AQUIFER CHARACTERISTICS AND GROUNDWATER RESERVOIR PROTECTIVE CAPACITY RATING IN OBAFEMI-OWODE LOCAL GOVERNMENT AREA, OGUN STATE SOUTH-WEST NIGERIA

Supported by tetfund

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Received: December 14, 2023 Accepted: March 28, 2024

Abstract: Aquifer potentials characteristics and its impacts on the groundwater subsurface protection of the aquiferous zone using electrical resistivity method of hydrogeophysical prospecting was carried out at Obafemi-Owode Local Government Area, Ogun State South-West Nigeria with the principal purpose of evaluating and rating aquifer protective capacity of the overburden units in the area. Twenty seven (27) vertical electrical sounding (VES) were probed using Schlumberger configuration with the maximum electrode spacing of 100m at each point using Allied OMHEGA Resistivity meter. The data were interpreted using partial curve matching techniques and computer iteration program using WINRESIST. Parameters such as aquifer resistivity, aquifer thickness, overburden thickness, basement resistivity, reflection coefficient and longitudinal conductance were calculated and used for evaluating the groundwater yields and vulnerability of the aquiferous zone to contaminant seepages. The reflection coefficient range is between 0.02 and 0.98 while protective capacity range is between 0.00135 and 0.510. Groundwater potentials of the area were classified as high Areas with high (overburden thickness $>$13m and reflection coefficient less than $<$ 0.8); medium (overburden thickness $\geq$13m and with reflection coefficient $\geq$0.8) and low (overburden thickness $<$ 13m and reflection coefficient $\geq or \leq$ 0.8. Also, the study area shows a very poor, poor, and moderate protective capacity rating. Seven (7) VES stations have very poor protective capacity, eighteen (18) VES stations shows poor protective capacity and only two (2) VES stations shows a moderate protective capacity rating. Since the longitudinal conductance illustrates the impermeability of the confining layers which is generally $<$ 1.0 Siemens; values $>$1.0 Siemens would indicate zones in which the confined aquifer would be protected; the revelations of the study area are possible indications that the groundwater quality status may have been impaired which necessitated the need for borehole water to be randomly sampled for contaminant loads based on this investigation.

Keywords: Aquifer, Groundwater, Ogun State, Capacity Rating, Resistivity meter

Introduction

The significance of groundwater quality for the overall health and general wellness of any community cannot be overemphasized (WHO, 1996; WHO, 2009; Ufuogbune *et al.*, 2001). The water scarcity experienced by the dwellers of Obafemi-Owode Local Government Area mostly in dry season, led to the search for surface water supply. Surface water, which mostly occurs as rivers are subjected to pollution; the streams and rivers, may be highly polluted judging by the increasing wastes that emptied on them on daily basis. The first alternative opened to man is ground water, which may be defined as "water in the zone of saturation and from which wells, springs and underground run off are supplied". In addition, and most importantly, very minor water treatment is often required to make it usable and portable. Groundwater is largely protected from pollution by natural barriers however, in areas with thin weathered layers and where aquifers are in hydraulic continuity with the ground surface, groundwater could be vulnerable to pollution from surface water sources (Bayewu *et al.,* 2018). Geologically, in the basement terrain, groundwater has been found to occur within the overlying unconsolidated material derived from in-situ weathering of rocks and perhaps the fractured/faulted bedrock while in the sedimentary terrain, it is accumulated within the porous and permeable layer of the saturated zone in the subsurface (Clark, 1985; Jones, 1985; Bala and Ike, 2001; Ishola *et al.,* 2016; Ishola *et al.*, 2021). Although water is a renewable resource, yet its supply in suitable quality is steadily decreasing due to lack of proper and adequate water management techniques and effect of poor waste water management especially in developing countries like Nigeria. Moreover, the invasion of this unavoidable resource of the earth from internal and external sources has increased significantly throughout the world due to population growth, industrialization, socio-economic development, technological and climatic changes (Alcano, 2007; Ishola *et al.,* 2016; Ishola, 2019). The urge to sustain groundwater need by people has inadvertently strengthened the application of appropriate geophysical and/or hydrogeological search (Lashkaripour, 2003; Batayneh, 2010; Omosuyi, 2010; Anudu *et al.,* 2011) in order to locate areas of high and reliable groundwater prospects or characterize seasonal changes in the near-surface aquifer (Webb *et al.,* 2011; Bayewu *et al.,* 2018). In the past centuries, studies show that high rate of urbanization, industrialization and other human activities have resulted into the release of toxic substances into the ground which consequently migrate its way as discharge materials and percolate through the subsurface with unprecedented impacts on the aquiferous zone (Ishola, 2019; Ishola *et al.,* 2021). Groundwater reservoir in the Precambrian Basement Complex usually occur at shallow depths and hence, are vulnerable to surface or near-surface contaminants. As part of groundwater exploration programme, the task to assessing the protective capacity of groundwater becomes very important. Groundwater vulnerability assessment is vital not only for management of groundwater resources but also for subsequent land use monitoring control and urban planning (Rupert, 2001; Babiker *et al*., 2005).

