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Groundwater Potential Mapping in Part of Minjibir, Kano State, Northwestern Nigeria Using Integrated Remote Sensing, GIS, and Geophysical Methods

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Abstract: This study integrated Remote sensing, GIS and Electrical resistivity techniques to investigate groundwater potential zones in part of Minjibir Local Government Area, Kano State, Nigeria, located between 12°10'00"N to 12°13'30"N and 8°32'30"E to 8°36'00"E. A total of 45 Vertical Electrical Sounding (VES) stations were surveyed using the Schlumberger array configuration with data acquired using an ABEM Terrameter (SAS 1000). The coordinates of all VES points were recorded using a Global Positioning System (GPS). Remote sensing data were obtained from ASTER Digital Elevation Model (DEM) and processed to generate groundwater controlling factors such as slope, lineament distribution, lineament density, and drainage density. VES data were processed and interpreted using IP12Win, while spatial analysis and groundwater potential zoning were carried out using ArcGIS and Surfer 16 software. The geoelectric interpretation revealed variations in groundwater prospects across the study area. Several VES points indicated shallow aquifer units of limited thickness, suggesting low groundwater yield. Moderate groundwater potential was observed in areas where thicker aquifer layers occurred at depths between 34m and 40m.In some locations, such as VES 4, productive aquifers were inferred to occur at depths exceeding 450 m, indicating that deep drilling may be required and could be uneconomical. The groundwater potential map classified the area into very low, low, moderate, high, and very high potential zones. Validation was achieved by overlaying borehole yield data, hand pump records, and VES results. High potential zones correspond to areas with high lineament density, gentle slope, and low drainage density, while low potential zones were associated with clay/shale soils, high drainage density, and low lineament density. The study provides a reliable framework for selecting suitable borehole locations and reducing borehole failure.
Keywords: Geographic Information System, Groundwater Potential Zone, Remote Sensing Vertical Electrical Sounding.

I. INTRODUCTION

Water is essential for maintaining a healthy environment and is one of the most valuable natural resources for human survival (Osumeje & Recto, 2017). Groundwater stands out as a cost-effective water source because it can be accessed through hand-dug wells and boreholes, which are significantly more affordable than traditional surface water projects that require extensive infrastructure such as reservoirs and pipeline networks (Adeyeye *et al*., 2019).

Geophysical techniques, along with traditional methods like geological, hydrogeological, and photogeological approaches, have been used to delineate groundwater potential zones (Fernandez *et al.,* 2016). The application of geophysics for groundwater exploration has gained traction due to its ability to minimize the risks of drilling unproductive boreholes and reduce the costs associated with low groundwater yields (Ishola *et al*., 2023). Combining traditional approaches with Remote Sensing (RS) and Geographic Information System (GIS) technologies enhances the accuracy of identifying groundwater potential zones, mitigating biases from any single technique (Adeyeye et al., 2019). This integrated approach allows for detailed mapping of prospective groundwater targets and provides insights into the structural characteristics of the study area (Daniel et al., 2021).

Remote sensing offers a powerful tool for large-scale surface water surveys, providing high spatial and temporal resolution, multi-sensor capabilities, and near real-time data. It is particularly useful for monitoring and strategic planning by reducing costs and optimizing the use of limited human and scientific resources compared to direct field measurements (Yulianto *et al*., 2022).

Habeeb and Abdulkadir (2020) emphasized that satellite remote sensing enables broader observation and systematic analysis of geomorphic features. Similarly, Osinowo *et al*. (2020) noted that integrating multiple methodologies with RS and GIS techniques is essential for improving water exploration accuracy. Saravanan *et al.* (2021) used a combination of remote sensing and aeromagnetic data to delineate subsurface features in Northeastern Nigeria, while Osumeje *et al.* (2017) applied the resistivity method with Dar Zarrouk parameters to identify groundwater in Fika. Lawal *et al.* (2021) conducted a Multi-Criterion Decision Analysis near the study area to identify recharge zones.

Despite numerous studies conducted to identify groundwater potential zones, many boreholes in the study area experience significant dry spells, particularly during the dry season. This limitation may be attributed to the drawbacks of using single methods for groundwater exploration.

Therefore, this research focuses on identifying groundwater potential zones while addressing gaps that may arise from single-method approaches. An integrated approach involving remote sensing, electrical resistivity, and GIS techniques was employed to provide a more comprehensive understanding of groundwater distribution in the study.

II. LOCATION OF THE STUDY AREA

The study area is situated in Minjibir Local Government Area of Kano State, Nigeria (Figure 1.1). It is bounded by longitudes 12°10'0"N to 12°13'30"N and latitudes 8°32'30"E to 8°36'0"E, covering an area of approximately 16 km² with a population of 794 as of the 2006 census. The village is surrounded by about six other villages: Sabon Gari Mallam to the north, Gorrike Garfe to the northeast, Goda and Kabuge to the northwest, and Kantama to the southeast.

