Mapping of Potential Groundwater Recharge Zones: A Case Study of Maputaland Coastal Plain, South Africa

Denisha Ponnusamy
University of Zululand
N Rajmohan
King Abdulaziz University
Peiyue Li
Chang'an University
M Thirumurugan
University of Zululand
Chidambaram Sabarathinam
Kiwa Water Research: KWR Water Research Institute
Vetrimurugan Elumalai (evetrimurugan@yahoo.co.in)
University of Zululand https://orcid.org/0000-0003-0780-8806

Research Article

Keywords: Groundwater potential zones, remote sensing, AHP technique, Boolean logic, Maputaland, South Africa

DOI: https://doi.org/10.21203/rs.3.rs-566699/v1

Mapping of potential groundwater recharge zones: a case study of Maputaland Coastal plain, South Africa

Denisha Ponnusamy[1], N. Rajmohan[2], Peiyue Li[3], M. Thirumurugan[1], Chidambaram Sabarathinam[4], Vetrimurugan Elumalai[1*]

[1]Department of Hydrology, University of Zululand, Kwa Dlangezwa, 3886, South Africa.
[2]Water Research Center, King Abdulaziz University (KAU), Post Box 80200, Jeddah 21598 Saudi Arabia.
[3]School of Water and Environment, Chang'an University, No. 126 Yanta Road, Xi'an 710054, Shaanxi, China
[4]Research Scientist, Water Research Centre, Kuwait Institute for Scientific Research, Safat, Kuwait

[*]Corresponding author:

Prof. Elumalai Vetrimurugan

University of Zululand,

Kwadlangezwa-3886,

South Africa.
Telephone: (+27) 35-902 6404
Email: evetrimurugan@yahoo.co.in; ElumalaiV@unizulu.ac.za

Abstract

The potential groundwater zones of the Maputaland coastal plain of Kwazulu-Natal is identified by comparing the Analytic hierarchy process (AHP) - Multi criteria decision-making (MCDM) technique and Boolean logical approach. The map of groundwater potential zones was prepared by generation and integration of 8 thematic layers, i.e. geology, geomorphology, lineament density, soils, slope, rainfall and land use. Each thematic layer were assigned with subjective relative weights under AHP-MCDM technique and Boolean logic and were overlaid in a GIS platform to identify the groundwater potential zones. The groundwater potential zones were delineated under two different GIS techniques to obtain confident results. Weights of thematic layers were allocated using AHP normalized eigen vector methodology and weighted linear combination method was employed to find the groundwater potential index. Whereas in a Boolean approach, AND operator was applied in order to integrate thematic layers to delineate the groundwater potential zones. The delineated groundwater potential maps using AHP-MCDM technique indicates that 6.0% (310.5 km^2) from total area falls under very good; 67% (3467 km^2) good; 25% (1294 km^2) poor and 2% (103.5 km^2) under very poor, whereas in Boolean logic about 70 % of the area (i.e. 3623 km^2) constitutes good and 30 % (1552 km^2) of the areas constitutes poor groundwater potential zone. Further, the obtained results indicate that the geology, geomorphology, land use and slope played a vital role in groundwater recharge. This pioneer study in maputaland coastal plain explores the baseline data of the potential groundwater zones. The results emanating from this study can be used in further understanding of the available groundwater resources and can be helpful in future to find the suitable groundwater exploration sites in the area.

Keywords: Groundwater potential zones, remote sensing, AHP technique, Boolean logic, Maputaland, South Africa

Introduction

Water scarcity in South Africa is a reality due to a drastic increase in urbanization and industrialization which has put enormous pressure on the country's water resources. To meet the growing water demand in the country, the surface water resources from rivers, dams, and estuaries are utilized to supply most of the South Africa's domestic, industrial and agricultural needs (Du Plessis 2017). However, owing to the growing population and industrialization, current surface water resources are under threat (Huizenga 2011; Pitman 2011; Du Plessis 2017; Vetrimurugan et al., 2017a).

Groundwater has become an essential natural resource for the provision of water in many regions and countries of the world (He et al., 2020; Li et al., 2019; Su et al., 2020; Vhonani et al., 2018, Vetrimurugan et al., 2017b, Wu et al., 2020). Groundwater contributes between 13 % and 15 % of the total water need in South Africa (Mpenyana-Monyatsi et al., 2012). It is noted that groundwater is abstracted heavily for industrial, mining and agriculture purposes which has caused a rapid decline in groundwater levels. Hence a comprehensive study should be undertaken to locate and outline the groundwater potential zones before an exploration of groundwater (Fashae et al., 2014; Rahmati et al., 2015; Selvam et al., 2015;

Adeyeye et al., 2019; Qadir et al., 2019). This can be achieved using the Geographic Information System (GIS) and remote sensing techniques, which is cost and time effective (Chowdhury et al., 2010; Jha et al., 2010; Deepika et al., 2013; Nampak et al., 2014; Rahimi et al., 2014; Zaidi et al., 2015; Andualem and Demeke 2019). Remote sensing and GIS techniques utilize satellite data along with various thematic maps. Integration of remote sensing and GIS data with assigned weightage in a spatial domain was carried out to prepare various thematic layers such as geology, geomorphology, lineament density, drainage density, land use and land cover, slope gradient, soil texture and rainfall intensity in order to map out the groundwater potential zones.

Analytical Hierarchy Process (AHP) method is a commonly used Multi-Criteria Decision Making (MCDM) technique to delineate groundwater potential zones (Murmu et al., 2019). However, there are considerable research carried out through other methods such as probabilistic approach of frequency ratio (Manap et al., 2014), weights of evidence (Tahmassebipoor et al., 2016), fuzzy logic (Kumar et al., 2013), Shannon's entropy (Naghibi et al., 2014), machine learning techniques of maximum entropy (Rahmati et al., 2016) and index-based methods to assess the groundwater potential zones (Dar et al., 2010; Elewa and Qaddah 2011 Another beneficial technique for expanding the well-known logically-based GIS model for the integration of thematic layers is the Boolean logical approach. (Robinov 1989; Zaidi et al. 2015). It involves incorporation of several binary maps, which are the products of employment of conditional operators (Bohnam-Carter 1994).

Identification of groundwater potential zones through the application of remote sensing and GIS has been common amongmany studies done worldwide, yet there are limited studies carried out so far in South Africa. Local domestic and agricultural water needs in Maputaland coastal plain are supplied from the Mbazwana municipality and local borewells. However, supply of water through pipelines has been over-extended which has resultant inadequate flow and hence the households receive inadequate water supply for their daily needs. Lake Sibaya was the main source for freshwater in this area, which is also under stress due to inconsistent rainfall and over-abstraction (Simonis and Nweze, 2016). Therefore, groundwater has become the only alternative for freshwater, but it is impracticable due to the expensive drilling costs and lack of proper understanding of the aquifer framework. The groundwater in this region is most predominantly abstracted from unconsolidated sedimentary aquifers due to its wide distribution and easy accessibility (Margat and Van der

Gun 2013). In account to this, it is very important to study and explore about groundwater resources for present and future demand. Hence, this study was conducted with the aim of identifying and delineating zones of groundwater potential via the integration of several thematic maps through the use of GIS and remote sensing techniques. Delineating the groundwater potential zones will be helpful to the stakeholders and government organisation to locate the suitable locations for exploration of groundwater to supply demands.

Study area

The study area is situated within the Maputaland coastal plain in northern KwaZulu-Natal, South Africa. Stretching over 70 km wide beside the border of Mozambique, encompassed by the Lebombo Mountains on the west and its southern border to St. Lucia., The total area ranges about 5175 km^2. The area has a subtropical, humid climate with mean annual temperatures ranging from 21°C and average rainfall in the coastal areas is 1200-1300 mm per annum (Porter and Blackmore, 1998). The geological settings of the study area is Maputaland formation consisting of the Jozini formation, rhyolites from the Lebombo group (Jurassic period) (Watkeys et al, 1993). Lebombo mountain formation are inclined slopes of the Jozini rhyolites which is extended beneath the sea (Ceruti, 1999). The Makathini formation consists of non-marine, riverine coarse sandstone and conglomerate which forms the foundation of this regional aquifer. The formation possesses a very low hydraulic conductivity, porosity and storativity (acts as an aquiclude) and is overlain by t Mzinene Formation consisting of marine silts, clays and sands. The formation is varying with different aquifer types such as confined, unconfined and leaky aquifers. In Port Dunford, formations are laid down on top of the tertiary rocks which have low hydraulic conductivity and storativity and forms a leaky aquifer forming a connection to the Indian Ocean (Kelbe et al, 2016). This formation is overlain by Kosi Bay formations which are porous and more permeable promoting excellent recharge into the aquifers (Weitz & Demlie, 2014). The Maputaland coastal region is known for its barrier lakes, lagoons, swamps and well-vegetated coastal dunes. Further, off the coast, a counter-current exists formed by the local winds and wave refraction pushing the sand northwards and renews the sand on beaches creating the characteristic enormous dunes of the area which have reached the elevations of up to 180 m (Vaeret et al, 2009; Weitz and Demlie, 2014).

Methodology

The methodology adopted for this study is presented in Figure 2. There are different thematic layers like geology, geomorphology, land use, lineament density, drainage density, soil type, the slope of the area and rainfall of the region which are used to delineate the potential groundwater recharge zones. The data obtained from various organisations were utilized in the ArcGIS 10.5 software and was used for developing the various thematic maps. The maps of geology, land use and geomorphology were derived from data obtained from Council for Geosciences, South Africa and digitized using ArcGIS software. Land use data for the year 2010 was utilized in this study since no significant changes were observed in the last twenty years. Soil type data was obtained from Food and Agricultural Organisations. Rainfall data for the last twenty years (1999-2019) of 8 rain gauge stations were obtained from South African Weather Service (SAWS). These data were interpolated using Inverse Distance Weighted (IDW) tool in ArcGIS software to obtain the rainfall distribution all over the study area. Using satellite imageries for Shuttle Radar Topography Machine (SRTM) 30 m resolution and Digital Elevation Model (DEM) 30 m resolution satellite imageries were accessed freely from USGS-Earth Explorer and was utilized to derive the slope, drainage pattern and lineaments of the study area. The drainage density and lineament density of the study area was calculated using line density analysis tool in ArcGIS software.

