Analytical Hierarchical Processing to Delineate Artificial Groundwater Recharge Zones

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Abstract. Scarcity of water has impacted the Gulf countries and one of them is the United Arab Emirates (UAE). Among the many possibilities, a viable approach for water preservation in arid regions is Artificial Groundwater Recharging (AGR). Fresh water from multiple sources are fetched and reserved in aquifers and pumped out during lean phases. This research endeavors to delineate AGR zones in Northern part of UAE taking into account of precipitation, drainage density, geomorphology, geology, groundwater level, total dissolved solids, elevation, lineament density, and distance from residences with the aid of Remote Sensing (RS) and Geographic Information System (GIS). Parameters were measured to criteria weightings by Analytical Hierarchical Process (AHP), and then overlay analysis was performed to deduce the potential AGR map. The map was categorized in a scale ranging from very high suitability to low suitability. More than 20% of the total area was highly suitable for AGR. Geology and geomorphology were identified to be the significant factors for determination of the potential zones.

Keywords: Artificial groundwater recharge · Geographic information system · Remote sensing · United Arab Emirates · Analytical hierarchical process

1 Introduction

Urban sprawls and densely populated cities have created an immense urge on higher water consumption to fulfill several needs. The primary hurdle faced by any developing nation is inadvertent urbanization, deficient water resources and unproductive management of water supply and distribution. Developing nations specifically in arid and semi-arid climatic regions are still gathering reforms and resources to combat such issues [1]. Countries closer to sea or ocean focus on desalination and reservoir storage as water preservation practices. Since the 1990s, another technique that has gained attention is artificial groundwater recharge (AGR)[2]. It has paved the way for arid and semi-arid nations as one of the most sustainable approaches to water conservation due to higher evaporation rates [3].

The United Arab Emirates (UAE) is one of the most brisk developing nations. Its population leaped sharply from 531,265 in 1975 to 10 million in 2022 [4]. The niche

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lifestyle of the UAE population demands water consumption of about 550 L per capita per day in 2020 compared to the global average of 170–300 L per capita per day which is 82% higher than any countries [5]. Note that the UAE is located in an arid climate region with limited freshwater resources and scarce rainfall [6]. Approximately, 51% of the UAE's water supply comes from freshwater resources [7]. Thus the UAE depends on alternative water preservation practices such as desalination, water storage units, artificial groundwater recharge to meet demands during lean periods. As the country's temperature rises approximately 50 degrees Celsius in summers, any surface water storage takes a heavy toll on the economy due to high evaporation rates. Therefore the country is indulging into more sustainable practices of water conservation by adopting AGR. AGR is a scientific water storage technique of available water into aquifers and use it in dry periods for agriculture, industrial and potable purposes [8]. Many studies [8–14] have been implemented through Remote Sensing (RS) and Geographic Information System (GIS) for AGR demarcation and implementation. Primary step is to identify potential zones where RS & GIS comes to a rescue. Humble decision making approach is adapted for AGR demarcation and then tools of machine learning like artificial neural network, support vector machine, random forest and so on are further integrated to validate the data if we analyse previous researches for AGR across the globe [10, 11, 14–18]. Less AGR studies have been carried out in UAE and specially central northern UAE covering Emirates of Sharjah, Umm al Quwain, Ras al Khaimah, Fujairah and Ajman [19]. Therefore this research made an attempt to demarcate potential AGR sites for the previously mentioned emirates.

The research utilized multicriteria decision analysis by Saaty 1990 paired with weighted overlay analysis to identify potential zones for AGR. The study was carried out at the Central northern Emirates including emirates of Sharjah, Fujairah, ras al Khaimah, Umm al Quwain, Ajman, and portions of Oman. This study utlized more previous studies for analysing ranking and weighting of Analytical Hierarchical Process (AHP) compared to previous research [19] and also calculated the percentage of the area suitable and not suitable for AGR. Nine thematic layers were prepared: precipitation, drainage stream density (DSD), geomorphology, geology, groundwater level, Total Dissolved Solids (TDS), elevation, lineament density (LD), distance from residential areas. The research aims to delineate suitable locations for implementing AGR by employing RS, GIS, AHP, and the weighted overlay technique. The main objectives of this study is summarized within the following:

- Investigating suitable zones for AGR in Sharjah by utilizing RS and GIS.
- Identifying and mapping spatial thematic layers for AGR zonation: precipitation, drainage stream density (DSD), geomorphology, geology, groundwater level, Total Dissolved Solids (TDS), elevation, lineament density (LD), Euclidean distance from residential areas.
- Employing AHP and weighted overlay techniques to obtain AGR map.
- Calculating percentage of area suitable for AGR and the primary factors governing it.

2 Study Area

The United Arab Emirates is a Mediterranean country located in the western part of Asia and is surrounded by the Arabian Gulf in the west and north, Gulf of Oman in the northeast, Oman in the east, and Saudi Arabia in the south (Fig. 1) [6, 20–22]. The country's water demands are met by 43% of its available groundwater resources. However, due to its arid climatic condition, the country has reserves of only 640 billion cubic meters (BCM) of groundwater, and 20 BCM is fresh [21, 23]. The country receives approximately 102 mm of mean annual rainfall within cities and 130 mm in mountains with temperatures rising to 48 degrees during summer months in desert [21, 23, 24]. Majority of the land is covered with sand and so forth, the sand dune aquifer system dominates the geographic region. Other classifications of the aquifer system are northern limestone, ophiolite, eastern gravel, western gravel, and coastal marshes [25]. Five major cities of northern UAE have been covered in this study which includes Sharjah, Umm al Quwain, Ras al Khaimah, Ajman, and Fujairah. This region comprises equal proportions of all the aquifers classes.