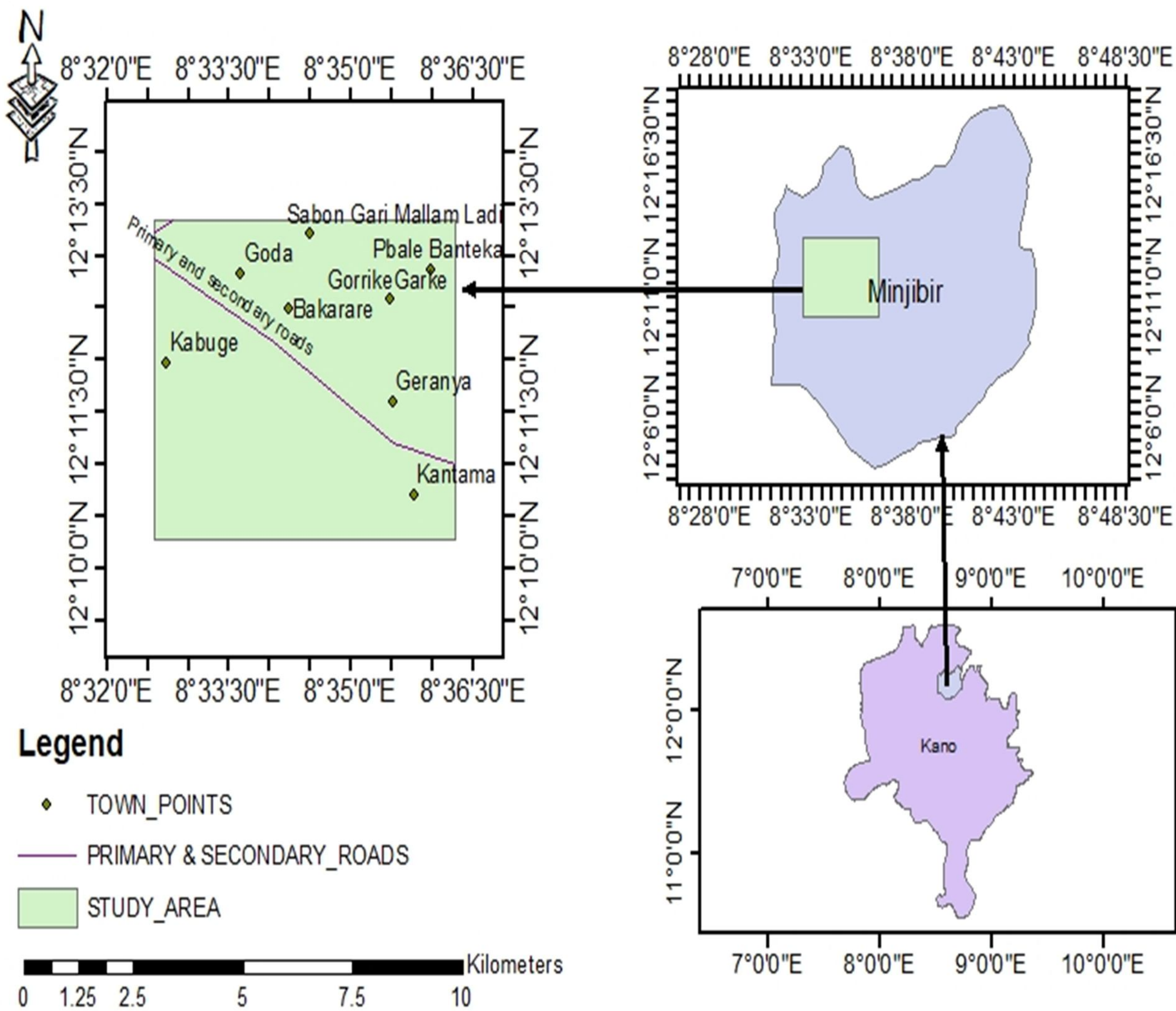

Figure1: Location Map of the Study Area

III. MATERIALS AND METHOD

This section focuses on the instruments used for data acquisition and the techniques adopted for data sourcing. It begins with a description of the various components of the instruments and their functions, followed by the procedures involved in field data collection. A brief explanation of the software employed for data processing and interpretation is also presented. In addition, remote sensing datasets, including Landsat 8 imagery and ASTER DEM, were obtained from the USGS database for analysis.

A. Materials

The materials required for this study are as follows:

1) ABEM Terrameter
2) Four cables on wheels and connecting wires.
3) Global Positioning System (GPS).
4) Metal electrodes.
5) Power supply
6) Hammer.
7) Tape.

a) ABEM Terrameter

The ABEM Terrameter is a geophysical instrument used to measure subsurface electrical resistivity and induced polarization (IP), commonly applied in Electrical Resistivity Tomography (ERT) and Vertical Electrical Sounding (VES). It is portable and reliable for field investigations. During data acquisition, electrodes are planted in the ground, current is injected through two electrodes, and the resulting potential difference is measured through the remaining electrodes to determine subsurface properties.

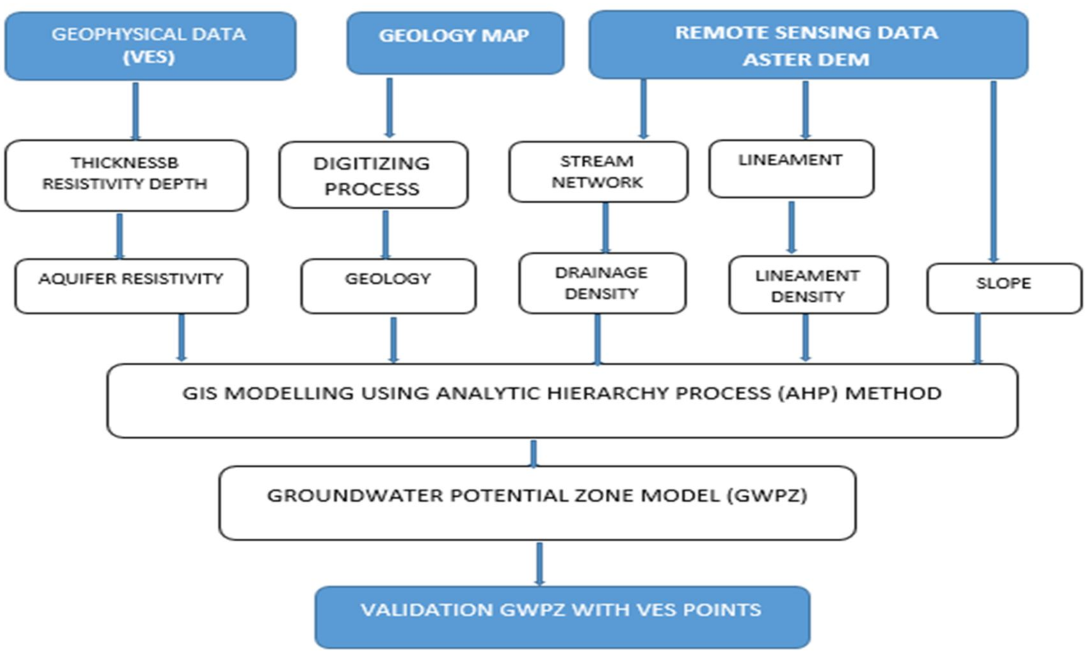

Figure: 2.Workflow of Groundwater potential model of study area.

B. Methods

In order to get the data, the following steps were taken:

a) Work schedule
b) Investigation and survey area division.
c) Examining and testing every item that will be utilized in the field
d) Conducting an area survey

1) Field Work Method

The Schlumberger array configuration was adopted for the electrical resistivity survey using an ABEM Terrameter. The field equipment included current and potential electrodes, measuring tape, hammer, spread cables, and a GPS for coordinate positioning. The half-current electrode spacing (AB/2) ranged from 1 m to 300 m, while the potential electrode spacing (MN) was progressively increased as required. During data acquisition, steel electrodes were hammered into the ground and arranged symmetrically about the sounding point. The Terrameter was positioned between the potential electrodes (P1 and P2), and all electrodes were connected to the appropriate terminals on the instrument. Measurements were taken by switching on the Terrameter, selecting resistance mode, and recording the displayed resistivity, induced polarization (IP), and self-potential (SP) values. The procedure was repeated by expanding the electrode spacing stepwise until the maximum spread was achieved, after which the instrument was moved to the next VES station.