Satellite imageries and various thematic data were geocoded with Geographic Coordinated System of WGS 1984 and Projected Coordinated System of UTM WGS-84, zone 36 south. Further, the thematic layers were converted into raster format to perform weighted overlay analysis. Groundwater potential map was prepared under weighted overlay analysis using Analytic Hierarchy Process (AHP) and Boolean logic technique. Weighted overlay analysis was performed by assigning ranks for individual parameters.

Multi-Criteria Decision Making (MCDM) using the AHP technique

AHP technique (Saaty R.W, 1987) was used in this study. The 8 parameters were allocated a weight (1-9) based on their relative importance. The subclasses (sub-criteria) of each thematic layers were also ranked on a scale of 1 to 9 (Table 1), based to their relative influence on the groundwater occurrence. (Al-shabeeb, 2016).

Weightage calculation

The multi influencing factors such as geology, geomorphology, drainage density, land use, lineament density, drainage density, soil type, the slope of the terrain and rainfall of the area were evaluated and allocated with an appropriate weight as shown in Table 1. All factors were assigned a weightage from 1 to 9 according to Saaty's scale based on the relative importance and its significance. Value 1 denotes the very less importance between other thematic layers and the value 9 denotes very high importance of the thematic layers compared to another (Saaty, 1980).

The weights were normalized with MCDM-AHP techniques with the help of eigen values to remove the bias from assigned weights. To check the consistency of the weights of the different thematic layers and their subclasses, a consistency ratio was computed. The consistency ratio (CR) was calculated using the consistency index (CI) and random consistency index (RCI) using the equation given below (Saaty 1980). The different random consistency index for various criteria used in calculation is given in Table (2). Each pairwise comparison matrix was analysed using the below formulae (Table 3)

$$\mathrm{CR} = \frac{CI}{RCI}$$

The principal eigen value was used to calculate the consistency index (CI) using the following equation (Saaty 1980).

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

where $\lambda_{\max}$ is consistency vector, n is the number of criteria used

The assigned and normalized weights of various thematic layers and the consistency ratio are shown in Table (4). The value of consistency vector (λ) was 7.84, the normalized weights were found to be consistent according to the consistency ratio (0.02) and found acceptable recommended by Saaty (1980).

Delineation of groundwater potential zones using Boolean logic

The Boolean logical approach is the most basic type of GIS model to integrate the thematic layers using binary code classification system. Each pixel of various thematic layers was assigned as zero for unsuitable locations and one for suitable locations. (Boole 1854; Freeze and Cherry 1979; Karanth 1987). The Boolean logic consists of its own operators Boolean AND & Boolean OR, which works with two or more datasets. The thematic layers and their subclasses were assigned with suitability limits of 0 and 1 based on their significance when delineating zones of groundwater potential (Table. 1).

Delineation of groundwater potential zones using MCDM approach

Zones of groundwater potential were delineated by applying (WLC) method (Malczewski 2000), which helps to integrate criteria and combine the maps to acquire the groundwater potential zone map by AHP-MCDM approach. All the thematic layers were integrated in the ArcGIS environment using weighted overlay tool. The groundwater potential index (GWPI) was calculated using the equation:

$$GWPI= (GM_W \times GM_N) + (GE_W \times GE_N) + (LC_W \times LC_N) + (SO_W \times SO_N) + (RF_W \times RF_N) + (LD_W \times LD_N) + (SL_W \times SL_N) + (DD_W \times DD_N)$$

Where; GWPI=Groundwater Potential Index, GM=Geomorphology, GE=Geology, LC=Land use, SO=Soils, RF=Rainfall, LD=Lineament Density, SL=Slope, DD=Drainage density, w=normalised weight of the thematic layer, n=normalised weight of sub-criteria.

The resultant maps of groundwater potential zones using AHP-MCDM and Boolean logic were verified by superimposing the point maps on raster data set.

Results and discussion

Interpretation of the groundwater potential indices

Groundwater potential zone is regulated and influenced by several indices. These indices can be either natural or human-related factors. Geomorphology, lineament density, slope, geology, rainfall, soil type and drainage density ca be considered as natural factors affecting groundwater occurrence, while land use can be considered as a human-related factor as it is significantly affected by human activities. These changes can also significantly affect the groundwater quality (He and Wu 2019b; He et al. 2019b). The factors are discussed in detail as follows.

Geology

Geology of an area performs a pivotal function when it comes to surface water infiltrating into an aquifer system through the features of porosity and permeability, these features vary for different geological formations. The study area is underlain by pre-

Cambrian granitoid basement which is overlain by unconsolidated to partially consolidated sediments derived from alluvium and aeolian deposits of the Late Pleistocene to Holocene (Barath 2015; Weitz and Demlie 2014). The study area comprises of Arenite, Rhyolite, Alluvium and siltstone which acts as aquifer in this region at varying thickness. Majority of the study area consists of sedimentary formations (Figure 3a). These sediments are highly permeable which ease rapid recharge to aquifer system. Geological formations were assigned with weights under AHP-MCDM technique and Boolean logic according to the significance of recharge (Table 1).

The alluvium and siltstone formation were assigned with the highest weight followed by arenite rocks in AHP-MCDM technique and these formations were considered as suitable for groundwater recharge in Boolean logic (Table 1). Rhyolite formation was assigned with low weight and considered as unsuitable for infiltration since, this formation has very less permeability and are incapable to transmit water.

Geomorphology

Geomorphology of a region is considered as an indicator for identifying groundwater potential zones as it influential on the hydraulic properties of the aquifer system. The prominent geomorphologic features identified in the study area are low mountains, moderately undulating plains and plains. Most of the area is covered by plains and part of south-western region is covered by moderately undulating plains and low mountain region (Figure 3b).

Plains has significant surface water infiltration potential areas, where the velocity of runoff is very slow and surface water tends to percolate into the aquifer owing to longer resident time. However, the moderately undulating plains and low mountain areas has lesser surface water infiltration when compared to plains having the highest infiltration capacity. Hence the highest weight of 7 was assigned to plains followed by moderately undulating plains with a weight of 5 using AHP-MCDM technique and these features were considered as suitable under Boolean logic, whereas low mountains were assigned AHP-MCDM weight of 3 and considered as unsuitable for groundwater infiltration under (Table 1).

Land use

A significant factor controlling the recharge of groundwater is the land use pattern. (Ghosh et al., 2016; Murmu et al., 2019). The land use pattern is significantly affected by human activities. Accurate and reliable information on the land-use pattern of an area is necessary to delineate the recharge zone (Singh et al., 2018). In the study area the major land use type is open land with less vegetation followed by agricultural land, degraded land without vegetation and plantation, water bodies and scrub/bushlands (Figure 4a).

Sugarcane cultivation is the major agricultural activity while maize, pineapple, citrus fruits, bananas and vegetables are cultivated in this area. A natural and commercial forest can be seen along the entire coast whereas commercial forest is the major resource for timber industries. Water bodies were given with the highest ranking of 8 due to the significance of continuous surface water recharge (Srivastava and Bhattacharya, 2006). The open land, agricultural land and grassland were provided with an assigned weight of 7 due to its potential surface water infiltration capacity through the roots of plants. Assigned weight of 6 was given to the degraded land and thick bushlands since evaporation rate is higher in these places. The weights assigned to different land-use types are given in Table (1). Other than degraded land and exotic plantations the rest of the regions were considered as suitable for infiltration, since degraded land has compact and very less permeable portions, the exotic plantation regions are dense where the less or no infiltration occurs. Most of the rainfall received in these areas has high runoff.

Slope

The slope of an area is the important factor to discriminate the surface morphology of an area (Zaidi et al., 2015) which governs the surface runoff velocity and erosion activity. Slope gradient governs the infiltration of surface water, where there is a lesser degree of slope, the recharge capacity is higher and at places of higher degree of slope, the recharge becomes lesser or negligible due to rapid runoff (Daher et al., 201 1; Magesh et al., 2012; Ghosh et al., 2016).

Degree of slope in the study area was classified into five classes like, 0 – 1.5 ° (very low) 1.5-2.5° (low); 2.5-5.5° (moderate); 5.5-12° (high); 12-30° (very high). Most parts of the study area having the lesser slope gradient (Figure 4b) has enhanced surface water infiltration. Hence the highest weight of 9 was assigned to very low slope gradient areas and were considered suitable for infiltration under Boolean logic approach. The assigned weight for different classes and suitability is shown in Table (1).

Lineament density

Lineaments are linear features found on the surface of the earth which reflects a superficial expression of subsurface structures like fault, fractures, dykes, etc., (Pradhan and Youssef 2010) which has highest secondary porosity and permeability (Magesh et al., 2012). Lineaments and its density are the important factors having more significance in the delineation of groundwater potential zones since it provides the information on pathways of groundwater flow (Magesh et al., 2012; Rahmati et al., 2015). Lineaments were identified in the northern and central part of the study area, which faces north-south direction extending 5 km – 25 km in length (Figure 5a). The lineament density was calculated from the total length of all lineaments divided by the area being investigated (Edet et al., 1998). It is derived by the following equation.

$$Lineament\ density = \sum_{i-l}^{i=n} \frac{Li}{A}\ (km^{-1})$$

where $\sum Li$ is the sum of the total length of lineaments (km); A is the area (km^2). The observed lineament density of the study area was classified in to 5 classes 0 – 0.1 km^{-1} (very low); 0.1 – 0.3 km^{-1} (low); 0.3 – 0.5 km^{-1} (moderate); 0.5 – 0.7 km^{-1} (high) and 0.7 – 0.8 km^{-1} (very high). Areas consisting of high lineament density are good for prospecting groundwater potential zones (Magesh et al., 2012). Hence highest weight of 9 and 8 were assigned under AHP-MCDM technique to very high and high lineament density zones and these regions were considered suitable under Boolean logic approach (Table 1).

