

Hydrogeochemical Signatures of Different Aquifer Layers in the Crystalline Basement of Oban Area (SE Nigeria)

A. S. Ekwere

Department of Geology, University of Calabar

E-mail: zerratta77@yahoo.com

A. Edet

Department of Geology, University of Calabar

Received: November 29, 2011 Accepted: December 16, 2011 Published: March 1, 2012

doi:10.5539/jgg.v4n1p90 URL: <http://dx.doi.org/10.5539/jgg.v4n1p90>

Abstract

The shallow and deep aquifer horizons of the crystalline basement of Oban massif of (SE Nigeria) were studied during the dry and wet seasons. The criteria were ascertaining hydrogeochemistry relative to seasonal and spatial variations across the study region. The results obtained show that major elements such as Ca, Mg, Na and K were higher in the shallow aquifers than in the deep aquifers, during the study period. The major anions Cl, SO₄, HCO₃ and NO₃ were higher in the deep aquifers compared to the shallow ones. Two water types were identified for both (shallow and deep) aquifers: Ca/Mg-HCO₃ and Ca/Na-Cl/SO₄. Most of the water parameters considered was within the international limits for drinking and domestic purposes. Assessment by use of Sodium Absorption Ratio (SAR), percent Sodium (% Na) and the Wilcox diagram reveal that the waters are suitable for irrigation purposes.

Keywords: Shallow aquifer, Deep aquifer, Seasonal variations, Hydrogeochemistry, Oban crystalline basement, SE Nigeria

1. Introduction

Hydrogeochemical studies have over the years played an essential role in interpreting mineralogical composition of the sub-surface and inherent conditions in most geological settings. However, this approach has produced more comprehensive interpretation when applied together with other Earth science studies such as structural geology, photo-geology, remote sensing as well as deep geophysics.

In contrast to the large amount of work aimed at quantifying the permeability of unconsolidated and sedimentary rocks, little work has been reported on igneous and metamorphic rocks. Norton and Knapp (1977) stated that the fact that minerals tend to form along the walls of fractures and in veins demonstrates that fluid flow in sub-surface systems is controlled by fracture distribution. The major factor that controls or increases the permeability of igneous and metamorphic rocks is weathering. The combination of near surface weathering and fracturing will increase the permeability by two or four orders of magnitude (Davies and De Weist, 1966 and Davis, 1969). In general these effects are apparent only within the first 20 m below the surface, but can extend down to as much as 100 m in tropical zones (Scheytt, 1997). Variations in groundwater geochemistry have also been shown to be related to the position of the aquifer units (Scheytt, 1997).

In basement terrains, there is a general belief that water exists in fractured rocks and overlying regolith and that such water is usually structurally controlled.

The study area (the Oban massif) forms part of the south-eastern basement complex of Nigeria, which lies between the Archaean cratons of west and central Africa. Recent and on going investigations within the study area notably Edet (1993), Edet *et al.*, (1994), Edet *et al.*, (1998), Okereke *et al.*, (1998), Edet and Okereke (2005) Okereke *et al.* (1998), have led to the delineation of groundwater productive zones, quantitative and qualitative estimation of aquifer parameters within the massif. These have been expressed by interrelations between lineaments frequency and density of regolith development. These assessments have all been achieved based on remotely sensed data, aerial photos, deep geophysics, and geologic logs from exploration boreholes within the

study area. This current research attempts to assess the hydrogeochemistry of the groundwaters relative to aquifer levels within the massif.

2. Description of Study Area

The Oban Massif lies between longitudes 8°00'E and 8°55'E and latitudes 5°00'N and 5°45'N covering an area of about 8,740 km² (Edet *et al.*, 1998), Figure 1. This vast crystalline basement complex is characterised by isolated hills attaining a maximum height of about 1,200 m above sea level at locations on the eastern axis of the massif (Ayi, 1987). The topography exhibits sharp undulations with v-shaped valleys being typically forested at the highest peaks. The massif is well drained, controlled by weathered zones, fractured and jointed areas, coursing in two directions: southwards (seawards) and northwards to join the upper course of the Cross River in the Ikom depression.

The study area is characterized by a tropical climate with two distinct seasons: wet and dry. The wet season spans from May to October, while the dry extends from November to April. The general temperature trend for the study area is high with negligible diurnal and annual variations. The average monthly temperature in the area ranges from 29 to 34 °C. A mean annual rainfall of about 2,300 mm have been reported for the area, with annual mean daily relative humidity and evaporation of 86 % and 3.85 mm/day, respectively (CRBD, 2008). The regional run-off coefficient of the study area is in the order of 0.21-0.61 and is due to topography and evaporation, (Petters *et al.*, 1989).

2.1 Geologic and Hydrogeologic Setting

The Oban massif forms part of the huge spur of the western elongation of the Cameroon Mountains into the Cross River plains of south-eastern Nigeria (Ekwueme, 2003). Rahman *et al.* (1981) reported the rocks of the Oban massif to be dominated by: (1) locally migmatitic and shared gneissic rocks, parashists, phyllites, metaconglomerates and quartzites, amphibolites and metadolerites, foliated pegmatites and aplites, pyroxenites, etc, (2) older synkinematic to late-kinematic intrusive series comprising different rock types such as meladiorites, granodiorites, adamellites to granites and weakly foliated to unfoliated pegmatites, aplites and quartz veins, (3) unmetamorphosed dolerites to microdioritic intrusives. These rock series exhibit variations across the sectors of the massif.

In summary, the Oban massif is described as being underlain by highly deformed Precambrian crystalline rocks, mainly granites, gneisses and schists. These rocks exhibit varying degrees of weathering across the massif. They are intruded by pegmatites, granodiorites, diorites, tonalites, monzonites, charnockites and dolerites (Ekwueme, 1990).

Based on a regional hydrogeological differentiation by Petters *et al.* (1989), the study area has been identified to belong to the basement complex province of the Cross River area of south-eastern Nigeria. Okereke *et al.* (1998) describe the Oban massif to be a three layer hydro-geoelectric stratigraphic model composed of:

- a top unsaturated clayey sand (lateritic);
- middle gravelly sand and decomposed bedrock and;
- fresh bedrock (fractured).