2) Data Analysis

IP2WIN and Surfer software were used for computer-assisted interpretation of the VES field data. The acquired resistivity values and corresponding electrode spacing (AB/2) were first input into IP2WIN to generate sounding curves and geoelectric models. IP2WIN displays field data points, fitted curves, and model parameters such as layer resistivity, thickness, and depth. The interpreted layer parameters were used to construct the geoelectric section based on the local geology. Finally, the modelled depths with their corresponding GPS coordinates were imported into GIS for the production of contour and basement topography maps.

Figure 3: Digitized model of interpreted VES 1

IV. RESULTS AND DISCUSSION

A. Results

In this section, we presented and analyse the results obtained from integrating geophysical and remote sensing data, including electrical resistivity, induced polarization (IP), and self-potential (SP) measurements. These results offer valuable insights into the groundwater potential of the study area. The discussion highlights the significance of the combined methodologies in understanding subsurface conditions and their implications for groundwater recharge end management.

1) Contour Maps

To make contour maps, Surfer is used to griddle the resistivity data. All of the VES stations in each aquifer's designated site had their expected layer's resistivity value, thickness, depth IP and SP documented. Each resistivity and location's information was griddled once it was loaded into an Excel file known as Surfer. The thickness, depth, and arrangement of layers. Gridding was done, and then the contour maps were made and exported. We generated five maps: a resistivity thickness, a depth, a, IP and SP contour maps respectively.

2) Resistivity Map

Figure 4 High resistivity values are found at the northern end of the study area, while low resistivity is indicated in the northwest, southwest, and southeast, with moderate resistivity observed in the north-eastern part of the area Therefore, groundwater is expected to be found in areas between the low and moderate resistivity zones, as these regions likely represent transitions between fully saturated and partially saturated materials, indicating a higher potential for water-bearing formations.

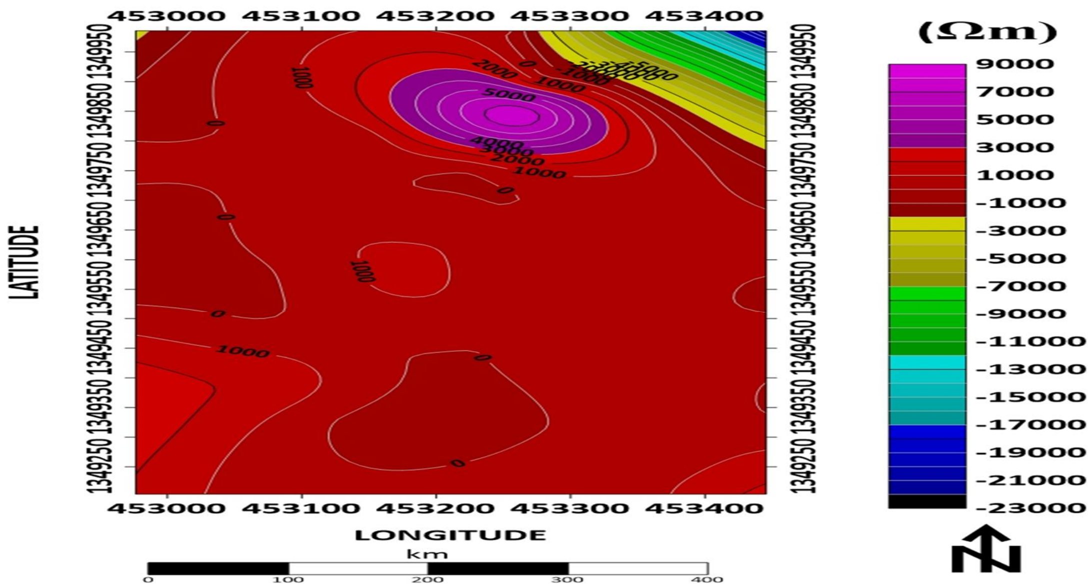

Figure 4 Resistivity Contour Map

3) *Depth Map*

The figure 5 displays the depth of the study area. It shows that the good depth aquifer, where groundwater potentiality is expected to be found at low depth, is located at NE central part and some part of NW, while the shallow depth aquifer spans from -350.3 to 50m and is found from the NE top ending, central part, and NW. The deeper depth aquifer is primarily found at NW at latitudes 134990N and longitude 453000E.

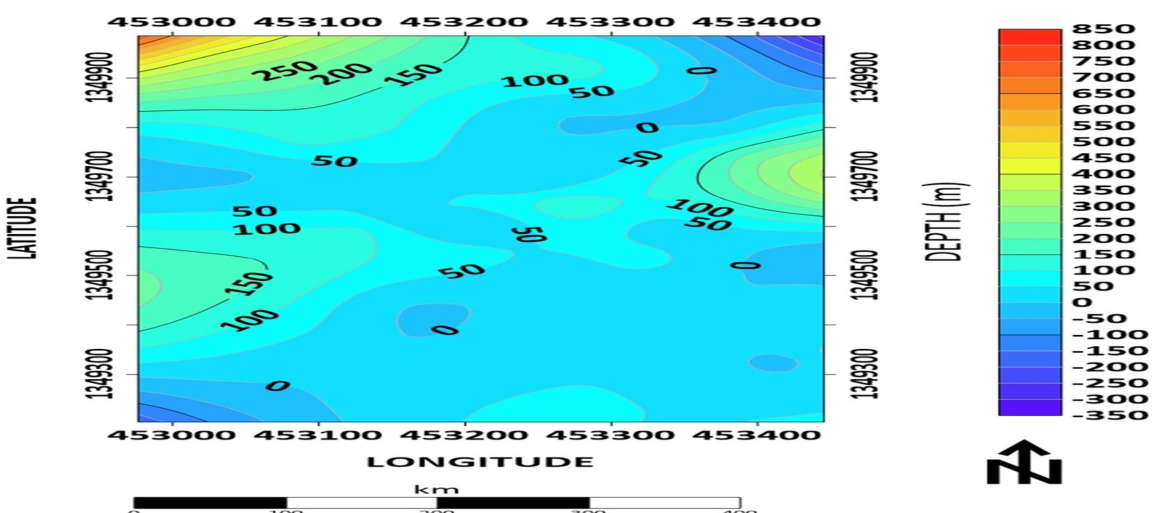

Figure: 5 Depth Contour Map of the Study Area

4) *IP Map*

Figure 6 Induced Polarization (IP) surveys, regions exhibiting low IP values are typically found at NE and SE part associated with favourable groundwater potential. Low IP values indicate materials with lower chargeability, such as permeable, water-bearing formations, which allow groundwater to accumulate and move. On the other hand, areas with high IP values were found at NW and generally reflect the presence of fine-grained materials like clay or mineralized zones, which can impede water flow and reduce groundwater potential.

