Tanzania Journal of Engineering and Technology 2023, **42**(**3**): 89-100
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Websites: https://ajol.org/tjet; https://tjet.udsm.ac.tz

ISSN 1821-536X (**print**); ISSN 2619-8789 (**electronic**)
https://doi.org/10.52339/tjet.v42i3.955

Regular Research Manuscript

Assessment of Spatial Variability of Groundwater Potential using Remote Sensing and GIS-based-Criteria Evaluation for Dar es Salaam, Tanzania

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ABSTRACT

Groundwater is an important resource for the continuous provision of water supply in both urban and rural areas. Lack of enough knowledge about the spatial variability of groundwater potential zones (GWPZS) has a negative impact on groundwater extraction development and management and may result into over exploitation. In this study, analytic hierarchy approach (AHP)-coupled with multi criteria decision analysis (MCDA) and GIS techniques were employed to integrate hydrogeological, geological as well as topographical data to assess spatial variability of groundwater potential zones of Dar es Salaam city. Seven thematic layers such as lithology, slope, land-use, lineament, drainage, soil, and rainfall were processed in ArcGIS and assigned appropriate weightage and theme classes' ranks using Saaty's AHP. The rasterized and reclassified thematic layers was integrated using weight overlay to generate the overall groundwater potential map. The generated GWP map indicates that 75% of the study to has favorable groundwater potential about 23 % of study area has (23% "very good" and, 52 % as "good"). The produced GP map can be used for a quick identification of the prospective GP zones thus narrowing targeted area and cost for groundwater developing.

ARTICLE INFO
First submitted: **May 20, 2023**

Revised: **Aug 13, 2023**

Accepted: **Sept. 15, 2023**

Published: **Oct., 2023**

Keywords: *Groundwater Potential, Remote sensing, GIS, MCDA, and Dar es Salaam*

INTRODUCTION

Groundwater (GW) resource is an important natural resource for its use in domestic, agricultural and industrial purposes. There has been a tremendous increase in the demand for GW due to increase in population (Jha et al., 2010, 2007). Due to this increase in demand mapping of groundwater potential zones is essential for planning the location of new abstraction wells to meet this demand. The occurrence and movement of GW in an area is governed by several factors such as lithology, geological structures, soil, lineament features, slope, drainage pattern, land use/land cover and interrelationship between these factors (Jha et al., 2010; Chowdhury et al., 2010; Greenbaum, 1985; Jaiswal et al., 2003). Researchers have used GIS for demarcation of groundwater potential zones in their areas of interest (Saraf and Choudhury, 1998; Jha and Peiffer, 2006; Solomon and Quiel, 2006; Jha et al., 2007; Ganapuram et al., 2009; Saha et al., 2010; Al-Adamat et al., 2003).

The use of GIS and remote sensing is a preferred because it cannot be constrained by observational data, provides spatially extensive, multi-temporal and cost-effective data which has become a very handy tool in identifying hydro geological processes. It also helps in GW exploration by narrowing down the target areas for conducting detailed hydro geological and Geo-physical surveys on the ground.

Multi criteria decision analysis (MCDA) techniques have been used for identifying the groundwater potential zones and favourable artificial recharge sites (Jha and Chowdary, 2007; Jenifer and Jha, 2017; Jha and Chowdary, 2006). The choice of MCDA approach is based on the fact that it enables decomposition of a problem into hierarchy and assures that both qualitative and quantitative aspects of the problem are incorporated during the evaluation process. MCDA is a family of techniques that aid decision makers in formally structuring multi-faceted decisions and evaluating alternatives. The Saaty's AHP is a widely used MCDA technique in the field of water resource engineering (Kaliraj et al., 2014). Therefore, this study will employ AHP-coupled MCDA and GIS techniques to integrate hydro geological, geological as well as topographical data to evaluate groundwater resources. The major purpose is to delineate the groundwater potential zones of the study area and to develop a prospective guide map for GW exploration so as to ensure sustainable development and management of this vital resource[23].

MATERIAL AND METHOD

Description of study area

Dar es Salaam is the largest city in Tanzania located at coordinates 6.7924° S and 39.2083° E with an elevation of 55m (180 ft) above mean sea level. It covers an area of 1493 km² bordered with Indian Ocean and Pwani region. It's an important economic centre and one of fastest growing cities in the world with an estimate of over 5.38 million people (2022). It is administratively divided into five districts Kinondoni in north, Ilala in the centre, Ubungo and Temeke in south and Kigamboni in the east. The climate is tropical, with average annual temperature at 26.1°C and about 1114 mm of precipitation falls annually.

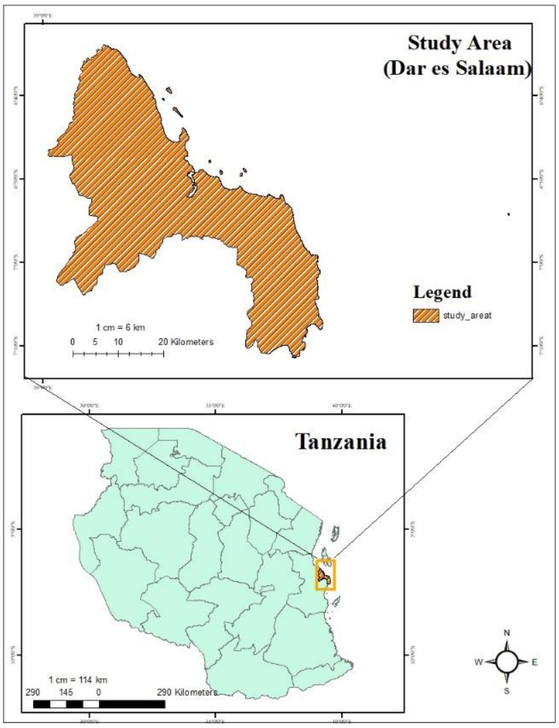


Figure 1: Location of the study area.

