has limited hydraulic properties and due to its widespread salinization (best quality about 3500 mg/L) is

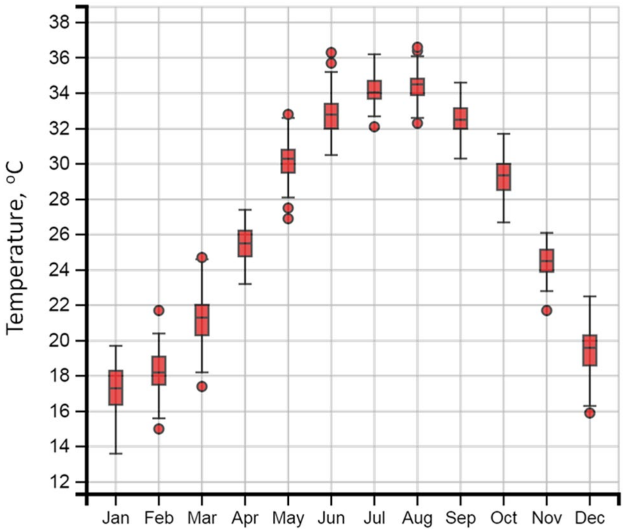
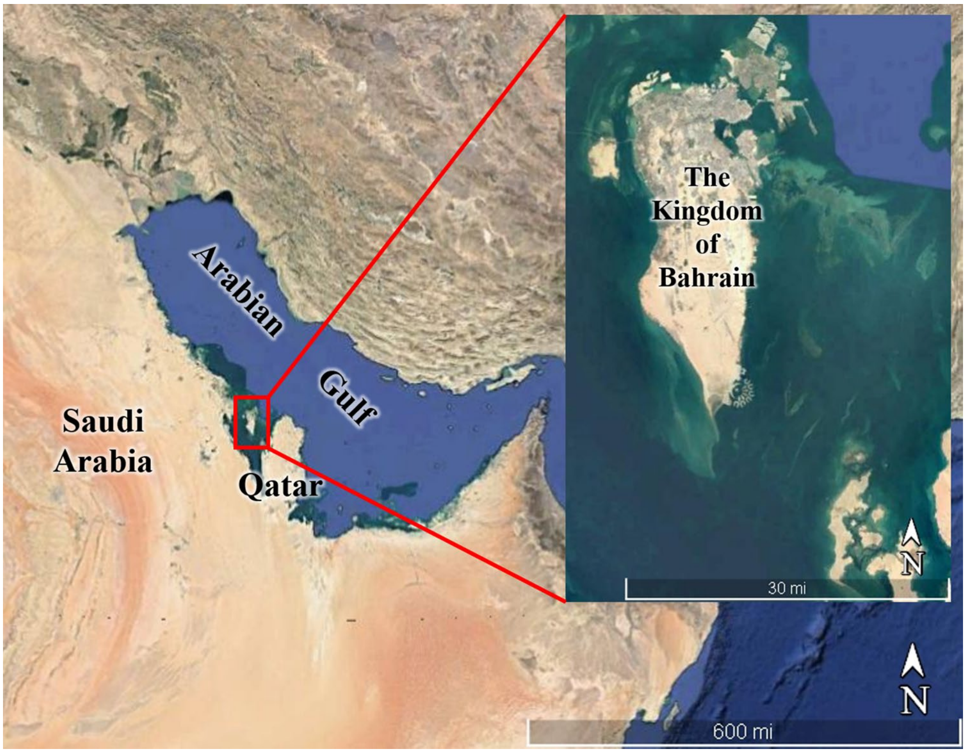


Fig. 2 Box plot of temperature distribution showing the average, 25th and 75th percentiles, and minimum and maximum extreme values recorded for the period 1928–2019 in Bahrain International Airport based on data from NOAA (Technische Universitat Dresden 2020)

Fig. 1 The Kingdom of Bahrain location



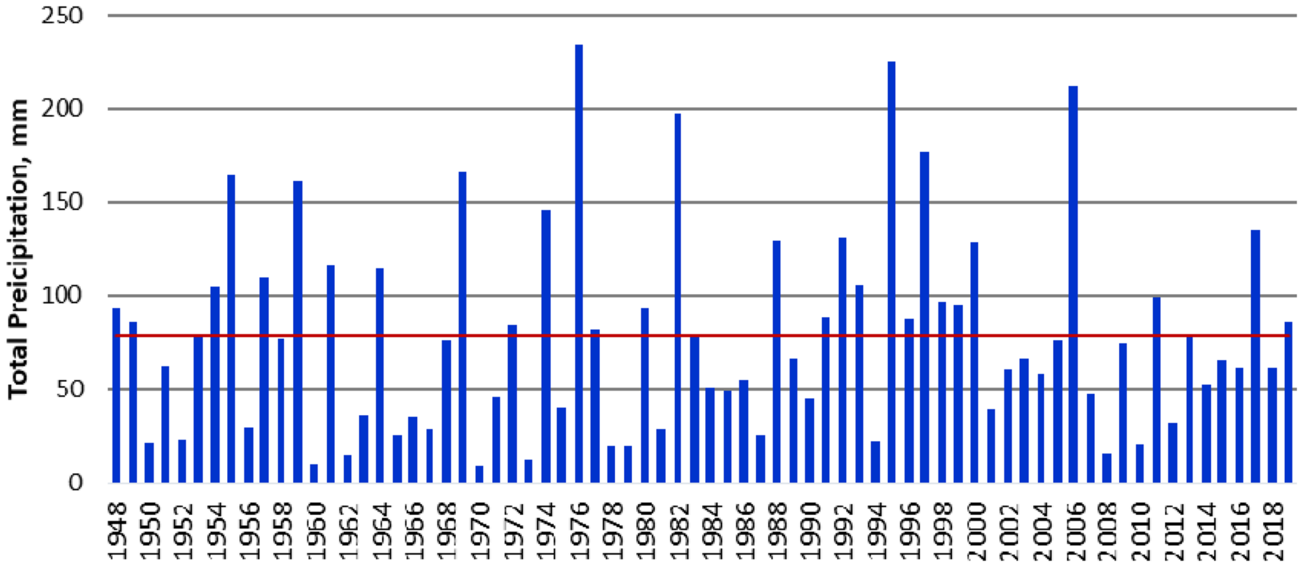


Fig. 3 Recorded Annual rainfall and average rainfall recorded in Bahrain International Airport for the period 1948–2019 (Meteorological Directorate 2019)