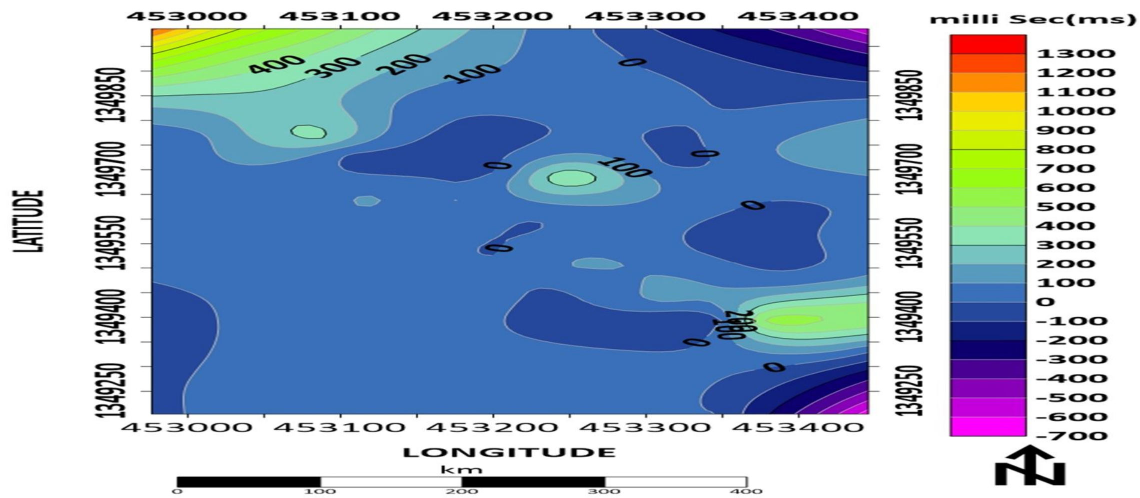

Figure: 6 IP Map of the Study Area

5) SP Map

Figure 7 SP anomalies are particularly useful for identifying the movement of groundwater and for mapping the flow direction in aquifers. Regions with a consistent low SP response usually suggest favourable groundwater recharge zones or active water-bearing formations (Abdel Aal et al., 2017; Revil et al., 2013). Areas with high SP values, on the other hand, may be associated with impermeable zones or mineralized areas, where the flow of groundwater is restricted or absent.

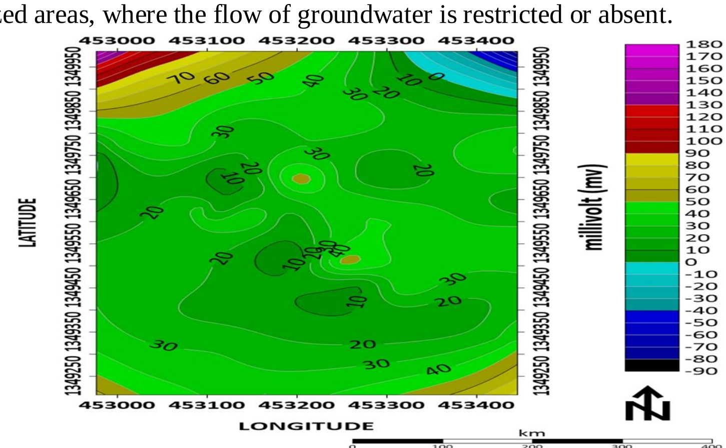

Figure:7 SP Map of the Study Area

6) Remote Sensing and GIS Techniques

Landsat 8 imagery was used to map land use/land cover and lineaments, which represent fractures that enhance groundwater movement. Lineament density indicates areas of high permeability and recharge potential. ASTER DEM was used to generate topographic parameters such as slope and drainage density. Gentle slopes and low drainage density favor infiltration and groundwater recharge, while steep slopes and high drainage density promote runoff and reduce groundwater potential.

7) Factors Governing Groundwater Occurrence in the Study Area

There are many control factors governing the occurrence and movement of water in any place. However, in this study area, six factors are considered. Each factor was analyzed separately in respect to the Groundwater occurrence in the study area.The groundwater potential map is established in ArcGIS's spatial analyst weighted overlay analysis tool using (Aslan & Celik, 2021) equation 1..

$$\text{GWP} = \sum_{i=1}^{7} \left(F_{iW_i}\right) \quad (1)$$

Where F_i is a control factor under consideration, W_i is a corresponding weight of the factor

8) Rainfall (RF)

Rainfall is a key determinant of groundwater potential because it controls aquifer recharge and sustains the hydrological cycle. In this study, rainfall was classified into five categories (very low to very high), where very low and low rainfall zones indicate poor recharge and possible water scarcity, while moderate rainfall supports fair replenishment. High and very high rainfall zones enhance infiltration and recharge, leading to improved groundwater availability and more sustainable aquifer storage (Sahoo et al., 2023; Vörösmarty et al., 2021).

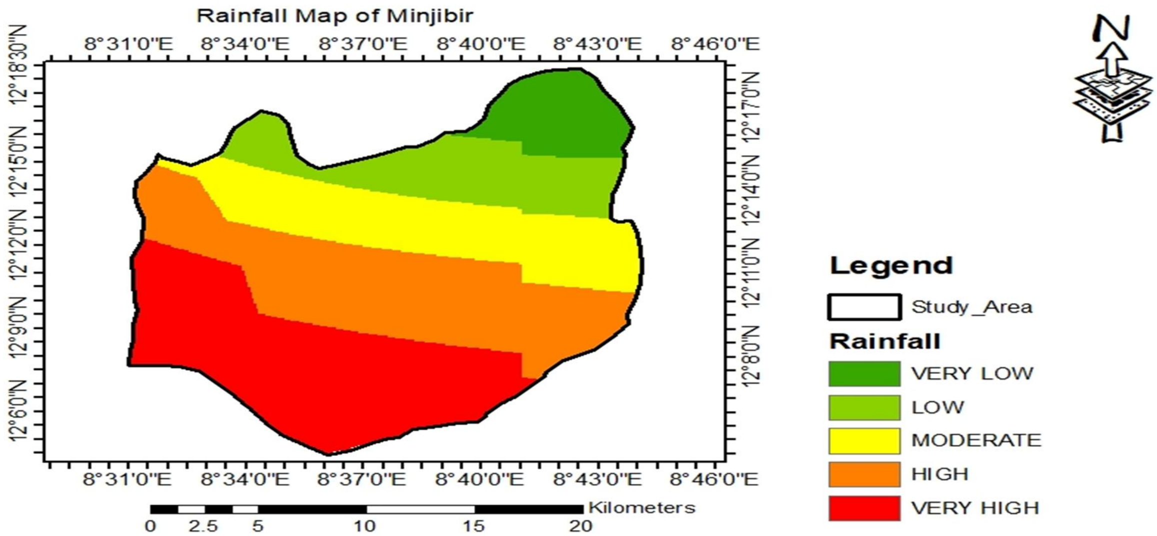

Figure 8: Rainfall Map of Minjibir LGA

9) Drainage Density Map (DD)

Drainage density is the ratio of the total length of streams within a basin to the basin area (Baker et al., 2020). Areas with low drainage density usually have higher infiltration and improved groundwater recharge, making them favorable for groundwater accumulation (Sahu & Bansal, 2021). In contrast, high drainage density indicates increased runoff and reduced recharge, resulting in poor groundwater potential (Kumar et al., 2022). Thus, drainage density is an important indicator for groundwater potential assessment and water resource planning.