Obafemi-Owode is a fast growing area in Ogun State coupled with its proximity to Abeokuta; the ancient administrative city and Capital of Ogun State, South-West Nigeria. It lies in the basement terrain and has been experiencing problem of decrease in the quality and quantity of groundwater. The continuous increase in population and the progressive infrastructural development within Obafemi-Owode Local Government Area necessitated the quest for further emphasis for the development of a sustainable water supply network. Groundwater exploration within the Basement Complex rocks of Africa is usually carried out with the use of Vertical Electrical Sounding (VES) (Omosuyi *et al.*, 2003; Olasehinde and Bayewu, 2011; Oloruntola and Adeyemi, 2014; Ishola *et al.*, 2016). This is because the successful exploration and exploitation of groundwater in basement terrain requires a reliable understanding of the hydrogeological characteristics of the Aquifer units in relation to its vulnerability to contaminant seepages and overall consequent environmental pollution. Also, many dug wells that were sunk in the study area without an initial proper investigation failed and so were abandoned. There are several reasons for the failure of boreholes and these include inadequate or lack of pre drilling investigation, lack of expertise on the part of personnel handling the drilling and sometimes lack of proper development of a successfully dug hole. Consequently, a detailed geoelectric survey and mapping of the study area was undertaken to determine the geoelectric parameters (resistivities, thicknesses, number of layers) of subsurface layers and their hydrogeological properties. The study is equally aimed at assessing the groundwater potentials of the area, establishing and rating the aquifer protective capacity of the overlying formations (insulating the subsurface reservoir rocks from possible pollution) and recommending appropriate points for groundwater abstraction. Geophysical approach using electrical resistivity techniques is utilized as the key to exploration because it can give detailed information about the subsurface layer by passing electrical current down to the subsurface and also, its low cost of exploration. This method has been successfully applied for several research works, environmental and other developmental purposes.

Study Area

Obafemi-Owode is situated in Ogun State within the southwestern part of the Nigerian Precambrian basement complex rocks and lies within longitudes 3^0 20 617’ with 3^0 45 236’E and latitudes 7^0 00 102’ and 7^0 11 897’ N. The map of surveyed and sampled locations for the study area is shown in (Figure. 1**).** The study area is accessible via Lagos-Abeokuta express road; two major roads, few minor roads and footpaths making conveyance and mobility accessible and convenient. The study areas fall within the humid tropical region which is characterized by two distinct seasons which characterized the tropics in the southern part of Nigeria namely; the wet and dry seasons. The physiography of the study area results from the geomorphic processes that have shaped the terrain (Kehinde-Phillips, 1990); the topography is undulating and ranges from high to low relief. The crystalline basement complex rocks of Nigeria are well represented in specified study areas of Ogun State (Kehinde-Phillips, 1990). These rocks belong to the youngest of the three major provinces of the West African Craton recognized by Hurley and Rank (1976).

