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Groundwater Potential Mapping in Lapan Gwari Community Using Integrated Remote Sensing and Electrical Resistivity Soundings

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Abstract

This research aims to address the pressing issue of failed and abandoned wells, causing water scarcity in Lapan Gwari Community, through an improved groundwater exploration approach integrating remote sensing and electrical resistivity soundings. The study area, located within the Zungeru Sheet 163 SE, spans Latitudes 9˚30'00"N to 9˚32'00"N and Longitudes 6˚28'00" to 6˚30'00". The surface geologic, structural, and hydrogeological mapping provided essential insights into the hydrogeological framework. Leveraging SRTM DEM data, thematic maps were created for geomorphology, slope, land use, lineament density, and drainage density. These datasets were then integrated using ArcGIS to develop a preliminary groundwater potential zones map. Further investigations were conducted using Vertical Electrical Sounding (VES) and Electrical Resistivity Imaging (2D VES) surveys at targeted locations identified by the preliminary map. Results show that the study area predominantly consists of crystalline rocks of the Nigerian Basement Complex, primarily comprising schist and granite with minor occurrences of quartz vein intrusions. Surface joint directions indicated a dominant NE-SW trend. The VES data revealed three to four geoelectric layers, encompassing the topsoil (1 to 5 m depth, resistivity: 100 Ωm to 300 Ωm), the weathered layer (in the 3-layer system) or fractured layer (in the 4-layer system), and the fresh basement rock characterized by infinite resistivity. The shallow weathered layers (3 to 30 m thickness) are believed to hold aquiferous potential. Hydrogeological interpretation, facilitated by 2D resistivity models, delineated water horizons trapped within clayey sand and weathered/fractured formations. Notably, the aquifer resistivity range was found to be between 3 - 35 m and 100 - 300 Ωm, signifying a promising aquifer positioned at depths of 40 to 88 m. This aligns with corroborative static water level measurements. Given this, we recommend drilling depths of a minimum of 80 m to ensure the acquisition of sufficient and sustainable water supplies. The final groundwater potential zones map derived from this study is expected to serve as an invaluable guide for prospective groundwater developers and relevant authorities in formulating effective water resource management plans. By effectively tackling water scarcity challenges in Lapan Gwari Community, this integrated approach demonstrates its potential for application in similar regions facing comparable hydrogeological concerns.

Keywords

Vertical Electrical Sounding, Electrical Resistivity Imaging, Fractured Aquifer, Groundwater Exploration

1. Introduction

Water is important in all aspects of life endeavours. Sustainable supplies of water of adequate quality and quantity are needed for the inhabitants of an area to thrive economically and socially. In likewise manner, the hydrological, biological, and chemical functions of ecosystems, adapting human activities within the capacity limits of nature, and combating vectors of water-related diseases must be preserved [1]. Water resources are essential natural resources that are necessary for a variety of activities, including agriculture, industry, household use, recreation, and environmental purposes. The rapid urbanisation and increase in population in the study have put a strong demand on the almost non-existent water resources [2]. This has not been helped by the fact that the streams that drain the area are seasonal, lack of public water supply infrastructure, and few commercial boreholes that are grossly inadequate to meet the populace's needs. Consequently, attempts to address these challenges focused on the exploitation of groundwater to meet the ever-increasing needs [3].

Approximately 2.5% of the Earth's total water supply is comprised of fresh water, which primarily exists as groundwater. A minor portion of fresh water is observable above ground or in the atmosphere. Groundwater is contained in aquifers. These are sediments, rocks, or weathered rock bodies that store and yield significant water to wells or springs [4]. However, they exhibit significant spatial heterogeneity across different geological formations. The producibility and renewability of groundwater resources in crystalline bedrock are constrained and challenging to forecast due to the heterogeneity and anisotropy present in rock fracture systems. The hydrogeological characteristics of groundwater in a typical crystalline foundation complex terrain are primarily influenced by the composition and distribution of weathered and fractured zones. This suggests that the identification of appropriate groundwater zones can pose challenges in areas predominantly characterised by intact or unaltered crystalline rock formations [5].

Fractured crystalline and deeply weathered rock units are usually the major targets in groundwater exploration surveys in Basement Complex terrains. These fractures constitute secondary porosities that endow crystalline rocks with aquifer attributes [6]. These are usually mapped using a combination of geologic fieldwork, remote sensing, and resistivity geophysical techniques. Numerous documented inquiries have substantiated that geophysical methods are often regarded as the most dependable and precise procedures for conducting subsurface structural examinations and assessing rock variations. Geophysical techniques are employed to identify deviations in physical characteristics or anomalies of geophysical parameters within the earth's crust. The most often measured physical parameters are density, magnetism, elasticity, and electrical resistivity [7]. The primary objective of geophysical surveys is to identify and delineate areas with indirect signs that may indicate the presence of exploitable resources. Geophysical investigations employing electrical, electromagnetic, gravitational, and magnetic techniques have proven to be highly valuable in resolving hydrogeological challenges [8]. Electrical resistivity surveys have been widely employed in hydrogeological, mining, environmental, and geotechnical studies for several decades due to their cost-effectiveness and ease of application in the field. The characterization of Earth materials benefits significantly from the analysis of electrical properties, which are highly valuable geophysical parameters [9]. This phenomenon arises due to the observed correlation between variations in electrical resistivity (or its inverse, conductivity) and variations in lithology, water saturation, fluid conductivity, porosity, and permeability.

