Multicriteria Spatial Analysis to Map Artificial Groundwater Recharge Zones: Northern UAE

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Abstract: United Arab Emirates (UAE) ranks among the list of most water-stressed countries. Various sustainable water policies are suggested and adopted to tackle water scarcity issues. One of them is the implication of Artificial Groundwater Recharge (AGR) sites. AGR is a novel approach to collect freshwater in the aquifers and meet the water demands at lean periods for semi-arid countries like UAE. This research scrutinizes the primary thematic layers required for AGR zonation in the Central Northern Emirates and parts of Oman integrating with Remote Sensing (RS) and Geographic Information System (GIS). Several factors, which involve hydrological, geological, water quality measured in terms of total dissolved solids (TDS), groundwater level, euclidean distance from residential areas, were weighted using Analytical Hierarchical Process (AHP), and the weighted overlay was applied to derive the potential AGR map. The AGR map depicts the three best locations within the study area. Geology and geomorphology were the most influential factors affecting the AGR.

1 INTRODUCTION

Globally, water demands are being elevated day by day due to the higher population and rapid urban development. The scenario aggravates more for semi-arid and arid climatic set-up locations like in the United Arab Emirates (UAE) (Dawoud, 2013). To combat these issues, multiple sustainable water policies are being adapted. One such technique is artificial groundwater recharge (AGR), which widely came into practice in the early 1990s (Bhunia, 2020). Recent developments of technologies associated with AGR have made it a common practice for arid and semi-arid regions for sustainable water development (Al-Othman, 2011).

The study considered combined Analytical Hierarchical Process (AHP) and weighted overlay analysis techniques to prepare an AGR map for the Northern Emirates comprising Emirate of Sharjah, Fujairah, Ras-al- Khaimah, Umm-al Quwain, and part of Oman adjacent to borders of Sharjah and Fujairah in the eastern part of the study area. Hydrological, geological, geomorphological, water quality, groundwater level, height from the terrain, lineaments, and distance from urban areas were considered and deduced to thematic layers. 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 are summarized within the following:

- Demarcate suitable locations for AGR zonation by utilizing RS and GIS.

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- Mapping geospatial layers associated with AGR that include: precipitation, geology, geomorphology, drainage stream density (DSD), groundwater level, Total Dissolved Solids (TDS), lineament density (LD), elevation, and Euclidean distance from residential areas.
- Apply AHP and weighted overlay techniques to construct AGR map.

2 STUDY AREA

UAE lies in the south-eastern part of the Arabian Peninsula bordering the Gulf of Oman and Saudi Arabia, Figure 1 (Al-Ruzouq, Shanableh, Yilmaz, et al., 2019; Al-ruzouq & Shanableh, 2018; Murad et al., 2007; Shanableh et al., 2018).

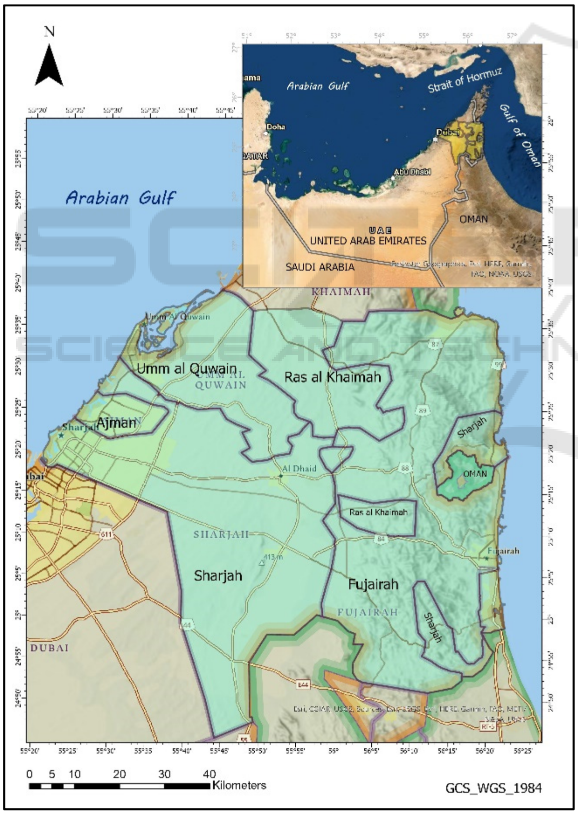


Figure 1: Study Area.