Drainage density

Drainage density of an area is an important indicator to determine the hydrologic features which depicts the attributes of surface and subsurface formations. Drainage density can be defined as the closeness of spacing of streams, which can be measured as the total length of the drainage segment of all stream orders per unit area. Drainage pattern is affected by the qualities and structure of host rock, land use pattern, permeability of soils, vegetation covers and nature of slope gradient (Manap et al., 2013; Rahmati et al., 2015). Dendritic drainage pattern was observed throughout the study area, the drainage density was calculated by the proportion of the sum of lengths of streams to the total area being investigated. The drainage density was calculated by the equation given below.

$$Drainage\ density = \sum_{i-l}^{i=n} \frac{Di}{A}\ (km^{-1})$$

In an area if the drainage density is lesser then a higher infiltration rate and decreased runoff is observed. Hence, the areas having low drainage density are highly considered in delineating the groundwater potential zones. The drainage density of the study area was classified into five classes: 0 – 0.5 (very low); 0.6 – 1.0 (low); 1.1 – 1.5 (moderate); 1.6 – 2.0 (high); 2.1 – 2.5 (very high) as shown in Figure (5b). Most parts of the study area were characterised with very low to low drainage density, which enhances the greater infiltration rate. The highest weight of 8 and 6 were assigned respectively to very low and low drainage density classes under AHP-MCDM technique and were considered as suitable under Boolean logical binary code (Table 1).

Soil type

Soil type is also a major factor that controls the infiltration capacity and governs groundwater recharge (Jang et al., 2013). Different soil types usually possess diverse soil permeability, which is highly dependent on the soil texture, soil structure and land cover of the area. The three main soil types present in the study area are; arenosols, chromic luvisols and lithosols, (Figure 6a).

Arenosols are dominant in majority of the study area followed by chromic luvisols (Figure 6a). Arenosols comprises of sandy soils, developed in residual sands with highly siliceous having the highest permeability to infiltrate the surface water. Chromic luvisols are highly enriched with clay materials and lack of abrupt textural change and provide a slower infiltration rate compared with arenosols. Highest weight was assigned to Arenosols followed by chromic luvisols and lithosols (Table 1). Arenosols and chromic luvisols were considered as suitable for infiltration whereas lithosols was considered unsuitable to delineate the groundwater potential zones under Boolean logic approach (Table 1).

Rainfall

A major source of groundwater recharge is rainfall; hence it is considered as a significant input when delineating groundwater potential zones. (Adiat et al., 2014; Shekar and Pandey, 2014). Rainfall helps to determine the quantity of water that will be recharged into the aquifer system. Maximum rainfall rate in the particular area enhances the possibilities of highest infiltration rate.

Annual average of the last 20 years (1999-2019) rainfall data were used in this study. The results obtained from these data were classified into five classes (Figure 6b) namely; (547-600 mm), (601 – 650mm), (651-700mm), (701-750mm) and (751-800mm). The highest weightage was assigned in the areas of higher rainfall observed (Table 1). However, rainfall has significant contribution in groundwater recharge, all the subclasses in rainfall were considered suitable for infiltration under Boolean logic binary code (Table 1).

Integration of thematic layers to delineate the groundwater potential zones

The final map of groundwater potential zones was generated through remote sensing and GIS techniques by integrating the various thematic maps viz., geology, geomorphology, Land use type, lineament density, drainage density, type of soil, and slope gradient. The pictorial explanation of integrated thematic layers as overlay analysis is shown in Figure (7).

The groundwater potential zone prepared using the AHP-MCDM techniques in the study area was categorised into four sub-classes, namely very low, low, good, and very good groundwater potential zones (Figure 8a). the map of groundwater potential developed with Boolean logic was subdivided into two classes viz, poor and good groundwater potential zones (Figure 8b). About 6.0% (310.5 km^2) from the total area falls under very good; 67% (3467 km^2) good; 25% (1294 km^2) poor and 2% (103.5 km^2) very poor. The groundwater potential map developed using the Boolean logic approach have demarcated that about 70 % of the area (i.e. 3623 km^2) constitutes for good and 30 % (1552 km^2) of the area constitues poor groundwater recharge capacity. Due to high altitude and low mountains in the eastern and south-western part the study area the potential groundwater recharge is identified as Very poor which makes runoff more rather than recharge. Poor groundwater potential zones are due to the presence of undulating topography, in the eastern and western stretches of the study area. It is observed from the topography that eastern border is dominated by sand dunes of about 180 m, and western part is covered by moderately undulating plain which favours more runoff. The presence of Luvisols in the western part has lesser permeability which is also the major reason for being categorised as a poor groundwater potential zone. The very good groundwater potential zones are identified in the northern part and it is due to geology, geomorphology and especially the cluster of lineament density were observed. Most of the agricultural areas in the study region allows groundwater recharge. This indicates that soil, geology, geomorphology, lineament density, land use and slope plays a vital role in groundwater potential zone mapping. The delineated groundwater potential zones under the two different GIS technique give similar kind of results, which confirms the results. However, it is important to delineate the groundwater potential zones with more than one aspect to obtain confident results.

Conclusions

Integration of thematic layers of the various parameters such as geology, geomorphology, land use, lineament density, drainage density, soil type, slope and rainfall of the study area using the AHP-MCDM approach and Boolean logic to delineate the groundwater potential zones in Maputaland coastal region, Kwazulu Natal, South Africa was carried out. The study reveals that 73 % and 70 % of areas falls under good groundwater potential zone based on AHP-MCDM and Boolean logic respectively. The results indicated that the geology, geomorphology, slope and rainfall plays a crucial role in the delineation of groundwater potential zones. The overall results conclude that geospatial techniques like, GIS, remote sensing, AHP-MCDM and Boolean logic can provide the platform to delineate the groundwater potential zones. The study shows the importance of studying the two different integration methods, it is essential to delineate the groundwater potential zones with a different approach to obtain the accuracy of results. The results emanated from this study could be useful for sustainable groundwater pumping and in identifying the suitable location for implementation of groundwater exploration wells. Obtained results have proven that integration of GIS techniques under AHP-MCDM and Boolean logic are efficient to enable decision-making tool for sustainable groundwater resources management, as it provides the preliminary information on groundwater recharge.

Acknowledgement

Authors from the University of Zululand express their gratitude to National Research Foundation (NRF), South Africa (NRF/NSFC Reference: NSFC170331225349 Grant No: 110773) for providing grants and Department of Research and Innovation, the University of Zululand for support in buying Ion Chromatography instrument for this research. iSimangaliso Wetland Park Authority is thanked for permission to collect the water samples in the Park. Dr. Peiyue Li is grateful for the financial support granted by the National Natural Science Foundation of China (41761144059).

References

1. Adeyeye OA, Ikpokonte EA and Arabi SA. 2019. GIS-based groundwater potential mapping within Dengi area, North Central Nigeria. Egypt. J. Remote Sensing Space Sci.22(2):175-181.doi:10.1016/j.ejrs.2018.04.003
2. Adiat KAN, Nawawi MNM and Abdullah K. 2012. Assessing the accuracy of GIS-based elementary multi criteria decision analysis as a spatial prediction tool–a case of predicting potential zones of sustainable groundwater resources. J. Hydrol. 440:75-89. doi: 10.1016/j.jhydrol.2012.03.028
3. Al-shabeeb, AR. 2016. The Use of AHP within GIS in Selecting Potential Sites for Water Harvesting Sites in the Azraq Basin—Jordan. Journal of Geographic Information System. 8(1):73. doi: 10.4236/jgis.2016.81008
4. Andualem, T.G. and Demeke, G.G., 2019. Groundwater potential assessment using GIS and remote sensing: A case study of Guna tana landscape, upper blue Nile Basin, Ethiopia. J. Hydrol: Regional Studies, 24:100610. doi: 10.1016/j.ejrh.2019.100610
5. Bonham-Carter GF. 2014. Geographic information systems for geoscientists: modelling with GIS (Vol. 13). Elsevier.
6. Boole G. 1854. An investigation of the laws of thought: on which are founded the mathematical theories of logic and probabilities. Dover Publications.
7. Burrough PA, McDonnell R, McDonnell RA and Lloyd CD, 2015. Principles of geographical information systems. Oxford university press.
8. Ceruti P O. 1999. Crushed rock and clay amelioration of a nutrient deficient, sandy soil of Maputaland. Cape Town. University of Cape Town.
9. Chowdhury A, Jha MK and Chowdary VM. 2010. Delineation of groundwater recharge zones and identification of artificial recharge sites in West Medinipur district, West Bengal, using RS, GIS and MCDM techniques. Environ Earth Sci. 59(6):1209. doi: 10.1007/s11269-010-9749-y
10. Daher W, Pistre S, Kneppers A, Bakalowicz M and Najem W. 2011. Karst and artificial recharge: Theoretical and practical problems: A preliminary approach to artificial recharge assessment. J. Hydrol, 408(3-4):189-202. doi: doi:10.1016/j.jhydrol.2011.07.017