Lapan Gwari village is experiencing an upsurge in development and population growth, a factor which is attributable to its proximity to the Gidan Kwano campus of the Federal University of Technology, Minna. Like every other peri-urban community in the country, the lack of an adequate supply of potable water has been prevalent for years. A limited number of functional wells and boreholes have not successfully cushioned the effect of the unavailable municipal water supply in the city. Most wells are seasonal, thriving best in rainy seasons; most boreholes too have been improperly cited and developed, thus, providing a low yield of water throughout the seasons [10].

The study area has over time been surveyed and studied by several geoscientists, particularly for geological and hydrogeological investigations. The subsurface geological mapping has minimally been performed by integrating geological and geophysical data. The current practice for locating sites for borehole drilling has been to incorporate only Vertical Electrical Sounding (VES) without recourse to its attendant limitations. Despite this, only a little attempt has been made so far to understand the detailed relationship between structural features observed on the ground and those extending into the subsurface. Communities within the Basement Complex terrains commonly suffer acute potable water needs arising from the complex hydrogeological setting of the terrains [11] [12] [13] [14]. The poor success rate in the water borehole drilling in the Basement Complex regions has been attributed to the non-incorporation of hydrogeological concepts into the Vertical Electrical Sounding (VES) anomaly interpretations in borehole siting [15].

Hence, to improve success rates in such hydrogeological difficult terrains, there is a need to interpret complimentary geophysical anomalies by exploiting the strengths of Vertical Electrical Sounding (VES) and remote sensing techniques in resolving geophysical anomalies that may make the rock units auriferous. This research is intended to delineate hydrogeological significant structures within 1:50,000 Sheet 163 SE (Zungeru) North-Central Nigeria via exploitation of synergy in integrated remote sensing, geological fieldwork, and resistivity geophysical techniques.

This study aims to investigate the hydrogeological setting and groundwater potential of the Lapan Gwari community using remote sensing and geoelectric imaging techniques.

The objectives of the study are to:

1) Produce a geological map of the study area.

2) Produce thematic maps of groundwater controlling parameters from remote sensing data.

3) Produce groundwater potential zones map from integrated analysis and interpretation of the datasets.

4) Conduct geophysical studies using the electrical resistivity method from promising areas deduced from 3) above.

5) Correlate the groundwater potential map with existing boreholes and study the relationship between the groundwater potential zones map and the groundwater yield of the area.

2. Study Area

Lapan Gwari is located around the Gidan Kwano campus of the Federal University of Technology, Minna within the south-eastern part of Zungeru Sheet 163 and it is bounded within latitudes 9˚30'N and 9˚32'N and longitudes 6˚28'E and 6˚30'E (**Figure 1**). The study area is accessible through the Minna-Zungeru Road and the Hanya Gwari Road. There are also footpaths connecting different settlements and houses. The area is drained mainly by River Kaduna. The tributaries of the river system include rivers Nawo, Gogonkura, and Weminafia. The drainage of the area is lithologically and structurally controlled. The study area falls within the Guinea savannah vegetation. Two distinct seasons characterise the climate: the rainy and dry seasons. Total annual rainfall ranges between 1270 mm and 1524 mm lasting from April to October with a mean of 1300 mm [16].