The country reserves approximately 640 billion cubic meters (BCM) of groundwater, out of which only 20 BCM is fresh (Al-ruzouq et al., n.d.; Al-Ruzouq, Shanableh, Yilmaz, et al., 2019). UAE's aquifer system is broadly classified as northern limestone, ophiolite, eastern gravel, western gravel, sand dune, and coastal marshes (Saif & Matri, 2008). Among these categories of aquifer systems, sand dune aquifer holds the major land. The Northern Emirates shares the fairly equal proportions of all the aquifers classes comprising coastal marshes in the western border of the country covering cities like Ajman and fewer portions of Sharjah and Emirate of Umm al Quwain. The Eastern border of the country comprises eastern gravel adjacent to the Gulf of Oman. UAE receives approximately the mean annual precipitation of 102mm with higher rainfall in the mountainous region in the eastern part of the country (Al-ruzouq et al., n.d.; Al-Ruzouq, Shanableh, Yilmaz, et al., 2019; Sherif et al., 2018).

3 METHODS AND DATA PROCESSING

The developed methodology for demarcating potential zones for AGR has been illustrated in Figure 2. Historical records of climate data and suitable remote sensing imageries were used to prepare desired thematic layers contributing to AGR map.

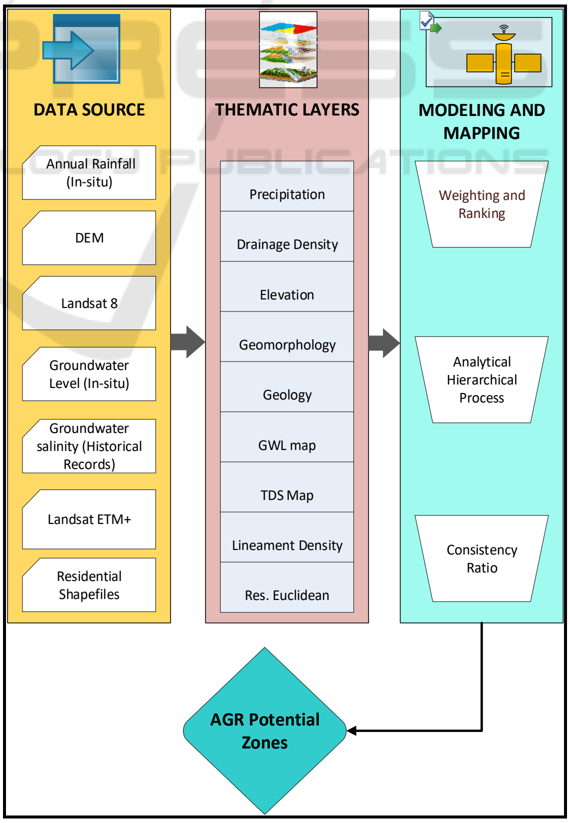


Figure 2: Methodology Framework.

Precipitation, DSD, geomorphology, geology, groundwater level, TDS, elevation, lineament density, euclidean distance from residential areas were developed as thematic layers. These layers were then processed to map the potential sites for AGR. The layers were reclassified up to 5 classes from 1 to 9 to attain the standardization applying the natural breaks technique. AHP approach was considered to determine the weighting of the layers.

3.1 Thematic Layers Preparation

AGR potential zones were determined using GIS methodologies in this research. The study considered several factors for delineating suitable sites for AGR: Precipitation, DSD, geomorphology, geology, groundwater level, TDS, elevation, lineament density, euclidean distance from residential areas (Alrehaili & Hussein, 2012; Chowdary, 2010; Rais & Javed, 2014). A brief description of these parameters are discussed below:

3.1.1 Precipitation

To develop the precipitation layer, UAE's National Centre for Meteorology was referred to procure the annual total rainfall data for the period of 2003-2017, Figure 3(a). The least average of annual total rainfall was recorded as 75mm for the study area and ranged maximum up to 103mm. Higher the rainfall values in a region higher the suitability of AGR. Regions receiving higher rainfall in the study area are considered to be suitable for AGR zonation as more amount of water is available to be stored artificially (Al-ruzouq et al., n.d.; Al-Ruzouq, Shanableh, Yilmaz, et al., 2019; Sherif et al., 2018).

