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To investigate groundwater potentiality, a GIS-based model was integrated with remote sensing data in the Northwest Gulf of Suez (Egypt)

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Abstract

As population and water demand increase, accurate assessment of water resources is imperative for sustainable development. This study aims to develop a map of the potential groundwater zone for the northwestern part of the Gulf of Suez. A hydrographical basin of the study area covers approximately 1007 km^2. A geographic information technique (GIS) with remote sensing (RS) dataset was used in a quantitative assessment approach for groundwater resource evaluation. This study applies a GIS-based model integrated with remote sensing data for groundwater potential zone mapping due to the industrial and touristic development in the area. The thematic layers used are allocated to scores and weights using a linear equation approach. High scores and weights are assigned to the higher controlling class of groundwater. However, the groundwater availability varies spatially and temporally depending upon various controlling factors. For this purpose, six groundwater occurrences and controlling factors, including elevation, slope, lineaments, curvature, lithological units, and stream network, were mapped. The most reliable outcome of this paper is that with a digital elevation model, slope, curvature, lithological units, lineaments, and stream network thematic layers, it is possible to develop a reliable groundwater potentiality zones map. The quaternary deposits and Wadi filling were identified as perfect groundwater potential zones with low elevation and slope, allowing a considerable volume of water and high infiltration rates. The final potential map showed different categories of suitability zones of potentiality in the site. The map of the potential groundwater zone was divided into the traditional five possible categories or classes: very low potentiality, low potentiality, moderate potentiality, high potentiality, and very high potentiality. Furthermore, the very high and high potential zones of groundwater classes represent approximately 38% of the total area. Additionally, two main trends of lineaments are NE–SW and NW–SE. Field data of productive water wells in the present study site were used to validate the model. The data showed that the predicted results were reliable, and the model performed well with the applicability of such an approach in similar areas.

Keywords Groundwater potentiality zones · GIS mode · Remote sensing · Gulf of Suez

Introduction

The rapid and sustained growth of heavy industry and other activities northwest of the Suez Gulf led to the urbanization of both this region and the watershed. In recent decades, significant development has been made in this area that requires a water source for domestic and industrial use. The Gulf of Suez (GS) and the southern Gulf of Suez region have been studied by many researchers from the geological, hydrological, and geophysical perspectives among them (Moustafa 1976; Abu El-Enain et al. 1995; Abd El Rahman 2001; Al Sharhan 2003; Abu El-Anwar and El-Gohary 2003; Masoud and Koike 2005; Hassan 2008; Sultan et al. 2015; Abu El-Magd 2019). The study site was divided into six essential geomorphic

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groups, namely the coastal plain in the Suez Gulf, the structural plain of Wadi Ghoweiba, El Galala El Bahariya, Akheider, Gebel Ataqa, and the structural plateau of Ke-haliya-Um Zeita. Wadi Hagul belongs to the morpho-structural province of Ke-haliya-Um Zeita (Abdallah 1993). Said (1962) and Abdallah (1993) concluded that the area of Wadi Hagul is a morpho-tectonic depression falling in the north between the area of the southern slopes of Gebel Ataqa and the south slopes of El Galala El Bahariya Plateau. Previous studies have used remote sensing data coupled with the delineation of hydrogeomorphological units in groundwater exploration and hydrogeological investigations (Krishnamurthy and Srinivas 1995; Ostad-Ali-Askari et al. 2018a, b; Salehi-Hafshejani et al. 2019; Ostad-Ali-Askari et al. 2019, 2020; Golian et al. 2020; Derakhshannia et al. 2020). Several researchers have applied the remote sensing dataset and probabilistic models for various methods for delineating the potential areas of groundwater and flash floods, such as the frequency ratio approach (Ozdemir 2011; Abu El-Magd et al. 2020; Abu El-Magd and Eldosouky 2021), numerical and analytical approaches (GCM and MODFLOW-2000) (Ostad-Ali-Askari et al. 2019, 2020; Golian et al. 2020), analysis of multi-criteria decision (Pradhan 2009; Kumar et al. 2020), weights of evidence method (Ozdemir 2011), and logistic regression (Pourtaghi and Pourghasemi 2014). With the current industrial activity and future development, the study area is in continuous need of water resources that cover the domestic and industrial requirements. In this regard, improving groundwater exploitation is vital to ensure the sustainability of water resource availability. Hence, this study's main objective is to provide a reliable, simplified method to characterize the existing groundwater potential zones in the Suez region northwest of the Gulf (Fig. 1) based on GIS modeling and remote sensing data integration. The integration of a GIS-based model with the remote sensing dataset has been used previously to identify groundwater potential zones in several areas such as the Wadi Feiran basin, South Sinai, and El Laqeita and its surroundings, Central Eastern Desert (Abdalla 2012; Arnous 2016). Gustafsson (1993) used GIS techniques to conduct groundwater potential mapping by extracting lineaments data derivative from the imagery of high resolution. GIS is a powerful tool in natural hazards (floods and landslides) and hydrological mapping and prediction. The controlling factors of the potential zones of groundwater used in this study were the following: elevation data, slope map, curvature, lithology, lineaments density, and steam density. However, from a hydrogeological perspective, the main water-bearing formations are the Quaternary alluvial sediments that are considered the area's main aquifer. Furthermore, the Quaternary aquifer is highly affected by faulting (El Sabri et al. 2017; Ostad-Ali-Askari and Shayannejad 2021).