Datasets and acquisition

Use of remotely sensed Global Digital Elevation Model (DEM), which was downloaded from USGS Earth explorer (http://earthexplorer.usgs.gov), Tanzania geology/lithology shape file was downloaded from Geological Survey of Tanzania, Geological and Mineral Information System (gmis-Tanzania) website, Landsat 8 image was downloaded from USGS website, Soil data shape file was downloaded from FAO website and Rainfall data map was downloaded from CHRS data portal website as summarized in Table 1. Preparation of thematic layers involved digitizing existing maps, digital image processing of remote sensing data, and integration of field data for extraction of pertinent information. All these thematic layers were processed and classified in the GIS environment.

Table 1: Datasets and acquisition

Thematic Layer	Source
1. Land Use/Land Cover	Landsat 8 image was downloaded from USGS website
2. Soil	Shape file downloaded from FAO website
3. Lineament Density	Created SRTM DEM using hill shade in spatial analyst tool to draw lineament density lines
4. Drainage Density	Generated from SRTM DEM (90 m × 90 m spatial resolution) using line density tool
5. Rainfall	Downloaded from CHRS data portal in persiann-CCS resolution
6. Slope	From SRTM DEM (90 m × 90 m spatial resolution)
7. Lithology	Geological and Mineral Information System (gmis-Tanzania) website,

Method

The approach utilized involves preparation of thematic layers digitizing existing maps, digital image processing of remote sensing data, and integration of field data for extraction of pertinent information. To produce a groundwater potential (GP) map of the study area, thematic layers of lithology, lineament density, soil type, slope, drainage density, rainfall and land use/ cover were generated from thematic maps, and field data in a GIS environment. GIS - based multi - criteria evaluation was used to determine rates for the classes in a layer and weights for each thematic layer based on Saaty's analytical hierarchy process AHP (Saaty, 2008) whereas aggregation of the thematic layers was done by the weighted linear combination (WLC) method to produce a ground water potential map. Methodological flow chat adopted for generation of Groundwater potential map in this study is summarized in Figure 2.

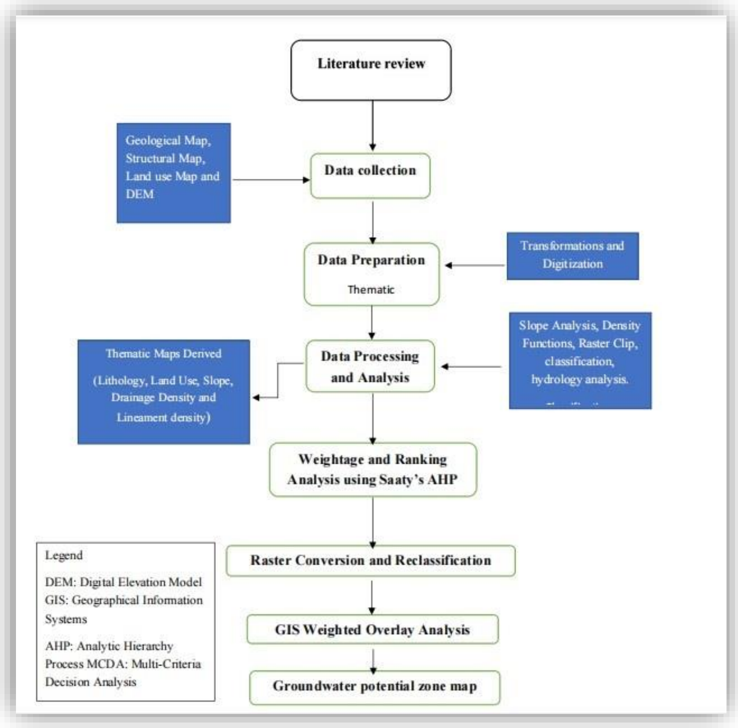


Figure 2: Groundwater potential map generation flow chart.

Multi criteria decision analysis for developing groundwater potential map

After all the thematic maps were created interrelationship was made between all these factors and the weights assigned to each factor depending on their interrelationship and influence capability. The interrelationship adapted in this study is based on the prior knowledge of different influencing factors for groundwater potential in different regions using the extensive literature review and also based on the knowledge of the study area. Saaty's AHP is the method used for scaling the rates/weights of factors whose entries indicate the strength with which one factor dominates over the other in relation to the relative criterion. In this method, the relative importance of individual class within the same map and thematic maps are compared to each other by pair-wise comparison matrices.