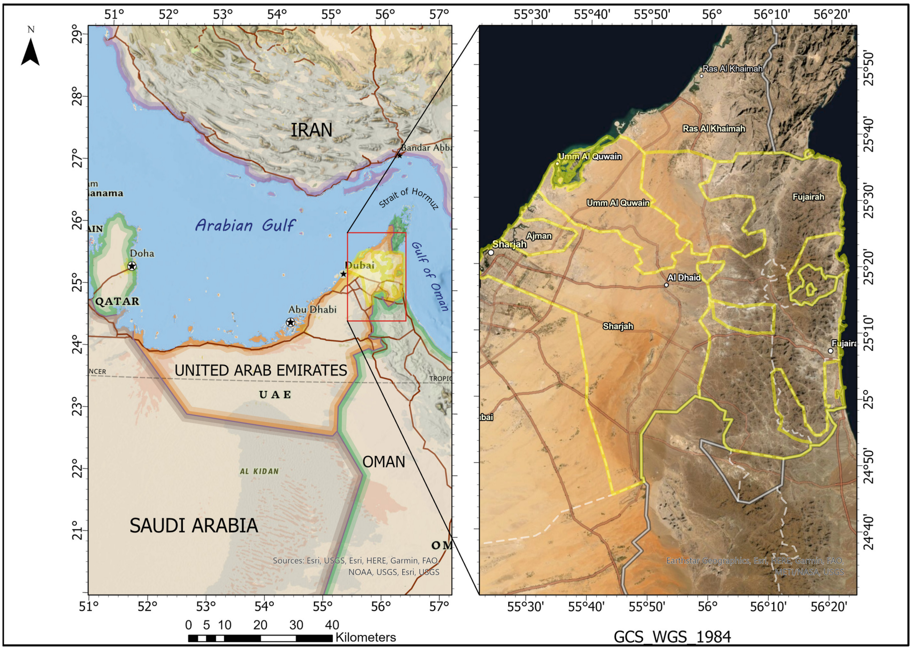

Fig. 1. Study Area.

3 Methodology and Data Processing

Figure 2 demonstrates the methodology developed for identifying potential zones for AGR. Suitable remote sensing imageries such as digital elevation model (DEM), Landsat 8, enhanced thematic mapper plus, historical data of precipitation, and salinity were used to prepare desired thematic layers contributing to AGR potential zones. The previously discussed factors pprecipitation, DSD, geomorphology, geology, groundwater level, TDS, elevation, lineament density, euclidean distance from residential areas were developed as spatial thematic layers in ArcGIS Pro. Five classes ranging from 1 to 9 derived from Natural Breaks technique, have been assigned to each layer, with 1 representing least suitability and 9 as most suitable. AHP technique helped to identify weights of each criteria. To obtain the final potential map, weighted overlay analysis was performed.

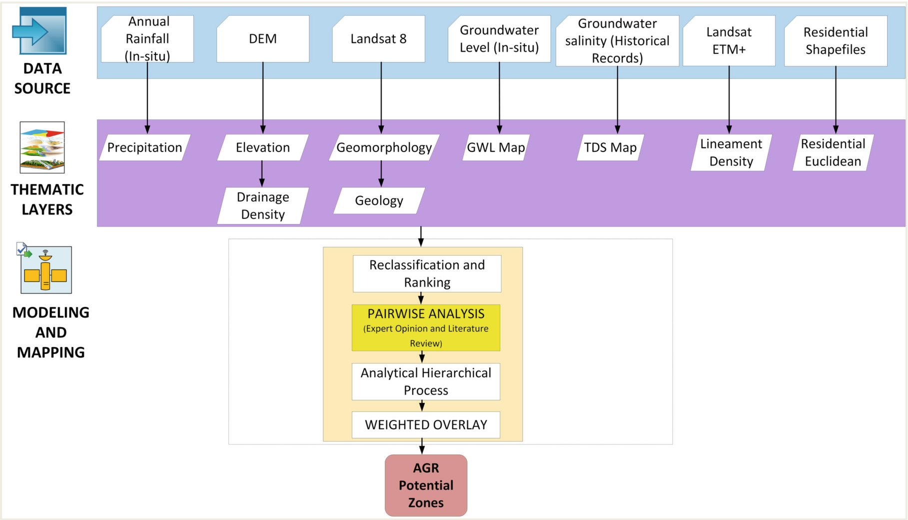

Fig. 2. Methodology Framework.

3.1 Thematic Layers Preparation

This section demonstrates the data collection, image processing aspects and its correlation to the potentiality of AGR, of each parameter primarily considered for the objective of the study. Delineating suitable AGR zones were achieved through nine spatial parameters: Precipitation, DSD, geomorphology, geology, groundwater level, TDS, elevation, lineament density, euclidean distance from residential areas [26–28]. The detailed discussion about the layers are mentioned in the following paragraphs.