Additionally, with the presence of the Quaternary aquifer, the study area contains additional water-bearing formations represented by the Tertiary aquifer (Pliocene–Miocene) and Cretaceous aquifer represented by a spring (Diab 1969). The thematic layers of groundwater controlling factors that have a direct influence on groundwater occurrences were prepared in the GIS environment. Moreover, the mapping results would set up the basis for future monitoring and 96 provide a measure of accessible information that will allow development plans and future assessments of changes in groundwater potentiality. This study was carried out in the Northwest Gulf of Suez, which is a part of the Egyptian Desert.The site is bordered from the east by the Gulf of Suez, while in the west, it gradually rises until the Eastern Desert merges with it. The study area contains two major wadis (Hagul and Bada'a) and represents approximately 1007 km^2(Fig. 1) running from northwest to southeast. Most of the rocks exposed in the area are sedimentary rocks ranging from the Upper Paleozoic to recent (CONOCO 1987; Abdallah 1993). The climate in the area under study is characterized by a hot condition prevailing along with the summer, minimal rainfall, and climatic conditions. The area is situated between the latitudes 29° 40′ 3.85″ N and 30° 0′ 7.26″ N and longitudes 31° 52′ 33.41″ E and 32° 23′ 9.58″ E.

Due to continuous industrial development and the high cost of supplying freshwater for industrial and domestic purposes, it is necessary to evaluate groundwater potentiality. It has become apparent that Wadi Hagul and its surroundings are promising areas for development but are constrained with water resource challenges. Therefore, the present work aims to (a) characterize and allocate the most relevant potential zonation of groundwater in the area and (b) propose appropriate measures and tools for water resource assessment and development.

Accordingly, this paper contributes in the area by providing delineation of groundwater potential zones through integration of remote sensing techniques and GIS tools to present proper administration and management of water resources.

Geology

Several extensive studies were carried out in the area (Strougo and Abdallah 1990; Strougo et al. 1992; Bignot and Strougo 2002). However, both pre-rift and syn-rift sedimentary successions have appeared in the area. The Tertiary rock units of Middle and Late Eocene exposures are represented by the exposed pre-rift sediments. The Neogene rock units belonging to Oligocene and Miocene exposures are represented by the syn-rift sediments. The Oligocene exposures are characterized by the Gabal El-Ahmer Formation's continental sands, quartzite, and gravel sediments that covered the Eocene rocks in the study area's northwestern and southeastern sections. The Miocene exposures are represented by the Hagul Formation, mainly composed of sands and gravel underlined

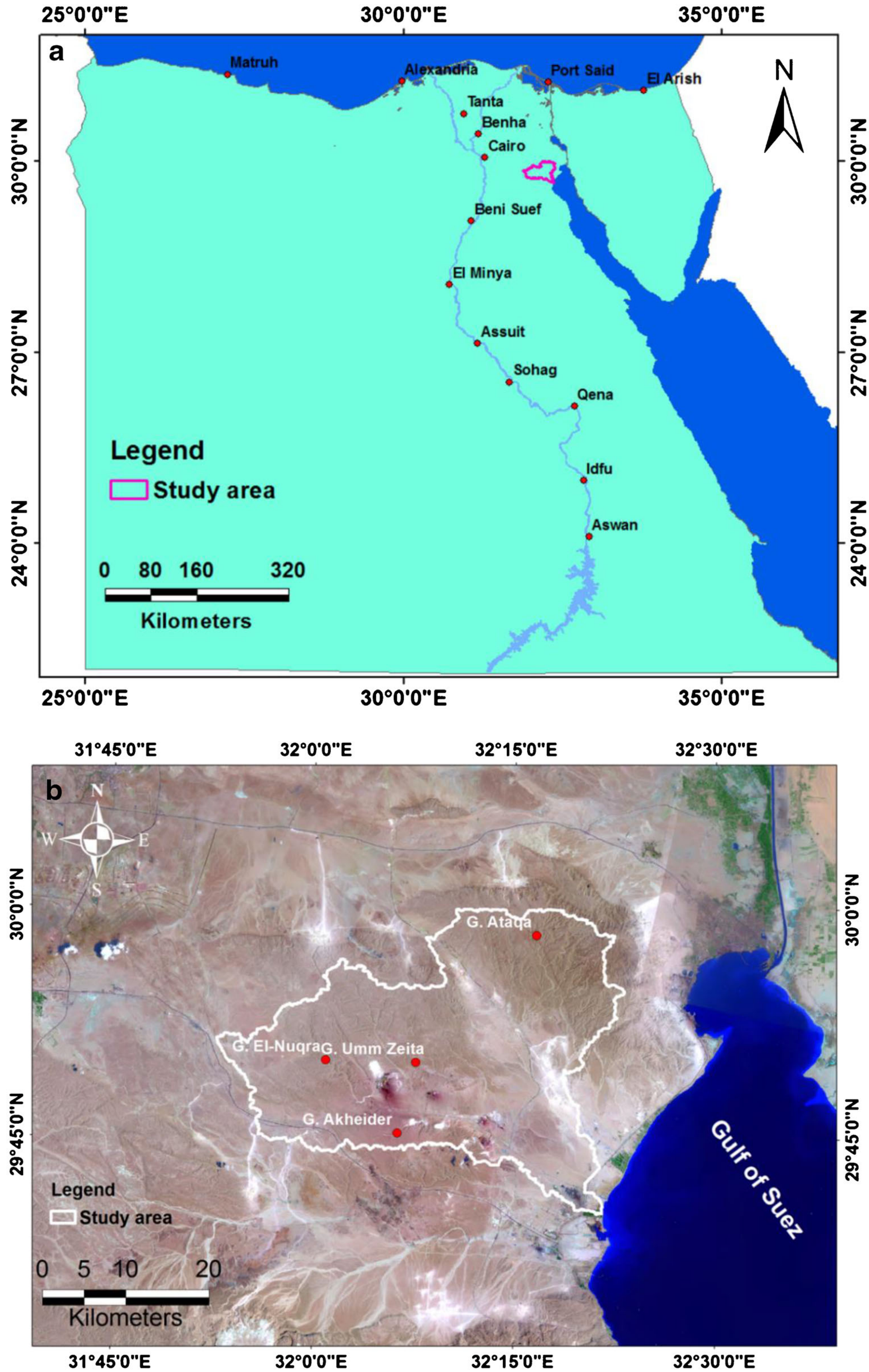

Fig. 1 Magnified map of the study site. **a** Map of Egypt and **b** magnified map of the study site location