Exposed lithologic units belonging to rocks of the Basement Complex of Nigeria

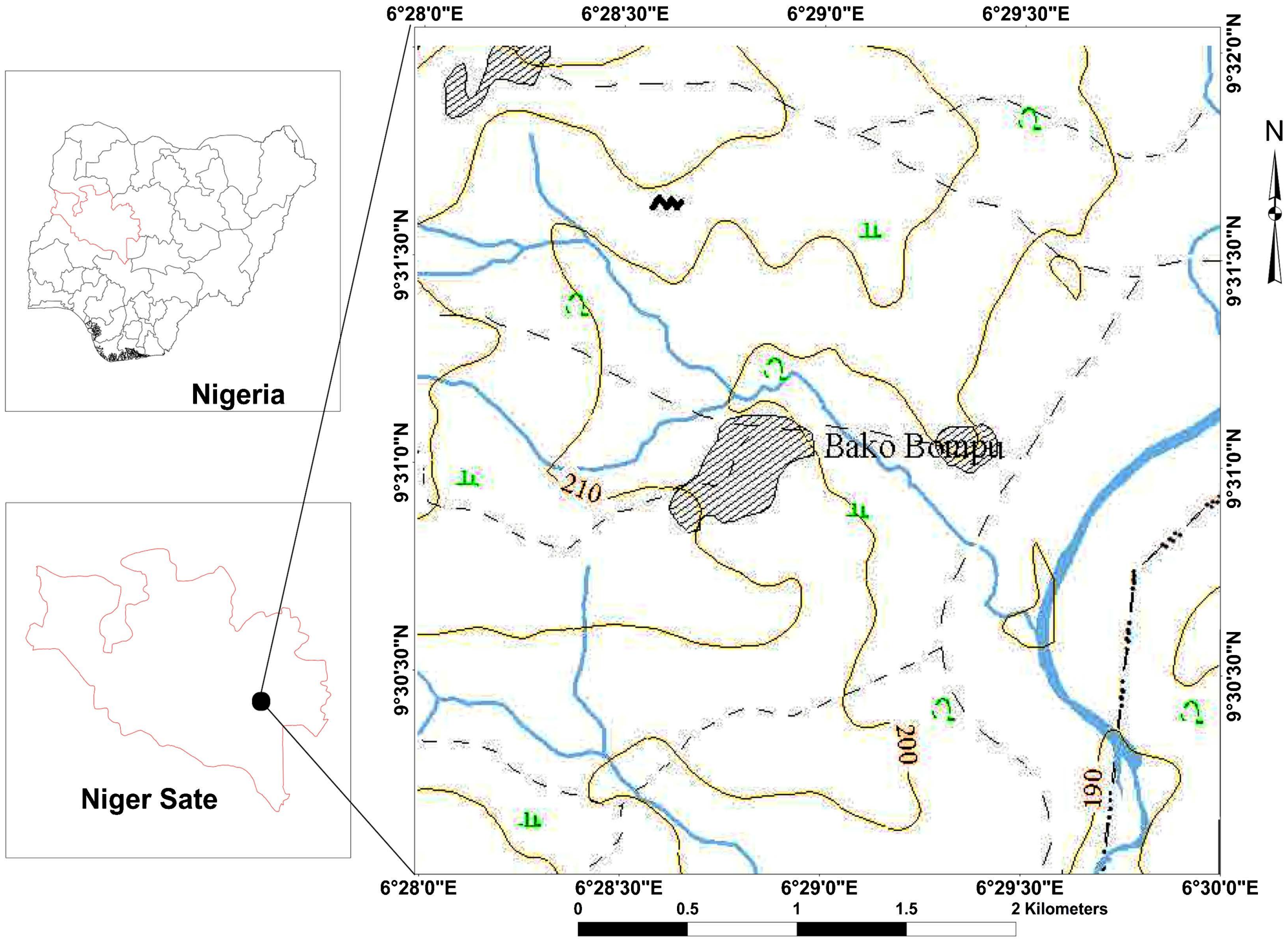


Figure 1. Location map of the study area.

comprise alluvial deposits, medium to coarse-grained biotite and biotite hornblende granites, and granite gneiss. The alluvium represents the youngest of all the geological materials in the study area and is believed to be of Tertiary or Recent age. River alluvium constitutes recent deposits and consists of sand, silt, and clay in various proportions with some pebbles and cobles. Medium-coarse-grained granites are jointed and sometimes marked out as linearly arranged boulders; occur as a group of minor discontinuous intrusions of small areal extent in the granite gneiss. They are equigranular, dark grey rocks; tend to have the same colour and mineral compositions as their hosts. The major visible minerals include plagioclase feldspar, biotite, and quartz (Figure 2). The granite gneiss has been reported to have suffered heterogeneous deformation as evidenced by subdued metamorphism and intrusion of large volumes of granitoids [17]. Portions of these appear granitic in texture and are characterised by some gneissose texture. Structural features as mapped in the various outcrops include Faults, joints, foliation, and lineation. The joints in granites have a predominant NE-SW and NW-SE trend. Some of the rocks have undergone a level of physical weathering process resulting in exfoliation. Some of the coarse-grained granitic rocks exhibit closely spaced jointing.

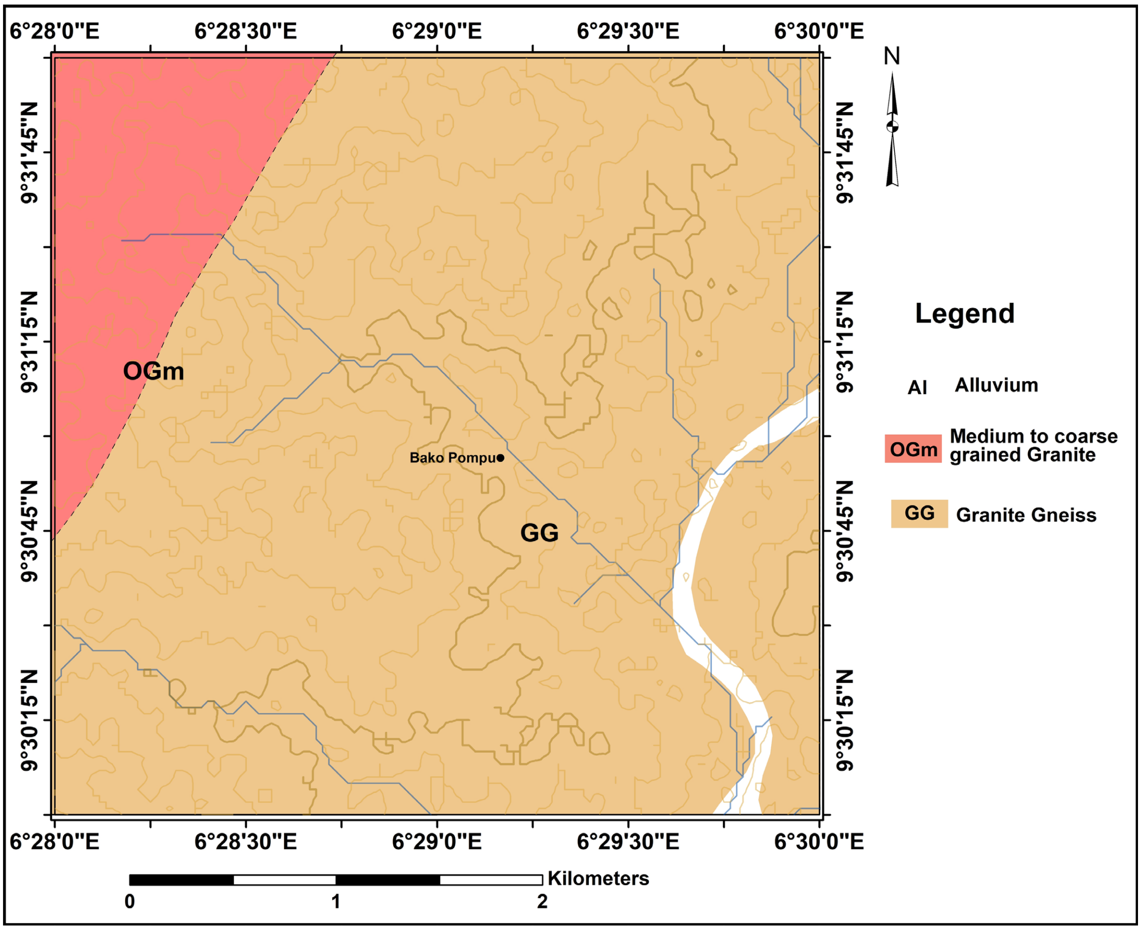


Figure 2. Geological map of the study area.