Precipitation. National Centre for Meteorology, UAE, was referred to deduce annual total rainfall historical data from 2003–2017 refer, Fig. 3(a). Data was collected from the rain gauge stations and coordinates of each station were utilized to develop the point map. Inverse distance weighting interpolation technique further obtained the spatial layer of precipitation. The data helped to understand that the least average of annual total rainfall was recorded as 75mm for the study and ranged maximum up to 103mm. From multiple research articles it is profound that the regions receiving more rainfall is directly proportional to AGR potential zones [21, 23, 24].

Drainage Stream Density. DSD of the study area ranged from 0 to .58 per km^2 Fig. 3(b). The parameter is defined as the capacity of the total water drained through stream channels within a watershed represented as the ratio of total stream length of all orders by the total area of the drainage basin. Permeability of water decreases if DSD is higher [17, 26]. It is one of the fundamental parameters for AGR demarcation. SRTM (Shuttle Radar Topography Mission) DEM spatial data were used to develop the thematic layer [23]. Increased regional DSD can be noticed in the eastern part of the Sharjah Emirate, north and northeastern part of Ras-al-Khaimah and Umm-al-Quwain, respectively [21, 23].

Geomorphology. Figure 3(c) represents the geomorphology map of the study area: fan deposits, high and low dunes, mountain, sand, urban areas, and vegetation [21, 23]. Geomorphological patterns allow us to understand the water flow and movement below the ground level and explains the water storage capacities depending on permeability and porous landforms [17, 29]. Spatial data from Landsat8 ETM+ of 30 m spatial resolution was collected and processed to develop the thematic layer [23]. This study showed that fan deposits are most favorable for AGR in the UAE and accordingly the highest rank has been assigned to this criteria. As the majority of the country is covered with desert sand, high dunes also come in a higher ranking with respect to AGR determination, refer.

Geology. Landsat 8 was downloaded and shortwave infrared band were geo-processed to develop the geology thematic layer. The geology of the study area comprises: alluvium, limestone, gabbro, metamorphic, sand and ophiolite [21, 23]. Sand covers more than 45% of the study area. Recharging volume can be determined by understanding the porosity and assigning spaces for water holding [17, 29]. Alluvium holds more water compared to other classes. This study marked the alluvium class with the highest rank followed by sand.

Total Dissolved Solids. Historical data from **the** Ministry of Environment and Water, UAE (2015) were considered to prepare the spatial thematic layer of TDS. TDS has a great impact on the quality as it exceeds the turbidity of water which eventually determines the fit and unfit for potable use. Permeability of water with high TDS can clog pores stopping the flow through the aquifer and risks of pathogen activities increases leading to many diseases to humankind. Regions with lower values of TDS are considered to be fit for AGR zonation [30, 31]. Generally, TDS values are enormously high near to the coastal shorelines. TDS map of this study conductively portrayed that regions closer to Gulf of Oman have values of 38000 mg/l whereas the west of the study area which is covered by Arabian Gulf have TDS values of 50000 mg/l. This demonstrates the outcome that Arabian Gulf is more saline compared to Gulf of Oman.

Groundwater Level. In-situ data from bore-wells were collected within the study area and combined together making interoperability in the GIS platform to deduce the thematic layer, refer Fig. 3(d). Inverse distance weighted interpolation technique was used in ArcGIS Pro to develop the layer. The units are meters above sea level (masl). This factor helps in analyzing the hydraulic gradient of the region which eventually depends on pore pressure and atmospheric pressure at the surface level [17, 27, 32]. Higher levels of groundwater is less likely suitable for AGR [17, 32]. The thematic layers shows that the southeast Sharjah and west of Ras al-Khaimah have higher values of groundwater levels. One of the primary explanation behind this is that the region is in close proximity to the foothills and receives more rainfall which up levels the groundwater. The IDW equation is as follows [13, 21, 33]:

$$Z_0 = \frac{\sum_{i=1}^{N} z_i x d_i^{-n}}{\sum_{i=1}^{N} d_i^{-n}} \quad (1)$$

Where Z = calculated value of Z at o;

z_i = observed value at sample point I; d_i is the distance between sample point i and o; N is the number of sample points used to estimate the value at o; n is a distance decay parameter [34, 35].

Elevation. SRTM DEM of 30m spatial resolution were downloaded and used for developing the thematic layer. The elevation is as low as zero meters above sea level (masl) near shore lines and as high as 1112 masl in the mountains for the study area, Fig. 3(e). Elevation is inversely proportional to AGR zonation which demonstrates that inferior elevation values are more appropriate for AGR [9, 27, 35–37]. It analyses the accumulation capacity of water and its flow direction through the aquifers. Few regions within Fujairah and Ras-al Khaimah have elevation above 1000 masl.

Lineament Density. Linear features such as fractures and folds were extracted from satellite images and then spatial maps were processed. It has direct proportionality to AGR suitability. Availability of groundwater and potential available aquifers can be determined from his parameter. It also determines the secondary porosity. Higher values of LD can be witnessed in Fujairah. Generally, from previous research it has been concluded that a zone of around 300m closer to any folds and fractures of the earth composition can be considered suitable for AGR [29].

Distance from Residences. To develop this layer, shapefiles of residential areas were mapped and then Euclidean distance was calculated to prepare the thematic layer, refer Fig. 3(f). For sustainable AGR sites the distance from residences factor needs to be considered. AGR needs to be designed at optimum distance from the densely located city considering water pumping factors to required places as well as closer proximity to pipelines [8, 35]. Higher the distance from residences more suitability for AGR.