by marine fossiliferous limestone with sandy intercalations near the base. The Miocene sediments are recorded at Wadi Hagul and Wadi Bada'a. The Pliocene and Quaternary deposits cover the major part of the low land of the study area and consist mainly of clastic sediments. The formal term "Mokattam Formation" was adopted (Said 1962) to include the lower Mokattam unit (Zittel 1983). The Mokattam Formation consists mainly of thin- to thick-bedded, yellowish, hard, and fossil (mostly Nummulitic) limestone. Figure 2 demonstrates the distribution of lithological units in the area.

Structures in the area of interest have been discussed by several authors (Salem 1988; Moustafa and Abd-Allah 1992; Abdallah 1993; Youssef and Abd-Allah 2003). Mohamed (2001) reported that the study area is situated on the mobile shelf together with the Gulf of Suez graben outlined as a taphro-geocyncline. The fault dislocations trending mainly from NE–SW to NW–SE and rejuvenation along these faults have affected the area. The two main provinces include the Gulf of Suez to the east and the district of Cairo Suez to the north and northwest, which form a junction point in the region between the Northern Plateau of Galala and Gebel Ataqa. The NNW–SSE faults are common and mostly gravitational connecting the main Wades (Wadi Hagul and Wadi Bada'a) and impact the plateau of Eocene limestone.

The E–W faulting ranges from the late Eocene to the Oligocene (Salem 1988). There are high dip angles, short lengths, and small throw ratios to the WNW faults. In the low hill area of the depression between Gebel, El Galala, El Bahariya, and Gebel Ataqaa, the faults are distributed.

Hydrology

Several hydrogeological studies and investigations have been conducted in the region under consideration (EL-Rayes et al. 2009; EL Sabri et al. 2017). The main aquifer in the study site and primary source of groundwater is the Quaternary aquifer. It is composed mainly of gravel and graded sand interspersed with lenses of clay. Wadi Hagul's water depth is 6 m and 157 m in Wadi Bada'a, below the ground surface. An additional source of groundwater is the Tertiary aquifer (Pliocene–Miocene). However, the Pliocene aquifer is identified in Wadi Bada'a and is predominantly composed of limestone, clay, sand, and gravel with dolomite (El Sabri et al. 2017). In the year 1999, a geological survey of Egypt (EGSMA) successfully drilled water wells in the area of interest. The subsurface geology of the water well indicated that approximately 4 m of the Quaternary deposits represents Wadi deposits, sand, and gravel. An iso-lines water map indicates that the groundwater flows through the Quaternary aquifer from the western to the central and the eastern area (El Sabri et al. 2017), while Quaternary deposits are overlaid on the Miocene deposits. The upper Miocene deposits are characterized by 45-m-thick calcareous and argillaceous sandstone deposits. The Middle Miocene aquifer was well illustrated by a thin layer of clay, deposits of sandstone (saturated with freshwater with a thickness reaching 40 m), and limestone at the water base.

Materials and methods

A flow chart was used to implement this study (Fig. 3). ArcMap (version 10.4) was used as it allows users to store large datasets and create, manipulate, and analyze geospatial data. The input digital elevation model (DEM) is required to generate slope and curvature maps. Each of the thematic layers was transformed to the corresponding projected coordinate system (CS) of UTM, Zone 36 N, and converted to a raster format. Then, all the maps were reclassified on a scale from 1 to 4, using the reclassify tool in ArcMap, where 1 denotes low groundwater potential and 4 denotes a very high groundwater potential. After reclassifying all thematic layers, the weight used for each class in the raster calculated tool of

