Assessment of Hydrogeological Potential and Aquifer Protective Capacity of Odeda, Southwestern Nigeria

Hidrogeološki potencial in ocena zaščitnih zmogljivosti vodonosnika na območju Odeda v Nigeriji

J.O. Aina*, O.O. Adeleke, V. Makinde, H.A. Egunjobi, P.E. Biere

Department of Physics, Federal University of Agriculture, Abeokuta, Nigeria

* johntemini20@gmail.com

Abstract

Hydrogeological assessment of groundwater resources was carried out with a view to evaluate the potential of the aquifers to provide portable water supply and access the distribution of electrical parameters of hydrogeologic units in some areas in Odeda, Ogun State, Nigeria. A geophysical survey using vertical electrical sounding (VES) with the Schlumberger electrode array, with half-current electrode spacing ($AB/2$) varying from 1 to 132 m was carried out at 30 different stations in the study area. The VES data were interpreted qualitatively and quantitatively. Three-to-five sub-surface layers consisting of topsoil, weathered layer consisting of clay, sandy clay, clayey sand and sand layers, and fractured/fresh basement were delineated. Layer resistivities and thicknesses obtained on the curves within the study area showed one main aquifer type, which is the fractured basement. The longitudinal unit conductance (ranging from 0.049720 to 1.452000 mhos) of the study area aided the protective capacity to be rated into good, moderate and weak. About 33% of the study area falls within the weak protective capacity, 57% falls within the moderate protective capacity and 10% falls within the good protective capacity.

Key words: Groundwater potential, protective capacity, vertical electrical sounding, longitudinal unit conductance, overburden thickness

Povzetek

Raziskava hidrogeoloških podzemnih virov je potekala z namenom ocenitve potenciala vodonosnika za zagotovitev preskrbe z vodo. Pri tem je bila narejena porazdelitev električnih parametrov hidrogeoloških enot na nekaterih območjih kraja Odeda. Uporabljena je bila geofizikalna raziskava z navpičnim električnim sondiranjem (VES) z uporabo Schlumbergerjeve elektrodne postavitve s polovično razdaljo elektrode ($AB/2$), ki je variirala med 1 in 132 m. Preiskava je bila izvedena na 30 različnih lokacijah. Izmerjeni podatki so bili interpretirani kvalitativno in kvantitativno. Razmejenih je bilo tri do pet podzemnih plasti, ki so jih sestavljale: vrhnja plast, preperela plast (sestavljena iz gline, peščene gline, zaglinjenega peska), peščena plast in razpokana sveža podlaga. Upornost in debelina posameznih plasti kaže na eno glavno vrsto vodonosnika (razpokana podlaga). Glede na vzdolžno prevodnost (v območju med 0.049720 do 1.452000 mhos) raziskovanega območja je mogoče zaščitno zmogljivost vodonosnika razvrstiti v dobro, srednjo in slabo. Okoli 33% raziskovanega območja leži znotraj slabe, 57% znotraj srednje in 10% znotraj dobre zaščitne sposobnosti.

Ključne besede: potencial podzemne vode, zaščitna zmogljivost, navpično električno sondiranje, vzdolžna prevodnost, debelina nadkritja

Introduction

In ensuring livelihood and sustainability across the world, groundwater resources play a major and concrete role. Consumption of groundwater as a feasible source of drinking, domestic, industrial and agricultural needs has proven to be not only safer but also more economical than surface water, as it is commonly unpolluted and available. In recent years, investigation of groundwater sources has become a burning issue and a major concern as groundwater basins are being rapidly stressed due to population explosion, high level of urbanisation, industrialisation and other human activities. Presently, the percentage increase in water usage on a global scale has exceeded twice that of the population [1].