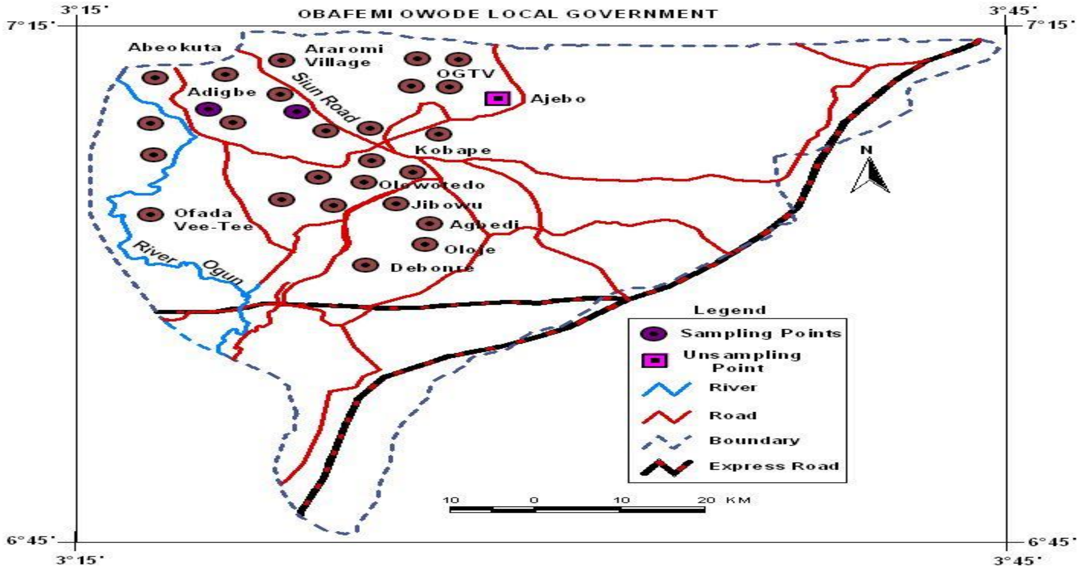

Fig. 1: Map showing the sampled location in Obafemi-Owode study area (Ishola, 2016).

Theoretical Basis and Methodology

Effect of Anisotropy on Resistivity

In any given geological environment, layering and fracturing is an indispensable parameters affecting resistivity measurement. Thus, there is no uniformity in the flow of electric current (Bayewu et al., 2018)**.** Anisotropy coefficient is a measure of inhomogeneity of a medium (Ishola et al., 2016); it increases linearly with increase in groundwater yield. In stratified conductors, identifiable parameters are of basic importance for the understanding and consequent interpretation of the geoelectrical model of stratified conductors. These parameters are related to different combinations of the thickness and resistivity of each geoelectrical layer in the model (Ishola (2019). The integration of the thickness and resistivity of the geoelectric layers into single variables; the Dar-Zarouk parameters of Transverse unit resistance (R) and Longitudinal unit conductance (S), can be efficiently utilized as a basis for the evaluation of aquifer properties such as transmissivity (T) and protective capacity (Pc) of the overburden rock materials in the course of geo-electrical section with a unit crossectional area.

For a geologic layer that is horizontal, homogenous and isotropic, the Dar-Zarouk parameters of transverse unit resistance and longitudinal unit conductance can be derived:

$$\mathrm{H} = \sum_{i=1}^{n} h_i \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \text{(1)}$$

The longitudinal conductance 'S' is given as

$$S_I = \sum_{i=1}^{n} h_{i/\rho_i} \ldots\ldots\ldots\ldots \text{(2)}$$

Where H is the summation of thickness while the transverse unit resistance 'R' is given as

$$R_i = \sum_{i=1}^{n} h_i p_i \ldots\ldots\ldots\ldots\ldots \text{(3)}$$

From equation (1) and (3) the longitudinal resistivity is

$$\rho_l = \mathrm{H/S} = \sum h_i / \sum h_i / p_i \ldots\ldots\ldots\ldots \text{(4)}$$

Where $\mathrm{H} = \sum_{i=1}^{n} h_i$ and $S_i = \sum_{i=1}^{n} h_{i/\rho_i}$

From equation (1) and (3) the transverse resistance is

$$\rho_t = R/H = \sum h_i p_i / \sum h_i \ldots \text{(5)}$$

Where T = $\sum \rho_i h_i$

H = $\sum_{i=1}^{n} h_i$

The Anisotropic coefficient (λ) $= \sqrt{\rho_t/\rho_l}$

$$(\lambda) = \sqrt{\frac{T}{H} \cdot \frac{S}{H}} \ldots\ldots\ldots\ldots\ldots\ldots \text{(6)}$$

T and S are represented as Dar-Zarrouk parameters.

For an isotropic medium, $\rho_t = \rho_l$ such that $\lambda = 1$

For an anisotropic medium, $\rho_t > \rho_l$ such that $\lambda > 1$

Equation (6) is used for layered rocks such as sedimentary rocks and it is also applicable to basement complex rocks that shows layered structured (Ishola, 2016). This was calculated using method of Bhattacharya and Patra (1968), Loke (1999), Olayinka (1996) and Ishola (2019).