3.2 Analytical Hierarchical Process

AHP is a structured multi-criteria decision making (MCDM) procedure. It utilizes experts' opinions to determine the weights and rank of each parameter. AHP has been used by researchers in various groundwater studies and site selection studies [8, 21, 23, 33, 38–41]. This study employs AHP for selecting potential zones for the AGR. An important step in AHP is prioritizing the parameters and assigning them weights, as discussed below.

Weighting the Parameters. The influencing factors were arranged as a structured hierarchy and the pairwise comparison matrix were formed to confirm the consistency of the weights. The weights of the all 9 selected parameters were placed in a square matrix

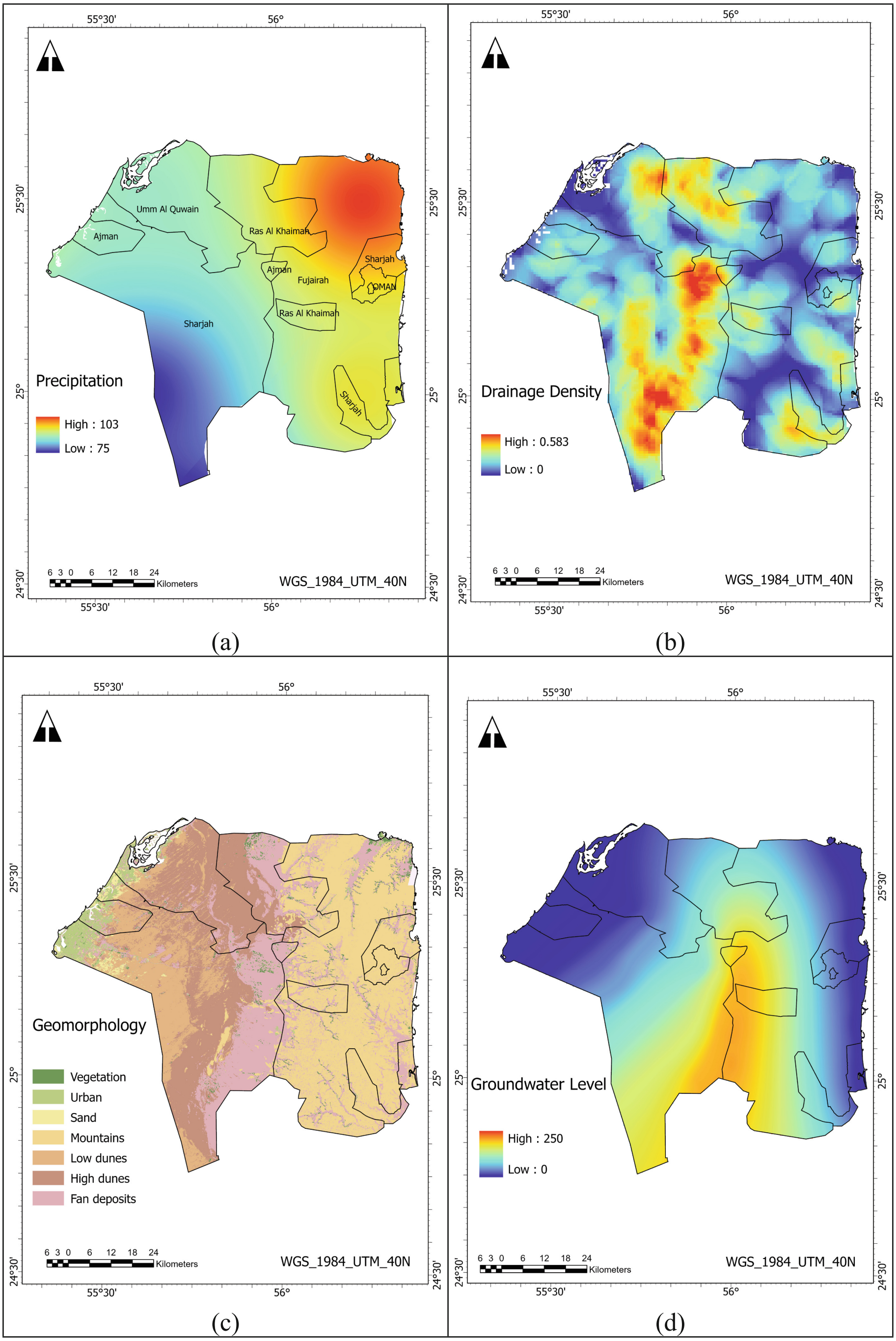

Fig. 3. Thematic Layers [19].