3.1.2 Drainage Stream Density

DSD is a measure of the quantity of water drained by the stream channels in a watershed. It is obtained via dividing the overall stream length by the drainage basin's overall area. DSD is inversely proportional to watershed permeability (Khan et al., 2020; Rais & Javed, 2014). Therefore, DSD is a crucial parameter to determine the suitability of the AGR. DSD is higher in the eastern part of the Sharjah Emirate and northern part and northeastern part of Ras-al-Khaimah Emirate and Umm-al-Quwain, respectively (Al-ruzouq et al., n.d.; Al-Ruzouq, Shanableh, Yilmaz, et al., 2019). The thematic layer was extracted from the STRTM DEM (Al-ruzouq et al., n.d.; Al-Ruzouq, Shanableh, Yilmaz, et al., 2019).

3.1.3 Geomorphology

Geomorphology of the Central - Northern Emirates has been broadly classified as high and low dunes, sand, fan deposits, mountain, urban areas, and vegetation (Al-ruzouq et al., n.d.; Al-Ruzouq, Shanableh, Yilmaz, et al., 2019). It helps to determine the natural water movement at the sub-surface level also helps to understand the possibility of the water holding and water existence. The development of various landforms can help in knowing about the porous and permeable zones (Khan et al., 2020; Senanayake et al., 2016). Fan deposits are considered to be most favorable for AGR in the UAE. Therefore highest rank has been assigned to fan deposits. As the majority of the country is covered with desert sand, high dunes also come in a higher ranking with respect to AGR determination. This layer was prepared from Landsat 8 ETM + satellite imagery at 30m resolution (Al-ruzouq et al., n.d.).

3.1.4 Geology

The geology of the study area comprises alluvium, limestone, gabbro, metamorphic, sand and ophiolite, refer to Figure 3(b) (Al-ruzouq et al., n.d.; Al-Ruzouq, Shanableh, Yilmaz, et al., 2019). Induced or original effective porosity can control the recharging capacity by allocating space to hold water (Khan et al., 2020; Senanayake et al., 2016). Alluvium has the highest water retention capacity, which makes it most suitable for AGR zonation, thereby owing to higher rank while reclassifying the thematic layer.

3.1.5 Groundwater Level

The hydraulic gradient of a particular area can be determined by analyzing the water level which is dependent on the pore pressure and atmospheric pressure at the surface (Alrehaili & Hussein, 2012; Hammouri et al., 2014; Khan et al., 2020). In-situ data of groundwater level have been compiled, and inverse distance weighting (IDW) interpolation technique has been used to derive the groundwater level map. The values are depicted in meters above sea level (masl). GWL is inversely proportional to the AGR zonation (Hammouri et al., 2014; Khan et al., 2020). The study area holds higher groundwater levels in the southeastern part of Sharjah and western part of Ras-al-Khaimah. The reason for higher GWL in these areas as it lies in the foothills of the mountainous region, thereby proportionately receiving more rainfall contributing to GWL. The IDW equation is as follows (Agarwal & Garg, 2016; Al-Ruzouq, Shanableh, Yilmaz, et al., 2019; Chandramohan et al., 2017):

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

Where Z is the estimated value of Z at o,
z_i is the 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 (da Costa et al., 2019; Rukundo & Doğan, 2019).