3. Methodology and Materials

3.1. Lineament Extraction

Suttle Radar Topographic Mission (SRTM) Digital Elevation Model (DEM) was processed using different visualization methods, especially shaded relief representations were used to enhance terrain features to support lineament extraction. Varying the sun illumination angle promotes the identification of more lineaments on the different views of the same area since the lineaments orthogonal to the illumination angle are enhanced. Sun illumination directions of 0˚, 45˚, 90˚, 270˚, and 315˚, perpendicular to the prominent lineaments in the region, were selected to enhance the linear features.

Topographic model parameters were calculated from the SRTM DEM and used for geomorphological analysis. The topographic model parameters such as slope, longitudinal curvature, cross-sectional curvature, plan convexity, and minimum curvature were calculated using a 5 × 5 kernel. They are used as input bands for landform feature classifications. Automatic drainage extraction was achieved through terrain pre-processing using the spatial analyst extension of ArcGIS 10.5. SRTM DEM of the study area was used as input for terrain pre-processing. The line density tool in ArcGIS was used in the processing of the drainage density.

Statistical analyses of the lineaments in the present study were based on the length and total number of the lineaments. The maximum, minimum, and average lengths, as well as the standard deviation of the length of the lineaments, were also analysed. Rose diagram analyses were generated to show the orientation distribution of the lineaments. Rockworks 16 (Rock Ware) software tools were utilized to construct rose diagrams. Thereafter, the Line Density tool of the Spatial Analyst extension of ArcGIS 10.5 was used to create the lineament density map.

3.2. Groundwater Potential zones (GPZ) Mapping

Thematic layers of lithology, drainage density, lineament density, and slope were reclassified to a common scale of 1 to 4 by intervals of 1, called scale values for the weighted overlay operation, with 4 being the highest potentiality score, 1 being the lowest, and 0 being restricted (unsuitable) values. The ArcGIS Weighted Overlay tool requires integers for the scale values, which were calculated by multiplying the grading values by 4 and rounding to the nearest integer. These scale values were used as the suitability scores. This produced the preliminary GPZ map of the study area. This was then used to design the field campaign for validating the GPZ map using Vertical Electrical Sounding (VES) geophysical survey.

Geophysical investigation sampling points were delineated with the aid of a location map and Global Positioning System (GPS). The Electrical Resistivity method of the geophysical survey was conducted, using a hybrid Werner-Schlumberger array. This involved a combination of both Vertical Electrical Sounding (VES) using the Schlumberger array and Constant Separation Traversing (CST) using the Werner array in the study area. For every point or station that a VES reading was taken while spreading out the cables, a CST reading was taken likewise while rolling back the cables. Forty-eight (48) VES and CST readings were taken concurrently, with a 200m station interval.

4. Results Presentation and Discussion

SRTM DEM yielded long and continuous lineaments of regional scale **Figure 3**. This can be attributed association of digitized lineaments to geomorphological features, mainly drainage channels. The lineament density map (**Figure 4**) reveals that areas having high lineament densities are the zones of highest porosity and permeability which in turn have a greater chance of accumulating groundwater. Spatially, very good and good groundwater potential categories are found where higher lineament densities were delineated. The north-western portion of the map has the highest lineament density. This is due to the intersection of several lineaments oriented in different directions. The Rose diagram (**Figure 5**) shows the presence of NW-SE to NE-SW lineaments, which imply the current tectonic regime. In addition, these lineaments/faults seem to correspond to stream segments.