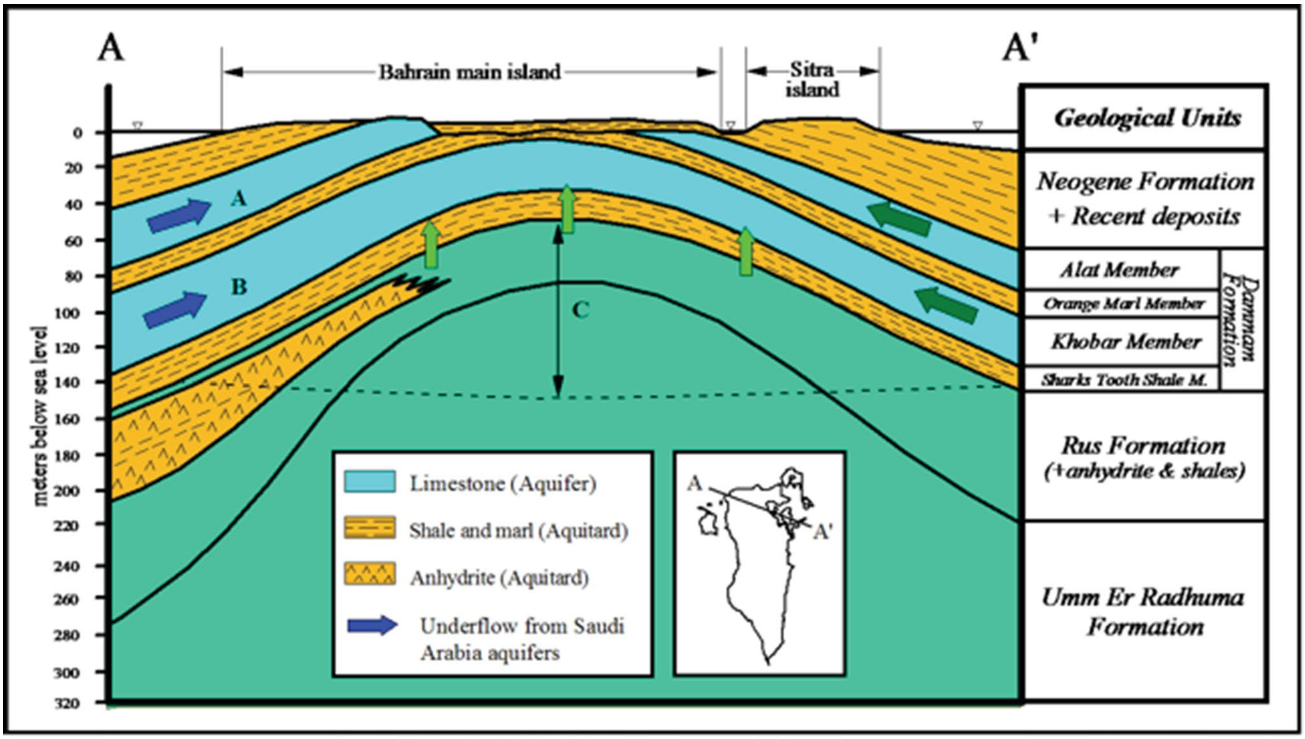


Fig. 4 Schematic Hydrogeological cross section for Bahrain Groundwater system (Zubari 1999). The colors of the zones denote the salinity categories: blue = relatively freshwater inflow from Eastern Saudi Arabia in the A and B aquifers; light green = brackish groundwater in the deeper C aquifer; arrows signify flow directions of water bodies: dark green arrows = lateral intrusion by saline seawater; light green arrows = vertical up-flow from brackish waters

being used at a very local scales by farmers. The Dammam aquifer system forms a small part of the extensive regional aquifer system, termed the Eastern Arabian Aquifer, which extends from central Saudi Arabia where the main recharge area of the aquifer is located to the shores of the Arabian Gulf, including Bahrain. Recharge to the Dammam aquifer system in Bahrain is considered as insignificant, estimated at a mean annual rate of 0.5 Million cubic meters (MCM) (Zubari 1999). In comparison, annual recharge by lateral inflow from eastern Saudi Arabia is estimated to range between 83 and 90 MCM (UNESCWA 2013). A third aquifer zone, termed 'C', underlies the Dammam aquifer system and is developed in the fractured limestone rooks of the Rus and Umm Er Radhuma Formations. The 'C' aquifer zone contains brackish to saline water occurs in the form of a large lens with downward increasing salinity (Zubari 1999; Zubari et al. 1993).

Heavy reliance, since the 1970, on groundwater from the Dammam aquifer, particularly for the development of the agricultural and municipal sectors, has increased groundwater abstraction rates to more than twice its recommended safe yield (Fig. 5). This over-exploitation has resulted in a severe decline in its water levels, leading to the cessation of natural springs flow, and deterioration of groundwater quality due to reversal of hydraulic gradients between the relatively freshwater aquifer and adjacent brackish and saline water bodies and their encroachment into the aquifer.

To meet Bahrain's increasing water demands and to conserve groundwater resources, the water authorities directed their efforts toward developing non-conventional water sources, namely expansion in desalination and reuse of treated wastewater. At present, municipal water supply in Bahrain depends almost completely on desalination, while treated wastewater supplements groundwater in the agricultural sector.

3 Methodology

To achieve the research objectives of identifying the potential surface locations for WH and MAR by rainfall, the MCDM methodology was implemented using the following sequential steps (Estoque 2011, 2012; Murayama 2012).

3.1 Data Collection and Pre-processing

Based on literature on MCDM application in arid regions and the hydrologically arid nature of Bahrain, eight parameters were selected in identifying the most suitable locations for WH and MAR. These parameters are:

1. *Geology* provides information on the underlying rocks layers properties. Rocks porosity differs from one type to another and it has an essential effect on the recharging capacity (Senanayake et al. 2016);
2. *Geomorphology* plays an important role in occurrence, movement and quality of groundwater. Porous and permeable zones could be detected by the landforms (Senanayake et al. 2016);
3. *Soil Type* an important parameter determining site suitability for recharge. Soil texture and hydraulic characteristics (permeability) influence rate of infiltration (Punmia et al. 2005);
4. *Land Use/Land Cover* impacts the rate of surface runoff, infiltration and utilization of the groundwater (Senanayake et al. 2016);
5. *Slope* directly influences infiltration, where steep locations have low level of recharging ability, while flat lands have higher suitability of recharging (Krishnamurthy et al. 2000);
6. *Curvature* Curvature is quantitative expression of the nature of surface profile, which can be concave or convex (ESRI 2019). A concave profile (positive values) will accelerate water flow while a convex profile (negative value) will decelerate water flow (Arulbalaji et al. 2019); and
7. *Drainage density* Highly influential parameter for suitable artificial recharge locations by indicating indirectly the permeability and porosity of the terrain related to the surface runoff (Krishnamurthy et al. 2000).

