Groundwater Vulnerability Assessment using Electrical Resistivity Method in the Northern part of Ado-Ekiti, Southwestern Nigeria

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Abstract. Over the years, the demand for clean and safe water has skyrocketed globally in response to rising population. Since groundwater is a more reliable source of potable water, assessment of aquifer vulnerability becomes a necessity. This research therefore aimed at delineating geo-electric parameters in form of layer resistivity and thickness, towards generating a second order geo-electric section. This study employed the use of electrical resistivity method to evaluate the vulnerability of aquifers to contamination in the northern part of Ado-Ekiti, southwestern Nigeria. Forty Vertical Electrical Sounding (VES) locations were studied using the Schlumberger array with current electrodes spacing (AB/2) of 150m. ABEM SAS 300 Resistivity Meter was useful for collecting the VES data which were presented as VES curves and quantitatively interpreted through partial curve matching and Computer Assisted 1-D forward modeling using the WinResist software. Geo-electric section along five (5) traverses, iso-resistivity map of the weathered layer and an isopach map showing the depth to aquifer were generated. Seven (7) different types of VES curves were identified, namely A, H, K, KA, HA, QA and KH types. The four geo-electric layers delineated include the topsoil (resistivity values between 29 – 1176 Ωm; thickness from 0.5 – 4.4 m), lateritic layer (resistivity values between 138 – 3787 Ωm; thickness between 1.0 – 63.6m), weathered layer (resistivity values between 6 – 298 Ωm; thickness between 0.7 – 17.8 m), and fresh basement (resistivity values between 331 – 7479 Ωm). The total longitudinal unit conductance (S) values obtained range from 0.009 to 2.972 mhos. This suggests that most parts (northern, central, western and eastern portions of the area) have medium to high protective capacity rating; except the eastern portion. Therefore, most parts (80%) of the study area appear to be less vulnerable to contamination.

Keywords: geo-electric, resistivity, thickness, contamination
1. Introduction

[10] reported that potable water is essential for survival of both mankind and the environment. Groundwater is described by [21] as water that occupied the saturated layers of soils and rocks (which are referred to as aquifers), while [3] emphasized the global rise in development of groundwater sources as a result of increased demands for drinking water, as it appears to be a more reliable source as reported by [5]. Aquifer vulnerability describes the comparative assessment of the potential exposure of groundwater as a result of anthropogenic activities to contamination [23]. [22] further describes it as a qualitative reflection of the natural tendency for an aquifer to be affected by human activities from surfaces such as chemicals, dumpsites and wastewater discharges. [25] further elucidates the extreme difficulty in detecting and controlling subsurface water pollution. Thus, aquifer vulnerability assessment comes in handy for recognizing and mapping areas that are susceptible to contamination resulting from human activities [8], [9] and [17] describe the ability of an overburden to retard the infiltration of percolating pollutants as being proportional to depth to aquifer and inversely proportional to its hydraulic properties. Summarily, [6] emphasizes that effective protection is as a result of sufficient thickness and low hydraulic conductivity; with [24] establishing the importance of the time element in defining any vulnerability evaluation. Therefore, [24, 16] conclude that the vulnerability is considered to be high if geologic materials above the aquifer are highly permeable and when recharge reaches the water table within a relatively short time; while [26] suggests that if the vadose zone which is equivalent to the static water level in the well is porous and permeable, then this may increase the vulnerability of the aquifer to contamination.

According to [11] and [13], various geophysical methods are useful for exploiting groundwater depending on depth of investigation and cost. These methods include electrical resistivity method, seismic refraction, electromagnetic, gravity, magnetic methods, however, electrical resistivity is more widely used [14].