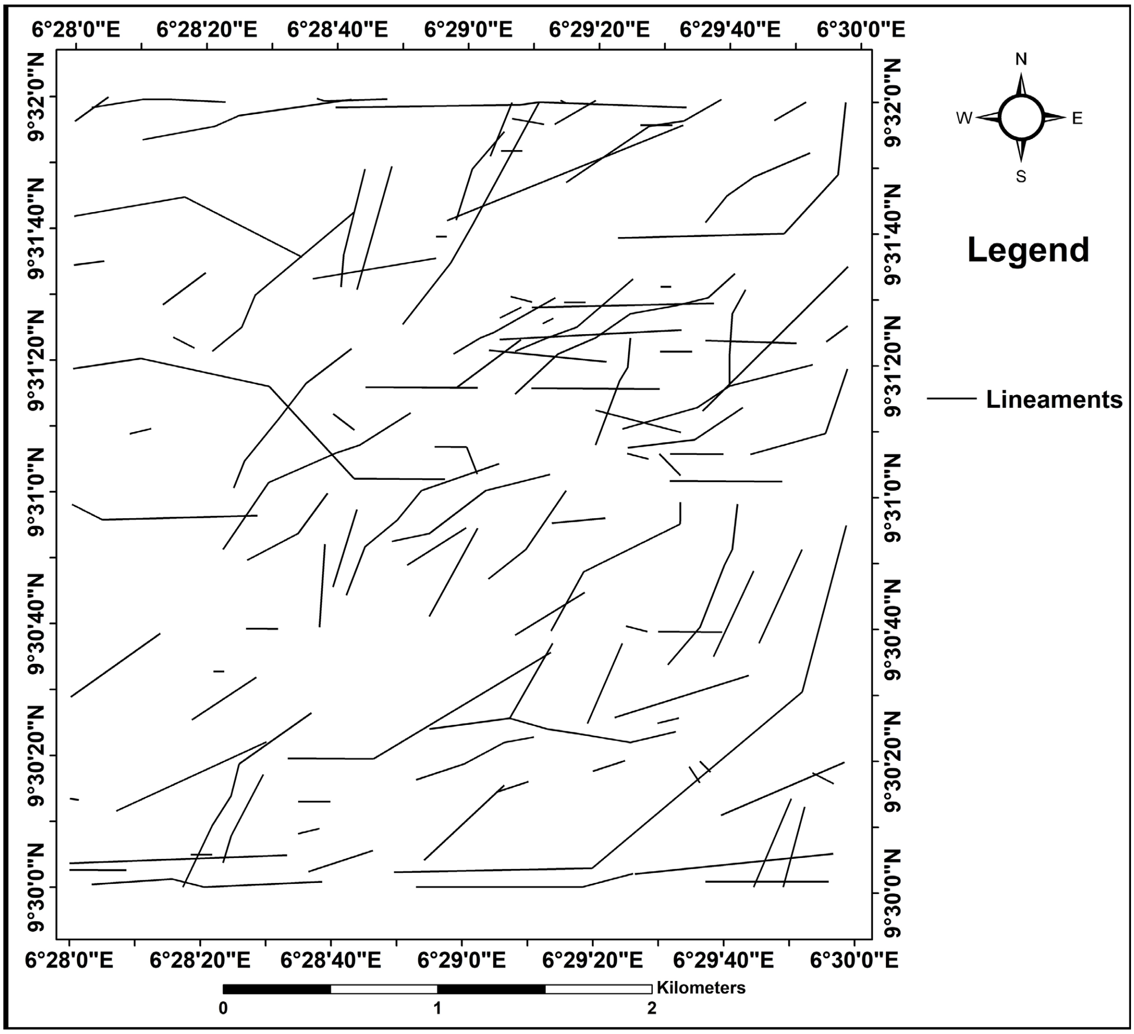


Figure 3. Lineaments extracted from SRTM DEM of the study area.

Drainage density plays a major role in groundwater infiltration and accumulation. It is an inverse function of permeability [18]. Areas with higher drainage densities are associated with less water infiltration to the ground, consequently leading to higher surface runoff [19]. Conversely, areas with lower drainage densities are associated with more water infiltration to the ground, consequently leading to lower runoff. Higher drainage densities are concentrated in the middle and southern portions of the map (**Figure 6**).

4.1. Groundwater Potential Zones Mapping

The spatial distributions of the various groundwater potential zones obtained from the GIS model generally show regional lineaments, drainage, landform, and lithology patterns. Spatially, very good to good categories are distributed in areas where the lithology is most appropriate to have primary porosities and around lineaments and drainage channels (**Figure 7**). This emphasises the importance of lithology, lineaments, and hydro-geomorphological units for groundwater exploration.

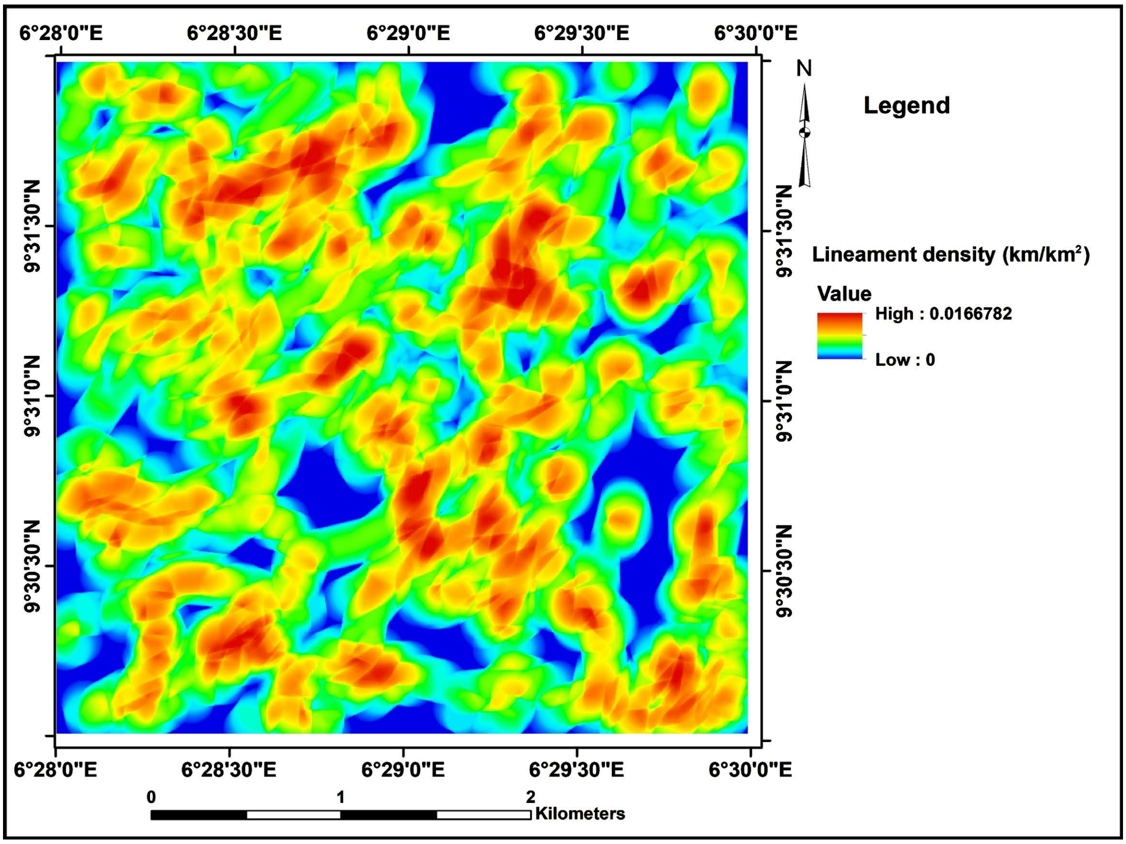


Figure 4. Lineament density map of the study area.