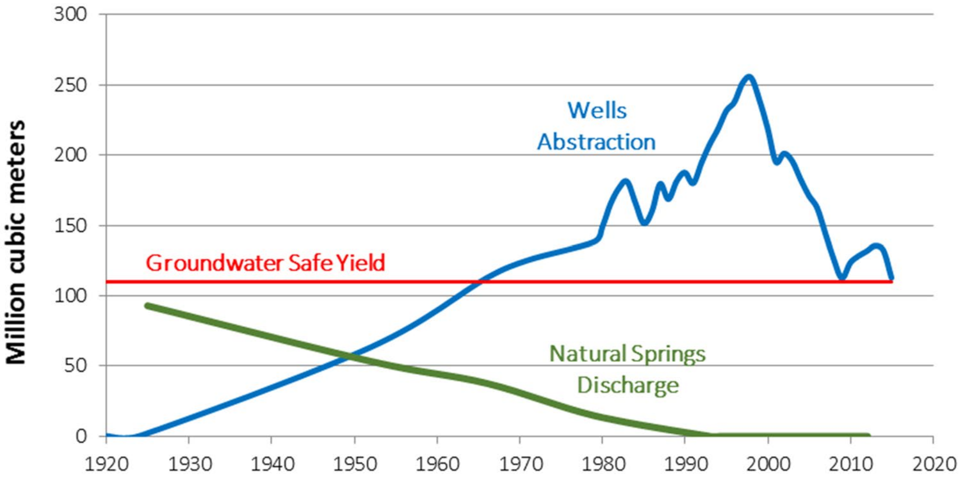


Fig. 5 History of groundwater exploitation from the Dammam aquifer in Bahrain, 1920–2015. Data source: Department of Agricultural Engineering and Water Resources, Ministry of Works, Municipalities and Urban Planning

8. *Lineaments* indicates zones of faults, fractures, and joints that help groundwater movement and storage (Senanayake et al. 2016); the distance to a major lineament was used in this analysis;

Data for these eight selected parameters were collected from various sources, as follows. Analog maps and shape file data were collected from the Agriculture Affairs in the Ministry of Works, Municipalities and Urban Planning, and from an official publication on the geology, geomorphology and pedology of Bahrain (Doornkamp et al. 1980). Digital elevation model (SRTM DEM) data were downloaded from the United State Geological Survey Earth explorer website (USGS 2019). The collected data were then underwent preprocessing stage as follows: Analog maps were geo-referenced and digitized on-screen; shape files and DEM were re-projected to the same UTM projection of the Kingdom of Bahrain; vector data were converted to raster model data toward their standardization to implement the WLC model; and digital elevation model (SRTM DEM) was mosaicked and extracted to match the study area. Base maps of Slope, Curvature, Drainage Density, and Distance to lineaments were generated from the DEM projected data (Fig. 6), while the base maps of the parameters of Geology, Geomorphology, Soil type, and Land Use/Land Cover were converted from the vector shapefiles that were digitized from analog maps (Fig. 7).

3.2 Criteria Determination

In the GIS environment, data layers of the phenomena or measurements are the criteria that used in implementing the MCDM. ArcGIS Desktop pack was used to create, generate and modify criteria layers to be appropriate for the analysis. In this step, a geo-database was created and loaded with all the vector layers and raster data. Then, vector layers were converted to raster in a pixel size of 30 × 30 m to be adequate with the SRTM DEM. Rasterizing the data was important also towards standardizing the criteria in the next step of applying the MCDM using the selected criteria of geology, geomorphology, soi type, land use/land cover, slope, curvature, drainage density, and distance from lineaments.

3.3 Factors Standardization and Ranking

The ranking of the selected parameters of Slope, Curvature, Lineaments, and Drainage was based on their floating values, while for the other four, i.e., Geology, Geomorphology, Soil Type, and Land Use/Land Cover, it was based on their types.

This is made as follows: (1) Slope: absolute values of slope were reclassified into 5 classes from 1 to 5, and then were ranked from 1 to 5 based on the slope value, where lowest slope class was given the rank value of 1, i.e., more favorable for a recharge site, and the highest slope class ranked 5, i.e., least suitable for a recharge site (Subagunasekar and Sashikkumar 2012; Bera and Bandyopadhyay 2012; Ndatuwong and Yadav 2014; Patil and Mohite 2014; Sajjad et al. 2014; Al-Ruzouq et al. 2015; Samson and Elangovan 2015; Al-Shabeeb 2015); (2) Curvature: obtained curvature values were reclassified into nine classes, and were ranked in that highest positive values have the highest ranks (Arulbalaji et al. 2019; Ayetan 2019; Zhang et al. 2019; Benjmel et al. 2020); (3) Lineaments: the distances from lineaments were reclassified into nine classes, and those classes were ranked from 1 to 5, where closer distances were given the rank of 1 and vice versa (Subagunasekar and Sashikkumar 2012; Ndatuwong and Yadav 2014; Patil and Mohite 2014; Samson and Elangovan 2015; Al-Shabeeb 2015); and (4) Drainage density: absolute values of drainage network density were re-classified into 9 classes, and then ranked from 1 to 5, where locations with high drainage density given higher ranking values (Sukumar and Sankar 2010; Ndatuwong and Yadav 2014; Patil and Mohite 2014; Sajjad et al. 2014; Samson and Elangovan 2015; Al-Shabeeb 2015). Figure 8 displays the reclassified maps of these four parameters. Tables of the reclassification and ranking of these four parameters are given in Appendix (A).

The ranking of the other four parameters (Geology, Geomorphology, Soil Type, and Land Use/Land cover) was based on ranks obtained from the literature, as follows: (5) Geology: Carbonate rocks, which are the dominant rock type in Bahrain, are considered as the most suitable for recharge and were given the highest rank of 1, while marls and shales are given lowest rank (Sukumar and Sankar 2010; Subagunasekar and Sashikkumar 2012; Bera and Bandyopadhyay 2012; Sajjad et al. 2014; Al-Ruzouq et al. 2015; Samson and Elangovan 2015); (6) Geomorphology: ranking of geomorphological features was based on their porosity and permeability, where features with high porosity and permeability were given the highest rank of 1 (Subagunasekar and Sashikkumar 2012; Bera and Bandyopadhyay 2012; Ndatuwong and Yadav 2014; Patil and Mohite 2014; Sajjad et al. 2014; Al-Ruzouq et al. 2015; Samson and Elangovan 2015; Al-Shabeeb 2015); (7) Soil Type: soil types consisting of gravels or coarse sand were given the highest rank, while those with finer grains, such as shale, were given lower ranks (Sukumar and Sankar 2010; Subagunasekar and Sashikkumar 2012; Bera and Bandyopadhyay 2012; Patil and Mohite 2014; Samson and Elangovan 2015; Al-Shabeeb 2015); and (8) Land Use/Land cover: vacant lands were given the highest rank of 1, while the built-up areas are given the lowest as they impede infiltration (Subagunasekar and Sashikkumar 2012; Bera and Bandyopadhyay 2012; Patil and Mohite 2014; Sajjad et al. 2014; Al-Shabeeb 2015). Tables of the ranking of these four parameters are given in Appendix (B).