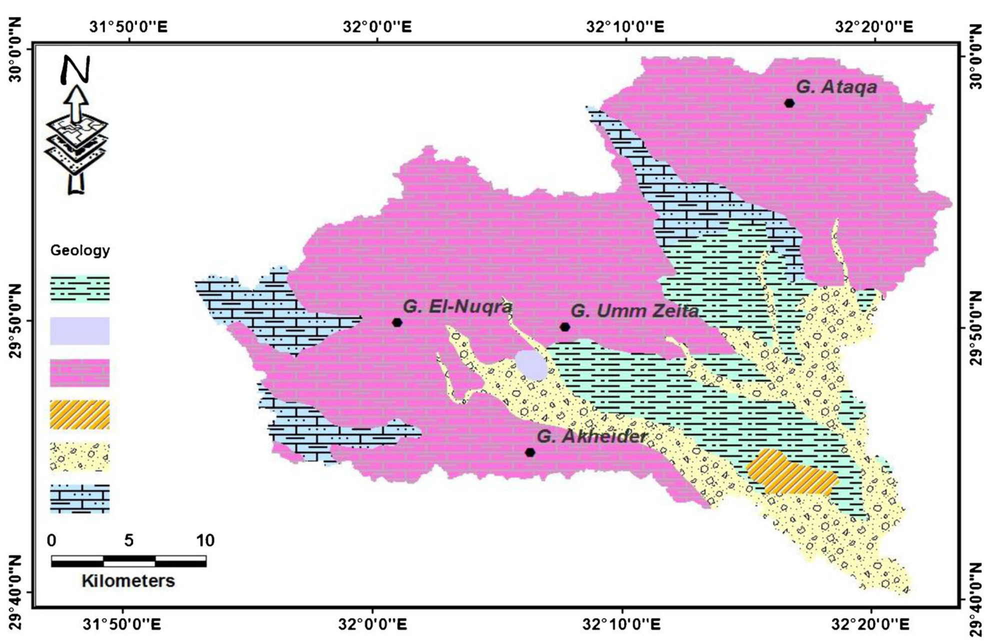

Fig. 2 Lithological map of the study area

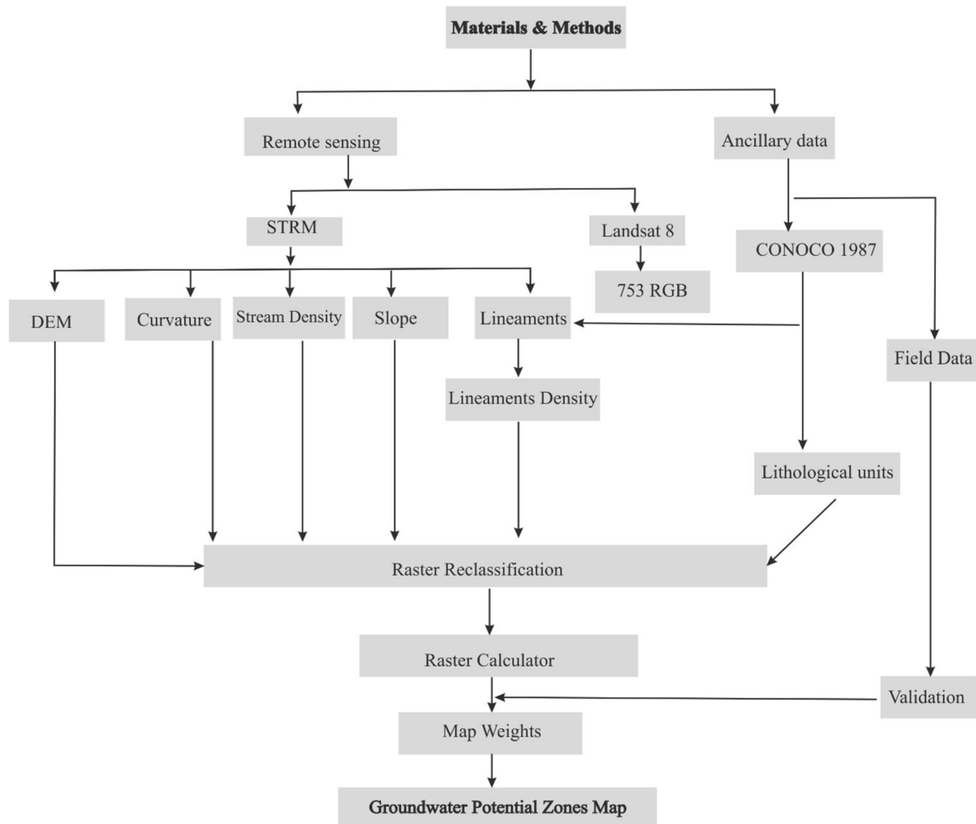

Fig. 3 A flow chart representing the applied methodology for the study area

ArcMap was used to carry out the groundwater potential zone map (Fig. 3).

Results and discussion

Groundwater controlling factors

Many conditioning factors are contributing to groundwater potential mapping, and there is no consensus on the criteria that should be included to develop the groundwater potential zones. Some criteria that contribute to flood susceptibility used in previous studies are elevation, slope, curvature, stream density, lineament density, and precipitation (Abdalla 2012; Arnous 2016). In this study, DEM, slope, curvature, lineament density, and density of the stream network in the area were included.

Elevation

A 30-m resolution represents Shuttle Radar Topography Mission (SRTM), where the digital elevation model (DEM) data is housed on the USGS Earth Explorer (Fig. 4a). Spatial and temporal groundwater availability can vary depending on terrain (Kumar et al. 2008). In this area, the elevation of the ground surface ranges from 0 to 872 m (above sea level); this sporadic variety between the lowest and highest areas creates slopes that monitor the movement of water to the lowlands. This allows water to accumulate and recharge the groundwater zones.

Therefore, four classes were identified for DEM: 0–150 m, 150–300 m, 300–500 m, and > 500 m.

Slope angle

A slope map can be created using DEM; the surface analysis method was used in ArcGIS 10.4. The slope map (Fig. 4b) is important in groundwater potential zone mapping to identify areas with high slopes with high runoff and hence low infiltration rate (Arnous and Green 2011, 2015; Vanani et al. 2017). However, the map of the slope was categorized into four classes: 0–5, 5–10, 10–15, and > 15°. The main channels of Hagul and Bada'a have low slope values and are associated with low runoff and high infiltration rates. The low slope value has been assigned a high rank.

