# Hydrogeologic and hydrochemical framework of the shallow regolith aquifer, southern Oban massif (Nigeria)

# (Cadre hydrogéologique et hydrogéochimique d'un aquifère de socle fracturé altéré, massif du sud de l'Oban, Nigéria)

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**Abstract** Detailed geological, geoelectrical and hydrogeological investigations were carried out in Oban massif (southeastern Nigeria) to delineate and characterize the architecture of the shallow regolith aquifer. Surface resistivity data were used to develop a generalized hydrogeological model. Aquifer parameters (porosity, yield, hydraulic conductivity and transmissivity) were estimated from empirical relations, while estimates of recharge from chloride mass balance approach gave an annual recharge of 11.2% of annual precipitation. Computed groundwater reserve for the regolith aquifer is about 96,834 x $10^6$ $m^3$. Groundwater in the region is good for drinking, domestic and irrigation applications. The chemistry of groundwater is controlled by water-rock interactions mainly silicate weathering and ion exchange. Management problems include lack of pre-drilling investigations, poor well construction, lack of maintenance and poor waste management. In conclusion, proper harnessing of the groundwater resource will depend on the identification and evaluation of the water bearing unit on a site-to-site basis.

**Keywords**: Aquifer, Geoelectrical, Precambrian Oban massif, Nigeria

## 1. INTRODUCTION

Over the last decade, the development of groundwater resources in the Oban massif region of south-eastern Nigeria underlain by crystalline basement complex rocks has been the focus of several stakeholders including some international donor organisations. Despite these efforts, many regions, especially the rural populations, are yet to benefit. This situation has been attributed to the fact that basement complexes are problematic aquifers the world over, in terms of exploration and exploitation of groundwater resources. This is partly due to their massive nature and the complex fracture system and variable weathered overburden that host the groundwater (Jones 1985, Acworth 1987, Hazell et al 1992, Chilton and Foster 1995, Edet 1993, Edet et al 1994, 1998, Edet and Okereke 1997, 2005, Okereke et al 1994, 1998). Thus the evaluation of groundwater resources to meet its ever increasing demand requires an understanding of the hydrogeological and hydrochemical properties of the aquifer. Some regional studies have been carried out on the geology and hydrogeology of the region in an attempt to unravel the hydraulic characteristics of underlying formation. Such studies include the works of Okonny (1984), Okonny and Odigi (1987), Edet (1993), Edet et al (1994) and Edet and Okereke (1997).

However, the high failure rates of drilled boreholes (Edet 1993) show the need for better understanding of the hydrogeological and hydrochemical setting of the massif. This article is aimed at defining the different hydrogeoelectric layers and their characteristics and understanding the relations among groundwater chemistry and geology for effective management and future development.

## 2. STUDY REGION CHARACTER

Oban massif is located between latitudes $5^{0}$ 07’ and $5^{0}$37’ N and longitudes $8^{0}$ 07’ and $8^{0}$ 48’ E (Fig. 1) in southern Nigeria. The entire region is under the influence of tropical climate with average annual temperature and rainfall of 28$^{o}$C and 3000mm.

### 2.1 Geological setting

A lot of research results have been published on the geology, geochemistry, geochronology and tectonics of the Oban massif. The lithologic units based on these contributions are mainly schists, gneisses and granodiorites. The schists are fine grained, banded, dominated by phyllosilicates and quartz and generally associated with pegmatites. The schists cover about 14% of the Oban region. The gneisses are of three major types: biotite-hornblende gneiss, kyanite gneiss, and migmatite gneiss (Ekwueme 1987). The gneiss covers about 76% of the region. The granodiorites are the most conspicuous intrusive rock of the region. The rocks are massive to weakly foliated, medium-coarse grained and covers about 10% of the region.

The main structural features here are foliations, lineations and schistosity. Fractures crosscut the schistosity. Most of the fractures are closed while the open ones are filled with chlorite, biotite and quartz (Ekwueme 1987).