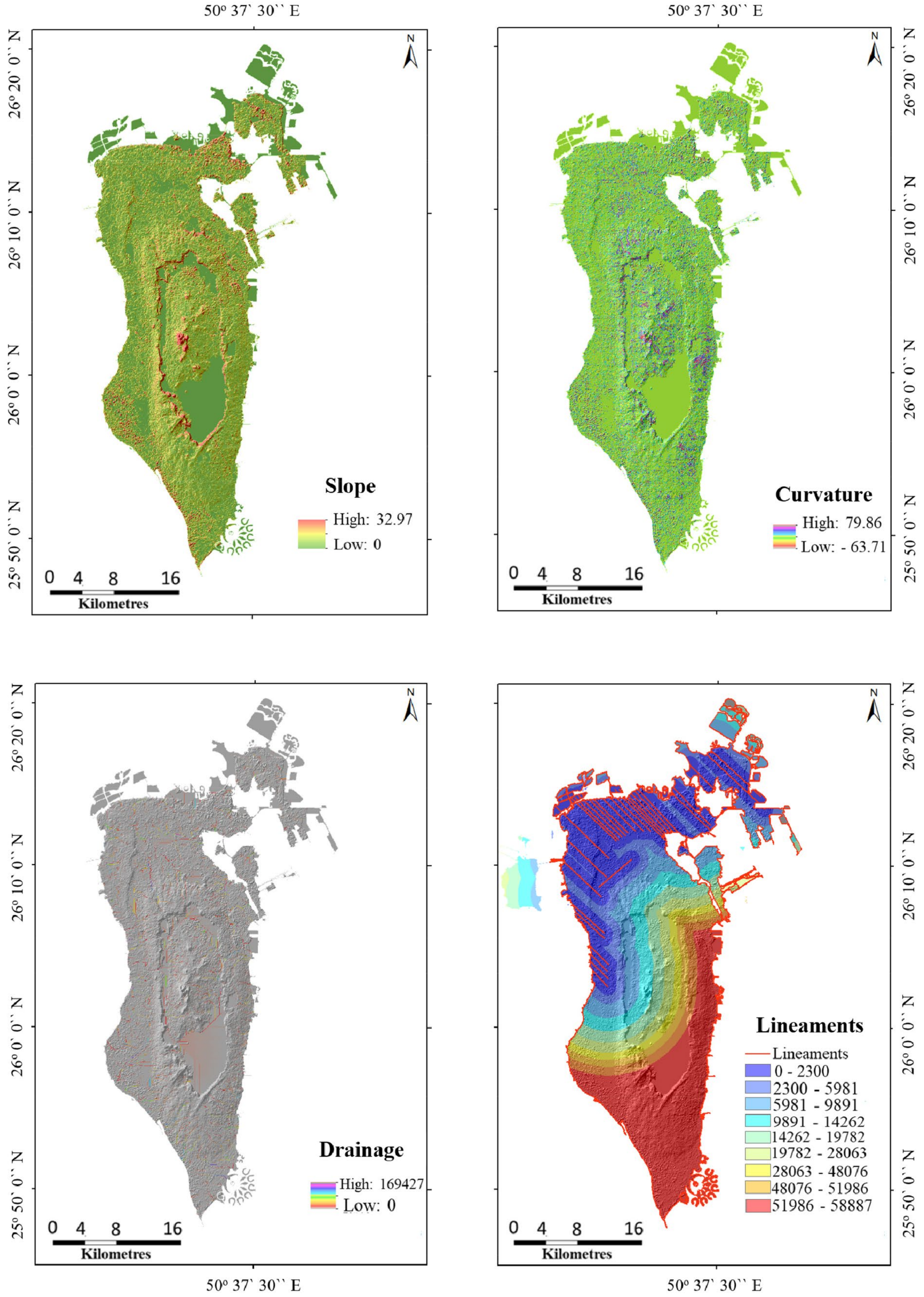


Fig. 6 Base maps generated from SRTM DEM: Slope (degrees), Curvature (meters), Drainage Density (meters), and Distance from lineaments (meter)