Several researches have been carried out on aquifer vulnerability in various parts of Nigeria. [6] employed the use of geoelectric parameters on near-surface materials to assess the vulnerability of the aquifer at Oke-Ila, southwestern Nigeria and discovered that the aquifer within the weathered basement rock occurs at a relatively shallow depth (3.9 m – 15.7 m) and therefore prone to near-surface contamination. [18] employed geophysical and hydrogeologic techniques to assess the aquifer vulnerability at Odigbo, Nigeria with resulting geoelectric parameters indicating that 45.5% of the study area had aquifers with resistivity values ranging from 101 to 2990 Ωm suggesting that they were overlain by pervious materials and were therefore prone to contamination. [7] evaluated aquifers at a dumpsite in Ozoro Isoko South Local Government Area of Delta State using four VES and four dipole-dipole. The longitudinal conductance values (< 0.1 mhos) in all parts of the studied area were interpreted as possessing poor protective capacity, while the inverted 2D resistivity structure indicates leachate flow direction (downward) towards the aquifer. [4] investigated some towns in Yenagoa using fifteen VES stations under the Schlumberger configuration and quantitatively modeled the VES data to produce Dar-Zarrouk parameter. The southern part exhibited good to moderate protective capacity rating while the Northern part of the study area showed poor to weak aquifer protective capacity. [19] undertook geophysical investigation in 41 different locations at Igbara Oke, Southwestern Nigeria and compared Longitudinal Conductance (LC), GOD (Groundwater occurrence, Overlying lithology and Depth to the aquifer) and GLSI (Geoelectric Layer Susceptibility Indexing); all of which suggests a higher vulnerability of aquifers in the southern part than in the northern part of the study area.

Few researches have been conducted in the Southwestern part of Nigeria, with none in the Ado-Ekiti zone; therefore, this study aims at evaluating the vulnerability of the aquifers in the
northern part of Ado-Ekiti for its closeness to Ilokun dumpsite. This study employs geophysical methods (Vertical Electrical Sounding, VES) to evaluate aquifer vulnerability to contamination.

2. Study Area

The study area lies within latitudes 7° 39’ N and 7° 40’ N and longitudes 5° 11’ E and 5° 15’ E (Figure 1) at the northern part of Ado-Ekiti Metropolis. The study area is accessible through the Ado-Iworoko highway and minor roads connecting different sections of the Metropolis. The study location is a tropical rainforest with well distinguished wet (between November and April) and dry seasons (between May and October) and a mean annual temperature ranging between 21ºC and 28ºC. The average annual rainfall is about 1800mm. [15], with humidity above 70%; this yields a huge influence on vegetation type present.

![Figure 1: Base Map of the study location.](image)

The Metropolis is underlain by the Precambrian basement complex rocks of Southwestern Nigeria (Figure 2) as opined by Odeyemi (1989) and Rahaman (1989); with crystalline units of granite-gneiss and migmatite. Drainage pattern is dendritic probably as result of the structural features within underlying rocks.
3. Methodology

A base map for the study area was generated using Surfer 11.0.642 software. Electrical resistivity survey utilizing the ABEM SAS 300C resistivity meter (through the Schlumberger system of arrangement of electrodes using 40 points (Figure 3) and current electrodes separation AB/2 of 150m) was used for acquiring data using. The data gathered were immediately processed and interpreted for 1-D forward modelling using WinResist1.0 software. The VES data were interpreted in terms of layers parameters underneath the sounding positions. Partial curve matching, as described by [12] and corresponding auxiliary curves [20] were useful for interpreting the field curves. The results obtained from the partial curve matching were later refined using the WinResist software [27] which reduced the interpretation errors to acceptable levels. 2-D geoelectric sections and maps with Surfer 11.0.642 software were generated from the VES interpretation results.

The Dar Zarrouk parameter (longitudinal unit conductance) of each VES station was calculated using the equation below [9]:

\[
\text{Total longitudinal unit conductance} = \sum_{i=1}^{n} \frac{h_i}{\rho_i}, \text{ Where } h_i \text{ is the layer thickness and } \rho_i \text{ is the apparent resistivity of the layer.}
\]

The longitudinal unit conductance, which is also known as the protective capacity rating, was classified as > 0.5 (highly protected- Clay), 0.1-0.5 (fairly protected), 0.05-0.1 (poorly protected) and < 0.05 (highly protected- Laterite) [1]. The longitudinal unit conductance maps were generated using the Surfer software.

Hydrogeologic survey was also carried out with thirty-five (35) wells at the first consecutive VES locations sampled (Figure 4) and the static water levels at each well measured.
4. Results and Discussion

The results are presented as curves (Figure 5 a-g); and reveal presence of curve types ranging from 3-layer H-type (18), K-type (3), A-type (4) to 4-layer QA (3), KA (4), KH (6), and HA(2); with H-type curve as the most dominant curve while the least dominant is HA curve type as shown in the distribution of the curves (Figure 6) and Table 1 shows the lithological identification in the study area.
Figure 5a: H-type Curve.  
Figure 5b: K-type Curve.  
Figure 5c: A-type Curve.  
Figure 5d: KA-type Curve.  
Figure 5e: QA-type Curve.  
Figure 5f: KH-type curve.
Figure 5g: HA-type curve.