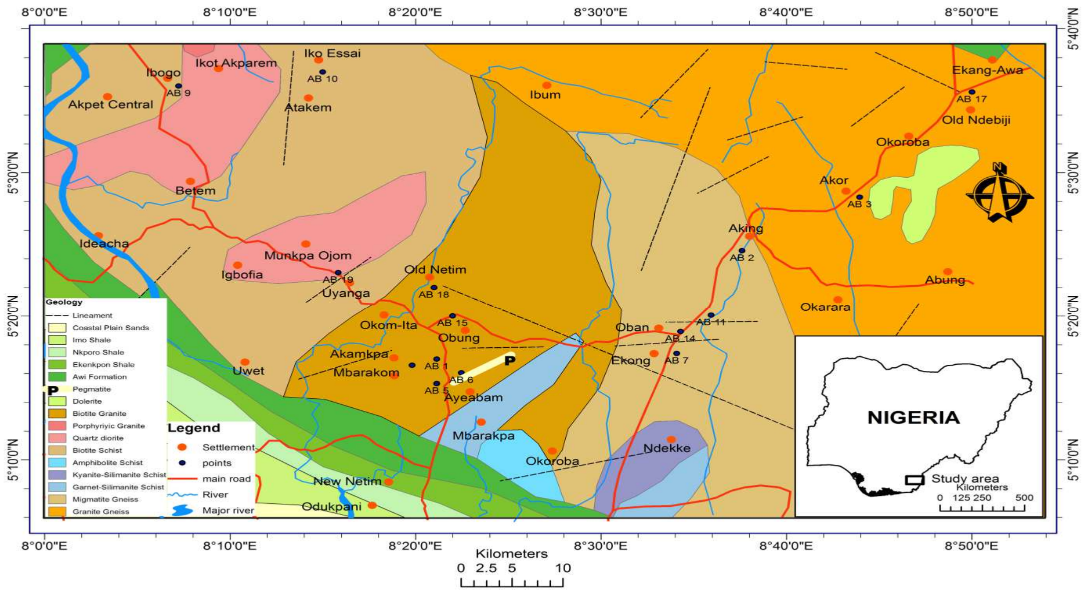


***Figure 1** Geological map of Oban region showing localities covered by the study*

## 2.2 Hydrogeological setting

The occurrence of groundwater in the region is controlled by weathering and fractures. Groundwater recharge in the aquifer occurs by direct infiltration of rainfall, infiltration through river and lateral subsurface flow. Depth to the water level is highly variable (0.20 - 8.0 m). The surface of Oban massif is characterized by a layer of reddish unconsolidated material produced by prolonged insitu weathering of bedrock. The intensity of weathering decreases downwards until freshrock is reached. The relative positions of water table and base of regolith also dictate the approach to groundwater development. Shallow water levels and substantial thickness of saturated regolith, permits simple approaches to borehole siting, with abstraction from either hand-dug wells or shallow boreholes. Deeper water levels with thin saturated regolith often necessitate the drilling and/or rather expensive deep boreholes into the basement to intercept structures (Chilton & Foster 1995).

## 3. LITHOLOGICAL AND GEOELECTRICAL DATA

The study involved surface geological and hydrogeological mapping in addition to geoelectrical measurements. The geological mapping was mainly to record the site geology and confirm the cited lithology in the literature. The hydrogeological mapping consisted of measuring of static water level and acquiring of data from files of water supply agencies.

During the geoelectrical survey, vertical electrical soundings (VES) data were acquired using the ABEM SAS 300B terrrameter and based on the Schlumberger array described by Zohdy et al. (1974). The apparent resistivity value was plotted against the corresponding current electrode half separation (AB/2) on a log-log paper. Auxiliary point diagrams and inverse forward modeling were then used to interprete the data (Zohdy et al., 1974).

## 4. HYDROGEOLOGIC CHARACTERISTICS OF OBAN REGION

### 4.1 Hydrogeoelectric Framework

Vertical electrical sounding (VES) results reflect two-, three- and four- layer conditions (Table 1). The character of each layer is presented below.

*2-layer resistivity model*
The average resistivity of the first layer of this model is 310 Ω m (Table 1). This layer represents highly weathered/decomposed lateritic sandy, gravelly cohesive clay (Fig. 2) and represents regolith layer 1. It has an average thickness of 1.2m. The second layer of this model with average resistivity value of 1750 Ω m constitutes fractured gneissic rock. Groundwater abstraction for the 2-layer model is through hand-dug wells from regolith layer 1 and deep boreholes from fractured bedrock.