The occurrence of groundwater in the study area has been established to be controlled by structural discontinuities such as fractures, joints, fissures and regolith, (Petters *et al.*, 1989; Edet 1993; Edet *et al.*, 1994). Rates and levels of recharge to porous aquiferous media in the study area, suffer impedance due to the top lateritic cover characteristic of the area, Petters *et al.* (1989). This is attributed to the high clay contents of these lateritic top soils, hence their low permeability.

A low to moderate lineament density has been ascribed to the Oban massif (Edet *et al.*, 1994). This reflects on the depth and extent of weathering profiles and consequently their groundwater potential. There is no general water table for the area, due to the variability of structural and geological controls. However groundwater generally occurs under water table conditions across the massif.

Edet and Okereke, (2005) estimated the water bearing formations of the Oban massif to have a thickness of about 5-140 m. Okereke *et al.* (1998) employing Schlumberger electrical soundings and Werner profiling measurements, reported a 5 m average thickness for the dry overburden and aquifer components between 15-70 m. These layers overly highly resistive fresh bedrock. Groundwater sources from the basement are few, a scenario ascribed to the level of uncertainty and cost of groundwater exploration in the area. Aquifer parameters from the study area are reported in Table 1. Lithologic logs show the main rock types (*e.g.* gneisses, schists, granites, granodiorites, quartzites and amphibolites) revealing four to six layers across the massif. These layers

represent different degrees of weathering processes. Representative sections (A-A' and B-B', Figure 1) across the area, based on drilled data, are presented in Figures 2 a and b.

Two basic aquifer units were identified and boreholes penetrated these layers at different levels across the massif. The aquifers are classified as shallow and deep aquifers relative to depth from surface with respect to the study area. The shallow aquifer boreholes were those with a maximum drilled depth of less than 15 m, hand dug and constituting about 60 % of the total number of sampled bores. The deep wells were those drilled at depths greater than 15 m, extending up to 30 m and beyond representing the remaining 40 % of sampled bores.

The deep aquifer boreholes were mechanically drilled and usually hand pump or motorized pump fitted. This scenario will hence entail the transfer of groundwater between these seemingly successive layers of different degrees of cross-cutting and depth of weathering. The fractures and lineaments act as conduits of groundwater from shallow aquifers to deeper levels. Data from drilled holes litho-sections were obtained for the borehole/deep wells as these were well documented by the government intervention agencies that were responsible for the drilling. Such information were poorly documented or lacking for the shallow hand dug wells, as they were drilled by the local population with no recourse for data documentation.

The drilled well in Oban town shows that the aquifer units are weathered gneissose units with depth between 5 and 10m. The aquifer layer at Abiati village spans between the second and third layers down the drilled section (3-9m) and is characterised by a granitic-gneissic lithology. At Aningeje village the aquifer layer is gneissic-granitic extending from 6 to 15 m down profile. These are for locations on the eastern sector of the massif.

For the western sector, drilled holes at Iko Essai shows a granitic-gneissic unit extending from about 9 to 20 m being the aquifer layer. At Ibogo village the aquifer layer is a micaceous-schistose layer extending from about 4 to 35m down the profile. Lithologic log at Old Netim shows the aquifer layer to be granite-gneiss and biotite-granite-gneiss extending from 3 to 39 m. Ayaebam has a biotite-gneissic aquifer unit (between 6 and 32 m depth), while at Obung village the aquifer unit is pegmatitic-micaceous-gneissic with a depth extent of about 3 to 39m down hole.

Measured aquifer parameters are as presented in Table 2. Static water level was determined by the use of a water depth probe meter. Water levels for the open wells were determined for both dry and wet seasons. This was not possible for the boreholes as such information was only obtainable during borehole construction, prior to their sealing. Static water level varied across the massif through the seasons rising to surface at Camp IV, New Ndebiji and Igbofia in the wet season. The lowest depth of water was recorded at Oban at 6.20 m in the dry season.

3. Physicochemical Characteristics

The geochemical nature of groundwater may depend on the depth of flow paths reflecting effects of the weathered profile and cavity control at different horizons within sub-surface.

Aquifer units within the massif occur basically at two levels: within 15 m from the surface (shallow aquifers) and beyond 15m down hole (deep aquifers). The shallow aquifers were mainly exploited by hand dug open wells, while the deep ones were mechanically drilled, and down hole pumps have been set up. The groundwaters exhibit both physical and chemical variations, from the shallow to the deep aquifers, with recognizable influences of the sampling season. Results of chemical analysis of sampled groundwaters are presented in Tables 3(a) and (b). Assessment of quality of data was accomplished by calculating the ion balance error using equation (1), Hounslow (1995):

$$\text{Error of ion balance} = \frac{\sum \text{cations} - \sum \text{anions}}{\sum \text{cations} + \sum \text{anions}} \quad (1)$$

An error within limits of + or – 5% is tolerable. Approximately all water quality data for this study were within this range. A statistical summary of measured parameters are shown in Tables 4(a) and (b).

3.1 Deep Aquifers

Data from dry season sampling revealed groundwaters from deep aquifers/boreholes to exhibit: pH values between 5.08 and 6.34, temperature ranging from 26 to 32 °C, while electrical conductivity (EC) values are between 34.6 and 326 µS/cm and Total Dissolved Solids (TDS) from 22.18 to 208.97 ppm. In the wet season, pH values ranged from 6.27 to 8.65, temperature from 26 to 30.4 °C, EC from 60 to 430 µS/cm, while TDS values were between 40 to 570 ppm.