11. Dar IA, Sankar K and Dar MA. 2010. Remote sensing technology and geographic information system modeling: an integrated approach towards the mapping of groundwater potential zones in Hardrock terrain, Mamundiyar basin. J. Hydrol. 394(3-4):285-295.doi: https://doi.org/10.1016/j.jhydrol.2010.08.022
12. Deepika B, Avinash K and Jayappa KS. 2013. Integration of hydrological factors and demarcation of groundwater prospect zones: insights from remote sensing and GIS techniques. Environ Earth Sci . 70(3):1319-1338. doi: 10.1007/s12665-013-2218-1
13. Du Plessis A. 2017. Freshwater Challenges of South Africa and Its Upper Vaal River. New York: Springer.
14. Elewa HH and Qaddah AA 2011. Groundwater potentiality mapping in the Sinai Peninsula, Egypt, using remote sensing and GIS-watershed-based modeling. Hydrogeol J.19(3):613-628.doi: 10.1007/s10040-011-0703-8
15. Fashae OA, Tijani MN, Talabi AO and Adedeji OI. 2014. Delineation of groundwater potential zones in the crystalline basement terrain of SW-Nigeria: an integrated GIS and remote sensing approach. Appl Water Sci, 4(1), pp.19-38. doi: 10.1007/s13201-013-0127-9
16. Freeze RA, Cherry. 1979. Groundwater. Prentice~ Hall, Englewood I Cliffs, N.]., USA, 12, pp.145-165.
17. Ghosh PK, Bandyopadhyay S and Jana NC. 2016. Mapping of groundwater potential zones in hard rock terrain using geoinformatics: a case of Kumari watershed in western part of West Bengal. Model. Earth Syst. Environ. 2(1):1. doi: 10.1007/s40808-015-0044-z
18. Haridas VR, Aravindan S and Girish G. 1998. Remote sensing and its applications for groundwater favourable area identification. Quarterly Journal of GARC, 6(6):18-22.
19. He S, Li P, Wu J, Elumalai V, Adimalla N. 2019b. Groundwater quality under land use/land cover changes: A temporal study from 2005 to 2015 in Xi'an, northwest China. Hum Ecol Risk Assess. doi: 10.1080/10807039.2019.1684186
20. He S, Wu J. 2019b. Relationships of groundwater quality and associated health risks with land use/land cover patterns: a case study in a loess area, northwest China. Human and Ecological Risk Assessment, 25(1-2):354-373. https://doi.org/10.1080/10807039.2019.1570463
21. Huizenga JM. 2011. Characterisation of the inorganic chemistry of surface waters in South Africa. Water SA. 37(3). doi: 10.4314/wsa.v37i3.68491

22. Jang CS, Chen SK and Kuo YM. 2013. Applying indicator-based geostatistical approaches to determine potential zones of groundwater recharge based on borehole data. Catena, //doi.org/10.1016/j.catena.2012.09.003
23. Jha MK, Chowdary VM and Chowdhury A. 2010. Groundwater assessment in Salboni Block, West Bengal (India) using remote sensing, geographical information system and multi-criteria decision analysis techniques. Hydrogeol J. 18(7):1713-1728. doi: 10.1007/s10040-010-0631-z
24. Karanth KR. 1987. Ground water assessment: development and management. Tata McGraw-Hill Education.
25. Kelbe B E, Grundling A T, Price J S. 2016. Modelling water-table depth in a primary aquifer to identify potential wetland hydrogeomorphic settings on the northern Maputaland Coastal Plain, KwaZulu-Natal, South Africa. 24(1): 249-265. doi: 10.1007/s10040-015-1350-2
26. Kumar U, Kumar B and Mallick N. 2013. Groundwater prospects zonation based on RS and GIS using fuzzy algebra in Khoh River watershed, Pauri-Garhwal District, Uttarakhand, India. Global Perspectives on Geography (GPG). 1(3):37-45.
27. Li P, He X, Guo W. 2019. Spatial groundwater quality and potential health risks due to nitrate ingestion through drinking water: a case study in Yan'an City on the Loess Plateau of northwest China. Hum Ecol Risk Assess, 25(1-2):11-31. doi: 10.1080/10807039.2018.1553612
28. Magesh NS, Chandrasekar N and Soundranayagam JP, 2012. Delineation of groundwater potential zones in Theni district, Tamil Nadu, using remote sensing, GIS and MIF techniques. Geoscience Frontiers(GSF), 3(2):189-196. doi:10.1016/j.gsf.2011.10.007
29. Malczewski, J., 2000. On the use of weighted linear combination method in GIS: common and best practice approaches. Transactions in GIS 4(1)5-22. https://doi.org/10.1111/1467-9671.00035
30. Manap MA, Sulaiman WNA, Ramli MF, Pradhan B and Surip N. 2013. A knowledge-driven GIS modeling technique for groundwater potential mapping at the Upper Langat Basin, Malaysia. Arab J Geosci. 6(5):1621-1637. doi: 10.1007/s12517-011-0469-2
31. Margat J and Van der Gun J. 2013. Groundwater around the world: a geographic synopsis. CRC Press. ISBN: 978-1-138-00034-6 (Hbk); 978-0-203-77214-0 (eBook)
32. Mpenyana-Monyatsi L, Onyango MS and Momba MNB. 2012. Groundwater quality in a South African rural community: A possible threat to public health. Pol J Environ Stud, 21(5):1349-58.

33. Murmu P, Kumar M, Lal D, Sonker I and Singh SK, 2019. Delineation of groundwater potential zones using geospatial techniques and analytical hierarchy process in Dumka district, Jharkhand, India. Groundw Sustain Dev., 9:100239. doi: 10.1016/j.gsd.2019.100239
34. Naghibi SA, Pourghasemi HR, Pourtaghi ZS and Rezaei A. 2015. Groundwater qanat potential mapping using frequency ratio and Shannon's entropy models in the Moghan watershed, Iran. Earth Sci Inform. 8(1): 171-186. doi: 10.1007/s12145-014-0145-7
35. Nampak H, Pradhan B and Manap MA. 2014. Application of GIS based data driven evidential belief function model to predict groundwater potential zonation. J Hydrol . 513:283-300. doi: 10.1016/j.jhydrol.2014.02.053
36. Pitman WV/ 2011. Overview of water resource assessment in South Africa: Current state and future challenges. Water SA, 37(5):659-664.
37. Porat N and Botha G. 2008. The luminescence chronology of dune development on the Maputaland coastal plain, southeast Africa. Quat Sci Rev. 27(9-10):1024-1046. doi: 10.1016/j.quascirev.2008.01.017
38. Porter, R. N., and Blackmore, A. C., 1998, St Lucia System South Africa, South African
39. Pradhan B and Youssef AM. 2010. Manifestation of remote sensing data and GIS on landslide hazard analysis using spatial-based statistical models. Arab J Geosci. 3(3):319-326. doi:10.1007/s12517-009-0089-2
40. Qadir J, Bhat MS, Alam A and Rashid I. 2019. Mapping groundwater potential zones using remote sensing and GIS approach in Jammu Himalaya, Jammu and Kashmir. GeoJournal.1-18. doi: 10.1007/s10708-019-09981-5
41. Rahmati O, Samani AN, Mahdavi M, Pourghasemi HR and Zeinivand H. 2015. Groundwater potential mapping at Kurdistan region of Iran using analytic hierarchy process and GIS. Arab J Geosci. 8(9) :7059-7071. doi:10.1080/24749508.2020.1728882
42. Robinove, C.J., 1986. Principles of logic and the use of digital geographic information systems (No. 976-979). Department of the Interior, US Geological Survey.
43. Saaty TL. 1980. The analytical hierarchy process, planning, priority. Resource allocation. USA. RWS publications.
44. Saraf AK and Choudhury PR, 1998. Integrated remote sensing and GIS for groundwater exploration and identification of artificial recharge sites. Int J Remote Sens., 19(10), pp.1825-1841. doi: 10.1080/014311698215018
45. Selvam S, Magesh NS, Chidambaram S, Rajamanickam, M and Sashikkumar MC. 2015. A GIS based identification of groundwater recharge potential zones using RS and IF

technique: a case study in Ottapidaram taluk, Tuticorin district, Tamil Nadu. Environ Earth Sci. 73(7):3785-3799. doi: 10.1007/s12665-014-3664-0

46. Shekhar S and Pandey AC. 2015. Delineation of groundwater potential zone in hard rock terrain of India using remote sensing, geographical information system (GIS) and analytic hierarchy process (AHP) techniques. Geocarto Int. 30(4):402-421. 10.1080/10106049.2014.894584
47. Simonis JJ and Nweze A. 2016. A novel approach for providing potable water in rural Sodwana Bay, northern Kwazulu-Natal, South Africa. J Water Sanit Hyg De. 6(3):425-434. doi: 10.2166/washdev.2016.023
48. Singh SK, Laari PB, Mustak SK, Srivastava PK and Szabó S. 2018. Modelling of land use land cover change using earth observation data-sets of Tons River Basin, Madhya Pradesh, India. Geocarto Int. 33(11):1202-1222. doi: 10.1080/10106049.2017.1343390
49. Su Z, Wu J, He X, Elumalai V. 2020. Temporal changes of groundwater quality within the groundwater depression cone and prediction of confined groundwater salinity using Grey Markov model in Yinchuan area of northwest China. Expo Health. doi: 10.1007/s12403-020-00355-8
50. Tahmassebipoor N, Rahmati O, Noormohamadi F and Lee S. 2016. Spatial analysis of groundwater potential using weights-of-evidence and evidential belief function models and remote sensing. Arab J Geosci. 9(1):79. 10.1007/s12517-015-2166-z
51. Været L, Kelbe B, Haldorsen S and Taylor RH. 2009. A modelling study of the effects of land management and climatic variations on groundwater inflow to Lake St Lucia, South Africa. Hydrogeol J, 17(8):1949. doi: 10.1007/s10040-009-0476-5
52. Vetrimurugan E, Brindha K, Sithole B, Elango L (2017b) "Spatial interpolation methods and geostatistics to map groundwater contamination in a coastal area, Kwazulu-Natal, South Africa". Environmental Science and Pollution Research. DOI 10.1007/s11356-017-8681-6.
53. Vetrimurugan, E., Brindha, K and Elango, L. (2017a) "Human exposure risk assessment due to heavy metals in groundwater by pollution index and multivariate statistical methods: An application from South Africa". Water 2017, 9, 234; doi:10.3390/w9040234.
54. Vhonani, G.N., Vetrimurugan, E., Rajmohan, N., (2018). Irrigation return flow induced mineral weathering and ion exchange reactions in the aquifer, Luvuvhu catchment, South Africa. Journal of African Earth Sciences, 149, 517–528. doi.org/10.1016/j.jafrearsci.2018.09.001