3.1.6 Total Dissolved Solids

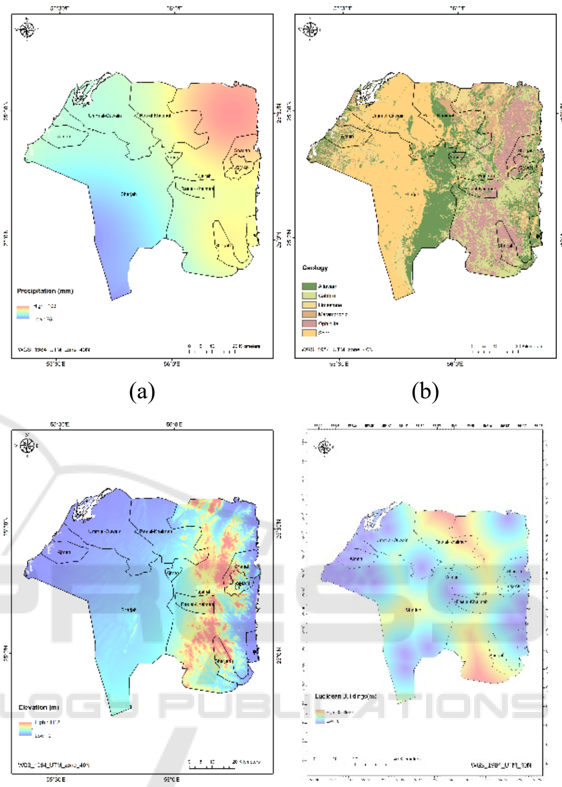
Water quality is affected by TDS. As the TDS value increases, the turbidity also increases, and the water becomes unsuitable for drinking and household purpose. When water with a high level of turbidity permeates to an aquifer, it corrupts the aquifer, neighboring aquifers, and the whole water network by giving rise to pathogens. Hence, lower TDS values are preferable for AGR zonation (Kazakis, 2018; Nasiri et al., 2013). TDS values are more in the proximity of the shorelines of the study area. The Gulf of Oman surrounds the eastern region of the study area and has a salinity of 38,000 mg/L as compared to the western region, which is surrounded by the Arabian Gulf and has a salinity of 50,000 mg/L. Salinity values are higher in the Arabian Gulf, resulting in higher TDS values in the western shoreline. The map was generated using TDS values published by the Ministry of Environment and Water, UAE (2015).

3.1.7 Elevation

The elevation is in an inverse relationship with AGR zonation. Lower elevation values are more suitable for AGR (Alrehaili & Hussein, 2012; da Costa et al., 2019; Mahmoud et al., 2014; Rahimi et al., 2014; Sharma, 2013). The thematic layer was developed from the SRTM DEM of 30m resolution. DEM predicts water accumulation and movements. The elevation ranged from 0 to 1112 m (above sea level) in the study area, Figure 3(c). The mountainous regions covering the parts of Fujairah and Ras-al-Khaimah holds the highest elevation range of above 1000 masl.

3.1.8 Lineament Density

Lineament density (LD) is useful in governing groundwater availability or the possibility of artificially constructing an aquifer and injecting water into it for storage. Higher LD is more suitable for AGR zonation. It also helps in understanding high secondary porosity in an area. A region of around 300m near a lineament is generally considered to be a suitable area for groundwater recharge (Senanayake et al., 2016).



(a) (b) (c) (d)

Figure 3: Samples for thematic layers.

3.1.9 Residential Euclidean Distance

AGR zonation for sustainable development also depends on the factor that at what distance it is from the residences (da Costa et al., 2019; Riad et al., 2011). AGR cannot be designed at the heart of the residential areas as it would disturb the environment of the residences and humankind. Therefore, a sustainable AGR project is considered to be designed far from the residential areas. Euclidean distance from the residential feature layer was calculated to develop the thematic layer, Figure 3(d). The higher the distance from the residential areas with the close proximity of pipeline conveyance were considered to be more suitable for AGR zonation (Riad et al., 2011).

3.2 Analytical Hierarchical Process

AHP is an important multi-criteria decision making (MCDM) aid. AHP has been used by researchers in various groundwater studies and site selection studies (Agarwal & Garg, 2016; Ahmadi et al., 2017; Al-ruzouq et al., n.d.; Al-Ruzouq, Shanableh, Yilmaz, et al., 2019; Chenini et al., 2010; Mahdavi et al., 2013; Rahman et al., 2012; Riad et al., 2011). This study utilizes AHP for selecting potential zones for the AGR. An important step in AHP is prioritizing the parameters and assigning them weights, as discussed below.

3.2.1 Weighting the Parameters

The weights of the all the 9 selected parameters, refer Table 1, were placed in a square matrix keeping all the diagonal values as 1. The relative importance of the parameters were analyzed using the principal eigenvalue along with the normalized right eigenvector of the matrix (Al-ruzouq et al., n.d.; Al-Ruzouq, Shanableh, Yilmaz, et al., 2019; Chezgi et al., 2016; Norouzi & Shahmohammadi-Kalalagh, 2019).