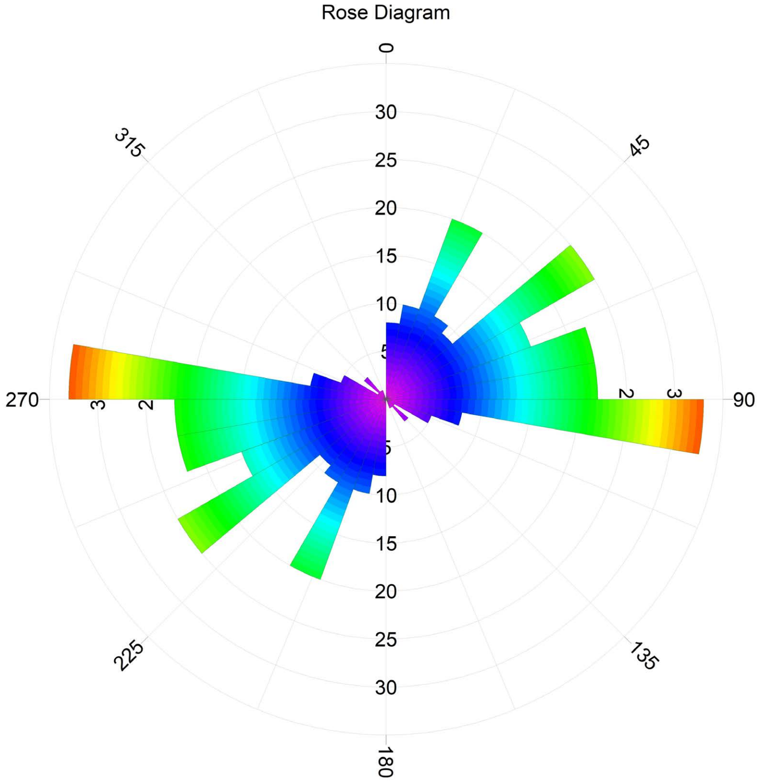


Figure 5. Rose diagram of orientations of lineaments extracted from SRTM DEM.

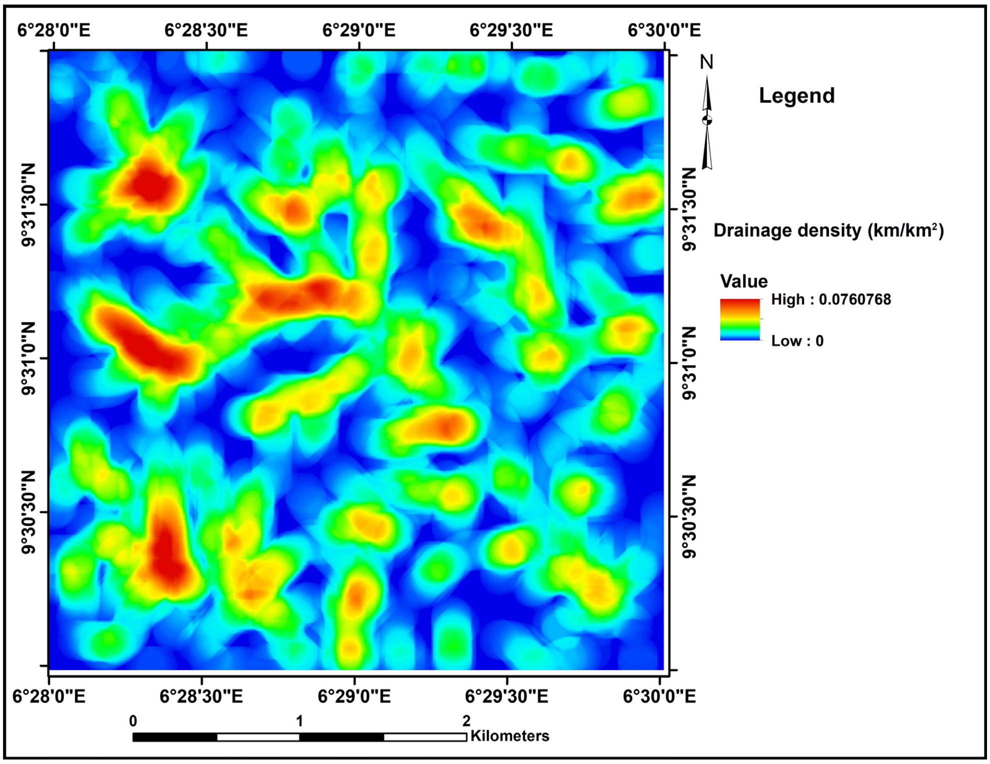


Figure 6. Drainage density map of the study area.