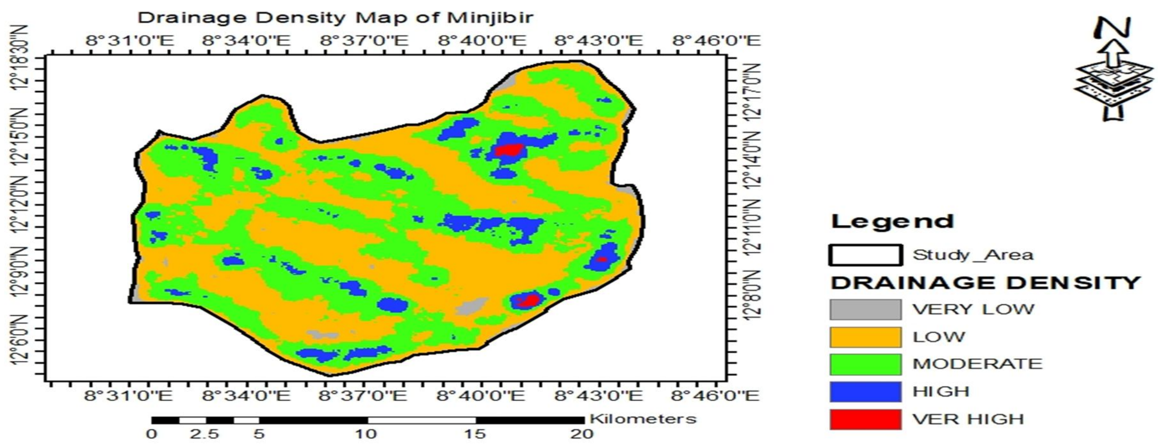

Figure 9: Drainage Density map of Study Area

10) Lineament Density (LD)

Lineaments are faults and fractures that enhance groundwater flow by increasing secondary porosity and permeability. In this study, lineament density was extracted from the DEM using Hillshade analysis with different azimuth and elevation settings. The mapped lineaments trend mainly from the northwest to the south, indicating widespread fracturing and favorable zones for groundwater accumulation.

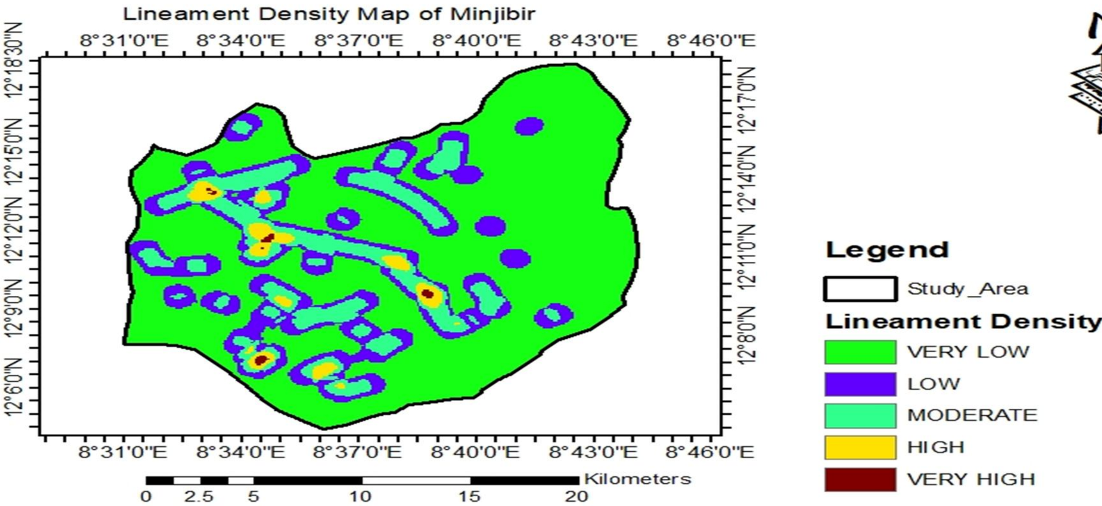

Figure 10: Lineament Density Map of Study Area

11) Soil Map (S)

Soil properties influence the relationship between runoff and infiltration rates which in turn control the degree of permeability, the principal factor in hydrogeology that determines the groundwater potential. Classification of soil types in relation to groundwater potential controlling was done based on FAO soil texture classification (FAO 1997) and the Land use/land cover practice of the area, see figure below. Soil is described as the product of the interactions of minerals, organic matter, water and air (Fashae *et al.* 2013).

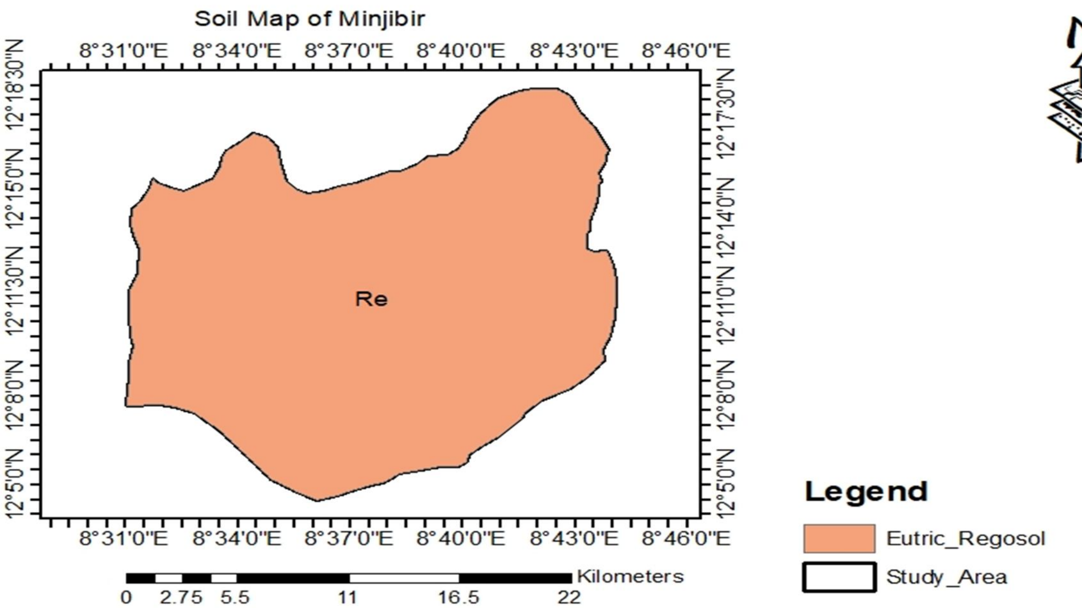

Figure 11: Soil Map of Study Area

12) Slope Map (SL)