Pores and fractured rock formations in the sub-surface are usually hosts of groundwater. In the basement terrain, groundwater occurs within the overlying unconsolidated material derived directly from weathering of rocks and fractured/faulted bedrock, while in the sedimentary terrain, groundwater occurs within the porous and permeable layer of the saturated zone in the sub-surface [2, 3]. Over the years, groundwater exploration has been carried out using geophysical methods, which include electrical resistivity surveying, electromagnetic techniques and seismic methods, to obtain accurate information about the sub-surface settings, such as aquifer's nature, type and depth of materials (consolidated or unconsolidated), depth of weathered or fractured zone, depth to groundwater, depth to bedrock and salt intrusions into groundwater [4].

Aquifers in the Precambrian basement complex are vulnerable to surface or near-surface contaminants as they commonly occur at shallow depths. Hence, successful exploration of groundwater in a basement terrain requires proper understanding of the hydrogeological characteristics of the aquifer units in relation to their susceptibility to environmental pollution and assessment of their protective capacity [3, 5]. One of the most effective ways of evaluating an environment without interfering with the hydrogeological system is through geophysical studies [6]. Over the years, geophysical survey using the vertical electrical sounding

(VES) method has been applied in groundwater exploration within the basement complex rocks in Nigeria [7–10].

VES using the Schlumberger array method was carried out at 30 different stations in the study area with the aim to determine the geoelectric parameters, such as resistivities and thicknesses of the sub-surface layers and their hydrogeological properties. This study was also aimed at evaluating the groundwater potential of the area, establishing the aquifer protective capacity of the overlying formations, especially its isolation from contamination, and recommending suitable points for groundwater positioning.

Location and Geology of the Study Area

The study area, as shown in Figure 1, is located between latitudes 7°10'N and 7°12'N and between longitudes 3°23'E and 3°28'E. The study area is characterised by tropical climate with distinct wet and dry seasons. The annual rainfall ranges from 1400 mm to 1500 mm; the mean temperature is 30°C and varies from 25.7°C in July to 30.2°C in February [11]. The study area is underlain by Precambrian basement rocks (Figure 2), which are innately characterised by near-negligible permeability and low porosity. These rocks, according to a previous paper [12], were acknowledged to belong to the youngest of the three major provinces of the West African Craton. These rocks are of Precambrian age to early Palaeozoic age, which extends from the Northeastern part of Ogun State and dips towards the coast [13].

Materials and Methods

The electrical resistivity survey method using the VES method was carried out in the study area. The resistivity data were acquired using Campus Ohmega Terrameter. Thirty VES points were positioned in the study area using Schlumberger electrode configuration with half-current electrode separation ($AB/2$) ranging from 1 m to 132 m. The apparent resistivity values were obtained as the product of the resistance read from the resistivity meter

Figure 1: Map of the study area showing the sounding points.

Figure 2: Geological map of Ogun State. Modified after Badmus and Olatinsu [14].

Table 1: Longitudinal unit conductance/protective capacity rating (source: Oladapo and Akintorinwa [18]).

Total longitudinal unit conductance (mhos)	Rating of overburden's aquifer protective capacity
<0.10	Poor
0.1–0.19	Weak
0.2–0.79	Moderate
0.8–4.90	Good
5.0–10.0	Very good
>10.0	Excellent

Table 2: Groundwater potential yield (modified after Bayewu et al. [3]).

Overburden thickness (m)	Reflection coefficient	Groundwater yield
>13	<0.8	High
>13	>0.8	Medium
<13	>0.8	Low
<13	<0.8	Very low

and its corresponding geometric factor (K) for each electrode separation. The apparent resistivity data were then plotted against AB/2 on a bi-logarithm graph as sounding curves. The plotted sounding curves were interpreted manually by partial curve matching using different master curves [15]. The geoelectric parameters from the partial curve matching served as the input model for computer-assisted iteration using WINRESIST.

The values of the longitudinal unit conductance of the overburden rock units in the study area serve as the basis for the characterisation of its aquifer protective capacity. The longitudinal unit conductance gives a measure of the impermeability of the confining clay layer, which has low resistivity and low hydraulic conductivity. The protective capacity of the overburden layers in a particular area is proportional to the longitudinal unit conductance [16]. The longitudinal layer conductance (S) of the overburden at each VES station was obtained as shown in Equation (1) [17].

$$S = \sum_{i=1}^n \frac{h_i}{\rho_i} \quad (1)$$

where h_i is the layer thickness, ρ_i is the layer resistivity, while the number of layers from the surface to the top of the aquifer varies in the range $i = 1, \dots, n$. The results of the longitudinal

unit conductance were used to classify the areas into good, moderate, weak and poor aquifer protective capacity (Table 1). This was done using the classification given by Oladapo and Akintorinwa [18].