Curvature

Subba (2006) and Elmahdy (2012) suggested that in flat and highly negative curvature areas, groundwater potential is much higher. The most negative curvature values are in the valleys and channels, while the ridges are the most positive values. The curvature values can be categorized into three groups: positive values indicating upward-convex in the area, negative curvature

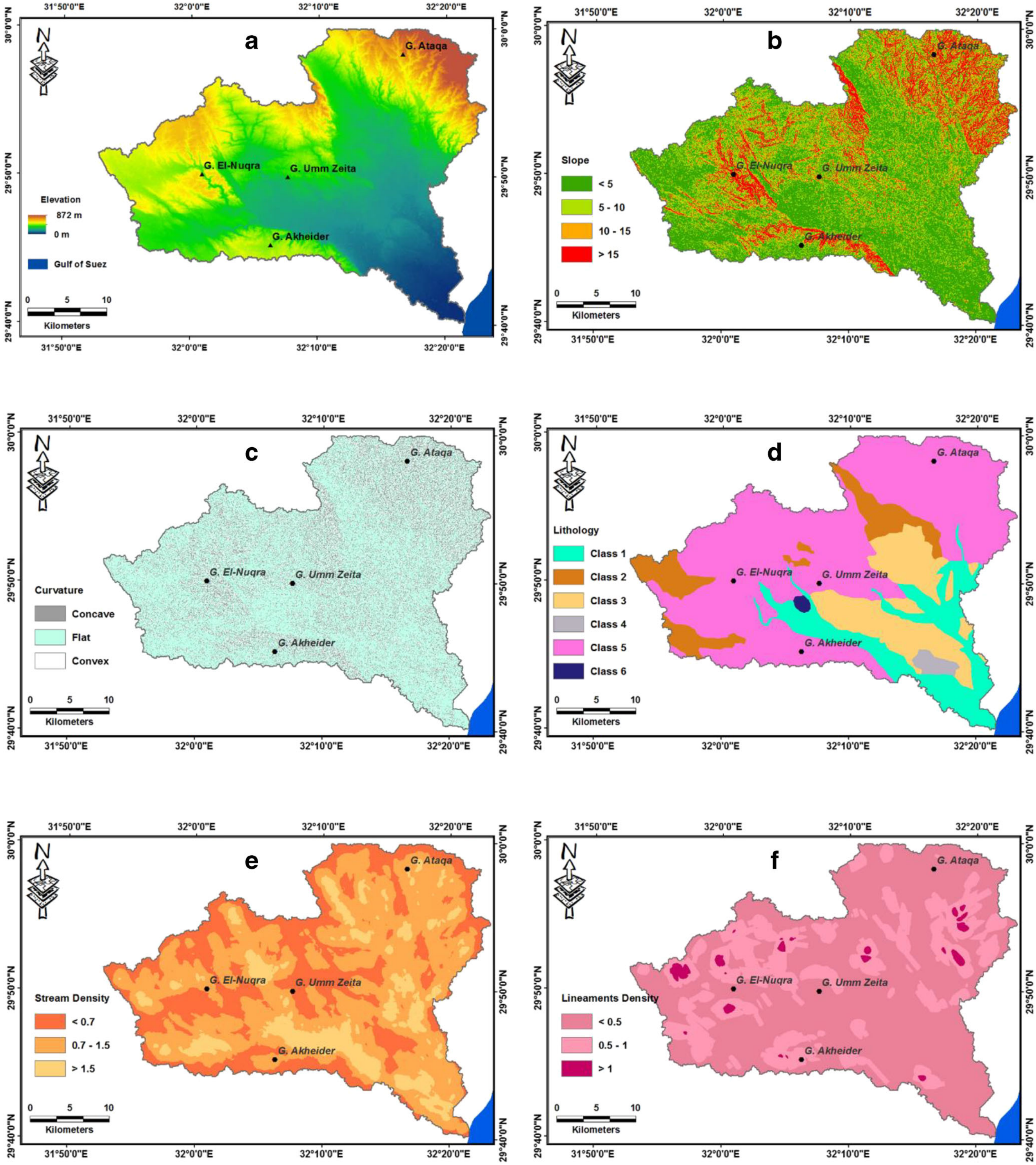

Fig. 4 Groundwater controlling factors: **a** elevation map, **b** slope degree, **c** curvature, **d** lithological units, **e** stream density, and **f** lineament density

indicating upward-concave, and zero indicating a linear area. Arnous and Green (2011) concluded that a curvature value of zero gives more potential for groundwater accumulation. However, the flat and negative curvature value areas signed with high ranks and are associated with the low overland flow and high infiltration rates (Fig. 4c).

Lithology

The geological map by CONOCO (1987) was used to identify the rock units; digitization on ArcGIS was used to create the raster rock units (Fig. 4d). Six classes of rock units were created in ArcGIS, namely Quaternary deposits, Fluviatile sand and gravels, Pliocene deposits, shallow marine shale and limestone, colored sand, and gravels, and the Mokatam Group involves bedded limestone with local chert.

Stream density

The Arc Hydro tool of ArcGIS 10.4 was used to create and obtain the drainage network and watershed system. The DEM derived from the SRTM data was used for terrain input pre-processing. The drainage network built from the DEM already exists in the literature (Gurnell and Montgomery 1999; Maidment 2002). A topographic map (of scale 1:50,000) was used in conjunction with Thematic Mapper Landsat mosaic with 30 m ground resolution for the drainage basin analysis. All maps were geo-referenced in ArcGIS 10.4 using UTM coordinate system zone 36. However, the stream order was extracted and coded in the GIS environment; the line density tool within the ArcMap package was used to create the raster map of drainage network density (Fig. 4e).The linear drainage basin characteristics were calculated according to Horton (1945) and Strahler (1952) and included stream ordering. The drainage density map (Fig. 4e) postulated that lower-density values show poor or unfavorable groundwater accumulation sites, and higher-density values indicate higher permeability of surface material and consequently improved groundwater recharge. The occurrence of rock units with high competence, which forms several additional flow paths, leads to high-density values (Shaban et al. 2004).

Lineament density

The SRTM dataset was used to extract lineaments and verify the lithological units of the geological map of the area of interest (Fig. 4f). Structurally, the study area is described as a vast graben, complicated by several areas of salient horst and possibly somewhat subdued grabens. Eocene and Miocene rock units in the study area are affected by approximately 392 faults and have been grouped into NW, E–W, and NNW trend sets, with the NW set including the largest number of faults in the study area (Abdallah 1993; Youssef and Abd-Allah 2003). NNW–SSE set faults are common and mostly gravitational. The main wadis (e.g., Wadi Hagul and Wadi Bada'a) in the study area are bounded by the Eocene limestone plateau.