Concerning the dry season sampling, chemical species such as Ca^{2+} , Mg^{2+} , Na^+ and K^+ presented concentrations in the order of 12.26 - 122.10 mg/L, 0.42 - 5.38 mg/L, 1.99 - 9.0 mg/L and 0.89 - 3.46 mg/L respectively. Anion analysis of these groundwaters revealed concentrations of 2.50 - 56.98 mg/L for Cl^- , 12.25 - 97.60 mg/L for HCO_3^- , 1.09 - 564.10 mg/L for SO_4^{2-} and 0.003 - 47.51 mg/L for NO_3^- . In the wet season, cation concentrations ranged between 7.06 - 60.11, 0.27 - 3.67, 1.76 - 5.71 and 0.19 - 4.69 for Ca, Mg, Na and K, respectively (all values in mg/L). Anions ranged from 27.99 - 596.60, 18.25 - 213.50, 15.34 - 839.60 and 0.09 - 10.04 for Cl^- , HCO_3^- , SO_4^{2-} and NO_3^- respectively (all values in mg/L).

3.2 Shallow Aquifers

Groundwater samples collected from the shallow wells during the dry season show pH values ranging from 5.12 - 6.86, temperatures between 26 to 28 °C, EC values in the range of 24.8 to 622 $\mu\text{S}/\text{cm}$ and TDS values between 15.90 and 398.72 ppm. In the wet season, pH values ranged from 5.94 to 7.69, temperature was between 27 and 30 °C, while EC values ranged from 80 to 580 $\mu\text{S}/\text{cm}$ and TDS values were in the range 60 to 890 ppm. Chemical analysis of groundwater samples from the dry season had Ca^{2+} ranging from 9.00 to 135.20 mg/L, Mg^{2+} from 0.45 to 5.59, Na^+ from 1.16 to 4.55 mg/L and K^+ ranged from 0.54 to 5.92 mg/L. Anion analysis for these samples revealed Cl^- from 1.02 - 87.47 mg/L, HCO_3^- ranged from 18.30 to 122.30 mg/L, SO_4^{2-} from 1.28 to 117.90 mg/L and NO_3^- from 0.009 to 45.89 mg/L.

In the wet season, Ca^{2+} ranged from 6.04 to 97.14 mg/L, Mg^{2+} from 0.32 to 3.42 mg/L, Na^+ from 2.45 to 7.00 mg/L and K^+ ranged from 0.99 to 45.89 mg/L. Anions showed concentrations values ranging from 22.14 to 308.70 mg/L for Cl^- , from 12.14 to 384.30 mg/L for HCO_3^- , from 13.64 to 471.70 mg/L for SO_4^{2-} and from 0.23 to 11.72 mg/L for NO_3^- .

4. Discussion

For both shallow and deep wells the difference in the physical parameters and average temperatures are insignificant. The difference in pH values is also negligible. pH values close to 7 or higher are characteristic of deep wells and groundwaters of artesian origin (Langmuir, 1997).

Electrical conductivity (EC) and total dissolved solids (TDS) were higher for the shallow wells than the deep wells. The shallow wells are characterized by higher degree of regolith development and abundance of free ions in waters. This can be attributed to equilibrium between the water and soluble rock type (Hem, 1986).

Assessment of results from chemical analyses shows that concentration levels of the major elements are higher for the shallow wells than for the deep wells. These variations in the concentration levels could be attributed to high weathering levels and development of regolith as considered for shallow wells. Clay content decrease down hole due to weathering decreasing and the more open joints or fractures. With greater depth however, the joints are closed yielding less groundwater. Maturity of waters relative to resident times and history of travel along interconnected pore spaces also determine concentration levels of these mobile chemical species in shallow aquifers (Sears and Langmuir, 1982).

Concentration levels of anions are higher in the deep wells than in the shallow wells, with exception of NO_3^- which is higher for the shallow wells. Nitrate concentrations can be used as an indicator of anthropogenic pollution. Levels of about 8.5 mg/L are considered to represent low level contamination (Hallberg, 1989). This could be interpreted for the groundwaters from shallow wells based on their proximity to surface anthropogenic inputs. Probable source of nitrate would be the use of fertilizers in farming and dumping of human and animal waste in the environment.

The noticeable anion content variation trend between shallow and deep waters, could be attributed to higher *in-situ* concentrations of chemical species in the waters of the deeper aquifers with longer resident times of water-rock interaction.

4.1 Hydrochemical Facies

Observations across the massif, shows that shallow groundwaters are diluted waters, slightly acidic with mean pH values of 6.02, and belong mainly to the $\text{Ca}/\text{Mg}-\text{HCO}_3/\text{SO}_4$ facies, and in a lesser extent to the $\text{Ca}/\text{Mg}-\text{SO}_4/\text{HCO}_3$ water type. As the depth of aquifer increases the shallow groundwaters evolve to higher mean pH values of 7.17, become slightly alkaline and $\text{Ca}/\text{Na}/\text{Mg}-\text{HCO}_3/\text{SO}_4$ type waters. The prevailing geochemical signatures of the groundwaters are $\text{Ca}-\text{HCO}_3/\text{SO}_4$. This classification was also proposed by Langmuir (1997), and reflects the processes involved in chemical weathering of silicates and the common occurrence of calcium carbonate.

The apparently dominant $\text{Ca}/\text{Mg}-\text{HCO}_3$ water type is defined as the normal alkaline group of water. Amadi (1987) describes this type of water as typical of Nigerian basement terrain with limited mixing, perhaps

reflecting a primary stage of evolution of its groundwater system. A similar water type has been reported for the western basement complex of Nigeria by Elueze *et al.*, (2004) and Tijani (1994). The chemical composition of this water type is ascribed to the dissolution of silicate minerals in the bedrock and aluminosilicates in the weathered regolith, Tijani (1994). In these waters, $\text{Ca}^{2+} + \text{Mg}^{2+}$ concentrations are higher than HCO_3^- concentrations. Such water type is believed to show permanent hardness with no bicarbonate hazard for irrigation (Naik *et al.*, 2001).

4.2 Irrigation Suitability

The major characteristics of water that determine its suitability for irrigation purposes are: (i) total concentration of soluble salts (ii) relative proportion of sodium to other principal cations and (iii) bicarbonate concentration in relation to the concentration of $\text{Ca}^{2+} + \text{Mg}^{2+}$. These have been called as salinity hazard (Wilcox, 1995), sodium hazard and bicarbonate hazard.