Figure 5(a-g): Typical VES Curve Types within the Study Area.

Figure 6: Bar chart showing different curve types in the Study Area.
| VES No. | Curve Type | Layer No. | Resistivity (Ω m) | Thickness (m) | Depth (m) | Lithology         |
|---------|------------|-----------|-------------------|---------------|-----------|-------------------|
| 1       | H          | 1         | 62                | 1.3           | 1.3       | Topsoil           |
|         |            | 2         | 18                | 8.1           | 9.4       | Weathered Layer   |
|         |            | 3         | 485               | -             | -         | Fresh Basement    |
| 2       | H          | 1         | 55                | 0.8           | 0.8       | Topsoil           |
|         |            | 2         | 15                | 3.3           | 4.1       | Weathered Layer   |
|         |            | 3         | 906               | -             | -         | Fresh Basement    |
| 3       | QA         | 1         | 833               | 1.4           | 1.4       | Topsoil           |
|         |            | 2         | 337               | 2.6           | 3         | Lateritic Layer   |
|         |            | 3         | 18                | 5.1           | 7.1       | Weathered Layer   |
|         |            | 4         | 4600              | -             | -         | Fresh Basement    |
| 4       | A          | 1         | 49                | 1.1           | 1.1       | Topsoil           |
|         |            | 2         | 160               | 6.8           | 7.9       | Weathered Layer   |
|         |            | 3         | 465               | -             | -         | Fresh Basement    |
| 5       | H          | 1         | 146               | 1.3           | 1.3       | Topsoil           |
|         |            | 2         | 18                | 10.3          | 11.3      | Weathered Layer   |
|         |            | 3         | 810               | -             | -         | Fresh Basement    |
| 6       | H          | 1         | 134               | 0.9           | 0.9       | Topsoil           |
|         |            | 2         | 27                | 5.7           | 6.6       | Weathered Layer   |
|         |            | 3         | 551               | -             | -         | Fresh Basement    |
| 7       | H          | 1         | 94                | 0.8           | 0.8       | Topsoil           |
|   |   |   |   |   |
|---|---|---|---|---|
| 2 | 12 | 9.0 | 9.8 | Weathered Layer |
| 3 | 518 | - | - | Fresh Basement |
| 8 | H | 1 | 108 | 0.7 | 0.7 | Topsoil |
|   |   | 2 | 15 | 3.6 | 4.3 | Weathered Layer |
|   |   | 3 | 2144 | - | - | Fresh Basement |
| 9 | H | 1 | 104 | 2.1 | 2.1 | Topsoil |
|   |   | 2 | 19 | 6.9 | 9.0 | Weathered Layer |
|   |   | 3 | 1431 | - | - | Fresh Basement |
| 10 | QA | 1 | 309 | 1.7 | 1.7 | Topsoil |
|   |   | 2 | 75 | 2.8 | 3.5 | Weathered Layer |
|   |   | 3 | 21 | 4.4 | 6.9 | Weathered Layer |
|   |   | 4 | 691 | - | - | Fresh Basement |
| 11 | H | 1 | 264 | 1.5 | 1.5 | Topsoil |
|   |   | 2 | 6 | 4.0 | 5.5 | Weathered Layer |
|   |   | 3 | 352 | - | - | Fresh Basement |
| 12 | H | 1 | 449 | 1.9 | 1.9 | Topsoil |
|   |   | 2 | 52 | 2.4 | 4.3 | Weathered Layer |
|   |   | 3 | 411 | - | - | Fresh Basement |
| 13 | KA | 1 | 29 | 0.6 | 0.6 | Topsoil |
|   |   | 2 | 247 | 1.2 | 1.8 | Lateritic Layer |
|   |   | 3 | 10 | 6.4 | 8.2 | Weathered Layer |
|   |   | 4 | 2613 | - | - | Fresh Basement |
| 14 | H | 1 | 366 | 1.9 | 1.9 | Topsoil |
| No. | Location | Layer 1 | thickness 1 | Layer 2 | thickness 2 | Layer 3 | thickness 3 | Layer 4 | thickness 4 |
|-----|----------|---------|-------------|---------|-------------|---------|-------------|---------|-------------|
| 15  | KA       | 1       | 131         | 0.9     | 0.9         | Topsoil |             |         |             |
|     |          | 2       | 245         | 1.4     | 2.3         | Lateritic Layer |         |         |             |
|     |          | 3       | 38          | 8       | 10.3        | Weathered Layer |         |         |             |
|     |          | 4       | 393         | -       | -           | Fresh Basement |         |         |             |
| 16  | KA       | 1       | 162         | 0.8     | 0.8         | Topsoil |             |         |             |
|     |          | 2       | 254         | 1.8     | 2.6         | Lateritic Layer |         |         |             |
|     |          | 3       | 87          | 8.3     | 10.9        | Weathered Layer |         |         |             |
|     |          | 4       | 1003        | -       | -           | Fresh Basement |         |         |             |
| 17  | A        | 1       | 95          | 2.4     | 2.4         | Topsoil |             |         |             |