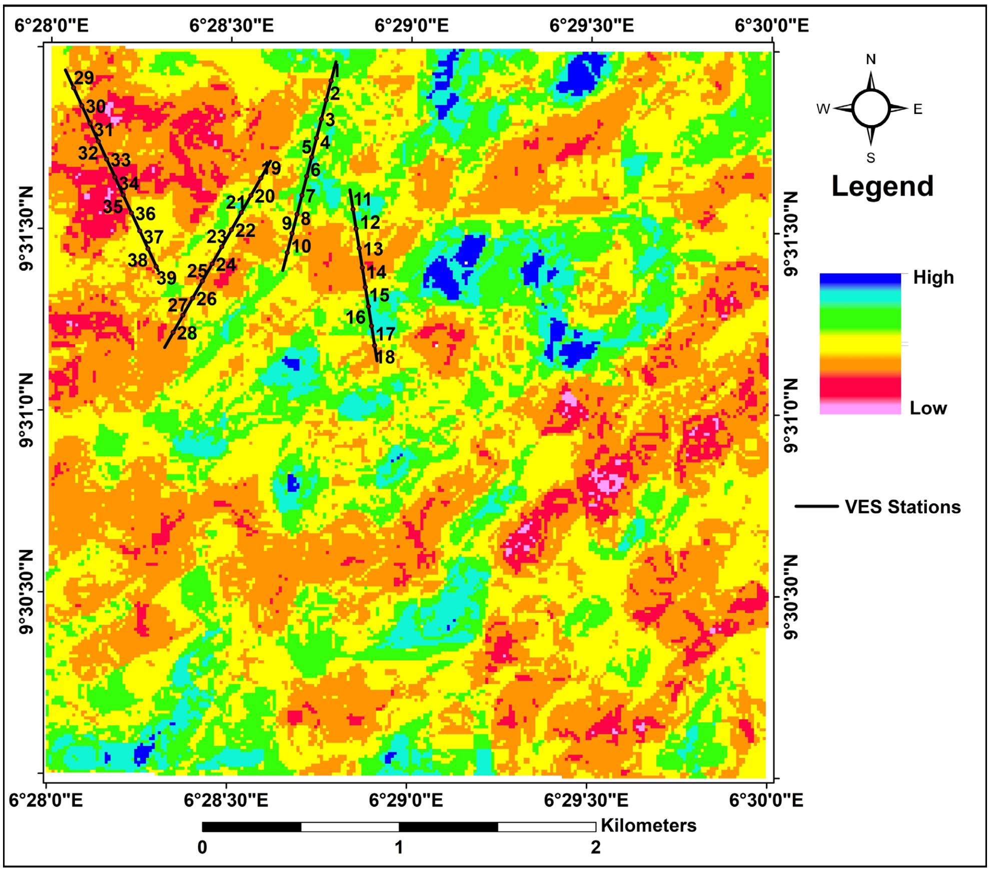


Figure 7. Vertical Electrical Sounding (VES) profile arrangement indicating some VES points.

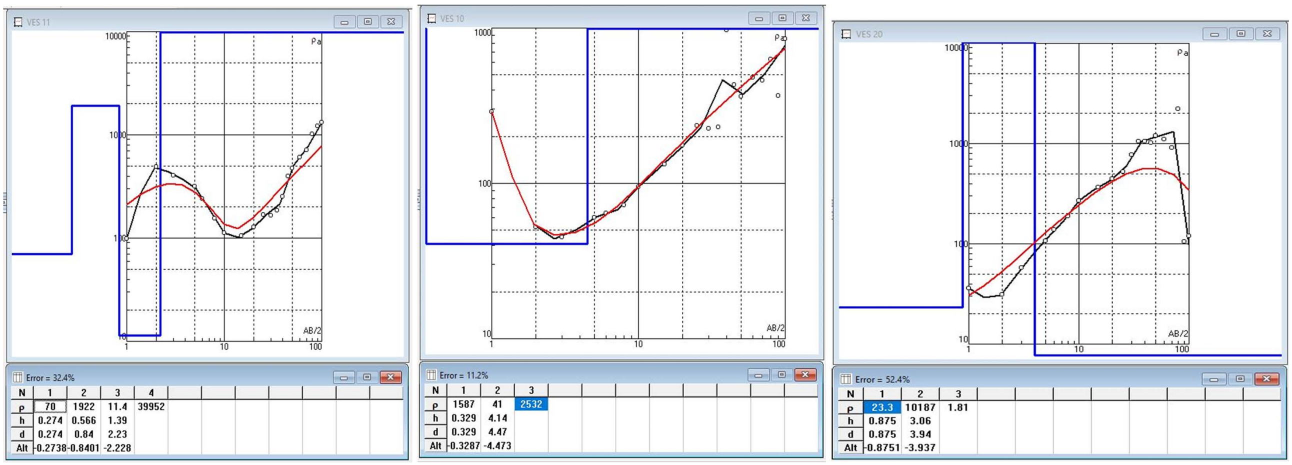
Areas having good to moderate groundwater prospects are attributed to contributions from combination moderate groundwater prospects are attributed to contributions from combinations of the lithology, slope, and landform. Areas having poor groundwater potential are spread mainly around ridges and peaks and to some degree where the lineament densities are low and slope classes are high. The granite gneisses are classified as moderate groundwater potential zones. The alluvium at the map's central portion has very good groundwater potential. The most promising targets in the alluvium constitute areas with dense lineaments. The plains in the crystalline rocks generally have moderate groundwater potential. Most of the zones with poor groundwater potential lie in crystalline rocks due to the slope of the landform.

4.2. Resistivity Surveys

Detailed analysis of the geometry of these curves shows a variation in the morphology of the curves. This is revealed by changes in resistivity values, and it reflects subsurface anisotropy. Graphical plots of the VES data for some stations are presented in **Figure 8** shows different curve types encountered in the survey. The geoelectric section and profile for the different transects are presented in **Figure 9**.