The water suitability for irrigation purposes is better adjudged by its sodium hazard potential. This issue is being called sodium absorption ratio (SAR) and expresses the reactions with the soil. The SAR can be computed as follows:

$$\text{SAR} = \text{Na}^+ / [(\text{Ca}^{2+} + \text{Mg}^{2+})/2]^{0.5}$$

where all ionic concentrations are expressed in milliequivalents per litre (meq/L).

The classification of groundwaters from the Oban massif with respect to SAR is presented in Table 5. The waters from the shallow and deep aquifers from both sampling seasons are found to be less than 10 (limit for excellent water classification), thus they are classified as excellent for irrigation.

Deep aquifer waters have sodium contents between of 2.40 and 29.50 % in the wet season and in the range of 2.64 to 25.66 % in the dry season. The sodium contents in waters from shallow aquifers range from 3.60 to 27.53 % and from 2.53 to 19.12 % in the wet and dry seasons, respectively. These results show that the waters from both aquifer types are within excellent (< 20 % Na) to good (20 - 40 % Na) category.

All the water types sampled in both seasons plot within the excellent to good field of the Wilcox diagram (Figure 3).

5. Conclusions

The waters from the shallow and deep aquifers are slightly acidic in the dry season and evolve to a slightly alkaline nature in the wet season. Calcium and magnesium are the dominant cations which are generally higher in the shallow aquifers. Anions such as Cl^- , SO_4^{2-} , HCO_3^- and NO_3^- are higher in the deep wells for both sampling seasons. Two types of hydrogeochemical *facies* were identified in the area: Ca/Mg- HCO_3 and Ca/Na-Cl/ SO_4 . The water chemistry is influenced by rainfall, weathering processes (mainly silicate weathering) and water mixing. Deductions from SAR and % Na calculations as well as the Wilcox diagram, suggest that the waters can be used for irrigation purposes.

References

- Amadi, U. M. P. (1987). *Mixing phenomenon in groundwater systems and its relevance in water quality assessment in Nigeria*. In: K, Iwugo (ed.) paper presented at the second annual symposium/conference of the Nigerian water and sanitation associated. pp 17.1-17.31.
- Ayi, N. E. (1987). *Geology and Geochemistry of the Eastern part of the Oban massif*. M.Sc Thesis, Dept. of Geology, University of Calabar, Calabar, Nigeria.
- CRBD. (2008). *Hydrogeological survey of lower Cross River Basin: Final Report*. 158p. Cross River Basin Development Authority, Calabar, Nigeria.
- Davis, S. N. (1969). *Porosity and permeability of natural materials*. In: *Flow Through Porous Media*, De Wiest R/JM (ed). New York: Academic Press. pp 53-87.
- Davis, S. N., & De Weist, R. J. M. (1966). *Hydrogeology*. New York: John Wiley & Sons.
- Edet, A. E. (1993). *Hydrogeology of parts of Cross River State, Nigeria: Evidence from Aero-geological and surface resistivities*. PhD Thesis, Dept. of Geology, University of Calabar, Calabar, Nigeria.
- Edet, A. E., & Okereke, C. S. (2005). Hydrogeological and Hydrochemical character of the regolith aquifer, northern Obudu Plateau, Southern Nigeria. *Hydrogeology Journal*, 13, 391-415. <http://dx.doi.org/10.1007/s10040-004-0358-9>

- Edet, A. E., Okereke, C. S. Teme, S. C. *et al.* (1998). Application of remote-sensing data to groundwater exploration: A case study of the Cross River State, SE Nigeria. *Hydrogeology Journal*, 6, 394-404. <http://dx.doi.org/10.1007/s100400050162>
- Edet, A. E., Teme, S. C., Okereke, C. S., *et al.* (1994). Lineament analysis for groundwater exploration in Precambrian Oban massif and Obudu Plateau, SE Nigeria. *Journal of Mining and Geology*, 30(1), 87-95.
- Ekwere, A. S. (2010). *Hydrogeological and Hydrogeochemical Framework of the Oban Massif, south-eastern Nigeria*. Ph.D Thesis, Dept. of Geology, University of Calabar, Calabar, Nigeria.
- Ekwueme, B. N. (1990). Rb-Sr ages and petrologic features of Precambrian rocks from the Oban massif, south-eastern Nigeria. *Precamb. Res.*, 47, 271-286. [http://dx.doi.org/10.1016/0301-9268\(90\)90042-O](http://dx.doi.org/10.1016/0301-9268(90)90042-O)
- Ekwueme, B. N. (2003). *The Precambrian geology and evolution of the Southeastern Nigerian basement complex*. Calabar: University of Calabar Press. 135p.
- Elueze, A. A., Omidiran, J. O., & Nton, M. E. (2004). Hydrogeochemical investigation of surface water and groundwater around Ibokun, Ilesha area, southwestern Nigeria. *Jour. Min. Geol.*, 40(1), 57-64.
- Hallberg, G. R. (1989). *Nitrates in groundwater of United States of America*. In R. F. Follet (Ed.). Nitrogen management and groundwater protection: Developments in agriculture and managed forest ecology (pp. 2-21). Dordrecht: Elsevier.
- Hem, J. B. (1986). Study and interpretation of chemical characteristics of natural water. *US Geological survey water supply paper*, 2, 245-263.
- Hounslow, A. W. (1995). *Water quality data: Analysis and interpretation*. CRC Press LLC, Lewis publishers.
- Langmuir, D. (1997). *Aqueous Environmental Geochemistry*. New Jersey: Prentice Hall, Inc. Upper Saddle River. 07458.
- Naik, P. K., Awasthi, A. K., Anand, A. V. S. S., *et al.* (2001). Hydrogeologic framework of the Deccan Terrain of Koyna River Basin, India. *Hydrogeology Journal*, 9(3), 243-264. <http://dx.doi.org/10.1007/s100400100123>
- Norton & Knapp. (1977). Transport phenomena in hydrothermal system: the nature of porosity. *American Journal Science*, 277, 913-936. <http://dx.doi.org/10.2475/ajs.277.8.913>
- Okereke, C. S., Esu, E. O., & Edet, A. E. (1998). Determination of potential groundwater sites using geological and geophysical techniques in Cross River State, southeastern Nigeria. *Jour. of African Earth Sci.*, 27(1), 149-163. [http://dx.doi.org/10.1016/S0899-5362\(98\)00053-0](http://dx.doi.org/10.1016/S0899-5362(98)00053-0)
- Petters, S. W., Adighije, C. I., Essang, E. B., *et al.* (1989). A Regional Hydrogeological Study of rural water supply options for planning and implementation of phase II rural water programme in Cross River State, Nigeria. Report for Directorate of Rural Development. CRSG, Nigeria.
- Rahman, A. A. M. S., Ukpong, E. E., & Azmatullah, M. (1981). Geology of parts of the Oban massif, southeastern Nigeria. *Jour. Min. Geol.*, 18(1), 60-65.
- Scheytt, T. (1997). Seasonal variations in groundwater chemistry near Lake Belau, Schleswig-Holstein, Northern Germany. *Hydrogeology Journal*, 5(2), 86-95. <http://dx.doi.org/10.1007/s100400050123>
- Sears, S. O., & Langmuir, D. (1982). Sorption and clay mineral equilibria controls on moisture chemistry in a C-horizon soil. *Jour. Hydrol.*, 56, 287-308. [http://dx.doi.org/10.1016/0022-1694\(82\)90019-1](http://dx.doi.org/10.1016/0022-1694(82)90019-1)
- Tijani, M. N. (1994). Hydrochemical assessment of groundwater in Moro area, Kwara State, Nigeria. *Environ. Geol.*, 24, 194-202. <http://dx.doi.org/10.1007/BF00766889>
- Wilcox, L. V. (1955). Classification and use of irrigation water (US Department of Agriculture Circular 969). US Department of Agriculture, Washington.