Calculating weight factor

Score n of 1 to 9 was assigned to factors affecting groundwater potential as expressed in Table 2. Considering n criteria to be compared (in this case lithology, lineament density, soil type, landuse/landcover, drainage density, slope and rainfall.), a square matrix A =(aij) was produced (Eq 1).

$$A = \begin{pmatrix} \frac{P_1}{P_1}\cdots 1 & \frac{P_1}{P_j}\cdots & \frac{P_1}{p_n} \\ \frac{\dddot{P}_i}{P_1}\cdots & \dddot{1}\;\cdots & \frac{\dddot{P}_i}{P_n} \\ \frac{\dddot{P}_n}{P_1}\cdots & \frac{\dddot{P}_n}{P_j}\cdots 1 & \frac{\dddot{P}_n}{P_n} \end{pmatrix} \qquad (1)$$

Table Error! No text of specified style in document.**: Scale of preference between two parameters in AHP**

Scale	Degree of preference	Explanation
1	Equal Importance	Two activities contribute equally to the objective
3	Moderate importance	Experience and judgment slightly-to-moderately favour one activity over another
5	Strong importance	Experience and judgment strongly favour one activity over another
7	Very strongly	An activity is strongly favoured over another and its dominance is showed in practice
9	Extremely	The evidence of favoring one activity over another is of the highest degree possible of an affirmation

2,4,6,8 can be used to express intermediate values

Seven matrices were produced for each thematic layer to calculate rates for the classes in a layer and one matrix was produced to compute the weights of each layer. By solving the matrix, the rates/weights were computed. In order to solve for rates/weights, the relative ratio scale derived from pair-wise comparison reciprocal matrix of judgments was computed, first by summing of all elements of column j of the matrix A (Eq 2) which was then normalized by dividing the comparison $\frac{P_i}{P_j}$ by equation 2 (See equation 3). Rate/weight of row i (W_i) was calculated as an average of the elements (3) of the row I (4)

$$\frac{P_1}{P_j} + \cdots + \frac{P_i}{P_j} + \cdots \frac{P_n}{P_n} = \frac{\sum_{i=1}^{n} P_i}{P_j} \qquad (2)$$

$$\frac{\frac{P_i}{P_j}}{\frac{\sum_{i=1}^{n} P_i}{P_j}} = \frac{P_i}{P_j} X \frac{P_j}{\sum_{i=1}^{n} P_i} = \frac{P_i}{\sum_{i=1}^{n} P_i} \qquad (3)$$

$$W_i = \left(\frac{P_1}{\sum_{i}^{n} P_i} + \cdots + \frac{P_n}{\sum_{i=1}^{n} P_i} \right) \qquad (4)$$

Check for consistency of the matrix

To check the judgment consistency, I_{max} which is the largest eigenvalue of the pair-wise comparison matrix, was computed. I_{max} is obtained as the summation of product of normalized value (3) and their respective weight (4) as shown in (5):

$$I_{max} = \sum_{i=1}^{n} \left(W_i x \frac{P_i}{\sum_{i=1}^{n} P_i} \right) \quad (5)$$

Saaty, 1977 gave a measure of consistency, called the consistency index (CI), as deviation or degree of consistency (6).

$$CI = \frac{I_{max} - n}{n-1} \quad (6)$$

The consistency ratio (CR) which measure of consistency of the pair-wise comparison matrix was computed as a ratio of consistency index (CI) and Saaty's ratio index (RI) (Eq 7). Saaty, 1977 recommended that for matrices with CR rating greater than 0.1, the judgments are untrustworthy and some pair-wise values need to be reconsidered and the process is repeated until the desired value of CR <0.1 is reached.

$$CR = \frac{CI}{RI} \quad (7)$$

Generation of Groundwater Potential Map

Groundwater potential map was obtained by the weighted overlay analysis method using spatial analysis tools. During weighted overlay analysis, a rank was given for each individual parameter of each thematic layer map, and weights were assigned according to the output of the (AHP) technique to that particular feature on the hydro-geological environment of the study area. Groundwater potential map was produced by multiplying each rate value of the classified layer by the weight of the layer. The resulting cell values were added to produce the final output raster that represent GP areas (Eq 8). Higher sum values represent a greater potential for groundwater. The WLC was done using Raster Calculator tool in ArcGIS software.

$$GP = \sum_{i=1}^{n} W_i X_i. \quad (8)$$

where GP = groundwater potential, W_i = weight for each thematic layer and X_i = rates for the classes within a thematic layer.

RESULTS AND DISCUSSIONS

Thematic layers

Lithology**:** Figure 3 represent the lithology of the study area which is studied with special reference to groundwater holding and conducting capacity of the individual lithology unit. Usually, massive unfractured lithologic units has little influence on groundwater availability except in cases where there is secondary porosity through the development of weathered overburden and fractured bedrock units, which form GWPZ (Sangana et al., 2019). The map created features of sandy, gravelly, silty sediments which were defined as moderate feature for GW potential while sandy-clayey sediments which were defined as poor feature for GW potential due to presence of clayey characteristics.

Land use/Land cover**:** Land use/land cover plays an important role in the occurrence and development of groundwater. The land use/cover were ranked and reclassified based on the land-use type, area coverage, properties to infiltrate water and their characteristics to hold water on the ground surface (Sangana et al., 2019). Land use land cover map of an area was classified into 4 classes such as built up areas 71% considered to have very low potential, vegetation cover 18% considered to have good potential, barren land 10% considered to have low potential and water bodies considered to have very good potential 1%.