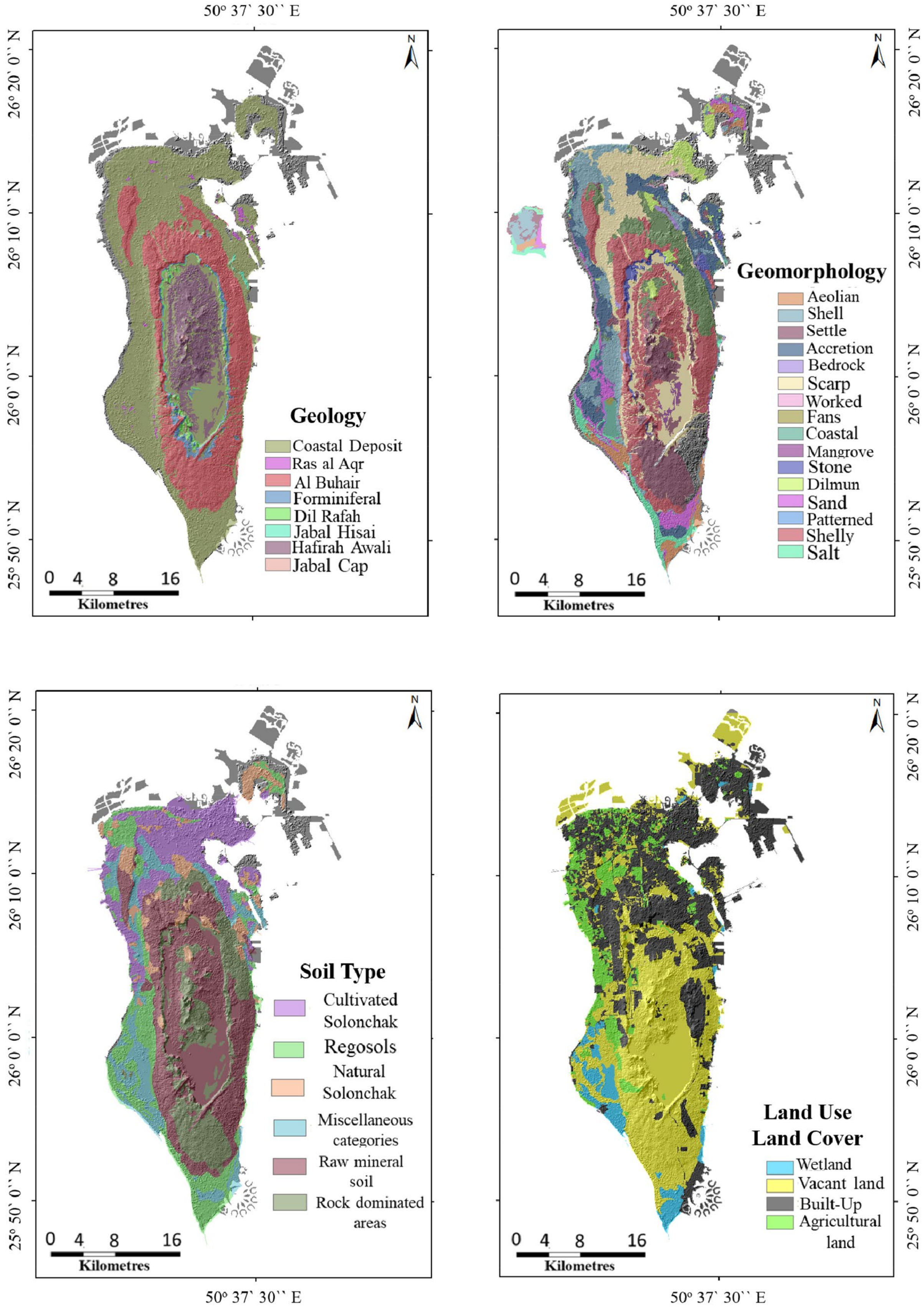


Fig. 7 Base maps converted from digitized analog maps and vector shapefiles: Geology, Geomorphology, Soil Type, and Land Use/Land Cover

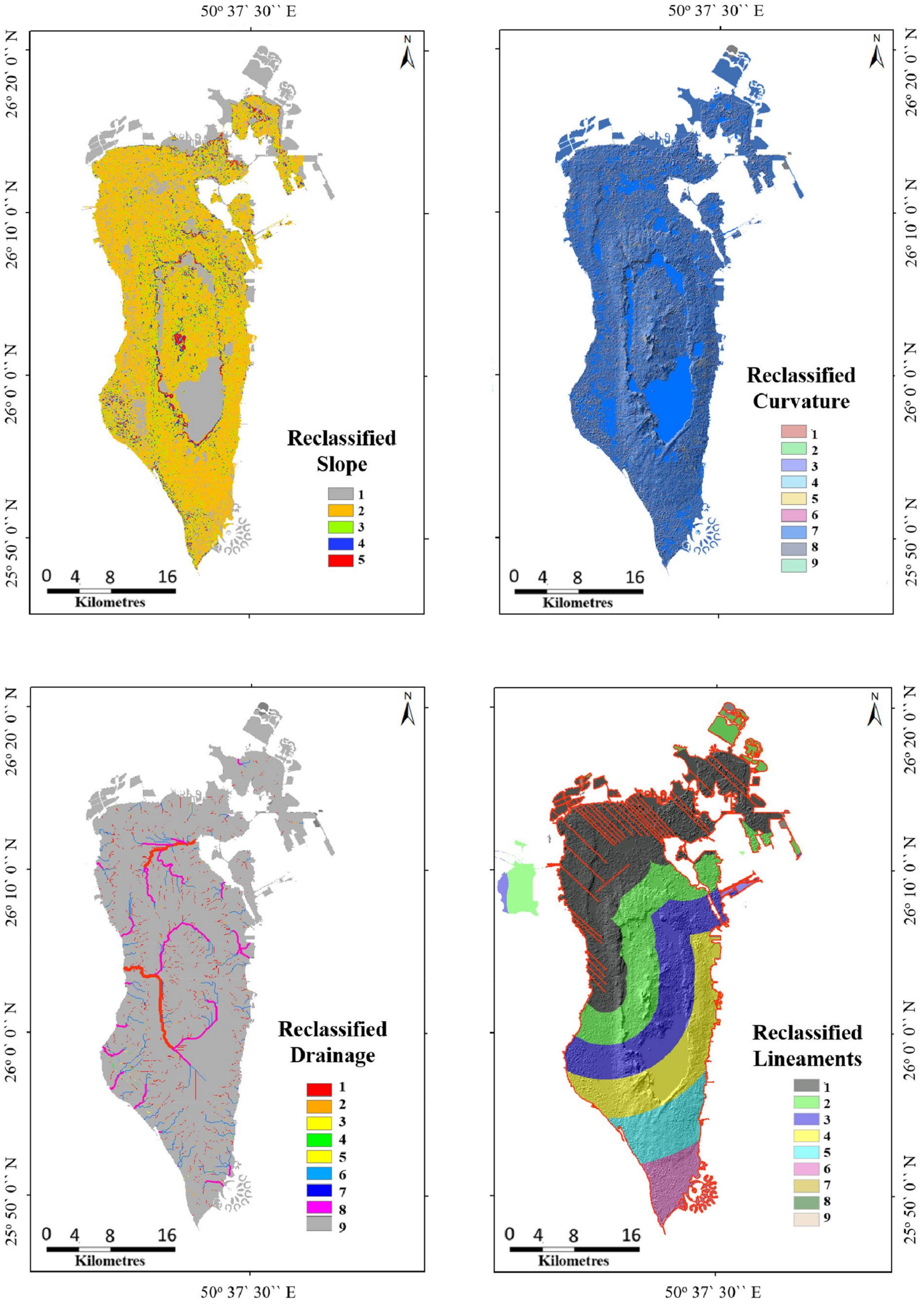


Fig. 8 Reclassified maps of slope, curvature, drainage, and distance from lineaments

3.4 Criteria Aggregation

The eight thematic raster layers were aggregated in ArcGIS system using the weighted overly analysis method. They were added to the weighted overlay tool table and the scale value and the influences of the criteria, which were determined from previous studies. It should be noted that in this analysis, the eight thematic maps were given equal weights an their influence on the end product was not differentiated.

3.5 Validation

In Bahrain, groundwater authorities have conducted a number of field projects and investigative pilot projects for MAR using rainfall water. The locations of these studies were decided by the authorities based on field observations of rainfall accumulations and flooding of urban areas. Typically, in these studies, the accumulated rainfall is moved to the aquifer by gravity through a large diameter well. The success of these pilot studies has been variable. The results of the MCDM methodology in identifying the optimal locations for WH and MAR were compared with the locations of these recharge projects to validate the ability and effectiveness of the implemented methodology in detecting the optimal locations for WH and MAR. To do this comparison, the resulted maps were converted to Keyhole Markup Language (KML), which is the Google Earth layers format (Google 2018), to overlay it on the latest satellite image of the Kingdom of Bahrain existing in the Google Earth engine.