*3 – layer resistivity model*
The average resistivity of the first layer for this model is 150 Ω m. The layer is composed of highly weathered/decomposed lateritic sandy, gravelly cohesive clay and corresponds to regolith layer 1. The mean thickness of this layer is 1.0 m (Table 1). The second layer is characterized by average resistivity value of 423 Ω m and average thickness of 27.4. This

layer is made up of moderately weathered schist and gneissic rocks and represents regolith layer 2 (Fig. 2). The average resistivity of the third layer is 1600 Ω m. The average depth to the top of this layer with respect to the ground surface is 28.4 m. The layer is composed of fractured bedrock (Fig. 2). Groundwater abstraction here is through hand-dug well (regolith layer 1), hand-pump fitted shallow boreholes (regolith layer 2) and deep boreholes from fractured bedrock.

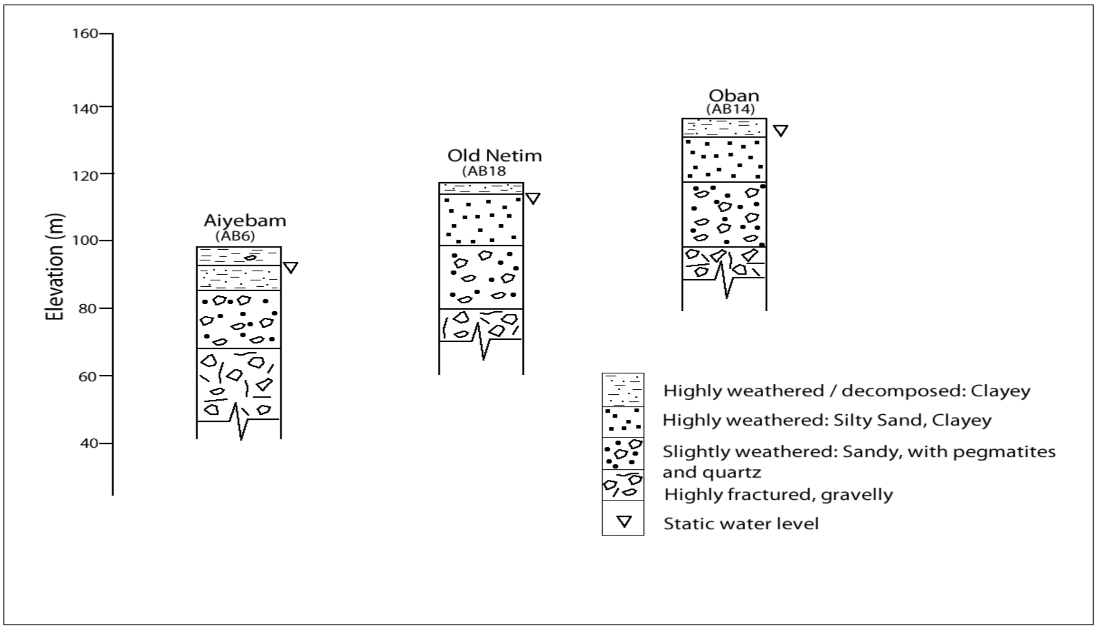


*Figure. 2 Lithological profiles across study region.*

Table 1 Average resistivity and thickness values for different geoelectric layers in Oban massif

| No of geoelectric | | Layer resistivity (Ω m) | | | Layer thickness (m) | | |
|---|---|---|---|---|---|---|---|
| layers | $\rho_1$ | $\rho_2$ | $\rho_3$ | $\rho_4$ | $t_1$ | $t_2$ | $t_3$ |
| 2 | 310 | 1750 | | | 1.2 | | |
| 3 | 150 | 423 | 1600 | | 1.0 | 27.4 | |
| 4 | 433 | 850 | 350 | 2067 | 0.9 | 11.1 | 77.1 |

*4-layer resistivity model*

The average resistivity of the first geoelectric layer of the four-layer model is 433 Ω m. The layer consists of highly weathered lateritic materials (regolith layer 1). The average thickness of this layer is 0.9 m. The second layer is characterized by average layer resistivity of 850 Ω m and thickness of 11.1 m. The layer is composed of moderately weathered basement rock (regolith layer 2). Layer 3 is made up of slightly weathered basement rock. The average resistivity and thickness of the layer is 350 Ω m and 77.1 m. The resistivity is considered to represent regolith layer 3 (Fig. 2). The fourth layer which constitutes the fractured bedrock has an average depth of 89.1 m with respect to the ground surface. The average resistivity of this layer is 2067 Ωm (Table 1). Groundwater abstraction in these locations here is through hand-dug well (regolith layer 1), hand-pump fitted shallow boreholes (regolith layer 2) and deep boreholes from regolith layer 3 and fractured bedrock. The geoelctric models were combined to defined a generalized hydrogeoelectric model for the Oban massif region (Table 2)