Slope describes the degree of land surface inclination and plays a major role in controlling runoff and groundwater recharge. In ArcGIS, slope is derived from a DEM using the Spatial Analyst Slope tool to compute slope values in degrees or percentage, producing a slope map that highlights terrain variations (Esri, 2021). Gentle slopes enhance infiltration and groundwater recharge, thereby improving groundwater potential. Conversely, steep slopes promote rapid runoff and erosion, reducing recharge and groundwater availability (Saha et al., 2023).

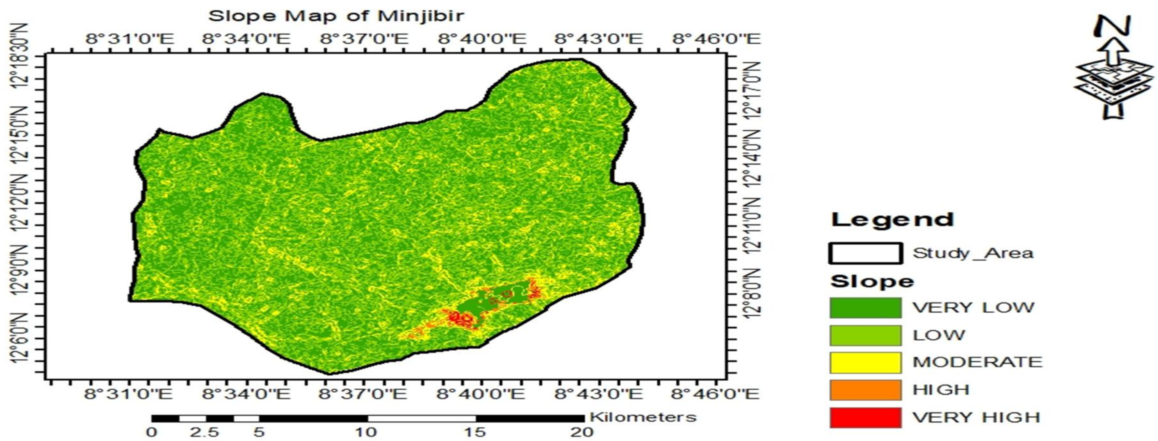

Figure 12: Slope Map of Study Area

13) Analytic Hierarchy Process (AHP)

The rainfall, slope, geology, lineament density, drainage density, land cover, and soil maps were converted into raster format for overlay analysis. Weights were assigned to each thematic layer using the Analytic Hierarchy Process (AHP) proposed by Saaty (1980) through pairwise comparison. The assigned weights are presented in Table 3.

14) Groundwater Potential Map

The groundwater potential map was established in ArcGIS's spatial analyst weighted overlay analysis tool using (Aslan & Celik, 2021) equation 2.

$$GWP = 0.207RF + 0.177LD + 0.197SL + 0.096DD + 0.106S + 0.068LC + 0.158G \quad (2)$$

The resulting maps were reclassified to five qualitative groups described as Very high, High, Moderate, Low, and very low, shown as in figure 13

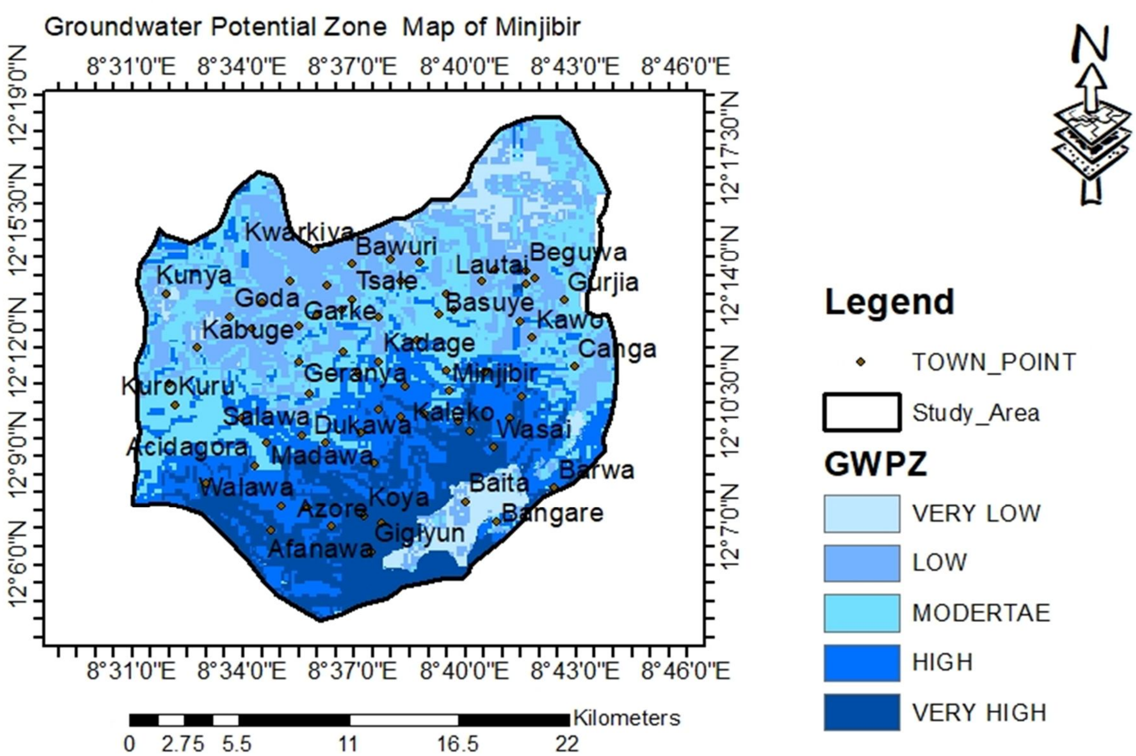

Figure: 13 Groundwater Potential Zone Map of the Study Area

15) VES Tables with Lithology and Curve Type

The tables 1 below shows the results of the different VES at various locations of the study area