4 Results and Discussion

The weighted overly analysis in ArcGIS has resulted in a map containing 18 classes distributed over the land area of Bahrain Island, as illustrated in Fig. 9a. A Minimum value at any location means that this location has the least suitability to be used as a recharge location for WH and MAR, and vice versa; in the case of maximum values and means, it is relatively the most suitable locations for WH and MAR.

The same results of the aggregation were converted into an ordinal-scaled map for better illustration of the results. Figure 9b displays the results of the aggregation in an ordinal scale. The figure shows that the sites with the highest potential for WH and MAR are located in the southwestern part of Bahrain Island, specifically in Mumtallah area.

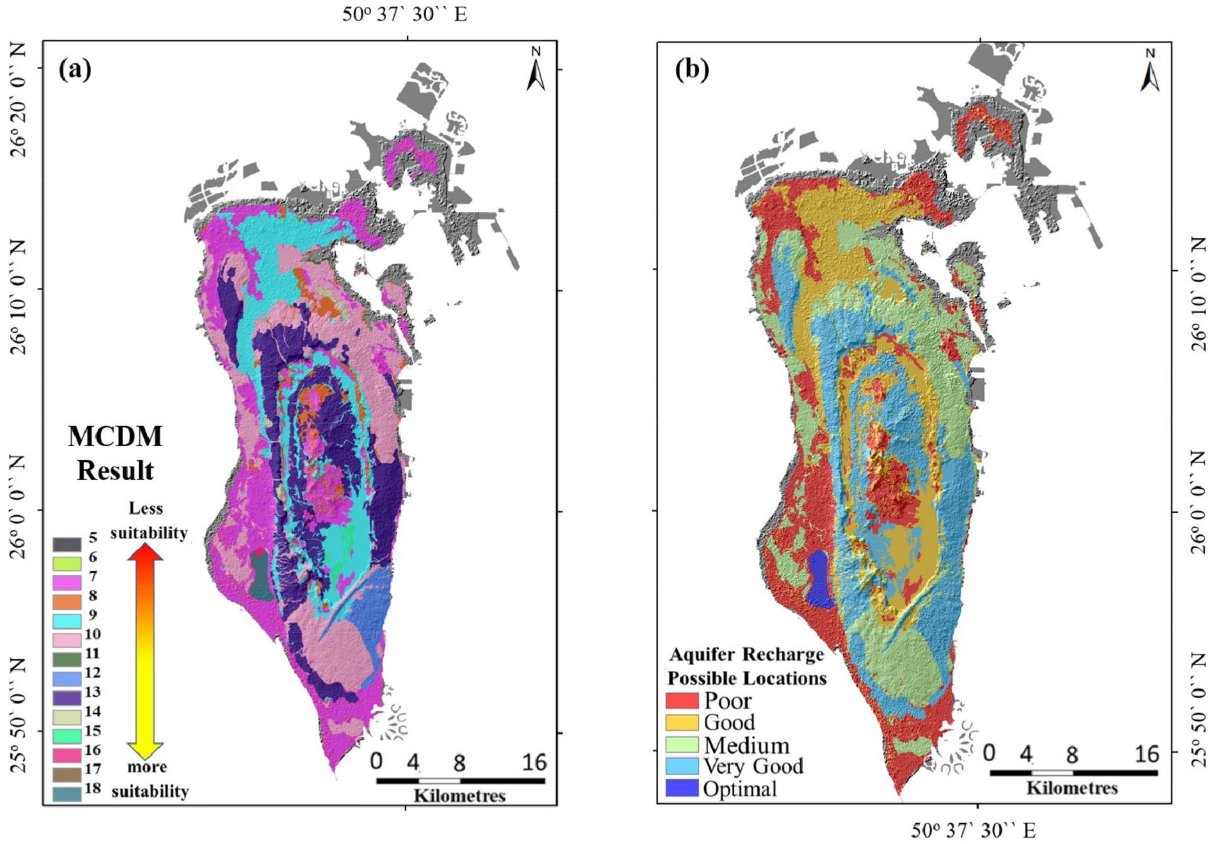


Fig. 9 **a** Resulted map of the MCDM and **b** Ordinal-scaled map for the optimal and best locations for aquifer artificial recharge in the Kingdom of Bahrain

Figure 10 shows the optimal location at Mumtallah after converting the map to a KML file format and exporting it to Google Earth.

The second best locations for aquifer artificial recharge are located in the areas that covers Al Buhayr carbonate formation, which has a very shallow groundwater with a stony soils or disturbed grounds. Only one of the previous groundwater artificial recharge experiments (1998–1999) was implemented in this area (Al-Noaimi 2012). It was in Al Hamala area next to Wali Al Ahed road indicated in Fig. 11. Unfortunately, this groundwater recharge project was not evaluated or monitored; hence, no conclusion could be made on validating the identified location using actual experimentation data.

Locations with medium potentiality for WH and MAR are indicated by the green color in Fig. 9b. Most of the previous groundwater artificial recharge experiments were implemented in this area, such as Al Rumaitha (1984), Al Zallaq basin (1992), Saffra (1996), Baghdad Road and Al Doha Road in Isa Town (1995–2007). Hydrological and chemical testing results and monitoring of these experimental wells in these locations were positive and were very good. The results of these experimental and pilot projects were encouraging for conducting more studies related to the MAR in these locations (Al-Noaimi 2012). Figure 12 illustrates five experimental locations in the green-colored area.

The yellow-colored areas in Fig. 9b illustrate relatively good locations for WH and MAR but are considered as the least option for WH and MAR experimental project. These areas have three previous groundwater recharge experimental projects: Zayed Town (2000), Al Buhair basin (1993), and Horat Aali (1995). Two of these experimental projects (Zayed town and Horat Aali) were not evaluated or monitored. The remaining Al Buhair basin experiment had negative results because of technical problems (Al-Noaimi 2012). Locations of the experimental projects lying on the yellow areas (i.e., good) were illustrated in Fig. 13. The relatively less favorable areas for WH and MAR are shown in red color in the resulted map of the MCDM (Fig. 9b); these areas are located mainly in the costal or residential locations.

5 Conclusion and Recommendations

The optimal locations for WH and MAR in Bahrain are identified using the MCDM methodology in a GIS environment. The results indicated that the implemented methodology is effective in identifying these locations with many of these are coinciding with actual MAR field projects conducted in Bahrain.