Drainage density**:** Drainage density is defined as the closeness of spacing of stream channels. The drainage density is an inverse function of permeability, the less permeable a rock is, the less the infiltration of rainfall, which conversely tends to be concentrated in surface runoff (Magesh et al., 2012). The area of very high drainage density represents more closeness of drainage channels and vice versa; hence, the higher the drainage density, the higher the runoff while the lesser the drainage density, the lower the run-off and the higher the probability of recharge or the higher is the potential for groundwater accumulation (Sangana et al., 2019). Figure 5 presents the drainage density map of the study area classified into five classes using breaks classification. Areas with 0 to 25 were categorized as very good GW potential areas, 26 to 60 as good, 51 to 100 as moderate, 101 to 150 as low and 151 to 222.7 as very low.

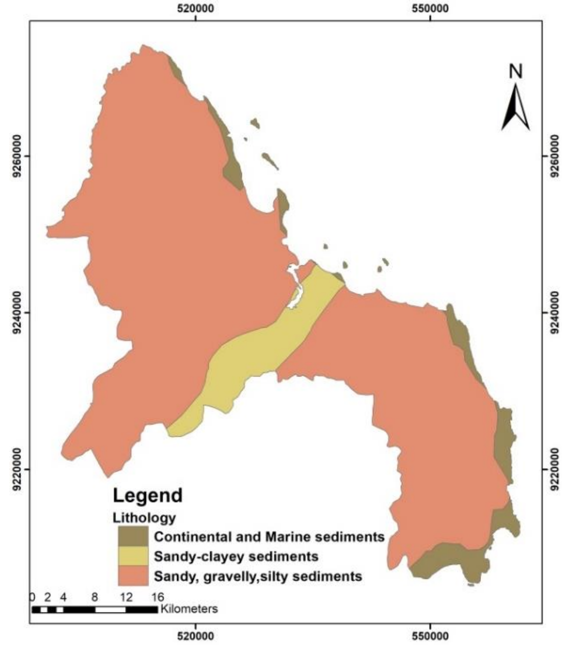


Figure 3: Lithology map.

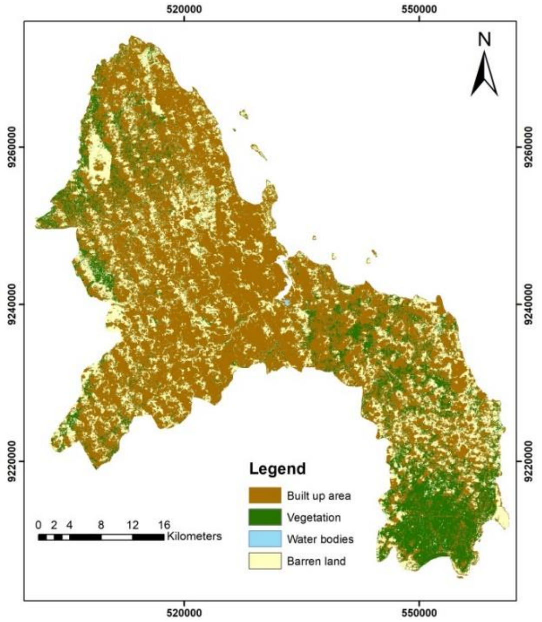


Figure 4: Land use land cover map.

Lineament density: Figure 6 shows the manifestation of linear features that was identified from remote sensing data. Lineaments and their intersections play a significant role in the occurrence and movement of groundwater resources as the structural weakness increases the infiltration capacity (Srinivasa Rao & Jugran, 2003). Areas having a higher density of lineaments are basically having a good groundwater potential (Das & Pardeshi, 2018). As shown in Figure 6, areas under 0 to 0.2 were categorized as very low GW potential areas, 0.2 to 0.64 as low GW potential areas, 0.4 to 0.6 as moderate GW potential areas, 0.6 to 1 good and 1 to 1.55 falls to very good.

Slope: As an aspect of geomorphologic features, slope is one of the key factors controlling the infiltration and recharge of groundwater system: thus, the nature of the slope alongside other geomorphic features can provide an insight of the potential groundwater prospecting areas. In low slope areas the surface runoff is low allowing more time for infiltration of rainwater, while high slope areas enhances high runoff with short residence time for infiltration and recharge (Magesh et al., 2012: Sangana et al., 2019). The resulting slope map was categorized into five classes as shown in Figure 7. Slope map shows areas with slopes 0° to 2° are categorized as very high GW potential areas, 2.1° to 5° as good, 5.1° to 8° as moderate, 8.1° to 12° as low and 12.1° to 36.5° to be of very low groundwater potential areas.

Soil: Soil type (Sand, Silt, Clay and Gravel) affects porosity, permeability, hydraulic conductivity and storativity hence it governs the infiltration and retention rate of water (Chowdhuryet al, 2014) Also soil type in an area has effect on groundwater potential as it controls the percolation and permeability of water into the subsurface (see Table 1). From the attribute table soils of the study were selected for extraction and the soil values were added as shown in Figure 8. Soil map (Figure 8) presents soil types of Orthic acrisols, Cambic arenosols, Ferralic cambisols and Haplic lixisols as the major soils found in study area.