|     |          | 2       | 261         | 3.9     | 6.3         | Weathered Layer |         |         |             |
|     |          | 3       | 1196        | -       | -           | Fresh Basement |         |         |             |
| 18  | H        | 1       | 168         | 2.8     | 2.8         | Topsoil |             |         |             |
|     |          | 2       | 20          | 4.4     | 7.2         | Weathered Layer |         |         |             |
|     |          | 3       | 9483        | -       | -           | Fresh Basement |         |         |             |
| 19  | KH       | 1       | 124         | 0.9     | 0.9         | Topsoil |             |         |             |
|     |          | 2       | 516         | 1.6     | 2.4         | Lateritic Layer |         |         |             |
|     |          | 3       | 185         | 10.5    | 12.9        | Weathered Layer |         |         |             |
|     |          | 4       | 1238        | -       | -           | Fresh Basement |         |         |             |
| 20  | K        | 1       | 75          | 1.0     | 1.0         | Topsoil |             |         |             |
|     |          | 2       | 3158        | 1.9     | 2.9         | Fresh Basement |         |         |             |
|     |          | 3       | 1949        | -       | -           | Fracture Basement |         |         |             |
|   |   |   |   |   |   |
|---|---|---|---|---|---|
| 21 | H | 1 | 107 | 1.6 | 1.6 | Topsoil |
|    |   | 2 | 16  | 3.4 | 5.0 | Weathered Layer |
|    |   | 3 | 202 | -   | -   | Fresh Basement |
| 22 | H | 1 | 115 | 0.9 | 0.9 | Topsoil |
|    |   | 2 | 49  | 2.5 | 3.4 | Weathered Layer |
|    |   | 3 | 596 | -   | -   | Fresh Basement |
| 23 | A | 1 | 261 | 4.4 | 4.4 | Topsoil |
|    |   | 2 | 267 | 17.4| 21.8| Weathered Layer |
|    |   | 3 | 1927| -   | -   | Fresh Basement |
| 24 | A | 1 | 66  | 0.8 | 0.8 | Topsoil |
|    |   | 2 | 126 | 5.6 | 6.4 | Weathered Layer |
|    |   | 3 | 597 | -   | -   | Fresh Basement |
| 25 | KH| 1 | 74  | 0.8 | 0.8 | Topsoil |
|    |   | 2 | 169 | 2.3 | 3.1 | Lateritic Layer |
|    |   | 3 | 74  | 5.4 | 8.5 | Weathered Layer |
|    |   | 4 | 602 | -   | -   | Fresh Basement |
| 26 | KH| 1 | 188 | 0.7 | 0.7 | Topsoil |
|    |   | 2 | 1073| 1.1 | 1.8 | Lateritic Layer |
|    |   | 3 | 298 | 29  | 30.9| Weathered Layer |
|    |   | 4 | 995 | -   | -   | Fresh Basement |
| 27 | KH| 1 | 135 | 0.8 | 0.8 | Topsoil |
|    |   | 2 | 176 | 2.9 | 3.6 | Lateritic Layer |
|    |   | 3 | 24  | 8   | 11.6| Weathered Layer |
| No. | Layer | 1 | 2 | 3 | 4 | 5 |
|-----|-------|---|---|---|---|---|
| 28 H | Topsoil | 188 | 2.6 | - | - | Weathered Layer |
|     |        | 69  | 5.5 | - | - | Fresh Basement |
| 29 KA | Topsoil | 175 | 1.0 | - | - | Lateritic Layer |
|      |        | 522 | 1.7 | - | - | Weathered Layer |
| 30 H | Topsoil | 339 | 1.2 | - | - | Fresh Basement |
| 31 H | Topsoil | 243 | 2.1 | - | - | Weathered Layer |
| 32 K | Topsoil | 273 | 1.5 | - | - | Fracture Basement |
| 33 H | Topsoil | 1176 | 3.1 | - | - | Weathered Layer |
| 34 HA | Topsoil | 354 | 3.0 | - | - | Fresh Basement |
|      |        | 27  | 4.5 | - | - | Partly Weathered Layer |
|  |  |  |  |  |
|---|---|---|---|
| 4 | 421 | - | - |
| 35 QA | 1 | 286 | 1.4 | 1.4 |
|  | 2 | 68 | 2.8 | 4.2 |
|  | 3 | 7 | 4.0 | 8.2 |
|  | 4 | 751 | - | - |
| 36 HA | 1 | 358 | 1.2 | 1.2 |
|  | 2 | 62 | 11.0 | 12.2 |
|  | 3 | 344 | 13.1 | 25.3 |
|  | 4 | 7479 | - | - |
| 37 K | 1 | 207 | 1.0 | 1.0 |
|  | 2 | 482 | 20.0 | 21.0 |
|  | 3 | 221 | - | - |
| 38 H | 1 | 1119 | 0.5 | 0.5 |
|  | 2 | 243 | 5.3 | 5.8 |
|  | 3 | 2123 | - | - |
| 39 KH | 1 | 248 | 1.1 | 1.1 |
|  | 2 | 458 | 5.2 | 6.3 |
|  | 3 | 37 | 6.6 | 12.9 |
|  | 4 | 331 | - | - |
| 40 AK | 1 | 333 | 1.5 | 1.5 |
|  | 2 | 23751 | 12.5 | 14 |
|  | 3 | 1121 | 48.4 | 62.4 |
|  | 4 | 6914 | - | - |
The geoelectric sections of the study area are plotted along five traverses (Figures 7 a-e). The geoelectric section along the first traverse connects VES 31, VES 32 and VES 35 in the northern direction and reveals four major geoelectric layers and three lithologic layers (Figure 7a); with 0.9 m to 1.4 m thick topsoil probably composed of sand/laterite as resistivity varies between 243 Ωm to 286 Ωm, and the weathered layer beneath the topsoil (VES 31 and 35) consisting of clay with resistivity values ranging between 7 Ωm to 91 Ωm with thickness ranging from 2.5 m to 6.2 m while the second layer for VES 32 is interpreted qualitatively as 2.5m thick fresh basement with resistivity value of 896 Ωm. The third layer (for VES 31 and 35) is delineated as the fresh basement with resistivity values of 751 Ωm to 1445 Ωm while that for VES 32 is the fractured basement with resistivity value of 91 Ωm.