LOCATION	LAYER	ρ (Ωm)	THICKNESS (m)	DEPTH (m)	LITHOLOGY	CURVE TYPE
VES 1 (	1	56.68	0.6498	0.6498	Top soil	H
	2	103.6	35.24	35.24	Shale	
	3	735.6	53.83	89.72	Sandstone	
	4	1289				
VES 2 (Tadangara)	1	42.55	0.6	0.6	Sand	K
	2	149.2	43.46	43.60	Mud	
	3	794.3	66.09	66.09	Fine sand	
	4				Clay	
VES 3 (D Kowa)	1	31.06	0.5158	0.5158	Top soil	H
	2	590.7	0.5308	1.047	Clay	
	3	81.97	4.33	5.877	Sandstones	
	4	159.4	33.02	38.4		
VES 4 (G Ari)	1	44.68	0.6	0.6	Top soil	K
	2	385.8	0.7204	1.32	Shale	
	3	71.52	1.584	2.906	Sandstones	
	4	399.9	3.489	6.395		
VES 5 (GGDK)	1	9.465	0.6	0.6	Top soil + sand	A
	2	2.706	0.7204	1.32	Sand	
	3	384.8	1.981	3.301	sandstone	
	4	384.8				

16) Weight of Thematic Layers

Table 2 shows the weight of thematic layers that were taken from the Analytic Hierarchical Process (AHP).

Table 3: Schematic layers and their Assigned Weight

S/N	Thematic Layer	Weight,%
1	Rainfall, (RF)s	20.7
2	Lineament Density, (LD)	17.7
3	Drainage Density (DD)	19.7
4	Slope, (Sl)	9.6
5	Soil, (S)	10.6
7	Land Cover, (LC)	6.8
8	Geology, (G)	15.8

17) Spreads of VES Points at Various GWPZ

The Table 3 below shows the VES points on Groundwater potential zones.

Table 3: Spreads of VES Points at Various GWPZ

S/N	VES	LONGITUDE (E)	LATITUDE (N)	GWP MODEL RESULT
1	Right hand side road VES 1	11.32346	11.05966	LOW
2	Right hand side road VES 2	11.3952	11.406	HIGH
3	Right hand side road VES3	11.31716	11.23465	VERY HIGH
4	Garin Ari VES 4	11.32563	11.46365	LOW
5	Right hand side road VES 5	11.30169	11.22495	HIGH
6	Layin yan gishiri VES 6	11.30131	11.22475	HIGH
7	Layin yan gishiri VES 7	11.691	11.504	HIGH
8	Kofar gidan ubale mai shayi VES 8	11.33201	11.12744	MODERATE
`10	Layin mai Unguwa VES 9	11.33109	11.13004	MODERATE
11	Rijiyar zakiVES 10	11.3324	11.12824	MODREATE
12	Cikin gari VES 11	11.3217	11.05757	LOW
13	Cikin gari VES 12	11.55627	11.1026	LOW
14	Cikin gari VES 14	11.48636	11.06641	LOW
15	Cikin gari VES 15	11.48524	11.08921	LOW
16	Cikin gari VES 16	11.34997	11.46376	LOW
17	Cikin gari VES 17	11.35239	11.46249	LOW
18	Cikin gari VES 18	11.34987	11.46458	LOW
19	VES 19	11.3217	11.05757	LOW
20	Rijiya VES 20	11.3209	11.05680	MODERATE
21	Mubi VES 21	11.19428	11.2093	HIGH
22	Gadana VES 22	11.33	11.29	VERY HIGH
23	Fika VES 23	11.28818	11.31145	LOW

B. Discussion of the Results

The interpretation of the VES data from Table 2 reveals varying groundwater prospects across the study area. In VES 1, the aquiferous zone is expected at Layer 2, with a resistivity value of 179 Ωm, thickness of 4 m, and occurring at a depth of about 11 m. This indicates a shallow aquifer, which may not be adequate for sustainable groundwater development. Generally, the result suggests that a productive aquifer may be difficult to obtain at this location. For VES 2, the aquifer is interpreted to occur at Layer 4, with a thickness of about 18 m at a depth of approximately 34 m. This depth is relatively moderate and may provide better groundwater potential compared to VES 1.In VES 3, groundwater prospecting indicates an aquifer zone at a depth of about 23 m, with a thickness of 20 m. However, the interpretation further suggests that a more productive aquifer may occur at depths beyond 68 m, implying that deeper drilling could yield better groundwater resources. The result from VES 4 indicates that the aquiferous unit is expected at a depth exceeding 450 m. This suggests that any aquifer encountered above this depth is likely to be shallow and possibly insufficient.

Therefore, groundwater development in this area may require very deep drilling, which may not be economically feasible. For VES 5, the aquifer is interpreted as a shallow groundwater zone with a thickness of about 4 m occurring at approximately 16 m depth. This shallow aquifer may be seasonal or limited in yield. In VES 6, the aquiferous zone is expected at Layer 2, with a thickness of about 32 m occurring at approximately 40 m depth. This relatively thick layer suggests better groundwater storage capacity compared to the shallow aquifers observed in VES 1 and VES 5.Similarly, VES 7 indicates that the aquifer is expected at Layer 3, with a thickness of 21 m at a depth of about 38 suggesting moderate groundwater potential. For VES 8,the aquifer is interpreted to occur at a very shallow depth of about 8 m. This could be associated with a clay-rich layer that temporarily holds water. However, such shallow groundwater is often unreliable and may not support large-scale groundwater development. Overall, the VES interpretation indicates that most of the aquifers identified within the study area are shallow and may not be capable of yielding significant groundwater resources. Hence, the study suggests that good aquifer zones are generally limited and may require deeper drilling in some locations.

1) Validation of Model

The GWPZ map reveals a distinct trend of increasing groundwater potential from the northwestern part toward the southern and southeastern part of Minjibir. The very low to low groundwater potential zones are mainly concentrated in the northwestern and northern areas around towns such as Kunya, Goda, Kaboge, Kurokuri, and Kwalkiya, approximately within 12°14′N–12°19′Nand 8°31′E–8°36′E.The moderate groundwater potential zone dominates the central portion of the study area, covering towns such as Bawuri, Lautai, Basuye, Tsafe, Karke, Kadage, and parts of Minjibir, within about 12°10′N–12°15′N and 8°34′E–8°42′E.

The high to very high groundwater potential zones are mostly found in the southern and southeastern parts, extending toward towns such as Wasai, Birwa, Bangare, Baita, Giginyu, Azore, Walawa, and Madawa approximately between 12°05′N–12°10′N and 8°37′E–8°44′E.