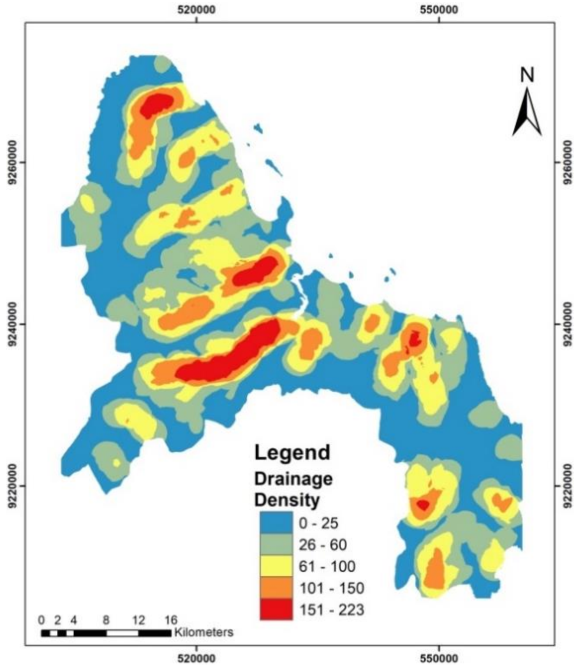


Figure 5: Drainage density map.

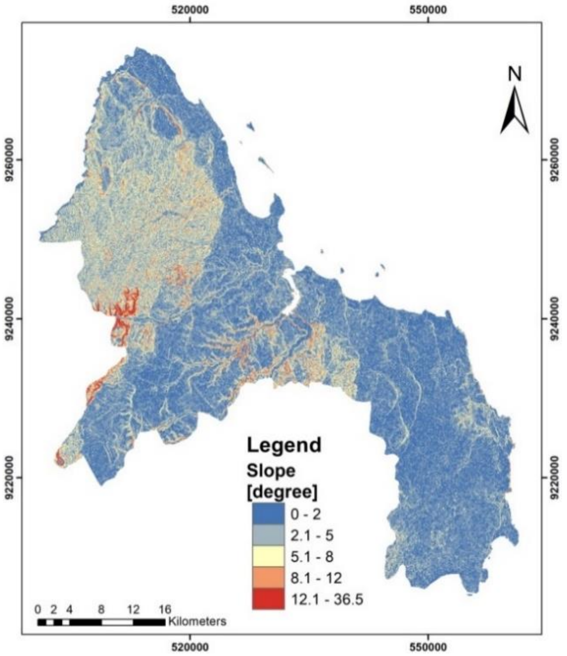


Figure 7: Slope map.

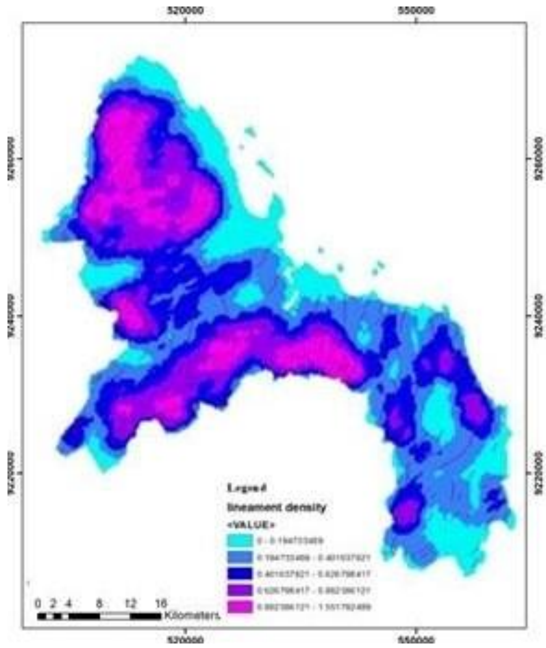


Figure 6: Lineament density map.

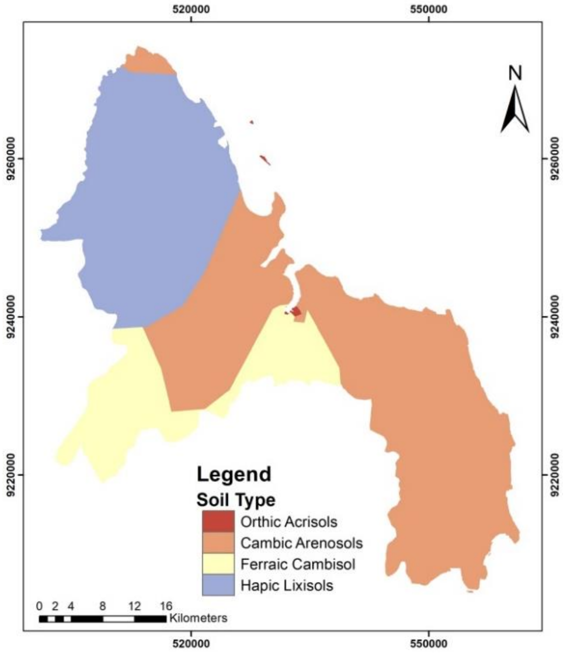


Figure 8: Soil type map.

Rainfall: Rainfall is one of the important variables that affect the groundwater recharge. Generally, high annual rainfall distribution indicates the presence of high groundwater potential (Das, & Pardeshi, 2018). The generated spatial rainfall map was classified into 5 categories as shown in Figure 9. The mean annual rainfall in the area ranges from 768 to 1401mm. Figure 9 shows areas with rainfall of 768mm to 900mm were categorized as very low GW potential, 900mm to 1000mm as low, 1000mm to 1100mm moderate, 1100mm to 1250mm good and 1250 mm to 1401mm fall under very good.