Figure 7a: Geoelectric Section along Traverse 1.

Along the second traverse which connects VES 23, VES 28 and VES 33 in the SW-N direction, three major geoelectric sections were identified (Figure 7b); with the first layer (Topsoil) of thickness varying between 2.6 m to 4.4 m and resistivity of 188 Ωm and 1176 Ωm; a 5.5 m to 17.4 m thick second weathered layer with resistivity values between 27 Ωm and 267 Ωm; and a third layer of fresh basement with resistivity values of 445Ωm and 1927Ωm.

Figure 7b: Geoelectric Section along Traverse 2.

Along the third traverse (Figure 7c) in the NE-SE direction, which comprises of the VES 02, VES 07 and VES 39, four major geoelectric sections were delineated viz: a 0.8 m to 1.1m thick top soil
composed of clay/sandy layer with resistivity values ranging from 55 Ωm to 248 Ωm; a second 4.5 m to 11.8 m thick weathered layer composed of clayey/sandy materials with resistivity values ranging between 12 Ωm to 458 Ωm; and a third layer of fresh basement rocks with resistivity values between 331 Ωm to 906 Ωm.

Figure 7c: Geoelectric section along traverse 3.

The fourth traverse in the NW-NE direction (Figure 7d) shows three geoelectric sections with the first layer of 0.8 m to 2.1 m thick topsoil and resistivity values between 94 Ωm and 193 Ωm, which is qualitatively interpreted to be made up of clay/sandy clay layer. The second (weathered) layer is composed of about 6.9 m to 20 m thick clayey/sandy materials with resistivity values ranging between 12 Ωm and 483 Ωm. The last layer comprises of the basement rock with resistivity of 518 Ωm to 1431 Ωm.