The reflection coefficient between the sub-basement and basement layer was calculated which is an indication that the fracture within the bedrocks are filled with water.

$$K_n = \frac{\rho_n - \rho_n - 1}{\rho_n + \rho_n - 1} \ldots\ldots\ldots\ldots\ldots \text{(7)}$$

Where Kn is the reflection coefficient

n is the no of layers

ρ_n *is the layer resistivity of the* nth layer

$\rho_n - 1$ is the layer resistivity overlying the nth layer.

The layer resistivity and thickness of the ith layer are respectively given as ρ_i and h_i are. The aquifer transmissivity (T) can therefore be expressed as the hydraulic conductivity (k) multiplied by the layer thickness (h),

$$T = Kh \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \text{(8)}$$

For pure saturated aquifers whose natural fluid properties are fairly constant (that is, no significant effect on the general subsurface water quality by surface contaminant loads), the hydraulic conductivity is therefore proportional to the aquifer resistivity. This implies that in the absence of a pumping test data, the aquifer hydraulic conductivity K can be approximated to the true resistivity of the aquifer derived from geoelectric investigation (Hubbard and Robin, 2002). Therefore,

$$T = Kh = \rho h \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \text{(9)}$$

But the product of the resistivity to its thickness is the transverse resistance (R), which is numerically equal to the transmissivity (T)

$$T = R \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \text{(10)}$$

The aquifer protective capacity characterization is based on the values of the longitudinal unit conductance of the overburden rock units. The longitudinal conductance (S) gives a measure of the impermeability of a confining clay/shale layer. Such layers have low hydraulic conductivity (k) and low resistivity. Protective capacity (P_C) of the overburden layers is proportional to its longitudinal conductance(S) (Olayinka and Yaramanci, 2008; Ishola, 2019).

$$P_{OC} = \mathrm{S} = \sum_{i=1}^{n} h_{i/\rho_o} \ldots\ldots\ldots\ldots\ldots \text{(11)}$$

(Olayinka and Yaramanci, 2008; Oborie and Nwankoala, 2012).

Data Acquisition and Interpretation

Allied Ohmega Resistivity meter was used to acquire seventeen (27) VES soundings data using the Schlumberger configuration and maximum electrode separation (AB/2) is restricted to 100 m. The Schlumberger configuration consists of a linear electrodes array (AMNB) as shown in Figure 2. Potential electrodes M and N are kept fixed at the centre of the array while current electrodes A and B are moved outward symmetrically (Telford, 1990; Pirttijärvi, 2009). The operational principle lay on the fact that ground injection of current through current electrodes A and B enables the measurement of the potential drop between potential probes M and N. The current penetrates deeply into the ground as the electrode A and B spacing increases**.** The interpretation of result was carried out both qualitatively and quantitatively the qualitative interpretation was achieved by plotting the obtain Resistivity data on the log-log paper which relate the resistivity data to the geology of the study area while quantitative interpretation is referring to a curve matching and computer assisted program called iteration (Ishola *et al.,* 2021). This provides a comparison of real resistivity data to synthetic data in other to make geologic interference from the features observed in the real data. The user iteratively changes the model to facilitate a sufficient match with the real data so that the model becomes a possible representation of the geologic condition that produced the real resistivity data. From the analysis of the values obtained from the sounding, aquifer parameters were calculated from the Geometric computations of Dar-Zarrouk parameter for each location using sing the classification (Oladapo and Akintorinwa, 2007; Ishola et al., 2016; Bayewu *et al.,* 2018).

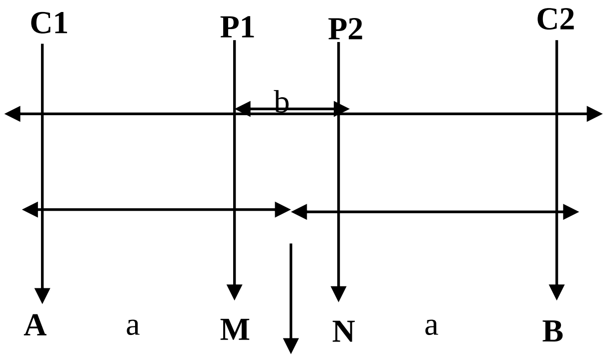

Figure 2: Field illustration showing Schlumberger arrays (Ishola *et al.,* 2016)**.**

Results and Discussions.