Surficial structural features include faults and joints that can be considered as potential groundwater zones (Pradeep 1998; Ganapuram et al. 2009). The normal faults with sinuous trends characterized the structure of the Suez Gulf, which strike parallel to the rift and delimit several tilted blocks (Said 1962). In order to generate a line density map, the lineaments were digitized on the ArcGIS environment, and structural elements were converted to a raster lineament density map (Fig. 4f).

Potential groundwater zones

Potential groundwater zone mapping was mainly constructed based on the integration of multi-criteria thematic layers, namely an elevation layer, slope map, curvature, lithology, lineaments, and stream network. Each controlling factor was given a weight according to its contribution to groundwater occurrence. Each thematic layer was categorized into classes, where different numerical categories (1 to 4) were provided by previous study methods (Krishnamurthy et al. 1996; Prasad et al. 2007). A higher numerical category was assigned when there was a higher ability to store and transmit groundwater (Table 1). The thematic layers obtained were assigned various classes and ranking in the present study. The capability values, obtained by dividing the layer class rank and total class rank as score, were further averaged into three to six classes (Table 1). DEM was classified into four classes, namely very high degree (0–150 m), high degree (150–300 m), moderate degree (300–500 m), and low degree (> 500 m). The low-elevation value has been assigned with high ranks in this study.

However, a value of 2 was assigned as the map rank for the DEM layer. The slope degree layer was classified into four classes including very high degree (0–5°), high degree (5–10°), moderate degree (10–15°), and low degree (> 15°). The curvature is therefore assigned three classes: high degree (< 0), moderate degree (0), and low degree (> 0). About 50.39% of landscape in the area is under the gentle slope (< 5°) class, and this could be a pointer of the occurrences of high groundwater potentiality (Hussein et al. 2016). The map rank of value 3 and 2 was applied to slope and curvature thematic layers respectively. Since the lithological units play an important role in the occurrence of groundwater, they were classified into 6 classes. The Quaternary deposits and Fluviatile gravels and sand were assigned very high to high degree of potentiality. Before the generation process of stream density, the stream network was extracted from the DEM. The stream of the study site was classified into three classes: low (< 0.70), moderate (0.70–1.5), and high (> 1.5) potentiality. The lineament density of the study area was classified into three classes including low (< 0.50 km/km^2), moderate (0.50–1.0 km/km^2), and high (> 1.0 km/km^2) potentiality. Furthermore, the more densely distributed lineaments along the study site (> 1.0 km/km^2) were considered as excellent groundwater potential zones. The linear combination of integrated thematic layers predominates in the GIS program raster files, and these files are given a composite map (Abdalla 2012). Under numerous circumstances, groundwater aquifers exist in the northern portion of the Gulf of Suez, indicating lithological, structural, and topographical variations (Snousy et al. 2016). However, groundwater provides water as the principal supply for domestic and industrial uses. The weighted for the thematic layers used in this work has been calculated using Eq. 1. The potential groundwater map

Table 1 Thematic map weight and capability value

Thematic layer	Classes	Map rank	Weight	Degree	Rank	Capability value
DEM	0–150	2	0.13	Very high	4	0.40
	150–300			High	3	0.30
	300–500			Moderate	2	0.20
	>500			Low	1	0.10
Slope	0–5	3	0.20	Very high	4	0.40
	5–10			High	3	0.30
	10–15			Moderate	2	0.20
	>15			Low	1	0.10
Curvature	<0	2	0.13	High	3	0.50
	0			Moderate	2	0.33
	>0			Low	1	0.17
Lithology	Quaternary/Wadi deposits	2	0.13	Very High	4	0.36
	Fluviatile sand and gravels			High	3	0.27
	Shallow marine shale and limestone			Low	1	0.09
	Colored sand, and gravels			Low	1	0.09
	Mokatam Group, bedded limestone with local chert			Low	1	0.09
	Pliocene deposits			Low	1	0.09
Stream networks	<0.7	3	0.20	Low	1	0.17
	0.7–1.5			Moderate	2	0.33
	>1.5			High	3	0.50
Lineament	<0.5	3	0.20	Low	1	0.17
	0.5–1.0			Moderate	2	0.33
	>1.0			High	3	0.50

(Fig. 5) has been computed mathematically using a raster calculator tool in ArcGIS as follows (Eq. 2):

$$W_i = \sum D_e + C_r + S_l + L_i + S_n + G_{eo} \quad (1)$$

where W_i denotes map weight, D_e denotes the digital 294 elevation model, C_r denotes the curvature, L_i denotes the lineament density, S_l denotes slope, S_n denotes stream network, and G_{eo} denotes geology class.

$$GWPZ = \sum W_i \times CV_i \quad (2)$$

where W = groundwater potential zone, CV_i = capability value, and W_i = map weight.

Accordingly, the final potential groundwater map was created on the GIS tool to describe the groundwater capabilities in the area of interest. The final potential groundwater map is grouped essentially into five groups including very low, low, moderate, high, and very high potential zones (Table 1, Fig. 5). The Wadi main channels are characterized by thick alluvium deposits and high lineament density, with gentle slopes that contributed to high potential zones of groundwater. However, in the high-altitude areas associated with a limestone plateau and high slope, such areas are considered to have low to very low groundwater potentiality. The final map of the potential groundwater zones indicates that the very low and low zones represent approximately 36% of the total area (Table 2). The area characterized by moderate groundwater potential represents approximately 26% of the total area. However, the very high and high potential areas represent approximately 38% of the total area which is composed of valley deposits and Quaternary sedimentary sequences.