Table 1. Representative aquifer parameters across the Oban massif

Location /aquifer depth	Static water level (m)	Hydraulic conductivity(m ² /day)	Yield (m ³ /day)	Aquifer thickness (m)	Transmissivity (m ² /day)
Abbiati / (shallow)	5.80	13.42	105.00	24.00	120.80
Akamkpa / (shallow)	4.00‡ 6.00	13.15	190.80	58.00	150.80
Awi / (deep)	10.50‡	13.18† 15.00‡	216.00‡	55.00† 63.10‡	159.12†
Mbarakom / (deep)	9.50‡	10.14†	180.00	40.50† 45.80‡	123.42†
Mfamosing / (deep)		8.53†	-	50.40†	51.00†
Oban / (shallow)	4.70	12.46	164.16 129.60	30.00	132.40
Uyanga / (shallow)	3.89 0.65‡	-	-	22.00	-

† Edet and Okereke (2005)

‡ Edet *et al.* (1998)

Table 2. Measured aquifer parameters from the Oban Massif (adapted from Ekwere, 2010)

Location	SWL (wet)	SWL (dry)	Aquifer layer (m)	Aquifer type
Oban 1	NR	6.20	5-10	deep
Oban 2	NR	3.21	2-10	deep
Abbiati	NR	5.80	3-9	deep
Aningeje	NR	6.00	5-15	deep
Camp 4	0.00	0.48	NR	shallow
New Ndebiji	0.00	0.18	NR	shallow
Iko Essai	NR	7.00	4-20	deep
Ibogo	NR	6.80	3-27	deep
Old Netim	NR	7.00	8-27	deep
Ayaebam	NR	6.20	6-32	deep
Obung	NR	5.80	4-39	deep
Uyanga 1	2.74	5.05	NR	shallow
Uyanga 2	0.38	1.36	NR	shallow
Uyanga 3	1.92	3.10	NR	shallow
Igbofia 1	0.27	0.65	NR	shallow
Igbofia 2	0.11	0.51	NR	shallow
Igbofia 3	0.00	0.62	NR	shallow
Akamkpa	1.51	3.76	3-25	deep
Obio Ntan	2.43	4.92	NR	shallow
Orida-Iwuru	0.67	1.87	NR	shallow
Ekpri Iko	0.18	0.78	NR	shallow
Mbarakom	3.82	5.34	NR	shallow
Ojor 1	2.69	5.36	NR	shallow
Ojor 2	3.88	4.40	NR	shallow
Ojor 3	3.60	5.67	NR	shallow

SWL stands for Static Water Level (m); NR stands for Not Reported.

Table 3(a). Results of representative analysis of sampled groundwaters (dry season)