55. Watkeys MK, Mason TR and Goodman PS. 1993. The role of geology in the development of Maputaland, South Africa. J Afr **Earth** Sci. 16(1-2):205-221. doi: 10.1016/0899-5362(93)90168-P
56. Wetlands Conservation Programme (April11, 2003); http://www.ngo.grida.no/soesa/nsoer / resource/wetland/st_lucia_ris.
57. Weitz J and Demlie M. 2014. Conceptual modelling of groundwater–surface water interactions in the Lake Sibayi Catchment, Eastern South Africa. J Afr Earth Sci. 99:613-624. doi: 10.4314/wsa.v43i3.13
58. Wu J, Zhang Y, Zhou H. 2020. Groundwater chemistry and groundwater quality index incorporating health risk weighting in Dingbian County, Ordos basin of northwest China. Geochem . 125607. doi: 10.1016/j.chemer.2020.125607
59. Zaidi FK, Nazzal Y, Ahmed I, Naeem M, Jafri MK (2015) Identification of potential artificial groundwater recharge zones in north western Saudi Arabia using GIS and Boolean logic. J Afr Earth Sci 111:156–169. https://doi.org/10.1016/j.jafrearsci.2015.07.008

Table: 1 Classification of weighted factor influencing the groundwater potential zones

Thematic layer	**Influencing factor (%)**	**Features**	**Area (sq.km)**	**Area (%)**	**AHP-MCDM Assigned Weight**	**Classes**	**Boolean Binary weight**
Geomorphology	18	Low mountains	36.0	0.7	3	Unsuitable	0
		Moderately undulating plains	248.0	4.8	5	Suitable	1
		Plains	4891.0	94.5	7	Suitable	1
Geology	16	Arenite	2718.0	52.5	4	Suitable	1
		Rhyolite	35.6	0.7	2	Unsuitable	0
		Alluvium	1849.3	35.7	7	Suitable	1
		Siltstone	572.1	11.1	6	Suitable	1
Rainfall (mm)	13	547 - 600	505.0	9.8	4	Suitable	1
		601 - 650	1286.1	24.9	5	Suitable	1
		651 - 700	883.0	17.1	6	Suitable	1
		701 - 750	1382.0	26.7	7	Suitable	1
		751 - 800	1118.9	21.6	8	Suitable	1
Lineament Density (km/km^2)	13	0 - 0.1	4778.0	92.3	1	Unsuitable	0
		0.1 - 0.3	253.6	4.9	5	Unsuitable	0
		0.3 - 0.5	129.1	2.5	7	Suitable	1
		0.5 - 0.7	10.1	0.2	8	Suitable	1
		0.7 - 0.8	4.2	0.1	9	Suitable	1
Land Use	11	Bare land	10.0	0.2	4	Suitable	1
		Agri land	412.0	8.0	5	Suitable	1
		Degraded land	687.0	13.3	3	Unsuitable	0
		Exotic plantations	175.4	3.4	3	Unsuitable	0
		Grassland	872.8	16.9	6	Suitable	1
		Forest	167.5	3.2	4	Suitable	1
		Thicket and bushland	942.7	18.2	4	Suitable	1
		Waterbodies	121.7	2.4	6	Suitable	1
		Wetland	404.5	7.8	7	Suitable	1
		Open land	1381.3	26.7	8	Suitable	1
Soils	11	Lithosols	22.0	0.4	6	Unsuitable	0
		Chromic luvisols	796.0	15.4	5	Suitable	1
		Albic arenosols	4357.0	84.2	8	Suitable	1
Slope (Degree)	11	0 -1,5°	4120.0	79.6	9	Suitable	1
		1,6 - 2,5°	560.0	10.8	8	Suitable	1
		2,6 - 5,5°	375.0	7.2	6	Unsuitable	0
		5,6 - 12°	95.0	1.8	5	Unsuitable	0
		12,1 - 30°	25.0	0.5	4	Unsuitable	0
Drainage density (km/km^2)	7	0 - 0.5	3516.0	67.9	8	Suitable	1
		0.6 - 1	1107.9	21.4	6	Suitable	1
		1.1 - 1.5	370.9	7.2	3	Unsuitable	0
		1.6 - 2	151.0	2.9	2	Unsuitable	0
		2.1 - 2.5	29.0	0.6	1	Unsuitable	0

Table 2: Random consistency indices for the different number of criteria (Sharaf and Choudhury 1998)

No of Criteria	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
Random Consistency indices (RCI)	0.0	0.0	0.58	0.9	1.12	1.24	1.32	1.41	1.45	1.49	1.51	1.54	1.56	1.57	1.59

Table 3: Pair-wise comparison matrix of thematic layers

Theme	**Geomorphology**	**Geology**	**Soils**	**Land use**	**Rainfall**	**Lineament density**	**Drainage density**	**Slope**
Geomorphology	1.0	2.0	3.0	4.0	5.0	6.0	7.0	8.0
Geology	0.5	1.0	2.0	3.0	4.0	5.0	6.0	7.0
Soils	0.3	0.5	1.0	2.0	3.0	4.0	5.0	6.0
Land use	0.3	0.3	0.5	1.0	2.0	3.0	4.0	5.0
Rainfall	0.2	0.3	0.3	0.5	1.0	2.0	3.0	4.0
Lineament density	0.2	0.2	0.3	0.3	0.5	1.0	2.0	3.0
Drainage density	0.1	0.2	0.2	0.3	0.3	0.5	1.0	2.0
Slope	0.1	0.1	0.2	0.2	0.3	0.3	0.5	1.0
Total	2.7	4.6	7.5	11.3	16.1	21.8	28.5	36.0

Table: 4 Normalized Pair-wise matrix and normalized weight of various thematic layers

Theme	Geomorphology	Geology	Soils	Landuse	Rainfall	Lineament Density	Drainage Density	Slope	Normalised weights	Consistency ratio
Geomorphology	0.4	0.4	0.4	0.4	0.3	0.3	0.2	0.2	0.33	0.02%
Geology	0.2	0.2	0.3	0.3	0.2	0.2	0.2	0.2	0.23	
Soils	0.1	0.1	0.1	0.2	0.2	0.2	0.2	0.2	0.16	
Landuse	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.11	
Rainfall	0.1	0.1	0.0	0.0	0.1	0.1	0.1	0.1	0.07	
Lineament Density	0.1	0.0	0.0	0.0	0.0	0.0	0.1	0.1	0.05	
Drainage Density	0.1	0.0	0.0	0.0	0.0	0.0	0.0	0.1	0.03	
Slope	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.02	

Figures

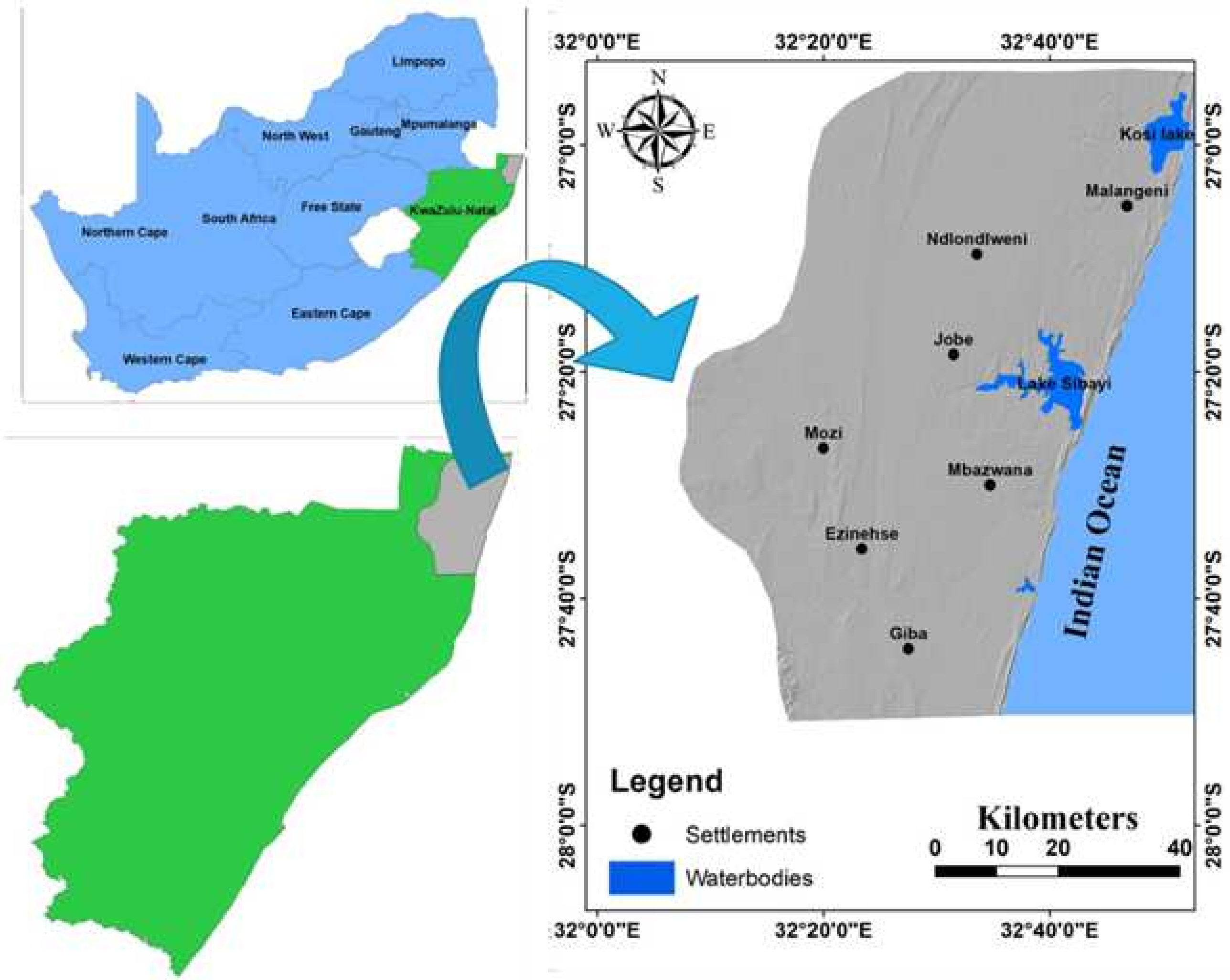

Figure 1

Map of the study area Note: The designations employed and the presentation of the material on this map do not imply the expression of any opinion whatsoever on the part of Research Square concerning the legal status of any country, territory, city or area or of its authorities, or concerning the delimitation of its frontiers or boundaries. This map has been provided by the authors.