Borehole and lineament density

The system of drainage in the area is following the lineament directions revealing that the drainage system is structurally controlled. Lineament directions and drainage patterns act as pathways or storage for groundwater recharge. Moreover, the fracture zones in Eocene limestone in the area usually exist along lineaments and are targets for the exploitation of groundwater. The relation between borehole locations and lineament density was subjected to other factors such as lineament density, availability of lineaments to conduit subsurface water, geomorphology, and hydrogeology, that may enhance the bore hole capacity.

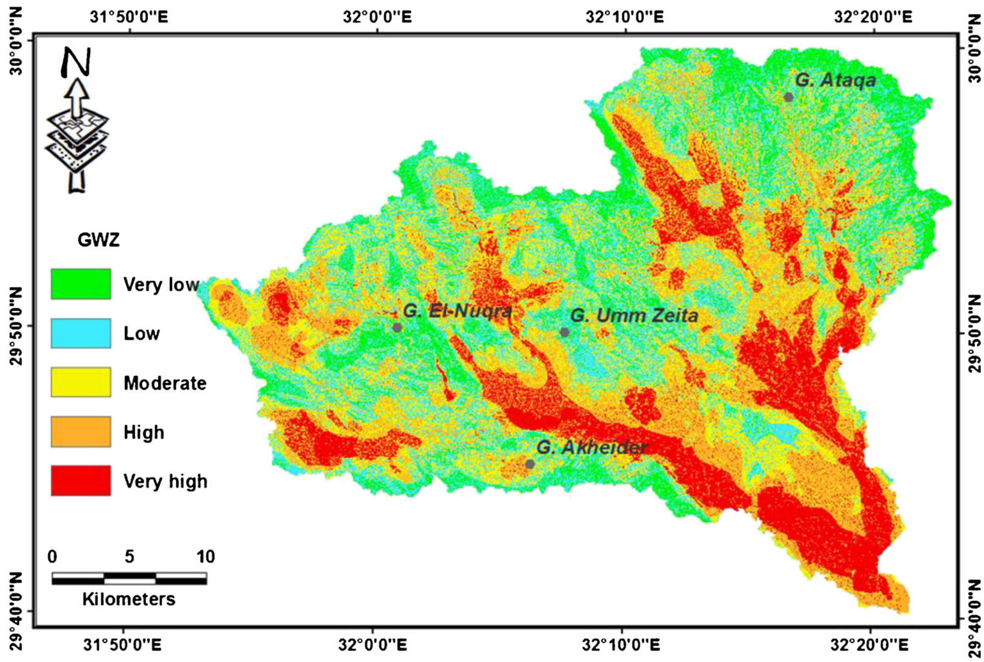

Fig. 5 The potential groundwater classification zones (GWPZ) for the area site

In our study, the borehole wells occur in the south-central and southeastern portions of the area (downstream) because of high lineament density, and Quaternary and Wadi deposits and fracture limestone deposits act as main and principal aquifers in the area. Finally, the relationship between borehole yield and lineament density (LD) is significant when assessing the influence of secondary porosity on the movement and storage of groundwater. The rose diagram shows two major predominant trends, NW–SE and NE–SW; the less predominant trend is N–S (Fig. 6). The trends of lineaments are corresponding to the tectonic setting of the Eastern Desert. The first trend in the Arabian Nubian Shield and Red Sea tectonic trend is NW–SE and parallel to the Najd Fault System (Mudhash 2011); the second trend is NE–SW and parallel to the Trans-African trend (Schandelmeier et al. 1987); and the Qena-Safaga trend, the less predominant trend, is the N–S trend.

Model validation

The validation step is important to confirm the result of model prediction; otherwise, the prediction model has low scientific significance (Chang-Jo and Fabbri 2003). Some dataset was collected during the fieldwork and investigation for the study area, which reflected the real groundwater level. The approach of water wells to validate the prediction of potential groundwater zones with the help of remote sensing data has been used in several studies (Abdalla 2012; Arnous 2016). Approximately 18 drilled wells in the study area were used to validate the model accuracy in both Wadi Hagul and Wadi Bada'a. Some of these wells were hand dug and ranged in depth from 6 to 260 m. The depth of water ranges from 6 m in Wadi Hagul to 157 m in Wadi Bada'a. Moreover, most of the water wells are in quaternary and Wadi filling deposits. The area was predominantly low to moderate in groundwater potential and represented approximately 50% of the total area. Figure 7 illustrates the relationship between the spatial distribution of drilled water wells and groundwater potential zones.

Table 2 Classification and distribution of groundwater potential zones

Class	Area (km^2)	Percentage
Very low	132.30	12%
Low	240.72	24%
Moderate	261.07	26%
High	226.86	23%
Very high	146.30	15%

Conclusions

The Gulf of Suez region is intimately linked to the complicated tectonic features of the subsurface and represents a part of the Eastern Desert with complex hydrological formations that dominate in the north. In the study site, the remote sensing datasets with GIS were able to identify the zones of groundwater potentiality. The geological and geomorphological features control the water resources of the area, which largely linked to the aquifer recharge and infiltration rates. The primary source of groundwater in the area is Quaternary sediments composed of gravel and sand units. These sediments represent the main deposits in the main