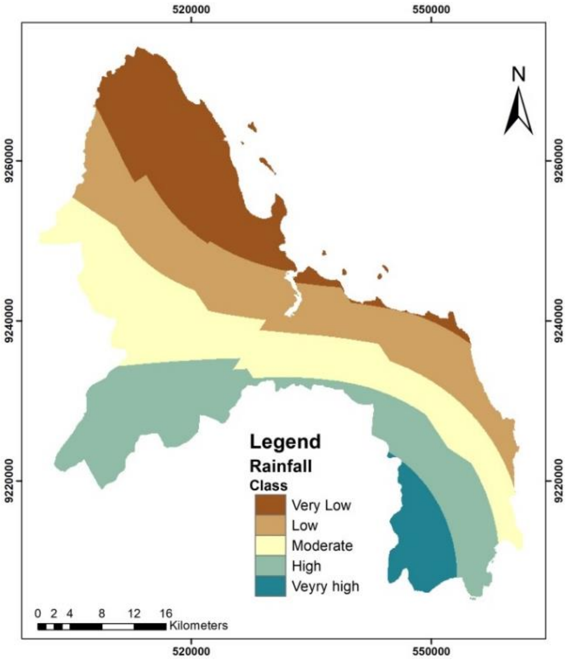
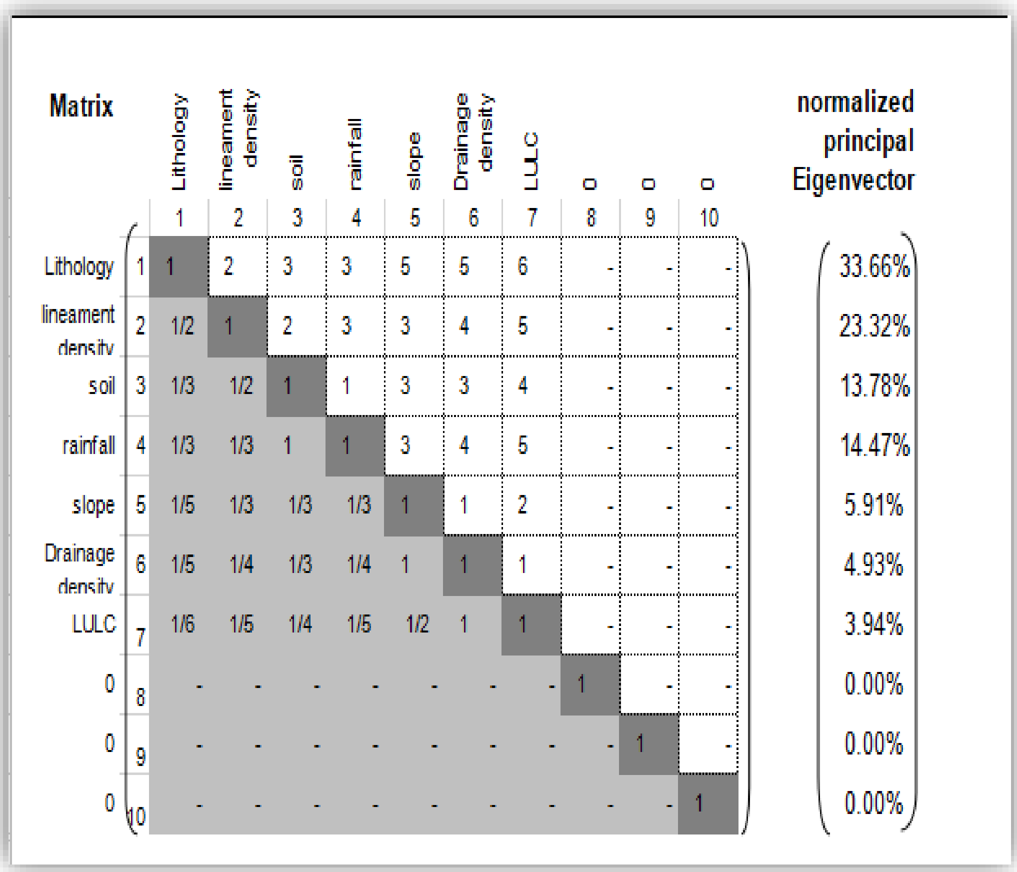


Figure 9: Rainfall map.

Factors influence on groundwater potential

The interrelationship between all seven factors and the weights assigned to each factor depending on their interrelationship and influence capability. The constructed Saaty's AHP matrices compared the relative importance of individual class within the same map and thematic maps to each other by pair-wise comparison matrices. Figure 10 shows comparison matrices of one criterion with the other criteria, relative to its importance on Saaty's scale of 1 to 9. Based on the influence of one factor over the other ranks were given as explained in Saaty's scale, pairwise comparison of factors were done and ranking produced a matrix shown in Figure 10. The importance of one factor over the other and on how they affect groundwater potential was described in the comparison matrix Figure 10.

The Figure 11 shows that lithology had more weight which means that it has strong influence compared to other factors on groundwater potential at a weight of 33.7±9%. The weight results were also calculated and results table with calculated weights and errors using eigenvector method in AHP excel tool as presented in Figure 11. The results obtained had a consistency ratio of 2.7% which is less than 10% suggesting that the data was consistent.