The output and distinct features of the acquired field data from the electrical resistivity soundings were interpreted quantitatively with the inferred lithologies from the geoelectric interpretation.

Aquifer Resistivity

The resistivity revealed the spatial distribution of resistivity across the study areas, thereby showing the groundwater potential zones and their ranking levels across at each VES station. Low to moderate grades of resistivity values were identified between 16**Ω**m and 84 **Ω**m. it is observed that VES 0B3, 0B4, 0B5, 0B7 and 0B13 have much higher groundwater potential values since the layer resistivity is between 0 and 100 **Ω**m. This study area underlain by granitic gneiss and migmatite gneiss with various quartzite intrusions and grades into the transition zone with the sedimentary basin and is duely characterized by fairly satisfactory hydrogeological history that is less porous. The area can sometimes be highly problematic and it is prone to low yield groundwater supply (Ishola *et al.,* 2016; Ishola, 2019; Ishola, 2021).

Aquifer Unit(s) Thickness

The aquifer unit(s) thickness map can be used in placing geology formation in ranks because groundwater productivity as inferred from each VES station depends on the aquifer thickness. This in turn reveals the different types of aquifer found in all sounded VES locations. Locations depicted by widely spaced closed contour lines are the region of possible fractures/deep-seated faults. The entire study areas can be classified as good, moderate and poor groundwater potential zones (Coker *et al.,* 2009; Ishola *et al.,* 2016). The highest recorded thickness value is 86.4m at VES 0B11 and the lowest 2.5m at VES 0B1 (Table 1).

Overburden Thickness

The term overburden refers to all formative materials overlying the basement. Overburden thickness map revealed the overburden/depression along different sections which conspicuously the depth to the aquifer. The area of thick overburden is indicated by dense contour closures. The overburden thickness can be used to evaluate cost effectiveness of the area in terms of the amount or cost of drilling and efficiency in terms of performance (Aucken and Christiansen, 2004; Coker *et al,* 2009; Ishola *et al.,* 2016; Ishola *et al.,* 2021). The depth to overburden is greatest at VES 0B22, it embraces VES 0B27 with the overburden thickness value of 32.3m and 31.2m respectively while the areas with the thinnest overburden is observed in VES 0B1 with the overburden thickness of 0.9m. VES stations whose value is greater than 26.0m is considered to be of good groundwater potential than other areas with lower overburden thickness.

Longitudinal Unit Conductance

Based on the reciprocal relationship of resistance and conductance i.e. $\boldsymbol{\sigma} = {}^{1}/_{\rho}$, it is understood that the more a geological formation is conductive, the less it is resistive indicating a permeable formation (Devi *et al,* 2001). As the conductance increases the resistivity naturally decreases pointing towards groundwater potential aquifer (Gowd, 2004; Ishola *et al.,* 2016; Ishola, 2019).

The confined aquifer would be protected in comparisons when the values of S > 1.0 siemens while zones in which values of S <1.0 Siemens would indicate zones of probable risks of of the aquiferous zones to contamination seepages. The longitudinal unit conductance is less than unity (S < 1.0 Siemens) in all the investigated locations of the study area, which ultimately revealed that the study area is vulnerable to external invasions.

Transmissivity

The Lowest transmissivity value is observed in VES OB4 which embraces OB6 with the value of $0.01\times10^{4}m^{2}/s$ while the highest transmissivity value is observed in VES OB10 with the value of $4.80\times10^{4}m^{2}/s$. In this study area different VES points exhibited similar pattern of transmissivity rate. This is seen in VES OB2 and OB14 with T value of $0.09\times10^{4}m^{2}/s$, VES OB5 and OB7 with the T value of $0.05\times10^{4}m^{2}/s$,VES OB4 and OB6 with the T value of $0.01\times10^{4}m^{2}/s$. VES OB13 and OB17 with the T value of $0.33\times10^{4}m^{2}/s$ and VES OB15,OB16,and OB19 with the T value of $0.40\times10^{4}m^{2}/s$. Points of drilling and installations of monitoring wells for unconfined aquifer are best suggested for zones of high transmissivities. Also, high transmissivities suggest that the aquifer materials in that area are permeable to fluid movement within the aquifer which possibly may enhance the migration and circulation of contaminant in the groundwater aquifer system (Gowd, 2004; Ishola *et al.,* 2016; Coker *et al*., 2019; Ishola, 2019).