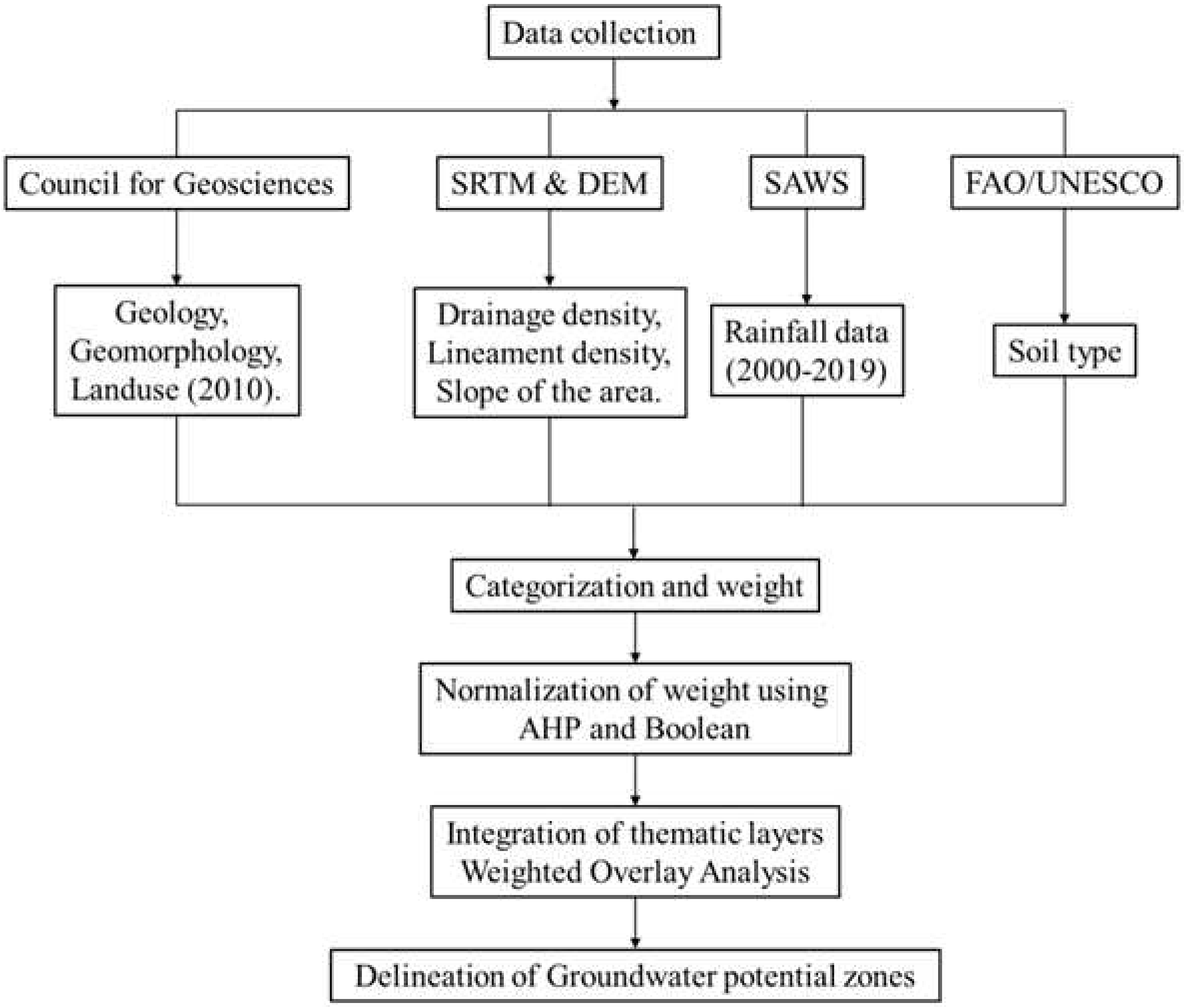

Figure 2

Flowchart of the adopted methodology

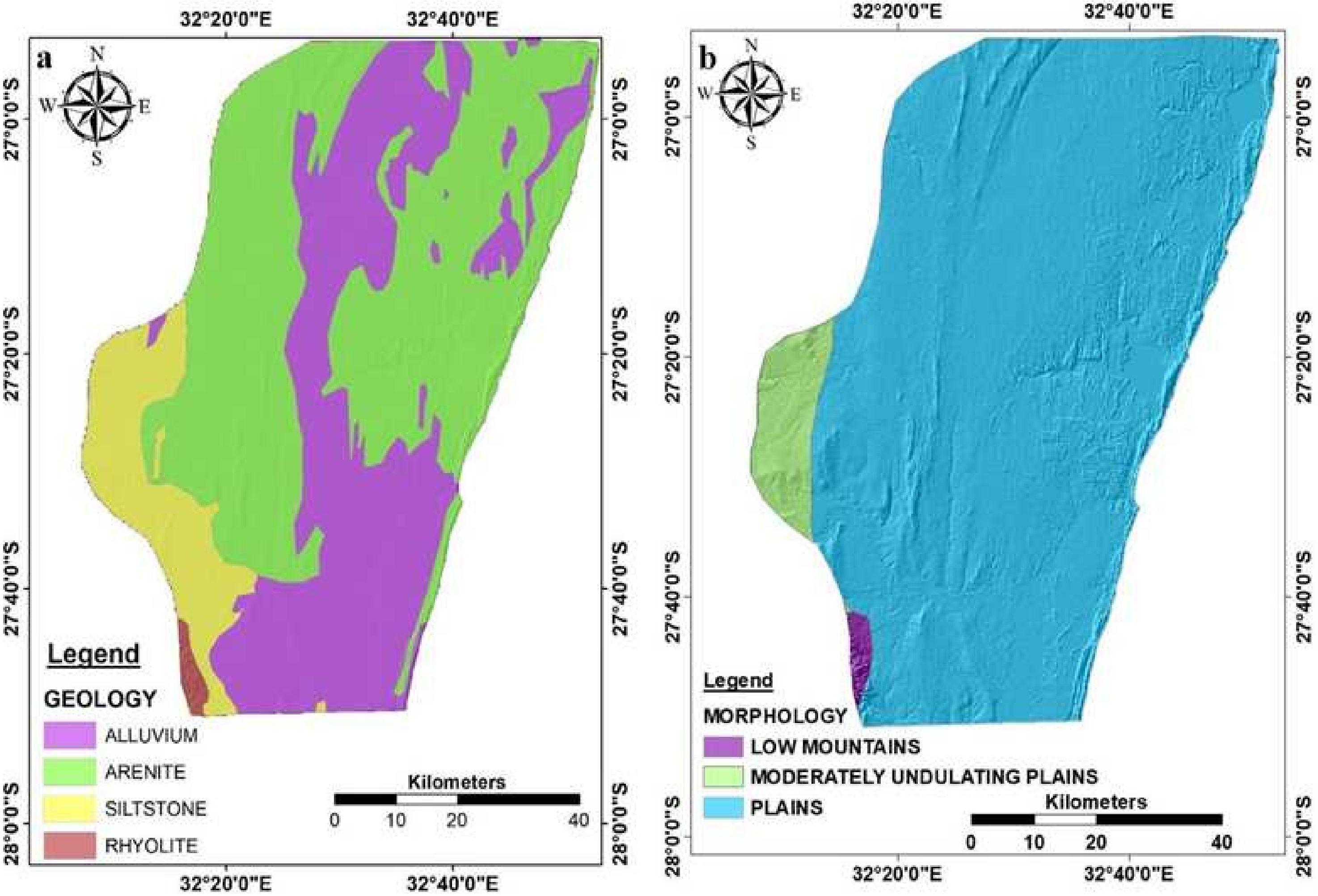

Figure 3

a) Geology and b) Geomorphology of the study area Note: The designations employed and the presentation of the material on this map do not imply the expression of any opinion whatsoever on the part of Research Square concerning the legal status of any country, territory, city or area or of its authorities, or concerning the delimitation of its frontiers or boundaries. This map has been provided by the authors.