Olayinka [19] opined that in identifying areas of favourable aquifers within a basement terrain, the resistivity of the basement cannot be exclusively relied upon; hence, one has to consider the basement's reflection coefficient in effectively evaluating groundwater potential in the study area. The degree of fracturing of the underlying basement is shown by the reflection coefficient [3]. The reflection coefficients (r) of the study area were calculated using Equation (2), as given by Bhattacharya and Patra [20] and Loke [21].

$$r = \frac{(\rho n - \rho(n-1))}{(\rho n + \rho(n-1))} \quad (2)$$

where ρn is the layer resistivity of the n th layer and $\rho(n-1)$ is the layer resistivity overlying the n th layer.

In a basement terrain, groundwater yield can be grouped into high, medium and low depending on the overburden thickness and/or reflection coefficient (Table 2), as stated by Bayewu et al. [3]. The highest groundwater yield is found in areas where thick overburden overlies the fractured zone [18].

Results and Discussion

The summary of the geoelectric parameters and inferred lithologies in the study area is presented in Table 3. The curve types obtained after partial curve matching ranges from the three-layer H type (66.7%), A type (3.3%) and K type (3.3%), through the four-layer KH type (23.3%), to the five-layer curve HKH type (3.3%). The predominant H type curve recorded in the study area further affirmed the findings of Oloruntola and Adeyemi [9], who recorded >72% of H curve type in the basement

geological terrain at Abeokuta. Figures 3 and 4 show the typical iterated curves generated from the field measurements. The geoelectric interpretations revealed three to five layers, as follows: topsoil (23–700 Ωm); the weathered layer, which is composed of clay/sandy clay and clayey sand/sand (4–790 Ωm); underlying this layer are the fractured layer (93–437 Ωm) and the fresh basement (532–2106 Ωm). The aquifer unit in the study area is basically found in the fractured layer, the yield being dependent on the amount of clay content.

Table 3: Summary of geoelectric parameters and inferred lithologies.

VES no.	No. of layers	Curve types	Resistivity (Ωm)	Thickness (m)	Depth (m)	Reflection coefficient	Inferred lithology
1	1	H	117	2.3	2.3	0.876	Topsoil
	2		29	25.5	27.8		Clay
	3		437				Fractured basement
2	1	H	211	0.9	0.9	0.421	Topsoil
	2		110	5.0	5.9		Sandy clay
	3		270				Fractured basement
3	1	H	324	1.3	1.3	0.437	Topsoil
	2		162	13.1	14.4		Clayey sand
	3		413				Fractured basement
4	1	H	75	2.1	2.1	0.843	Topsoil
	2		30	24.1	26.2		Clay
	3		352				Fractured basement
5	1	H	100	1.2	1.2	0.977	Topsoil
	2		5	7.2	8.4		Clay
	3		427				Fractured basement
6	1	HKH	134	0.6	0.6	0.899	Topsoil
	2		35	1.8	2.4		Clay
	3		79	3.4	5.8		Sandy clay
	4		17	8.8	14.6		Clay
	5		318				Fractured basement
7	1	H	94	0.8	0.8	0.778	Topsoil
	2		24	4.9	5.7		Clay
	3		192				Fractured basement
8	1	H	30	1.0	1.0	0.996	Topsoil
	2		4	2.0	3.0		Clay
	3		2106				Fresh basement
9	1	KH	94	1.2	1.2	0.701	Topsoil
	2		120	6.6	7.8		Sandy clay
	3		60	11.8	19.6		Clay
	4		342				Fractured basement
10	1	H	109	0.8	0.8	0.489	Topsoil
	2		32	7.2	9		Clay
	3		93				Fractured basement
11	1	KH	26	0.6	0.6	0.841	Topsoil
	2		655	5.1	5.7		Sand
	3		51	13.1	18.8		Clay
	4		592				Fresh basement
12	1	KH	161	0.9	0.9	0.315	Topsoil
	2		191	9.1	10		Clayey sand
	3		114	8.6	18.6		Sandy clay
	4		219				Fractured basement

Table 3: Summary of geoelectric parameters and inferred lithologies.