Table 2 Hydrogeoelectric model for Oban massif

| Hydrogeoelectric layer (regolith layer) | Geoelectric layer (s) | Resistivity range (Ω m) | Thickness range (m) | Remarks |
|---|---|---|---|---|
| 1 | 1 | 150-433 | 0.9-1.2 | highly-moderately weathered |
| 2 | 2 and 3 | 350-850 | 11.1-77.1 | moderately-slightly weathered |
| 3 | 4 | 1600-2067 | | slightly weathered-fractured bedrock |

**4.2 Regolith aquifer parameters**

The estimated and field hydrogeological data for each identified hydrogeological layer is presented in Table 3

Table 3 Average aquifer parameters from field surveys and empirical relations

| *Regolith Layer* | *Degree of weathering* | *Estimated parameters* Specific capacity $m^3/d/m$ | Transmissivity $m^2/d$ | Hydraulic conductivity m/d | Formation factor | Porosity % | Saturated thickness m | *Field parameters* Average resistivity ohm m | Average saturated thickness m | Depth to bedrock m | Depth to water level m |
|---|---|---|---|---|---|---|---|---|---|---|---|
| 1 | High | 1.32 | 48.65 | 3.73 | 11.11 | 42.44 | 15.10 | 371.50 | 1.05 | < 20 | 2.99 |
| 2 | Moderate | 3.70 | 350.63 | 7.82 | 12.39 | 29.46 | 45.33 | 1166.67 | 20.40 | 20-40 | 6.67 |
| 3 | Slight | 5.56 | 527.00 | 12.18 | 11.99 | 31.25 | 43.50 | 1810.00 | 77.13 | >40 | 5.17 |

***A broad classification based on the depth to basement derived from drill data gives (1) a shallow zone from the surface to about 20 m covering the regolith layer 1 aquifer, (2) an intermediate zone, 20 to 40 m covering the regolith layer 2 aquifer and (3) the deep zone, which extends beyond 40 m depth and is restricted to the lower regolith layer 3 aquifer.***

The average saturated thickness of the regolith aquifer varies from as low as 1.05 m for the upper regolith aquifer (regolith layer 1) to 77.13 m for the lower regolith aquifer (regolith layer 3). This indicates an enormous prospect in terms of quantity of water in the lower regolith aquifer in comparison to the upper and lower regolith aquifers. The average depth to water level (DWL) varies from 2.99 to 6.67 m (Table 3). Areas with shallow water level ( < 3.0 m) indicate that they are highly vulnerable to surface and near surface contamination. The mean specific capacity values (based on the relation, SC= 0.003R + 0.20 where SC is the specific capacity in $m^3/d/m$ and R the apparent resistivity in ohm m; Edet & Okereke 2005) for the regolith aquifers ranged from 1.32 to 5.56$m^3/m/d$. The values increase both with decrease in the rate of weathering and with increase in resistivity.

In this study, due to the lack of pump test data, the K values were estimated from $P_b = 1680{*}K^{-0.87}$ where $P_b$ is the bulk resistivity of rock and K the hydraulic conductivity (Frohlich et al, 1996). The results are presented in Table 3. From the table, the mean values of K for the upper, middle and lower regolith aquifers are 3.73, 7.82 and 12.18 m/day respectively, This shows an increase of K with decrease in degree of weathering. The mean transimissivity values for the upper, middle and lower regolith aquifers are 48.65, 350.63 and 527.00 $m^2$/day. Comparison of the transmissivity values with lithology shows that, it increases with decrease in the rate of weathering (Table 3). The porosities of the aquifer materials were estimated from Archie (1942) relation, $F = 1/\Phi^m$ where F is the formation factor (ratio of bulk rock resistivity saturated with water to resistivity of water contained in the pores), Φ is the porosity and m the cementation factor (m = 2, http://www.geo-hydrology.com). The estimated porosity data (Table 3) show that average porosity values for the regolith aquifers varied from 29.46 to 42.44%. The range of values suggests that porosity increase as weathering intensity increases. In addition, porosity increase as the specific capacity, transmissivity, hydraulic conductivity and resistivity of the regolith material decreases (Table 2).