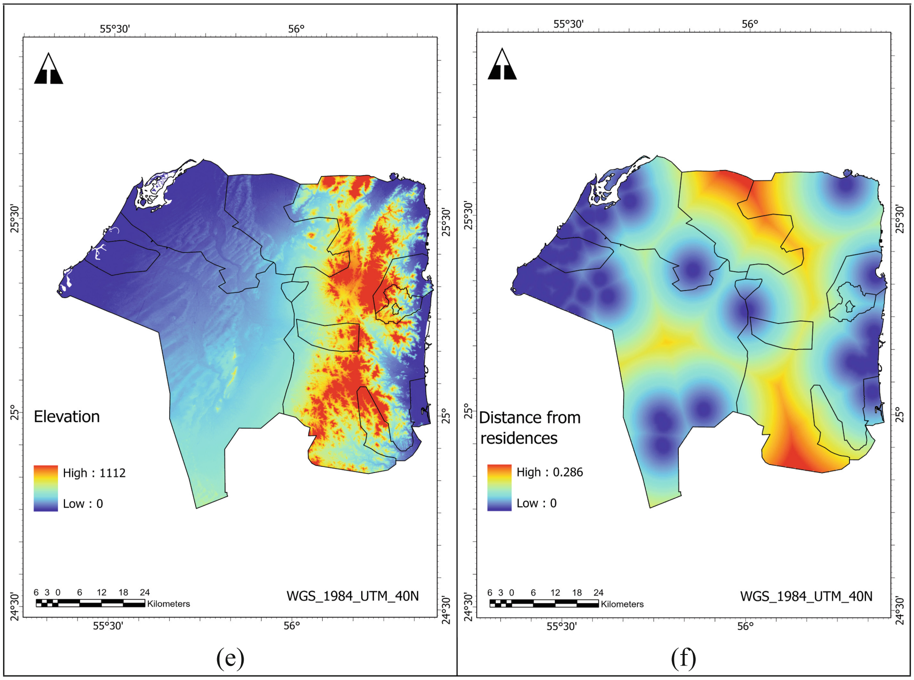

Fig. 3. (*continued*)

keeping all the diagonal values as 1. The diagonal of the pairwise matrix was kept 1 when both the parameters have equal importance over the other. The relative importance of the parameters were analyzed using the principal eigenvalue along with the normalized right eigenvector of the matrix [21, 23, 42, 43]. On a scale of 1–9 of relative importance by Saaty [44] all the parameters were ranked. Highest rank 9 was assigned to criteria with highest influence on the decision. Measurements of consistency were done by checking the randomized and consistency index as well as the consistency ratio.

Consistency Ratio. CR allows the glance for the subjectivity of determined weights through a pairwise matrix. In order to confirm the consistency of the pairwise comparison matrix, consistency index (CI), consistency ratio (CR) and randomized index (RI) were obtained. CR is defined as the degree of consistency of the comparison matrix prepared with respect to parameters and its weights. The value of CR must be less than 0.01 for the consistency of the matrix to be maintained [21, 23, 43]. The CR can be derived using the following equations [44]:

$$\mathrm{CI} = \frac{\lambda max - n}{n - 1} \tag{2}$$

$$\mathrm{RI} = \frac{1.98 \times (n - 1)}{n} \tag{3}$$

$$\mathrm{CR} = \frac{\mathrm{CI}}{\mathrm{RI}} \tag{4}$$

CI is a consistency index, RI is a randomized index (average of CI values of the comparison matrix), CR is a consistency ratio, λ_{max} is the maximum eigenvalue of a comparison matrix and n is the order of the comparison matrix. The calculated CR equals.007 < .01, which supports the weighting model and the AHP technique [21, 45]. Fig. 4 Demonstrates the weights of the utilized thematic layer associated with AGR in percentage.

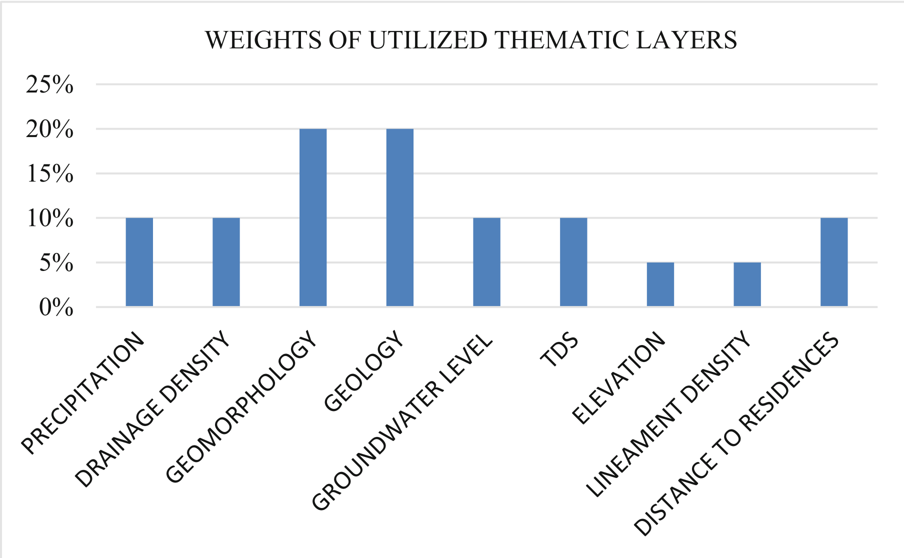

Fig. 4. Weights of utilized thematic layers for AGR zonation in percentage [19].

4 Results and Discussion

The potential AGR was estimated and mapped using AHP approach, refer Fig. 5. The map was categorized on the basis of ordinal scale into 6 classes: “very high”, “high”, “moderate high”, “moderate low”, “low”, and “very low”.

Following points were concluded from the AGR map:

(i) The very high zone is located in the central part of Ras al Khaimah. The properties of the input parameters have geology- alluvium, geomorphology -fan deposits, precipitation of 91 mm, groundwater level 102 masl, drainage density at .38 per km^2, TDS 1862 mg/l, distance from residences .14 m, elevation of 87 m and lineament density of .05 per km^2.