13	1	H	369	2.6	2.6	0.625	Topsoil
	2		62	19.7	22.3		Clay
	3		269				Fractured basement
14	1	KH	269	0.7	0.7	0.534	Topsoil
	2		327	3.2	3.9		Sand
	3		198	8.8	12.7		Clayey sand
	4		652				Fresh basement
15	1	H	167	1.2	1.2	0.576	Topsoil
	2		66	12.7	13.9		Clay
	3		245				Fractured basement
16	1	H	700	1.5	1.5	0.887	Topsoil
	2		38	8.3	9.8		Clay
	3		637				Fresh basement
17	1	H	417	1.0	1.0	0.744	Topsoil
	2		61	8.7	9.7		Clay
	3		415				Fractured basement
18	1	H	81	2.3	2.3	0.880	Topsoil
	2		27	10	12.3		Clay
	3		422				Fractured basement
19	1	KH	34	0.5	0.5	0.761	Topsoil
	2		790	2.5	3.0		Sand
	3		59	12.6	15.6		Clay
	4		435				Fractured basement
20	1	KH	103	1.0	1.0	0.615	Topsoil
	2		146	2.1	3.1		Clayey sand
	3		40	16.8	19.9		Clay
	4		168				Fractured basement
21	1	H	273	1.7	1.7	0.702	Topsoil
	2		35	11.1	12.8		Clay
	3		200				Fractured basement
22	1	H	329	3.5	3.5	0.237	Topsoil
	2		135	35.5	39		Sandy clay
	3		219				Fresh basement
23	1	H	226	2.0	2.0	0.921	Topsoil
	2		42	19.4	21.4		Clay
	3		1019				Fresh basement
24	1	H	285	0.8	0.8	0.759	Topsoil
	2		99	7.8	8.6		Clay
	3		722				Fresh basement
25	1	A	23	0.8	0.8	0.777	Topsoil
	2		49	16.6	17.4		Clay
	3		391				Fractured basement
26	1	K	63	1.0	1.0	0.553	Topsoil
	2		153	16.0	17.0		Clayey sand
	3		532				Fresh basement
27	1	H	149	1.0	1.0	0.643	Topsoil
	2		81	10.4	11.4		Clay
	3		373				Fractured basement
28	1	KH	108	1.6	1.6	0.889	Topsoil
	2		296	6.7	8.3		Sand
	3		82	9.2	17.5		Clay
	4		1391				Fresh basement
29	1	H	161	1.0	1.0	0.522	Topsoil
	2		65	10.0	11.0		Clay
	3		207				Fractured basement
30	1	H	274	2.6	2.6	0.830	Topsoil
	2		40	19.6	22.2		Clay
	3		431				Fresh basement

Figure 3: Typical VES curve in the study area.

Figure 4: Typical VES curve in the study area.

Assessment of Aquifer Protective Capacity

The resistivities and thicknesses of the underground layers were used to compute the longitudinal unit conductance (S) of the layers in the study area. Table 4 shows the calculated longitudinal unit conductance in mhos and the

protective capacity rating for the study area. The longitudinal unit conductance values of the overburden materials in the study area ranged from 0.049720 to 1.452000 mhos. It can be observed that the protective capacity in the study area reveals poor, weak, moderate and good capacity rating. Four VES stations have poor protective capacity, six shows weak protective

Table 4: Longitudinal unit conductance and aquifer protective capacity of the study area.