In Bahrain, if implemented properly, MAR represents a potential management option to enhance groundwater storage and help in the efforts of groundwater rehabilitation and recovery. The study investigation indicated there are in general six zones that are suitable for MAR (location ranked excellent to very good on the ordinal scale maps). One of the limitations of this research is that it was based on satellite data of a 30 × 30 m pixel size resolution, which affected its accuracy. Hence, this study could be considered as a reconnaissance study for identifying the optimal WH and MAR locations. It is recommended to isolate these locations and conduct further in-depth investigation at the identified locations using a higher-resolution satellite images and utilities infrastructure maps. Moreover, in this investigation, the

Fig. 10 Optimal location for the aquifer recharging as resulted from the MCDM and GIS techniques in Google Earth

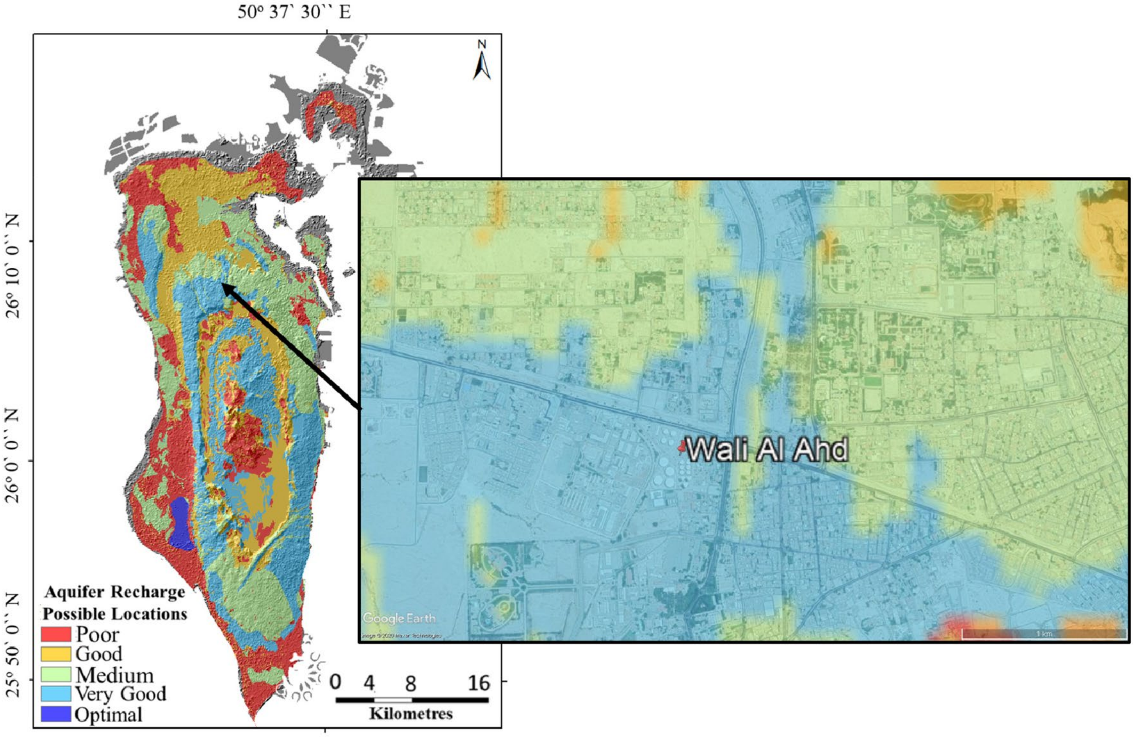


Fig. 11 Second best locations in blue color (category very good) for aquifer recharge and Wali Al Ahed road in Al Hamala injection experimental project

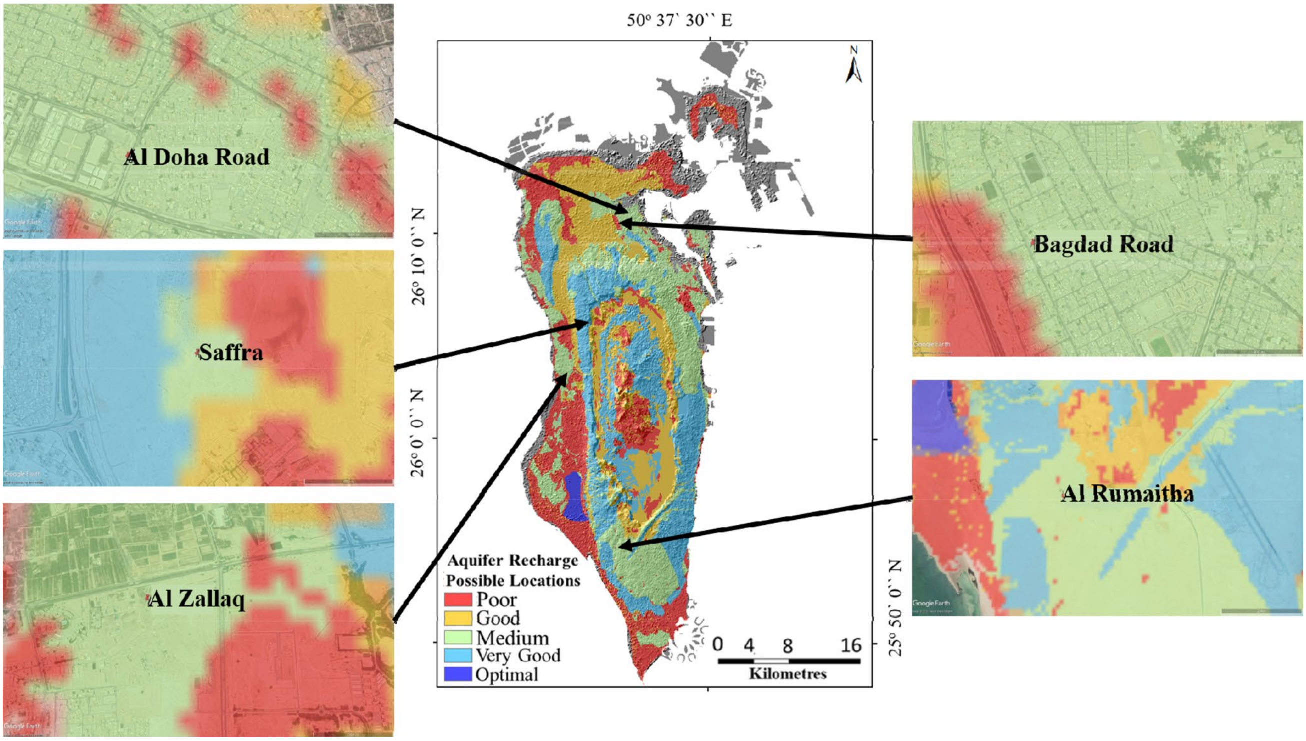


Fig. 12 The experiments' locations that are located in category medium aquifer recharge suitability zones