Matrix		Lithology	lineament density	soil	rainfall	slope	Drainage density	LULC	0	0	0	normalized principal Eigenvector
		1	2	3	4	5	6	7	8	9	10	
Lithology	1	1	2	3	3	5	5	6	-	-	-	33.66%
lineament density	2	1/2	1	2	3	3	4	5	-	-	-	23.32%
soil	3	1/3	1/2	1	1	3	3	4	-	-	-	13.78%
rainfall	4	1/3	1/3	1	1	3	4	5	-	-	-	14.47%
slope	5	1/5	1/3	1/3	1/3	1	1	2	-	-	-	5.91%
Drainage density	6	1/5	1/4	1/3	1/4	1	1	1	-	-	-	4.93%
LULC	7	1/6	1/5	1/4	1/5	1/2	1	1	-	-	-	3.94%
0	8	-	-	-	-	-	-	-	1	-	-	0.00%
0	9	-	-	-	-	-	-	-	-	1	-	0.00%
0	10	-	-	-	-	-	-	-	-	-	1	0.00%

Figure 10: Comparison matrix.

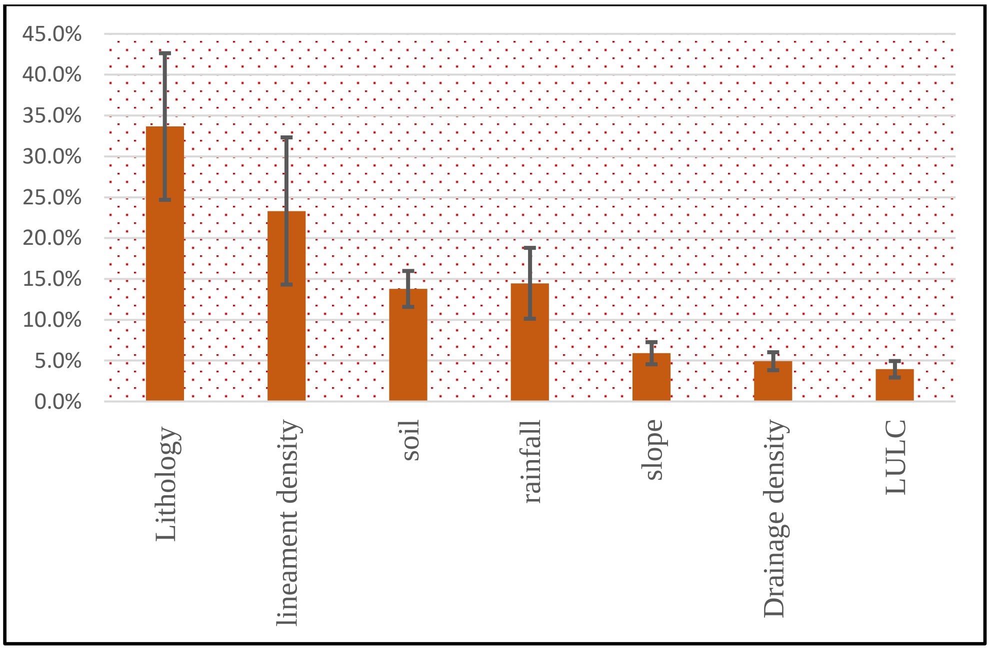


Figure 11: Factors influence on groundwater potential.

Generation of groundwater Potential map

Overall weightage for thematic layer produced a GWPZ map which was then reclassified into five zones namely "very good", "good", "moderate", "low" and "very low". GWPZ map shown in Figure 12 indicates that about 378 (23% of study area) has "very good" GP, 842 (52% of study area) is classified as "good", 372 (23% of study area) being "moderate", 19 (1%) is "low" and 17 (1%) is of "very low" GP (Table 4). The spatial distribution of the various zones of GP obtained generally shows regional patterns related to lithology, lineament, soil, slope, drainage and land use/cover. The 'very good' and 'good' GP zones are mostly in the alluvial plains/valleys, and coincide with flat to moderate slope classes. This highlights the importance of lithology and slope for groundwater investigations. Areas with 'moderate' GP are attributed to combinations of lithology, slope (moderate to steep slope), and land use/cover (barren land). The 'poor' and 'very poor' potential zones are distributed along hills, ridges and pediments, mainly comprising structural hills and escarpments which contribute high runoff (Figure 12).

Table 4: Theme feature weight based on the level of groundwater contribution

	Feature/class	Groundwater prospect	class rank	weight	overall
Lithology	sandy-clayey sediments	low	2	33.7	67.4
	sandy,gravelly and silty sediments	moderate	3		101.1
Soil	Orthic Acrisols	low	2	13.8	27.6
	Cambic Arenosols	Very good	5		69
	Ferralic Cambisol	Good	4		55.2
	Haplic Lixisols	Moderate	3		41.4
Land use Land cover	Built up areas	Very low	1	3.9	3.9
	Water bodies	Very good	5		19.5
	Vegetation	Good	4		15.6
	Barren land	low	2		7.8
Rainfall	768 - 936	Very low	1	14.5	14.5
	936 - 1,040	low	2		29
	1,040 - 1,109	Moderate	3		43.5
	1,109 - 1,235	Good	4		58
	1,235- 1,401	Very good	5		72.5
Drainage density	0 - 22.71	Very good	5	4.9	24.5
	22.71 - 55.03	Good	4		19.6
	55.03 - 89.97	Moderate	3		14.7
	89.97 - 137.14	low	2		9.8
	137.14 - 222.74	Very low	1		4.9
Slope	0 - 2.14	Very good	5	5.9	29.5
	2.14 - 4.29	Good	4		23.6
	4.29 - 7.15	Moderate	3		17.7
	7.15 - 12.15	low	2		11.8
	12.15 - 36.44	Very low	1		5.9
Lineament density	0 - 0.19	Very low	1	23.3	23.3
	0.19 - 0.40	low	2		46.6
	0.40 - 0.63	Moderate	3		69.9
	0.63- 0.88	Good	4		93.2
	0.88 - 1.55	Very good	5		116.5