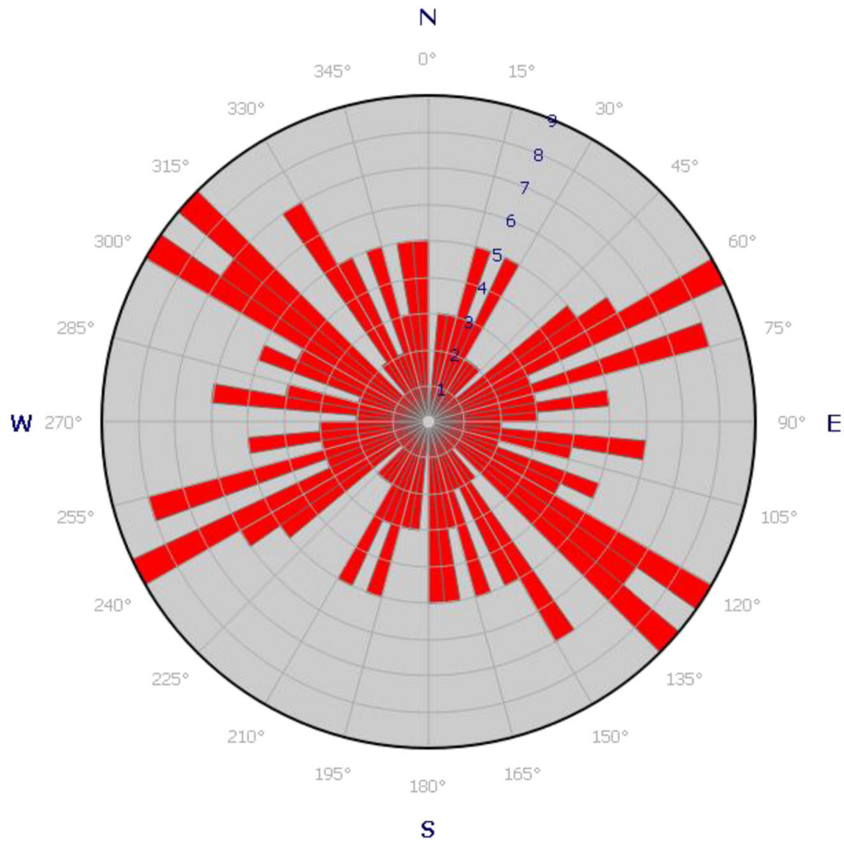

Fig. 6 Rose diagrams showing strike frequencies of the lineaments

channels in the northwestern Suez Gulf. Qualitative analysis was carried out in the present study, to evaluate and assess the groundwater potential zones using GIS and remote sensing approach. The work here integrates the effects of different controlling factors accounting for groundwater occurrence. The thematic layers that were used play a key role in controlling the water accumulation and transition and are elevation, slope, curvature, drainage network density, lineament density, and lithology. The sediments had a higher weighted value due to their high infiltration rate.

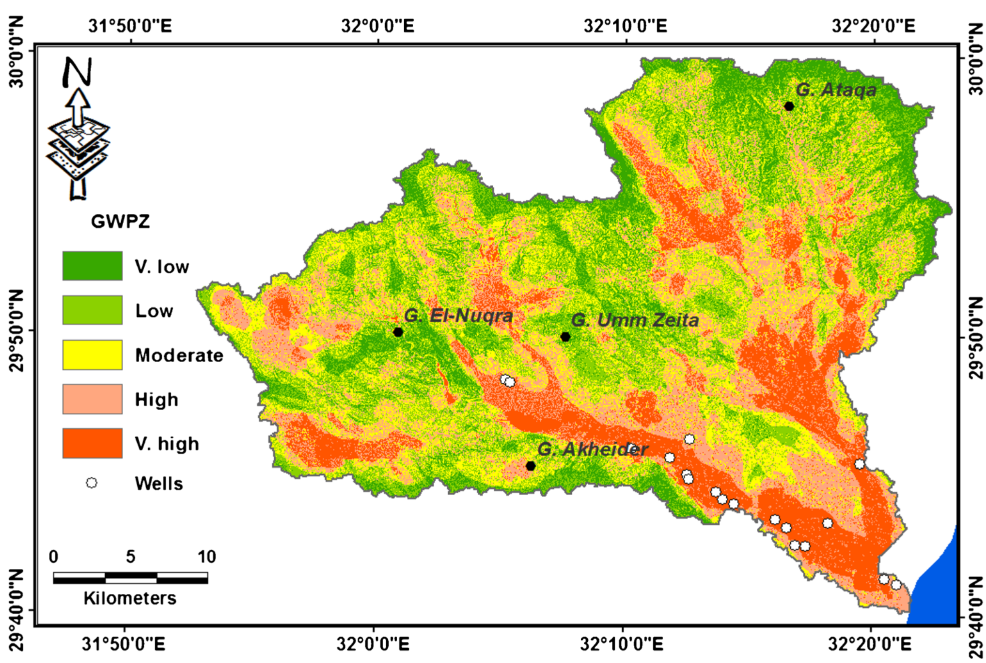

Fig. 7 Spatial distribution of the productive wells within the groundwater potential zones

Mapping of the groundwater potentiality in the area can be categorized into five essential categories involving very low potential zones and low potential zones associated with high-altitude areas, while moderate potential zones, high potential zones, and very high potential zones are concentrated in the main Wad's' channels. According to the groundwater potential zone (GWPZ) map, Wadi Hagul is categorized into five different zones, namely very low (12% of the area), low (24% of the area), moderate (26% of the area), high (23% of the area), and very high (15% of the area). Finally, the high to moderate potential zones characterized with low elevation and a gentle slope and cover approximately 49% of the area. These areas are composed of sand and gravel that allow for subsurface water accumulation and percolation. The model was validated by drilled wells and demonstrated that there are several unexploited areas with good groundwater capabilities. The groundwater potential zone (GWPZ) map can be used by decision-makers and planners for future development.

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Availability of data and material The data and materials of this study will be available upon request.

Code availability The ArcMap (10.4) package was used in the present work.

Declarations

Conflict of interest The authors declare no competing interests.

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