5. Conclusion

In conclusion, this study has effectively utilized an integrated approach, combining Remote Sensing, Geographic Information System (GIS), electrical resistivity surveys, and hydro-geologic mapping, to successfully map groundwater potential zones in the study area. The comprehensive analysis highlights geology and lineament density as the primary controlling factors of groundwater availability, while other factors demonstrate comparatively limited impact. The reliability and credibility of our methodology were established through a meticulous examination of the geoelectric section derived from Vertical Electrical Sounding (VES) data, which exhibited a strong correlation with lithologic sections in



Error = 32.4%

N	1	2	3	4
ρ	70	1922	11.4	39952
h	0.274	0.566	1.39	
d	0.274	0.84	2.23	
Alt	-0.2738	-0.8401	-2.228	

Error = 11.2%

N	1	2	3
ρ	1587	41	2532
h	0.329	4.14	
d	0.329	4.47	
Alt	-0.3287	-4.473	

Error = 52.4%

N	1	2	3
ρ	23.3	10187	1.81
h	0.875	3.06	
d	0.875	3.94	
Alt	-0.8751	-3.937	

Figure 8. Representative VES curves in the study area.

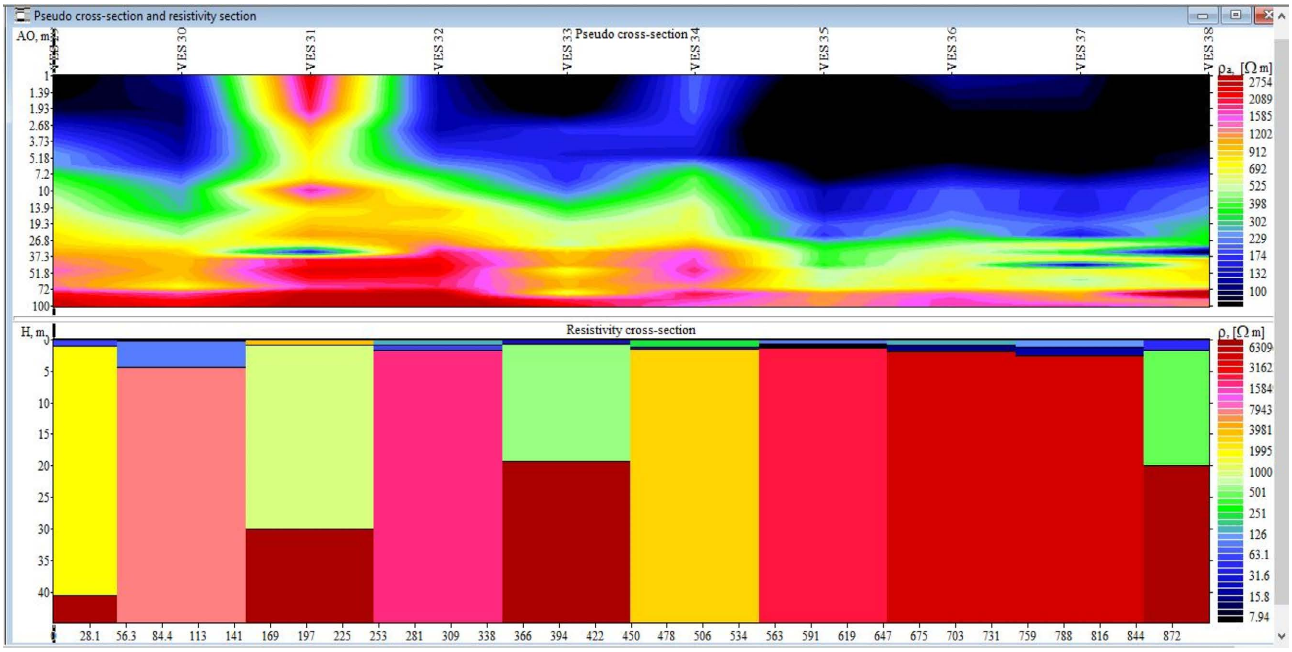


Figure 9. Pseudo-cross-section and Resistivity section of Profile A in the study area.

hand-dug wells. This underscores the accuracy of VES data in constructing reliable subsurface lithologic profiles. Furthermore, the validity of our groundwater potential mapping was reinforced by thorough validation of the GPZ map through cross-referencing with VES soundings and borehole inventory, providing additional affirmation of the credibility of our approach.

To enhance the overall understanding of groundwater dynamics, future studies should explore integrating additional hydroclimatic data into past research. This has the potential to yield valuable insights into the ever-growing complexity of the interactions between various environmental factors and groundwater availability. Furthermore, land use changes and their impacts on groundwater potential should be investigated since it is vital for devising sustainable water resource management strategies. Understanding how human activities influence groundwater dynamics is crucial for prudent water usage. To augment the precision and real-time applicability of groundwater potential mapping, incorporating advanced technologies for continuous monitoring and data collection is recommended. This proactive approach will enable researchers and water resource managers to respond promptly to any fluctuations or anomalies in groundwater availability. Lastly, it is pertinent to underscore the significance of considering socio-economic factors and community water needs in future research. Integrating the human dimension into groundwater studies will facilitate the development of pragmatic policies and equitable resource allocation, ultimately benefiting local communities. In implementing the above recommendations, the complex challenges related to groundwater resource assessment and management will be addressed, and contributions to ensuring sustainable water supplies for present and future generations will be perfected.

Conflicts of Interest

The authors declare no conflicts of interest regarding the publication of this paper.

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