Sample Code	Temp.	pH	EC	TDS	Na ⁺	Ca ²⁺	Mg ²⁺	K ⁺	HCO ₃ ⁻	SO ₄ ²⁻	NO ₃ ⁻	Cl ⁻
GWB 1	26	5.9	46.3	29.68	3.662	12.26	0.559	1.563	30.5	2.94	1.607	5.998
GWB 2	28	5.86	38.6	24.74	4.339	35.2	5.168	3.455	97.6	30.77	5.892	5.998
GWB 3	27	5.92	42.2	27.18	1.989	30.15	3.604	1.915	48.8	9.091	0.003	2.496
GWB 4	27	5.84	34.6	22.18	2.562	17.02	1.016	1.065	30.5	1.092	0.893	3.499
GWB 5	26	5.14	326	209	4.597	62.06	4.993	3.284	61.02	113.6	8.214	14.49
GWB 6	29	5.08	250	160.3	4.603	30.12	5.198	2.999	30.5	61.54	35.18	33.96
GWB 7	27	5.51	67	42.95	4.401	30.11	0.847	1.449	73.2	564.1	47.51	56.98
GWB 8	29	6.02	72.4	46.41	4.237	122.1	5.337	3.211	128.1	136.4	10.89	19.49
GWB 9	32	6.34	69.2	44.36	2.459	30.11	0.424	0.821	42.8	13.64	0.005	4.998
GWB 10	28	5.4	77.4	49.62	3.745	20.09	2.063	0.809	18.3	5.88	11.25	9.997
GWB 11	29	5.87	50.6	32.44	2.957	15.19	1.789	0.912	18.4	29.41	3.571	3.994
GWB 12	26	5.72	83	53.21	9.00	13.4	4.9	2.08	12.25	1.22	21.2	21.56
GWW 1	26	6.34	56.2	36.03	4.124	118.4	3.498	2.174	73.2	40.91	6.255	10.52
GWW 2	26	6.46	326	20.9	4.382	104.4	5.285	4.463	122.3	45.47	45.89	32.99
GWW 3	28	6.06	46.4	29.74	2.939	7.273	1.369	2.997	30.5	68.18	0.535	2.056
GWW 4	27	5.82	56.8	36.41	3.006	22.26	2.394	0.858	24.7	29.41	8.036	8.996
GWW 5	27	5.97	454	291	4.367	9.002	5.283	5.922	85.4	0.572	4.643	0.801
GWW 6	26	6.04	474	303.9	4.244	54.13	5.586	5.172	18.5	47.06	23.04	92.97
GWW 7	28	5.88	586	375.6	4.951	22.04	5.15	1.847	18.3	43.59	40.01	22.99
GWW 8	27	5.56	616	394.9	4.335	15.02	4.371	4.266	36.6	50.07	19.82	21.93
GWW 9	27	5.62	622	398.7	4.274	135.2	5.281	4.953	48.8	1.282	3.143	87.47
GWW 10	28	6.18	482	309	4.553	22.05	4.424	4.548	36.8	91.18	15.71	23.49
GWW 11	28	5.92	612	392.3	4.408	18.05	4.668	4.941	54.7	117.9	19.46	17.99
GWW 12	26	6.79	48.8	31.28	4.38	21.15	4.007	2.262	30.5	32.35	40.89	17.05
GWW 13	27	5.12	52.8	33.85	3.915	15.07	1.789	2.038	24.6	27.05	4.825	8.52
GWW 14	28	5.71	24.8	15.9	1.163	15.13	0.447	1.645	24.4	5.128	0.009	3.999
GWW 15	27	6.86	52	33.33	3.708	13.15	1.761	0.542	54.9	12.83	1.786	1.022

Notes: GWB – groundwater from deep aquifers; GWW – groundwater from shallow aquifers
 Concentrations in ppm; EC and temperature in $\mu\text{S}/\text{cm}$ and $^{\circ}\text{C}$, respectively

Table 3(b). Results of representative analysis of sampled groundwaters (wet season)

Sample code	Temp.	pH	EC	TDS	Na ⁺	Ca ²⁺	Mg ²⁺	K ⁺	HCO ₃ ⁻	SO ₄ ²⁻	NO ₃ ⁻	Cl ⁻
GWB 1	30.4	6.96	160	110	4.65	7.46	1.01	1.01	72.14	36.25	0.69	128.5
GWB 2	28	6.74	76	120	5.71	26.05	3.67	4.69	97.55	24.99	0.95	256.4
GWB 3	28	7.02	94	140	2.42	12.80	0.37	2.11	52.14	15.34	0.09	56.74
GWB 4	27	6.27	60	40	2.07	8.01	0.27	0.19	24.16	175.2	0.18	27.99
GWB 5	29	6.32	370	570	4.79	18.12	2.86	4.04	58.74	98.2	1.25	98.2
GWB 6	28	6.29	180	120	5.6	11.27	1.83	0.96	18.25	18.24	2.57	149.9
GWB 7	28	7.12	60	40	4.93	7.06	0.56	1.35	36.47	27.29	0.26	232.9
GWB 8	26	7.86	240	370	5.09	42.84	1.96	1.62	94.56	145.7	10.04	187.5
GWB 9	28	8.65	320	190	2.3	8.12	0.4	0.74	67.1	839.6	8.27	123.6
GWB 10	28.5	7.29	430	280	2.96	14.06	0.49	0.6	213.5	294.1	4.14	596.6
GWB 11	27	7.85	180	280	3.01	8.06	2.04	1.32	186.2	188.5	2.14	126.4
GWB 12	28	7.89	120	80	4.97	30.04	2.58	3.86	54.89	36.37	1.8	50.62
GWB 13	29	6.9	310	210	1.76	60.11	1.12	0.74	127.9	31.84	1.94	103.1
GWW 1	28.6	7.69	90	60	2.45	8.03	0.32	0.99	30.41	13.64	0.48	103.5
GWW 2	28	7.06	190	130	6.7	16.03	2.69	29.81	42.63	145.5	2.88	75.48
GWW 3	27	6.55	240	370	2.72	6.04	0.74	1.21	12.62	70.21	0.23	26.74
GWW 4	29.4	6.45	100	70	4.06	18.13	1.29	32.18	48.64	45.5	0.53	105.5
GWW 5	30	6.76	410	290	6.97	22.07	3.42	30.16	66.98	120.5	3.18	130.9
GWW 6	28	6.82	430	570	5.87	67.25	2.92	28.72	24.22	82.4	11.72	180.2
GWW 7	29	6.64	520	780	6.76	28.06	3.06	32.04	12.14	98.6	7.27	194.6
GWW 8	28	5.88	240	170	4.32	11.36	1.64	3.26	24.34	84.09	1.18	104.5
GWW 9	27	5.94	376	540	4.45	97.14	2.78	3.62	21.92	57.4	0.34	126.8
GWW 10	28	6.7	200	140	5.66	15.15	2.07	9.79	36.49	59.09	1.04	48.49
GWW 11	27	6.48	578	890	5.69	13.02	1.99	10.13	48.64	86.21	1.01	33.46
GWW 12	28	7.06	80	120	5.02	16.08	0.99	3.26	28.2	18.16	8.49	28.05
GWW 13	28.5	7.14	120	180	3.72	18.94	1.21	2.56	36.48	42.1	2.13	22.14
GWW 14	27	7.62	580	470	2.65	10.21	0.35	2.58	384.3	471.7	1.98	308.7
GWW 15	27.5	6.98	310	480	4.02	7.66	0.61	1.02	32.14	21.22	0.63	27.29
GWW 16	27	7.64	110	80	4.41	14.22	0.72	32.18	30.48	138.6	0.73	37.99