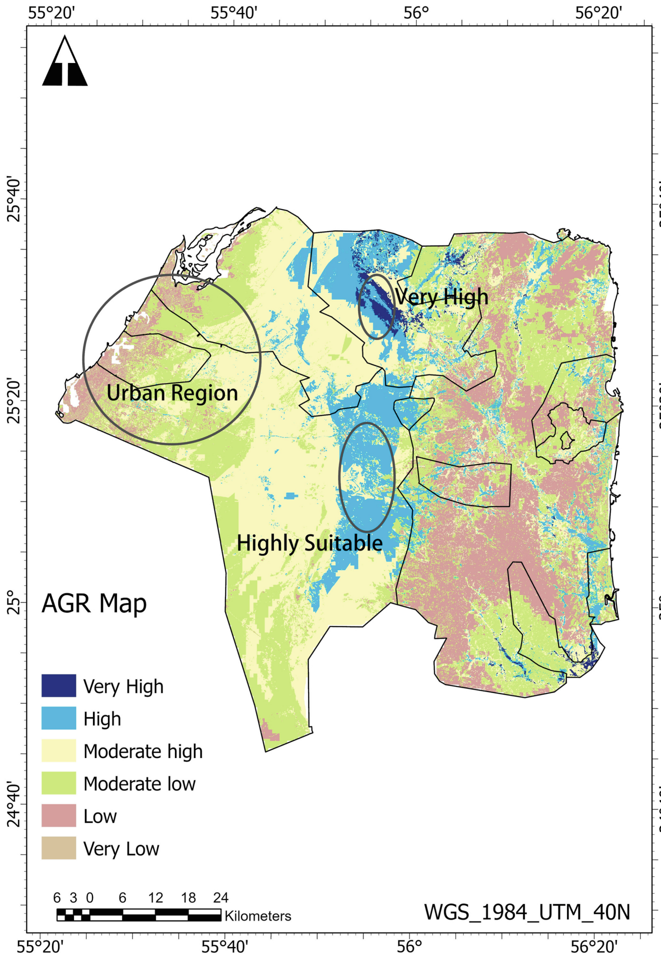

Fig. 5. Potential zones of AGR.

(ii) The "high" zone is located in the north-eastern and central-eastern part of Sharjah. This region also comprises geomorphology- fan deposits, geology-alluvium. This region is near the foothills of the Al-hajjar Mountains and thus comprises many suitable qualities of geology and geomorphological characteristics for AGR. TDS of 1300 mg/l were noted in this region.

(iii) Table 1 demonstrates the area in percentage for each class of AGR.

Table 1. Percentage of area for AGR classes.

AGR Classes	Percentage of Area
Very High	1%
High	21%
Moderate - High	30%
Moderate - Low	34%
Low	12%
Very Low	1%

5 Conclusion

The main objective of this paper was to determine locations which are suitable for AGR, delineate them using AHP and be able to get an estimate of the proportion of study area which can benefit from AGR techniques. To go about this approach, 9 main parameters were found to be governing AGR site suitability. A weighted AHP process was utilized to rank these parameters and then a weighted overlay analysis was done to obtain the final AGR suitability map. The map was clustered in 6 areas ranging from very high suitability to very low suitability. Several inferences were then drawn from the resulting map. The north-central part of Ras Al Khaimah was observed to be lying in the most highly suitable zone while another major portion of Ras Al Khaimah and Sharjah were seen to be lying in the zone characterized as high suitability for AGR. Another reason was the high elevation and mountainous region which received high amounts of precipitation and this in turn caused high amounts of fan and alluvial deposits in these regions. On the other hand, both the shorelines were found not suitable for AGR due to the presence of high salinity. Similarly, dense populations in the urban locations of the eastern parts also made these areas unsuitable for AGR. Out of the total study area, 20% was estimated to be a highly suitable category, 30% as moderate-high, and 12% as low. This was done using ArcGIS Pro and utilizing pixel sizes as the deciding factor. Semi-arid and arid countries such as those in the gulf can highly benefit from this research methodology to demarcate and locate potential locations and zones suitable for AGR techniques. As the world moves into a stage where water becomes more and more a scarcity, the methodology described in this paper can serve as a guiding tool at the least to help find suitable locations for AGR and reduce the stress caused by water scarcity.

References

1. Dawoud, M.A.: The development of integrated water resource information management system in arid regions. Arab. J. Geosci. **6**, 1601–1612 (2013). https://doi.org/10.1007/s12517-011-0449-6
2. Bhunia, G.S.: An approach to demarcate groundwater recharge potential zone using geospatial technology. Appl. Water Sci. **10**(6), 1–12 (2020). https://doi.org/10.1007/s13201-020-01231-1