Figure 7d: Geoelectric section along traverse 4.

The fifth traverse was taken along the SW direction (Figure 7e) through VES 26, VES 25 and VES 24 and reveals four geoelectric sections. The topsoil comprises of 0.7m to 1.1 m thick clayey/sandy clay with resistivity values of 66Ωm to 188Ωm while the second weathered layer gives resistivity values between 93Ωm and 298Ωm and a thickness of 5.6m to 29m, thus suggesting clayey/sandy materials. The fresh basement layer shows a resistivity value varying from 597Ωm to 1073Ωm.
Figure 7c: Geoelectric Section along Traverse 5.

Also, the isoresistivity map (Figure 8) displays the variations discovered within the delineated weathered layers in the study area. Here, the overall assessment suggests that this layer is generally composed of clay, sand and laterite with a broad resistivity value range from 6Ωm to 1949Ωm. The isopach map (Figure 9) also reveals that the variation in the thickness (also known as the depth to aquifer) of aquifer overburden ranges from 0.4m to 4.4m. The central, northern and southwestern portions of the study area have aquifer depths greater than 2m while the other parts possess relatively low depths ranging between 0.4m and 2m.

Figure 8: Isoresistivity Map of the weathered Layer.
Figure 9: Depth to Aquifer in the Study Area.

The static water levels as observed and measured in the study area (Figure 10) reveal that some parts of the western, southwestern, northwestern and the southeastern area are characterized by significant thickness of the vadose layer (5.5m - 9 m) while intermediate thickness of 3.5m - 5 m exist in the northwestern, south and southeastern, and low thickness of 1m - 3.5m dominate the remaining part of the study area.

Figure 10: Static Water Level Map Showing the Well Positions.

The aquifer vulnerability and the protective capacity rating were evaluated from the total longitudinal unit conductance, with the distribution indicating that the total longitudinal unit conductance (S) values obtained from the study area ranges from 0.009 mhos to 2.972 mhos (Figure 11). The protective capacity rating (Figure 12) was done with reference to the classification of ([1]; Table 2).
Figure 11: Longitudinal Unit Conductance Map of the Study Area.

Table 2: Longitudinal unit conductance/protective capacity rating after Adelusi, 2009 [1].

| Longitudinal Unit Conductance (mhos) | Protective Capacity Rating          |
|--------------------------------------|-------------------------------------|
| > 0.5                                | Highly Protected (Clay)             |
| 0.1-0.5                              | Fairly Protected                    |
| 0.05-0.1                             | Poorly Protected                    |
| < 0.05                               | Highly Protected (Laterite)         |

Figure 12 shows that most parts of the northern and central portions have high protective capacity with longitudinal unit conductance from 0.009 mho to 0.05 mho which indicate lateritic overburden and from 0.5 mho to 2.972 mhos which indicate clayey overburden. The western, southwestern,
northwestern and eastern portions of the study area are fairly protected with longitudinal unit conductance values ranging from 0.128 mho to 0.5 mho. However, southwestern and eastern parts of the study area are poorly protected with longitudinal unit conductance values ranges from 0.057 mho to 0.1 mho. The protective capacity rating map (Figure 12) further reveals that about 32% of the area falls within the high protective capacity rating, while 47% fall within the fair protective capacity rating and about 21% constitute the poor protective capacity rating.

5. Conclusion

Across the northern part of Ado-Ekiti, the weathered layers above the fractured and intact bedrocks appear to be major water bearing zones. The weathered layer frequently occurs at relatively shallow depth of about 0.4m to 4.4m across the site making it susceptible to contamination. Approximately 21% of the study area appears to lack protective capability while 47% possess fair protective capacity and 32% show high protective capacity. This suggests an abundance of pervious overburden material through which supports infiltration of contaminants. Hence, the aquifer is vulnerable to contamination at surface and shallow depths.

It is recommended that groundwater development in the study area must be planned around the zones of high aquifer protective capacity to circumvent contamination from anthropogenic sources. Also, control wells for observing groundwater quality should be constructed in the zones that have poor protective capacity rating. In addition, qualitative analysis of groundwater should be regularly carried out.

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