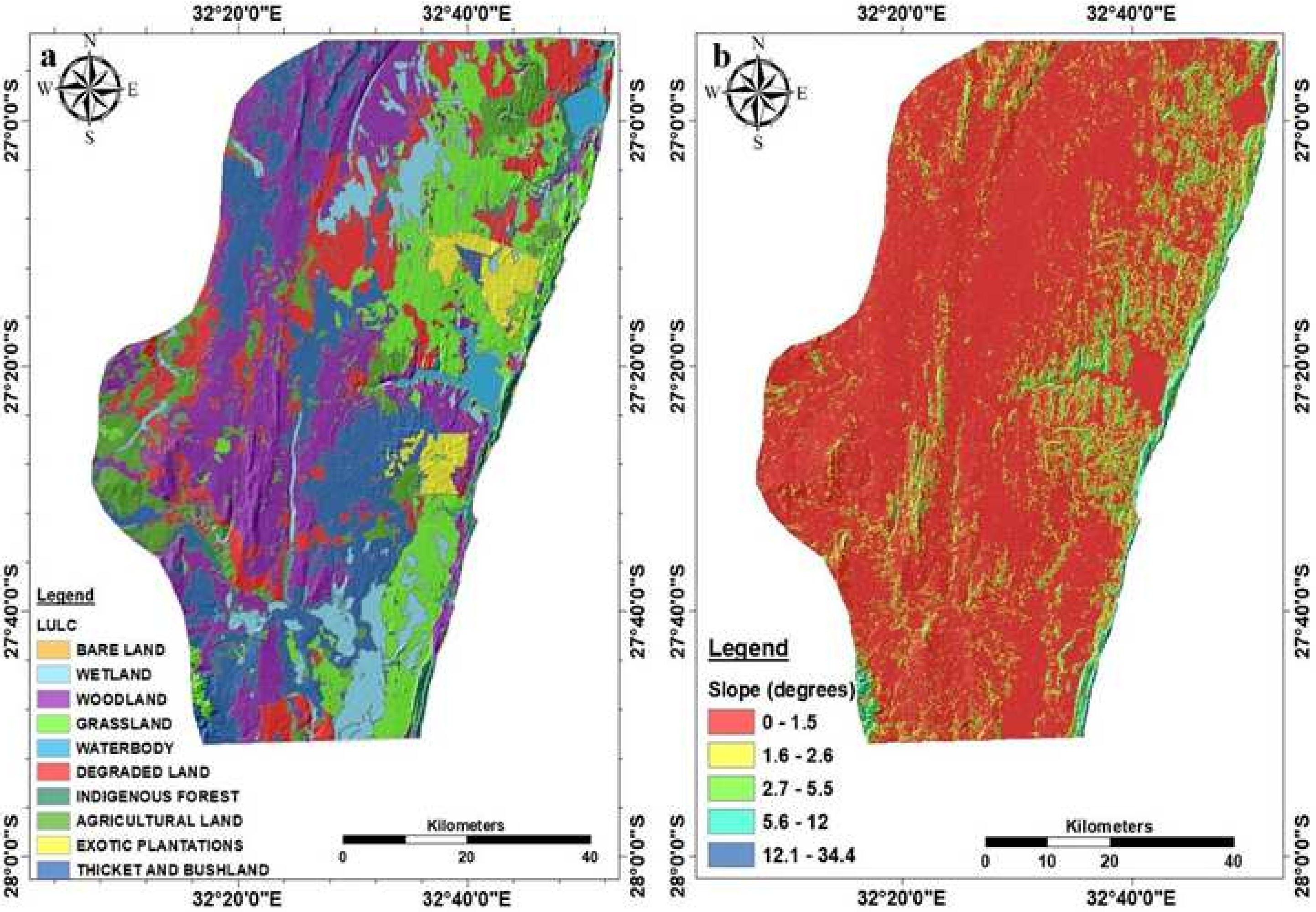

Figure 4

a) Land-use type and b) Slope of the study area Note: The designations employed and the presentation of the material on this map do not imply the expression of any opinion whatsoever on the part of Research Square concerning the legal status of any country, territory, city or area or of its authorities, or concerning the delimitation of its frontiers or boundaries. This map has been provided by the authors.

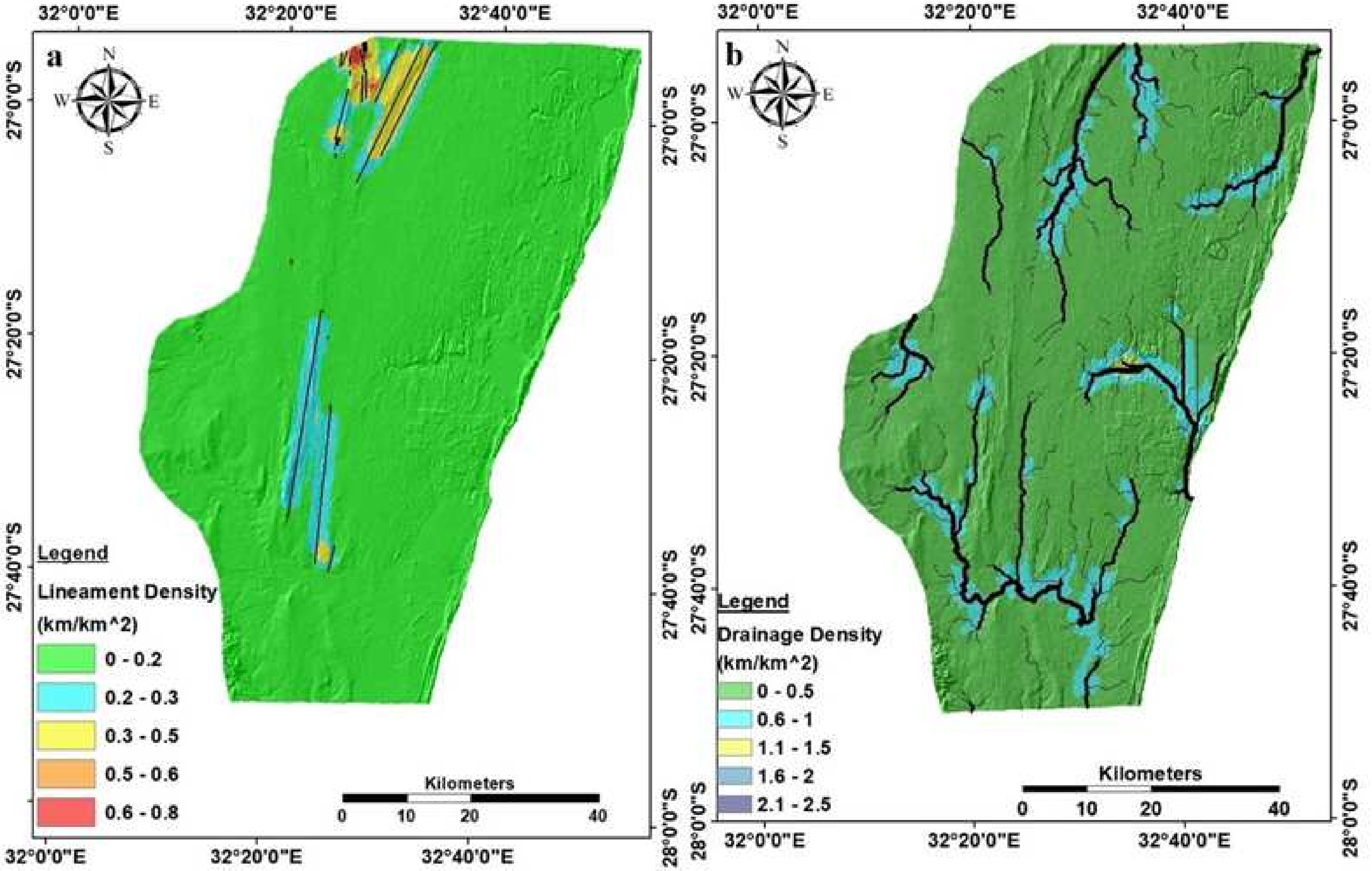

Figure 5

a) Lineament density and b) Drainage density of the study area. Note: The designations employed and the presentation of the material on this map do not imply the expression of any opinion whatsoever on the part of Research Square concerning the legal status of any country, territory, city or area or of its authorities, or concerning the delimitation of its frontiers or boundaries. This map has been provided by the authors.