Hydraulic Conductivity

The hydraulic conductivity value varies from $11.55\times10^{-3}m/s$ and $373.00\times10^{-3}m/s$. The hydraulic conductivity *(K)* is directly proportional to resistivity ($\boldsymbol{\rho}$) that is as K increases; $\boldsymbol{\rho}$ also increases unlike in longitudinal conductance where reverse is the case (Gowd, 2004; Ariyo and Adeyemi, 2009; Ishola *et al.,* 2016; Ishola, 2019).

In Obafemi-Owode, there are great variations in groundwater differentiation in terms of aquifer types. The boreholes around VES OB4, OB5, OB6, OB18, OB23, OB25, OB26 and OB27 are characterized by unconfined aquifer while the rest of these study locations are associated with confined aquifer which may not be really recommended for borehole installation though with appreciable thickness, the weathered layers are dominantly composed of shale/clay being an aquitard, it makes groundwater exploitations difficult. In all the investigated locations, the unconfined aquifers are susceptible or vulnerable to invasions from external sources. Since the longitudinal conductance illustrates the impermeability of the confining layers which is generally < 1.0, as values >1.0 Siemens would indicate zones in which the confined aquifer would be protected; in comparison, the values of S < 1.0 would indicate zones of probable risks of groundwater contamination (Omosuyi, 2010; Ishola *et al*., 2016; Ishola., 2019).

Evaluation of Aquifer Protective Capacity

The computation of longitudinal conductance of the layers can be achieved by utilizing the combination of the resistivity and layer thickness (Oborie and Udom, 2014; Ishola *et al.,* 2016; Ishola *et al*., 2021). The high longitudinal conductance observed indicated relatively high protective capacity and identified vulnerable zones which could help to protect groundwater resources and also evaluates the aquiferous zones for water quality improvement. The computed longitudinal conductance for the study area is therefore presented in Table 2. These computed values are favourably compared with the standard rating by (Oladapo and Akintorinwa, 2007 and Ishola *et al.,* 2016). It can be vividly observed from Table **2** that the study area shows a very poor, poor, and moderate protective capacity rating. Seven (7) VES stations have very poor protective capacity, eighteen (18) VES stations shows poor protective capacity and only two (2) VES stations shows a moderate protective capacity rating. This is expressed in a bar chart in Fig. 12. Altogether, the results revealed that the protective capacity rating of the hydrogeological formation of the study area is generally low except for VESOB8 and VESOB25 that displayed moderate protective capacity rating (Fig. 12). Areas that are classified as very poor and poor protective capacity rating are indicative of zones of high infiltration rates from precipitation; such areas are vulnerable to infiltration of leachates and other surface contaminant loads which migrate through the porous and permeable rock layers with unprecedented impacts on the subsurface groundwater system of the study area.

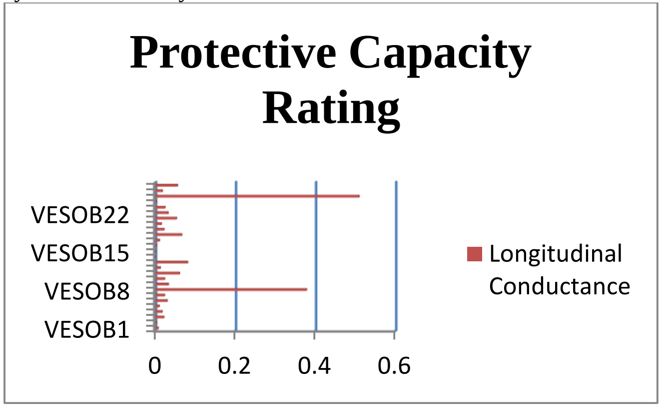

Fig. 3: Protective Capacity Rating of Obafemi-Owode

Conclusions

It can be concluded from the qualitative and quantitative data interpretation of the study area that 63% of the investigated locations possesses high groundwater potentials, 18% have moderate or medium investigated and

19% have low groundwater potentials in terms of yield or production. The study area is overlain by materials of weak protective capacity and only small area is of moderate protective capacity. It is therefore evident that groundwater in most part of the area is vulnerable to pollution that may arise from runoff water, sewage system, effluent and indiscriminate waste disposal in the study area.

Therefore, the revelations in the study area are possible indications that the groundwater quality may have been impaired which necessitated the need for borehole water to be randomly sampled for contaminant loads based on this analysis.

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