Generally, the map suggests that groundwater development is more favorable around the southern settlements, while the northern and northwestern towns may experience poor groundwater availability and may require deeper drilling for sustainable yields..Areas categorized as low groundwater potential zones coincide with regions characterized by low rainfall, poor lineament density, clay-rich soils, and high drainage density. In the land use/land cover (LU/LC) analysis, areas with vegetation cover correspond mainly to high and moderate groundwater potential zones due to enhanced infiltration. Conversely, bare land dominates large portions of the study area and is associated with moderate to poor groundwater potential zones.

The soil map also supports this interpretation, as regions dominated by shale and clay materials correspond to low groundwater potential zones due to reduced permeability. Similarly, the drainage density map shows that areas with high drainage density coincide with low groundwater potential zones, indicating high surface runoff and limited infiltration. The validated groundwater potential zoning map further indicates that VES 3, VES 5, VES 6, and VES 8 fall within the high groundwater potential zones. These VES locations exhibit H-type curve characteristics, which are generally regarded as favorable for groundwater accumulation.

However, VES 11, VES 12, VES 13, and VES 23 fall within the low groundwater potential zones. Their curve types (A, AH, and KA) suggest that aquiferous layers are either shallow and unreliable or that productive aquifers may only be encountered at depths exceeding 350 m,making groundwater development less feasible in these zones.

V. CONCLUSION

This study successfully applied an integrated approach involving electrical resistivity (VES and remote sensing/GIS techniques to delineate groundwater potential zones in part of Minjibir Local Government Area, Kano State, Nigeria. The results from the 45 VES stations revealed variations in subsurface lithology and groundwater occurrence across the study area. Interpretation of the geoelectric layers indicated that groundwater prospects are generally limited, as most of the identified aquiferous units occur at shallow depths with relatively small thicknesses. Locations such as VES 1, VES 5, and VES 8 revealed shallow aquifers of limited thickness, suggesting that groundwater in these zones may be seasonal and unreliable. Moderate groundwater potential was observed in areas such as VES 2, VES 6, and VES 7, where aquifer layers were thicker and occurred at depths between approximately 34 m and 40 m. However, the result from VES 4 indicated that a productive aquifer may only be encountered at depths exceeding 450 m, suggesting that groundwater development in such areas may require deep drilling and could be economically challenging. The groundwater potential zoning map generated from remote sensing and GIS analysis classified the area into very low, low, moderate, high, and very high groundwater potential zones. Validation using borehole yield information, hand pump records, and VES interpretation confirmed the reliability of the groundwater potential model.

High and very high groundwater potential zones were strongly associated with areas of high lineament density, gentle slope, and low drainage density, which enhance infiltration and groundwater recharge. Conversely, low groundwater potential zones corresponded with areas characterized by clay/shale soils, high drainage density, and low lineament density, which promote surface runoff and limit groundwater accumulation. Overall, the integrated methodology proved effective in identifying suitable zones for groundwater development and provides a reliable guide for borehole drilling in the study area. The findings also highlight that sustainable groundwater development in Minjibir may require drilling to moderate depths in structurally favorable zones, while some areas may not support economically viable groundwater exploitation due to the requirement for very deep drilling.

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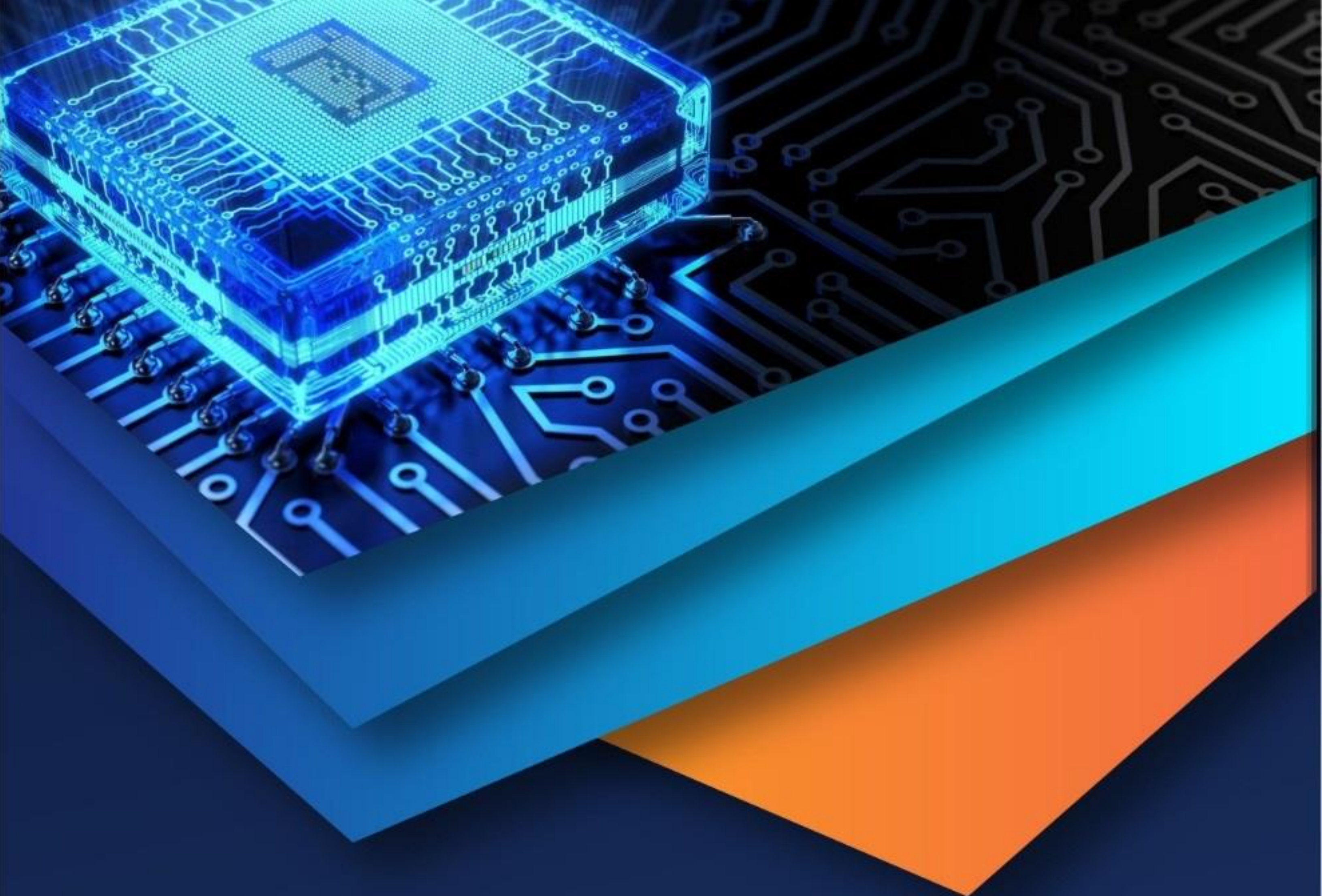

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