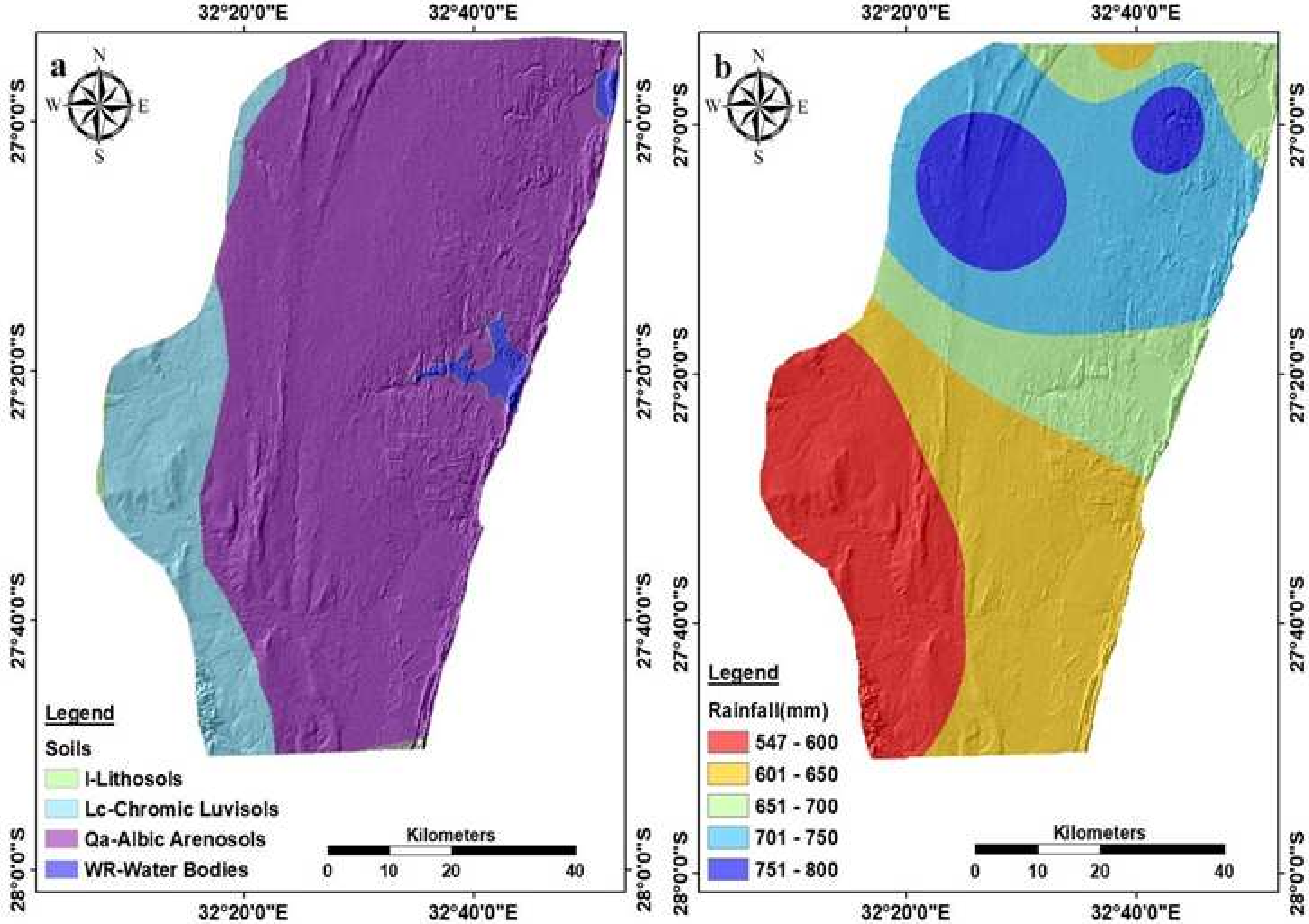

Figure 6

a) Soil type and b) Rainfall distribution map of the study area Note: The designations employed and the presentation of the material on this map do not imply the expression of any opinion whatsoever on the part of Research Square concerning the legal status of any country, territory, city or area or of its authorities, or concerning the delimitation of its frontiers or boundaries. This map has been provided by the authors.

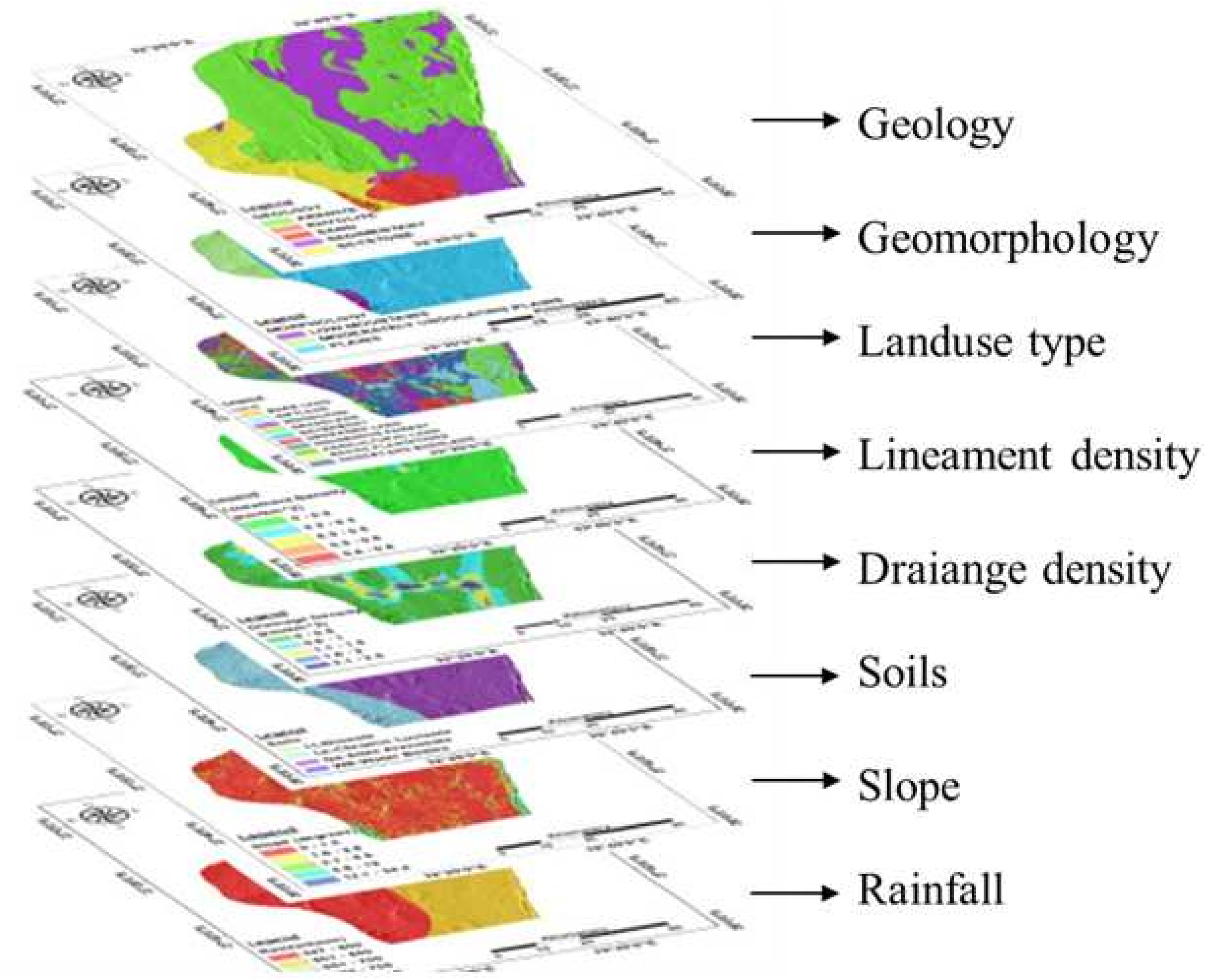

Figure 7

Integration of thematic layers in GIS Note: The designations employed and the presentation of the material on this map do not imply the expression of any opinion whatsoever on the part of Research Square concerning the legal status of any country, territory, city or area or of its authorities, or concerning the delimitation of its frontiers or boundaries. This map has been provided by the authors.

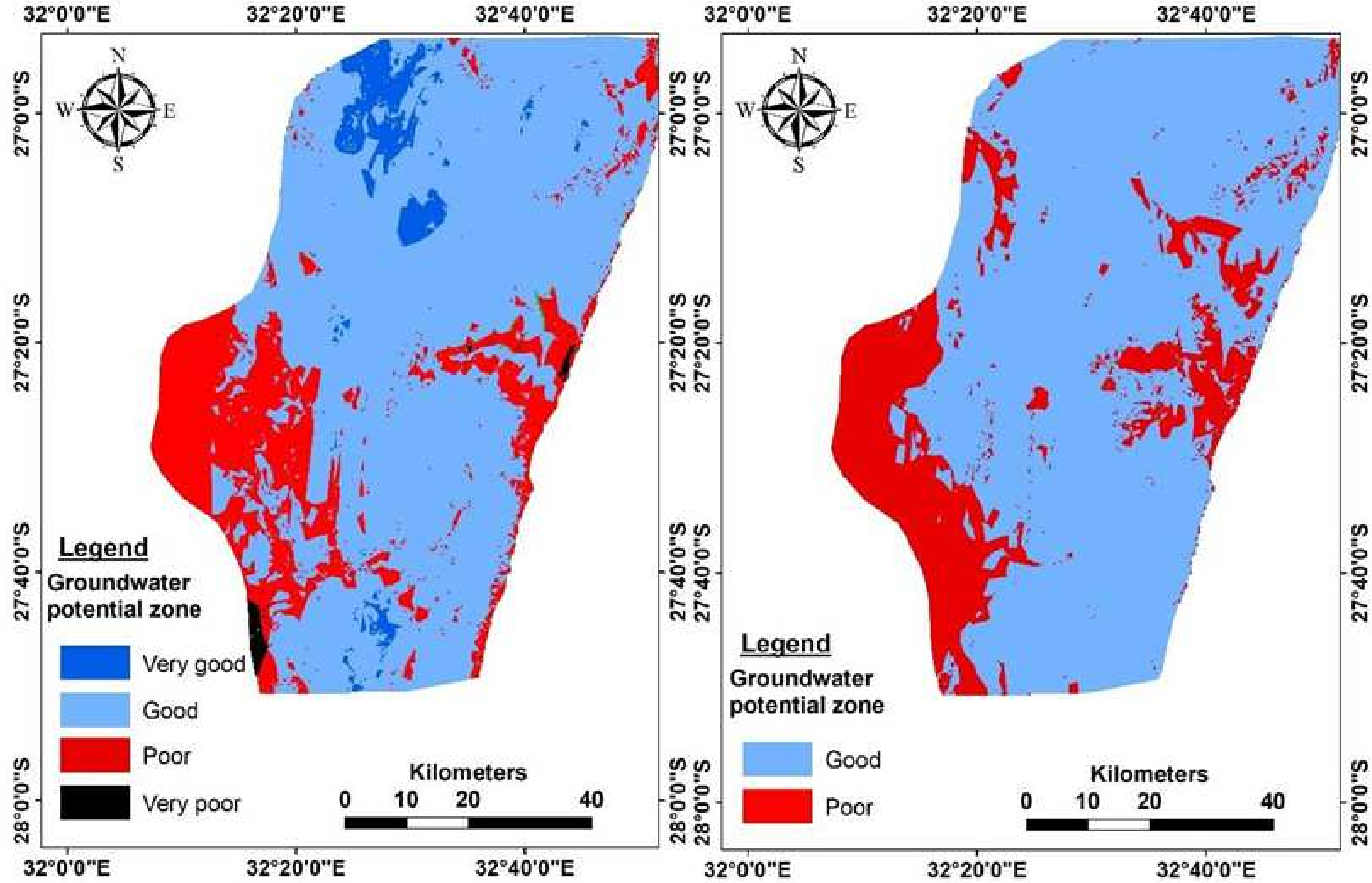

Figure 8

(a) Delineated groundwater potential zones using AHP-MCDM technique and (b) using Boolean logic
Note: The designations employed and the presentation of the material on this map do not imply the expression of any opinion whatsoever on the part of Research Square concerning the legal status of any country, territory, city or area or of its authorities, or concerning the delimitation of its frontiers or boundaries. This map has been provided by the authors.