Notes: GWB – groundwater from deep aquifers; GWW – groundwater from shallow aquifers

Concentrations in ppm; EC and temperature in $\mu\text{S}/\text{cm}$ and $^{\circ}\text{C}$, respectively

Table 4(a). Descriptive statistics of parameters as measured in the dry season

Well Type	Statistics	Temp. (°C)	pH	EC (µS/cm)	TDS (ppm)	Ca	Mg	Na	K	SO ₄	NO ₃	HCO ₃	Cl
Shallow aquifer	Min	26	5.12	24.8	15.9	7.27	0.447	1.163	0.542	0.572	0.009	18.3	0.801
	Max	28	6.86	622	398.7	135.2	5.285	4.553	5.922	117.9	45.89	122.3	92.97
	Mean	27.06	6.02	300.65	180.2	39.49	3.69	3.92	3.24	40.86	15.60	45.61	23.52
	SD	0.79	0.46	255.62	169.72	43.07	1.70	0.93	1.73	32.75	15.67	29.07	28.72
Deep aquifer	Min	26	5.08	34.6	22.18	12.26	0.424	1.989	0.809	1.092	0.003	12.25	2.496
	Max	32	6.34	250	209	122.10	5.377	9.0	3.455	564.1	47.51	97.60	56.98
	Mean	27.83	5.72	96.44	61.83	34.82	2.99	4.05	1.96	80.81	12.18	49.33	15.28
	SD	1.75	0.37	92.31	59.17	30.65	2.06	1.80	1.03	158.8	15.15	35.22	16.18
WHO (2001)			6.5-8.5	1400	1000	100	50	200	12	400	50		250

Table 4(b). Descriptive statistics of parameters as measured in the wet season

Well Type	Statistics	Temp. (°C)	pH	EC (µS/cm)	TDS (ppm)	Ca	Mg	Na	K	SO ₄	NO ₃	HCO ₃	Cl
Shallow aquifer	Min	27	5.88	80	60	6.04	0.321	2.499	0.986	13.64	0.231	12.14	22.14
	Max	30	7.69	580	890	97.14	3.418	6.996	32.18	471.7	11.721	66.98	308.70
	Mean	28	6.84	285.88	333.75	23.09	1.68	4.72	13.97	97.18	2.74	55.04	97.15
	SD	0.92	0.54	176.27	262.57	24.36	1.04	1.46	13.78	107.65	3.41	88.91	79.15
Deep aquifer	Min	26	6.27	60	40	7.46	0.27	1.76	0.19	24.99	0.09	24.16	50.62
	Max	30.4	8.65	430	570	60.11	3.67	5.71	4.69	839.60	10.04	213.5	596.6
	Mean	28.07	7.17	200	196.15	19.54	1.47	3.87	1.79	148.59	2.64	84.89	164.50
	SD	1.08	0.72	124	149.64	16.29	1.10	1.46	1.47	224.93	3.12	59.52	146.17
WHO (2001)			6.5-8.5	1400	1000	100	50	200	12	400	50		250

Table 5. Sodium hazard and percent sodium classification of groundwaters from the Oban massif

Bore depth	Season	SAR (epm)	% Na	SAR classification	% Na classification
Deep aquifer	Dry	0.013-0.181	2.64-25.66	S1(<10) Excellent	<20 Excellent
	Wet	0.012-0.221	2.40-29.50	S2(10-18) Good S3(18-26) Doubtful S4(>26) Unsuitable	20- 40 Good 40- 60 Permissible 60- 80 Doubtful
Shallow aquifer	Dry	0.013-0.138	2.53-19.12		>80 Unsuitable
	Wet	0.019-0.163	3.60-27.53		