### 4.3 Groundwater Recharge and resource

The chloride mass balance approach (Anderson 1945, Kitching et al 1980, Sharma and Hughes 1985, Cook and Herczeg 1998) was used to estimate groundwater recharge. The equation , $R=P[Cl]_p/[Cl]_g$ where P is the amount of precipitation, $[Cl]_p$ and $[Cl]_g$, are the concentration of Cl within the precipitation and groundwater. On the basis of this equation, the recharge was computed to be the annual recharge rate to be about 11.12%.
The total amount of groundwater reserve (GR) for the regolith aquifer was determined using the equation, $GR = Atn$ ($m^3$), where cross sectional region (A), t is the saturated thickness of the aquifer obtained from geoelectric sounding and water level measurements in m and n is the porosity. The computation gives a groundwater reserve of $96{,}834 \times 10^6$ $m^3$.

### 4.4 Water chemistry, quality, irrigation applications and management

The physicochemical parameters are presented in (Table 4). The concentrations of majority of the physicochemical parameters considered are within common average values and the WHO (1993) standard for drinking and domestic purposes. The concentrations of nitrate are higher than those normally expected for non-polluted groundwater, 0.12-10 mg/l (Custodio and Llamas 1983). The relatively high concentration of nitrate in the lower aquifer compared to the concentration in the middle aquifer is attributed to the difference in number of samples from each aquifer. A $Na^+/Cl^-$ ratio greater than 1 reflects $Na^+$ released from silicate weathering reaction (Meybeck, 1987). Silicate weathering is the probable source for $Na^+$ in groundwater in parts of study region especially regolith layer 2, the ratio of $Na^+/Cl^- < 1$ in regolith layers 1 and 3 meaning another source is contributing chloride to the groundwater.

Table 4 Physicochemical data for groundwater for the different hydrogeologic layers

| Geoelectric layer | Temp. | EC | TDS | pH | DO | TH | SAR | $Ca^{2+}$ | $Mg^{2+}$ | $Na^+$ | $K^+$ | $Cl^-$ | $NO_3^-$ | $SO_4^{2-}$ | $HCO_3^-$ | Facies |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Regolith layer 1 | 27.80 | 336.33 | 525.03 | 6.60 | 3.27 | 42.23 | 1.30 | 14.93 | 4.12 | 20.58 | 8.83 | 31.83 | 47.94 | 1.59 | 63.73 | $Ca^{2+}Na^+HCO_3^-$ |
| Regolith layer 2 | 28.93 | 101.00 | 157.53 | 6.60 | 3.73 | 54.44 | 0.67 | 14.78 | 3.77 | 10.79 | 2.60 | 4.87 | 10.70 | 3.55 | 68.21 | $Ca^{2+}Na^+HCO_3^-$ |
| Regolith layer 3 | 28.24 | 65.92 | 102.90 | 6.48 | 3.54 | 19.99 | 0.66 | 4.96 | 1.74 | 3.67 | 2.84 | 7.94 | 14.92 | 1.49 | 23.56 | $Ca^{2+}Na^+HCO_3^-$ |
| WHO | | 1400* | 1000* | 6.5-8.5* | | < 75* | | 200* | 150* | 200* | 30* | 250* | 10* | 400* | | |

The ion exchange process is characterized by an ($HCO_3^- + SO_4^{2-}$) excess over ($Ca^{2+}+Mg^2$), while the reverse ion exchange is marked by an excess of ($Ca^{2+}+Mg^2$) over ($HCO_3^- + SO_4^{2-}$) (Cerling et al. 1989; Fisher and Mulican 1997). For the region, the ratio ($Ca^{2+}+Mg^2$)/ ($HCO_3^- + SO_4^{2-}$) < 1 was obtained indicating ion exchange.

In the study region, $\%Na^+$ varied between 22 and 46% indicating suitability of the water for irrigation (percent of $Na^+$ <50%). This is also confirmed by the values of sodium absorption ratio, SAR (sodium hazard), and electrical conductivity, EC (salinity hazard), which showed that water samples are in classes $C_I$-$S_I$ (low sodium hazard-medium salinity hazard) based on the United States Salinity Laboratory (1954) diagram. Some of the management problems include siting of wells and boreholes without pre-drilling investigations, poor well construction, lack of maintenance of boreholes, and indiscriminate disposal of waste, which is threatening the water quality.

## 5. CONCLUSION

An integrated method has been used to delineate and characterize the different groundwater bearing units of the Precambrian Oban massif.

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