In addition to literature review and expertise survey, the pairwise comparison matrix were formed to confirm the consistency of the weights (Chandramohan et al., 2017; Kaliraj et al., 2013; Kazakis, 2018; Riad et al., 2011; Rukundo & Doğan, 2019; Sub et al., 2015; Yeh et al., 2016). Measurements of consistency were done by checking the randomized and consistency index as well as the consistency ratio.

Table 1: Weighting for thematic layers.

THEMATIC LAYER	THEMATIC LAYER WEIGHT
Precipitation	10%
Drainage Stream Density	10%
Geomorphology	20%
Geology	20%
TDS	10%
Groundwater Level	10%
Elevation	5%
Lineament Density	5%
Residential Euclidean Distance (m)	10%

3.2.2 Consistency Ratio

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 (Al-ruzouq et al., n.d.; Al-Ruzouq, Shanableh, Yilmaz, et al., 2019; Norouzi & Shahmohammadi-Kalalagh, 2019). The CR can be derived using the following equations:

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

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

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

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 (Al-Ruzouq, Shanableh, Merabtene, et al., 2019; Al-Ruzouq, Shanableh, Yilmaz, et al., 2019).

4 RESULTS AND CONCLUSION

Figure 4 represents the AGR map prepared using AHP technique and weighted overlay tool in ArcGIS Pro. The output map was categorized into 6 classes: very high, high, moderate-high, moderate-low, low, very low. The very high suitable area is mostly concentrated in the central part of Ras al Khaimah. The higher zones can be seen in the eastern part of Sharjah and also the central and northern parts of Ras al Khaimah. These regions have mostly alluvium geology and fan deposits geomorphology. Also, the region receives a higher amount of precipitation due to the mountains. Arabian Gulf borders the western part of the study area and has higher TDS values. Also, due to densely populated regions in this area, the region falls under low suitability for AGR potential zones.

Demarcating suitable potential zones for AGR is a tactical dynamism for semi-arid and arid countries. This study combines remote sensing images, AHP, weighting and ranking, and weighted overlay to procure an AGR map. To derive the AGR map precipitation, geology, geomorphology, drainage density, lineament density, groundwater level, TDS, euclidean distance from residential areas and elevation were considered. Geology and geomorphology are the foremost demanding factors.

The outcome of this study furnish a suggestion for scientific scholar community in identifying suitable potential zones for artificial groundwater recharging.

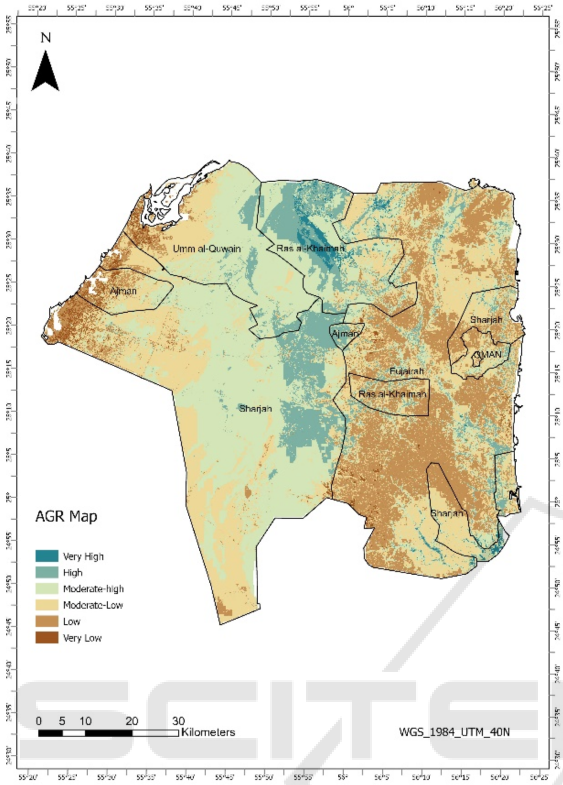


Figure 4: AGR Map.

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