VES no.	Longitudinal unit conductance (mhos)	Overburden's aquifer protective capacity rating
1	0.898968	Good
2	0.049720	Poor
3	0.084877	Poor
4	0.824333	Good
5	1.452000	Good
6	0.616591	Moderate
7	0.212677	Moderate
8	0.533333	Moderate
9	0.264433	Moderate
10	0.232339	Moderate
11	0.287726	Moderate
12	0.128673	Weak
13	0.324788	Moderate
14	0.056833	Poor
15	0.199610	Moderate
16	0.220564	Moderate
17	0.145021	Weak
18	0.398765	Moderate
19	0.231430	Moderate
20	0.444092	Moderate
21	0.323370	Moderate
22	0.273601	Moderate
23	0.470754	Moderate
24	0.081595	Poor
25	0.373558	Moderate
26	0.120448	Weak
27	0.135106	Weak
28	0.149645	Weak
29	0.160057	Weak
30	0.499489	Moderate

Figure 5: The longitudinal unit conductance map of the study area.

capacity, 17 show moderate protective capacity, while three show good protective capacity rating, with 33% of the study area falling within

the poor/weak overburden protective capacity. About 57% falls within the moderate range, while 10% falls within good overburden protective capacity. The longitudinal unit conductance map of the study area in Figure 5 shows that the northeastern and northwestern parts of the study area are characterised by moderate-to-good protective capacity, and this signifies that there is a little or no infiltration due to precipitation.

Assessment of Groundwater Potential

Figures 6 and 7 show the reflection coefficient and overburden thickness map of the study area. The reflection coefficient in the study area varies from 0.24 to 1.00. The groundwater prospects in the study area are categorised

Figure 6: The reflection coefficient map of the study area.

Figure 7: Isopach map of overburden thickness of the study area.

into high, medium and low potentials. In this study, zones where the overburden thickness is >13 m and the reflection coefficient is <0.8 are considered as zones with high groundwater potential, while zones with overburden thickness <13 m and reflection coefficient <0.8 are considered as zones having very low groundwater potential.

Generally, about 33% of the study area has high groundwater potential, which is restricted mostly to areas underlain by porphyritic granite and porphyroblastic gneiss, as established by a previous paper [22], while 23% of the study area has medium groundwater potential; moreover, 43% of the area has low groundwater potential. This result invariably indicates the significance of detailed groundwater survey and exploration in the study area for locating areas where successful boreholes can be sited.

Table 5: Groundwater potential across the VES locations.

VES no.	Overburden thickness (m)	Reflection coefficient	Groundwater yield
1	27.8	0.876	Medium
2	5.9	0.421	Very low
3	14.4	0.437	High
4	26.2	0.843	Medium
5	8.4	0.977	Low
6	14.6	0.899	Medium
7	5.7	0.778	Very low
8	3.0	0.996	Low
9	19.6	0.701	High
10	9.0	0.489	Very low
11	18.8	0.841	Medium
12	18.6	0.315	High
13	22.3	0.625	High
14	12.7	0.534	Very low
15	13.9	0.576	High
16	9.8	0.887	Low
17	9.7	0.744	Very low
18	12.3	0.880	Low
19	15.6	0.761	High
20	19.9	0.615	High
21	12.8	0.702	Very low
22	39.0	0.237	High
23	21.4	0.921	Medium
24	8.6	0.759	Very low
25	17.4	0.777	High
26	17.0	0.553	High
27	11.4	0.643	Very low
28	17.5	0.889	Medium
29	11.0	0.522	Very low
30	22.2	0.830	Medium

Conclusion

The geoelectric investigation of the study area has revealed three to five subsurface geoelectric layers: top soil, weathered basement and fresh basement rocks. The fractured layer constitutes the sole aquifer unit in the study area. The protective capacity in the study area is more of the moderate type and is therefore not exposed to pollution. About 33% of the study area falls within the high rated groundwater po-

tential zone, while the remaining 67% constituted the medium/low groundwater potential zone. Hence, the groundwater potential rating of the area is considered generally as medium/low. Therefore, areas for locating groundwater should be narrowed to zones of moderate/good groundwater protective capacity.

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