3. Al-Othman, A.A.: Enhancing groundwater recharge in arid region- a case study from central Saudi Arabia. Sci. Res. Essays **6**, 2757–2762 (2011). https://doi.org/10.5897/SRE11.173
4. United Arab Emirates Population Statistics 2022—GMI. https://www.globalmediainsight.com/blog/uae-population-statistics/. Accessed 24 Jan 2022
5. How much water does the UAE use per day? – SidmartinBio. https://www.sidmartinbio.org/how-much-water-does-the-uae-use-per-day/. Accessed 24 Jan 2022
6. Shanableh, A., Al-Ruzouq, R., Yilmaz, A.G., et al.: Effects of land cover change on urban floods and rainwater harvesting: a case study in Sharjah, UAE. Water (Switzerland) 10 (2018). https://doi.org/10.3390/w10050631
7. Country Commercial Guides: United Arab Emirates - Water. Int. Trade Adm. (2020). https://next.trade.gov/country-commercial-guides/united-arab-emirates-water. Accessed 24 Jan 2022
8. Riad, P.H.S., Billib, M., Hassan, A.A., et al.: Application of the overlay weighted model and boolean logic to determine the best locations for artificial recharge of groundwater. J. Urban Environ. Eng. **5**, 57–66 (2011). https://doi.org/10.4090/juee.2011.v5n2.057066
9. Rahimi, S., Shadman, M., Ali Abbaspour, R.: Using combined AHP-genetic algorithm in artificial groundwater recharge site selection of Gareh Bygone Plain. Iran. Environ. Earth Sci. **72**, 1979–1992 (2014). https://doi.org/10.1007/s12665-014-3109-9
10. Ghayoumian, J., Saravi, M.M.: Application of GIS techniques to determine areas most suitable for artificial groundwater recharge in a coastal aquifer in southern Iran. **30**, 364–374 (2007). https://doi.org/10.1016/j.jseaes.2006.11.002
11. Samadder, R.K., Kumar, S., Gupta, R.P.: Paleochannels and their potential for artificial groundwater recharge in the western Ganga plains. J. Hydrol. **400**, 154–164 (2011). https://doi.org/10.1016/j.jhydrol.2011.01.039
12. Dinesh Kumar, M., Patel, A., Ravindranath, R., Singh, O.P.: Chasing a mirage: water harvesting and artificial recharge in naturally water-scarce regions. Econ. Polit. Wkly. **43**, 61–71 (2008)
13. Chandramohan, R., Vignesh, N.S., Krishnamoorthy, R.: Remote sensing and GIS based approach for delineation of artificial recharge sites in Palani Taluk. Dindigul Dist. **8**, 698–706 (2017)
14. Mokarram, M., Saber, A., Mohammadizadeh, P., Abdolali, A.: Determination of artificial recharge location using analytic hierarchy process and Dempster-Shafer theory. Environ. Earth Sci. **79**,(2020). https://doi.org/10.1007/s12665-020-08994-5
15. Bhowmick, P.: A review on GIS based Fuzzy and Boolean logic modelling approach to identify the suitable sites for Artificial Recharge. Sch. J. Eng. Technol. (SJET) **2**, 316–319 (2014)
16. Mokarram, M., Negahban, S., Abdolali, A., Ghasemi, M.M.: Using GIS-based order weight average (OWA) methods to predict suitable locations for the artificial recharge of groundwater (2021)
17. Khan, A., Govil, H., Taloor, A.K., Kumar, G.: Identification of artificial groundwater recharge sites in parts of Yamuna River basin India based on remote sensing and geographical information system. Groundw. Sustain. Dev. **11**, 100415 (2020). https://doi.org/10.1016/j.gsd.2020.100415
18. Selvarani, A.G., Maheswaran, G., Elangovan, K.: Identification of artificial recharge sites for Noyyal River basin using GIS and remote sensing. J. Ind. Soc. Remote Sens. **45**, 67–77 (2017). https://doi.org/10.1007/s12524-015-0542-5
19. Al-Ruzouq, R., Shanableh, A., Yilmaz, A., et al.: Multicriteria Spatial Analysis to Map Artificial Groundwater Recharge Zones: Northern UAE, pp. 255–262 (2021). https://doi.org/10.5220/0010432802550262
20. Murad, A.A., Nuaimi, H., Hammadi, M.: Comprehensive assessment of water resources in the United Arab Emirates (UAE). Water Resour. Manage. **21**, 1449–1463 (2007). https://doi.org/10.1007/s11269-006-9093-4