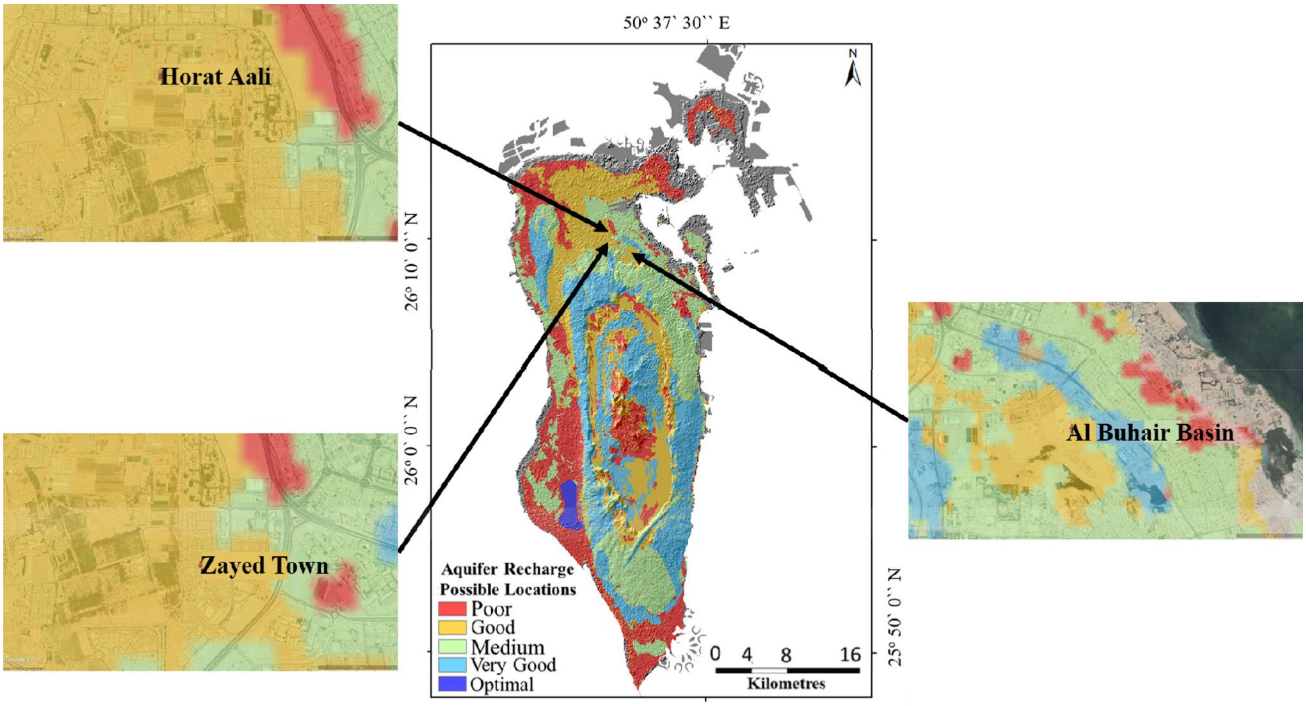


Fig. 13 The experiments' locations that are located in category "good" aquifer recharge suitability zones

parameter "depth to groundwater", which enhances groundwater recharge when groundwater is under unconfined conditions, and reduces the cost of recharging wells drilling when groundwater is under confined conditions, could not be included as a criteria for identifying the optimal locations for MAR due to lack of data. It is recommended that this criterion is included in the future follow-up investigation.

Furthermore, in this analysis, it is assumed that the influence of the eight parameters used in the investigation is the same and were given equal weights. It is recommended that future work defines the weights of these parameters, either by the AHP or MIF techniques, to differentiate their influence on the identification process. Finally, field investigation by pilot studies, monitoring water level and quality, and modeling at the selected locations will be required before the implementation of a large-scale MAR project.

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Compliance with ethical standards

Conflict of interest The authors declare that they have no conflict of interest.

Ethical approval This article does not contain any studies with human participants or animals performed by any of the authors.

Informed consent None.

Appendix A: Reclassification and Ranking Tables for the Parameters of Slope, Curvature, Drainage Density and Distance from Lineaments

Slope Parameter Reclassification and Ranking Table

Old values	New values	Ranks
0.0–0.1	1	5
0.1–2.5	2	4
2.5–4.0	3	3
4.0–6.0	4	2
> 6	5	1

Curvature Parameter Reclassification and Ranking Table

Old values	New values	Ranks
− 5.788 to 0.926	1	1
− 0.926 to − 0.347	2	1
− 0.347 to − 0.116	3	1
− 0.116 to 0.116	4	1
0.116 to 0.347	5	1
0.347 to 0.695	6	4
0.695 to 1.389	7	5
1.389 to 2.663	8	5
2.663 to 7.409	9	5

Drainage Parameter Reclassification and Ranking Table

Old values	New values	Ranks
0–401	1	1
401–1544	2	2
1544–3548	3	3
3548–7044	4	3
7044–15,283	5	4
15,283–28,802	6	4
28,802–45,921	7	5
45,921–66,743	8	5
> 66,743	9	5

Distance from Lineaments Parameter Reclassification and Ranking Table

Old values	New values	Ranks
0–2300	1	5
2300–5981	2	4
5981–9891	3	3
9891–14,262	4	2
14,262–19,782	5	1
19,782–28,063	6	1
28,063–48,076	7	1
48,076–51,986	8	1
51,986–58,887	9	1

Appendix B: Ranking Tables for the Parameters of Geology, Geomorphology, Soil Type and Land Use/Land Cover

Geology Parameter Ranking Table

Geological classes	Ranks
Coastal deposit	1
Ras al Aqr formation	2
Al Buhair carbonate formation	5
Forminiferal carbonate formation	5
Dil Rafah carbonate formation	5
Jabal Hisai formation	3
Hafirah Awali carbonate formation	4
Jabal Cap formation	2

Geomorphology Parameter Ranking Table

Geomorphological classes	Ranks
Aeolian	2
Shell	4
Settle	5
Accretion	2
Bedrock	5
Scarp	1
Worked	Restricted
Fans	2
Coastal	1
Mangrove	Restricted
Stone	5
Dilmun	5
Sand	3
Patterned	2
Shelly	2
Salt	1

Soil Type Parameter Ranking Table

Soil classes	Ranks
Cultivated Solonchak	3
Regosols	3
Miscellaneous land categories	3
Natural Solonchak	4
Raw mineral soil	5

Soil classes	Ranks
Rock dominated areas	5

Land Use/Land Cover Parameter Ranking Table

Land use/land cover classes	Ranks
Vacant land	5
Built-up	1
Agricultural land	2
Wetland	4

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