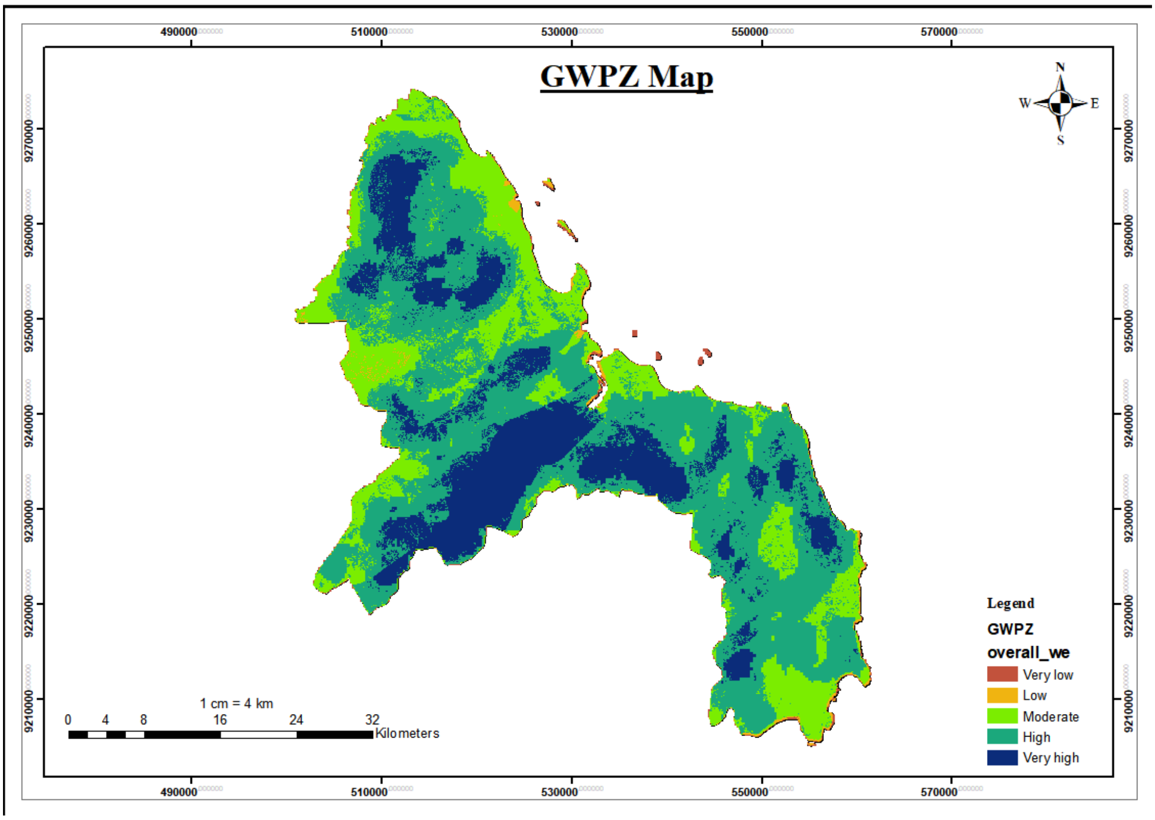


Figure 12: Groundwater potential zone map.

CONCLUSION AND RECOMMENDATION

In this study, spatial distribution of GP areas is assessed using seven thematic layers lithology, lineament density, soil, slope, drainage density, rainfall, and land use/cover derived from satellite images and existing data. GIS-based multi-criteria evaluation based on Saaty's analytical hierarchy process (AHP) is used to compute the rates for the classes in a layer and weights for thematic layers. The spatial distribution of the various GP zones obtained generally shows patterns mainly related to lithology, which means that lithology exhibited strong influence on groundwater potential compared to other factors. The generated GWP map designated the study area to be favorable in terms of groundwater potential as 75% of fall within the zone of "good" and "very good". The most promising GP zones in the area are found in alluvial deposits which are highly weathered and have high permeability. Areas with 'poor' and 'very poor' GP are around structural hills and escarpments, which contribute high runoff and, hence, comparatively less infiltration. The produced GP map can be used for a quick identification of the prospective GP zones for conducting site-specific investigations and as a guideline for integrated groundwater management in the study area. The study also demonstrates the applicability of GIS and remote sensing techniques in identifying groundwater prosperity thus narrowing down the suitable areas for groundwater exploitation and development. Thus, the generated GWP map coupled with detailed hydrogeological and geophysical surveys, can lead to a cost-effective way of identifying the most appropriate sites for groundwater developing.

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