21. Al-Ruzouq, R., Shanableh, A., Yilmaz, A.G., et al.: Dam site suitability mapping and analysis using an integrated GIS and machine learning approach. Water (Switzerland) **11**,(2019). https://doi.org/10.3390/w11091880
22. Al-ruzouq, R., Shanableh, A.: Macro and micro geo-spatial environment consideration for landfill site selection in Sharjah, United Arab Emirates, pp. 1–15 (2018)
23. Al-ruzouq, R., Shanableh, A., Merabtene, T., et al.: Potential Groundwater Zone Mapping Based on Geo-Hydrological Considerations and Multi-Criteria Spatial Analysis : North UAE, pp. 1–40 (2019)
24. Sherif, M.M., Ebraheem, A.M., Al Mulla, M.M., Shetty, A.V.: New system for the assessment of annual groundwater recharge from rainfall in the United Arab Emirates. Environ. Earth Sci. **77**,(2018). https://doi.org/10.1007/s12665-018-7591-3
25. Saif, A., Matri, A.: Assessment of Artificial Groundwater Recharge in Some Wadies in UAE by using Isotope Hydrology Techniques (2008)
26. Rais, S., Javed, A.: Identification of Artificial Recharge Sites in Manchi Basin, Eastern Rajasthan (India) Using Remote Sensing and GIS Techniques, pp. 162–175 (2014)
27. Alrehaili, A.M., Hussein, M.T.: Use of remote sensing, GIS and groundwater monitoring to estimate artificial groundwater recharge in Riyadh, Saudi Arabia. Arab. J. Geosci. **5**, 1367–1377 (2012). https://doi.org/10.1007/s12517-011-0306-7
28. Chowdary, V.M.: Delineation of groundwater recharge zones and identification of artificial recharge sites in West Medinipur district, West Bengal, using RS, GIS and MCDM techniques, pp. 1209–1222 (2010). https://doi.org/10.1007/s12665-009-0110-9
29. Senanayake, I.P., Dissanayake, D.M.D.O.K., Mayadunna, B.B., Weerasekera, W.L.: Geoscience Frontiers an approach to delineate groundwater recharge potential sites in Ambalantota, Sri Lanka using GIS techniques. Geosci. Front. **7**, 115–124 (2016). https://doi.org/10.1016/j.gsf.2015.03.002
30. Nasiri, H., Boloorani, A.D., Sabokbar, H.A.F., et al.: Determining the most suitable areas for artificial groundwater recharge via an integrated PROMETHEE II-AHP method in GIS environment (case study: Garabaygan Basin, Iran). Environ. Monit. Assess. **185**, 707–718 (2013). https://doi.org/10.1007/s10661-012-2586-0
31. Kazakis, N.: Delineation of suitable zones for the application of Managed Aquifer Recharge (MAR) in coastal aquifers using quantitative parameters and the analytical hierarchy process. Water (Switzerland) **10**,(2018). https://doi.org/10.3390/w10060804
32. Hammouri, N., Al-Amoush, H., Al-Raggad, M., Harahsheh, S.: Groundwater recharge zones mapping using GIS: a case study in Southern part of Jordan Valley, Jordan. Arab. J. Geosci. **7**, 2815–2829 (2014). https://doi.org/10.1007/s12517-013-0995-1
33. Agarwal, R., Garg, P.K.: Remote sensing and GIS based groundwater potential & recharge zones mapping using multi-criteria decision making technique. Water Resour. Manage. **30**, 243–260 (2016). https://doi.org/10.1007/s11269-015-1159-8
34. Rukundo, E., Doğan, A.: Dominant influencing factors of groundwater recharge spatial patterns in Ergene river catchment, Turkey. Water (Switzerland) **11** (2019). https://doi.org/10.3390/w11040653
35. da Costa, A.M., de Salis, H.H.C., Viana, J.H.M., Pacheco, F.A.L.: Groundwater recharge potential for sustainable water use in urban areas of the Jequitiba River Basin. Brazil. Sustain. **11**,(2019). https://doi.org/10.3390/su11102955
36. Mahmoud, S.H., Alazba, A.A.: Identification of potential sites for groundwater recharge using a GIS-based decision support system in Jazan region-Saudi Arabia. Water Resour. Manage. **28**, 3319–3340 (2014). https://doi.org/10.1007/s11269-014-0681-4
37. Sharma, C.S.: Artificial groundwater recharge zones mapping using remote sensing and GIS : a case study in Indian Punjab 61–71 (2013). https://doi.org/10.1007/s00267-013-0101-1

38. Mahdavi, A., Tabatabaei, S.H., Mahdavi, R., Nouri Emamzadei, M.R.: Application of digital techniques to identify aquifer artificial recharge sites in GIS environment. Int. J. Digit. Earth **6**, 589–609 (2013). https://doi.org/10.1080/17538947.2011.638937
39. Ahmadi, M.M., Mahdavirad, H., Bakhtiari, B.: Multi-criteria analysis of site selection for groundwater recharge with treated municipal wastewater. Water Sci. Technol. **76**, 909–919 (2017). https://doi.org/10.2166/wst.2017.273
40. Rahman, M.A., Rusteberg, B., Gogu, R.C., et al.: A new spatial multi-criteria decision support tool for site selection for implementation of managed aquifer recharge. J. Environ. Manage. **99**, 61–75 (2012). https://doi.org/10.1016/j.jenvman.2012.01.003
41. Chenini, I., Ben, M.A., El, M.M.: Groundwater recharge zone mapping using GIS-based multi-criteria analysis: A case study in Central Tunisia (Maknassy Basin). Water Resour. Manage. **24**, 921–939 (2010). https://doi.org/10.1007/s11269-009-9479-1
42. Chezgi, J., Pourghasemi, H.R., Naghibi, S.A., et al.: Assessment of a spatial multi-criteria evaluation to site selection underground dams in the Alborz Province. Iran. Geocarto. Int. **31**, 628–646 (2016). https://doi.org/10.1080/10106049.2015.1073366
43. Norouzi, H., Shahmohammadi-Kalalagh, S.: Locating groundwater artificial recharge sites using random forest: a case study of Shabestar region. Iran. Environ. Earth Sci. **78**, 1–11 (2019). https://doi.org/10.1007/s12665-019-8381-2
44. Saaty, T.L.: How to make a decision: the analytic hierarchy process. Eur. J. Oper. Res. **48**, 9–26 (1990). https://doi.org/10.1016/0377-2217(90)90057-I
45. Al-Ruzouq, R., Shanableh, A., Merabtene, T., et al.: Potential groundwater zone mapping based on geo-hydrological considerations and multi-criteria spatial analysis: North UAE. CATENA **173**, 511–524 (2019). https://doi.org/10.1016/j.catena.2018.10.037