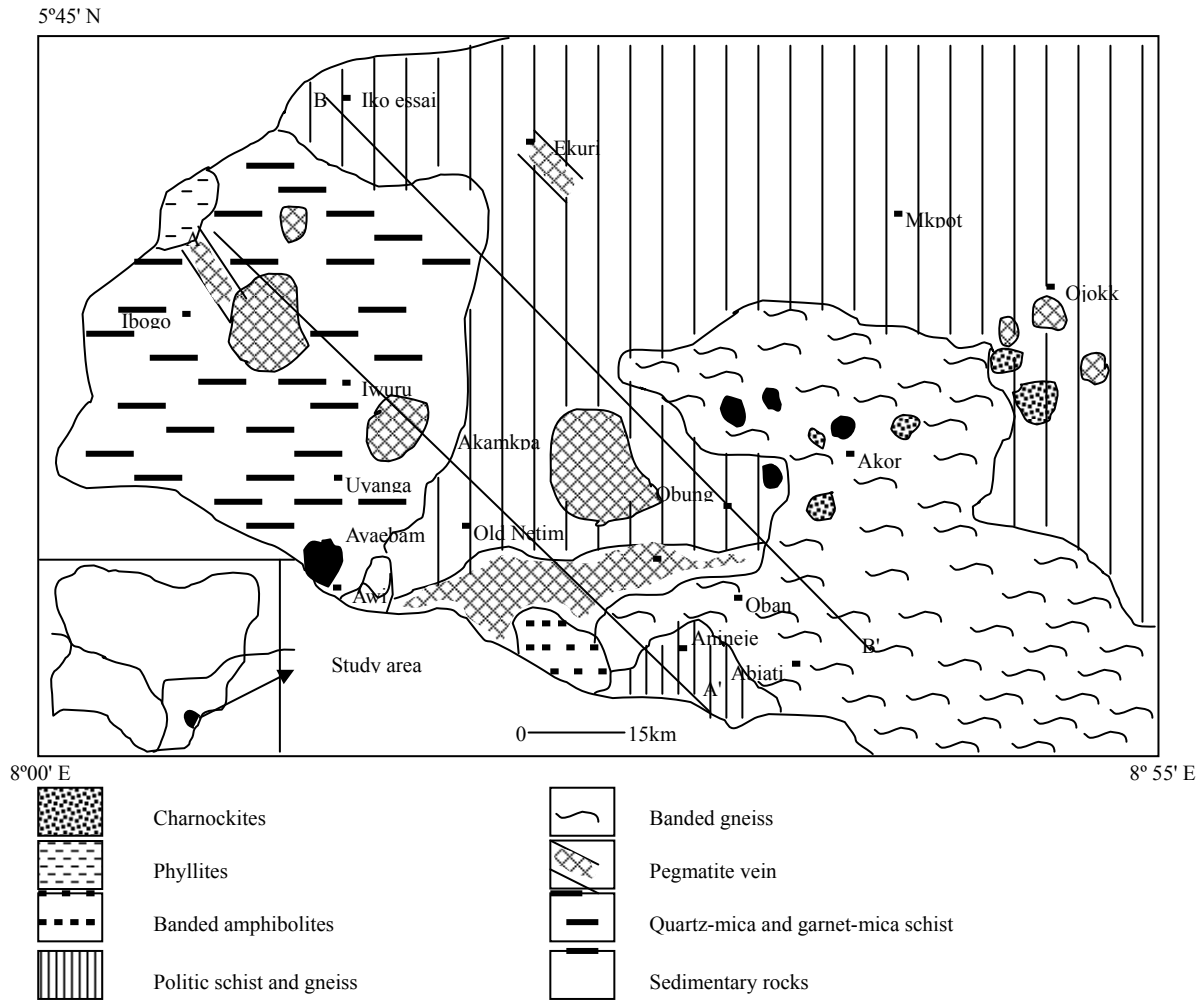
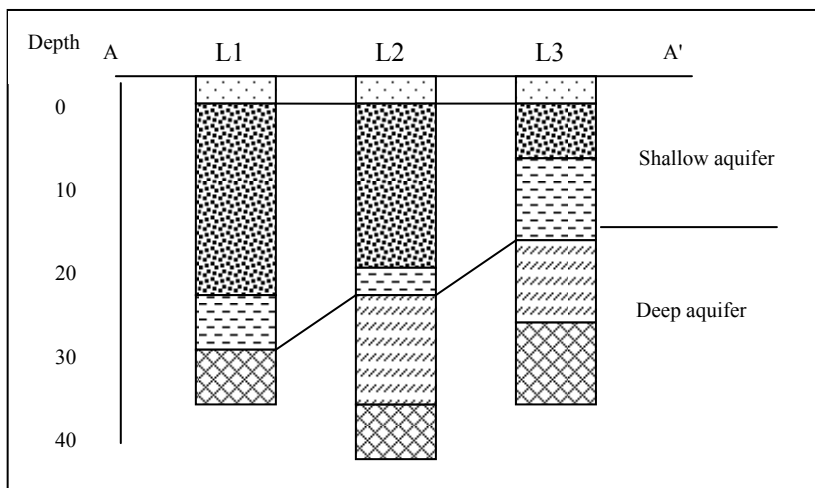
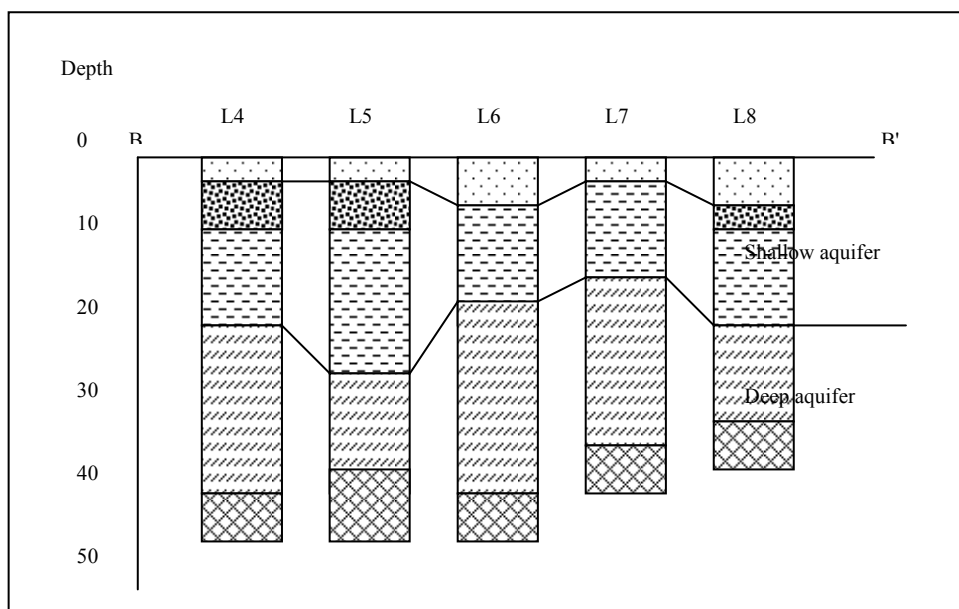


Figure 1. Schematic geological map of the study area (Oban massif): inserted is the map of Nigeria (modified from Ekwueme, 2003)



L1- Ibogo, L2- Ayaebam, L3- Abbiati



L4- Iko Essai, L5- Old Netim, L6- Obung, L7- Oban, L8- Aningeje

Explanation:

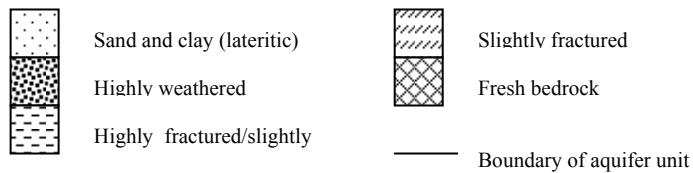
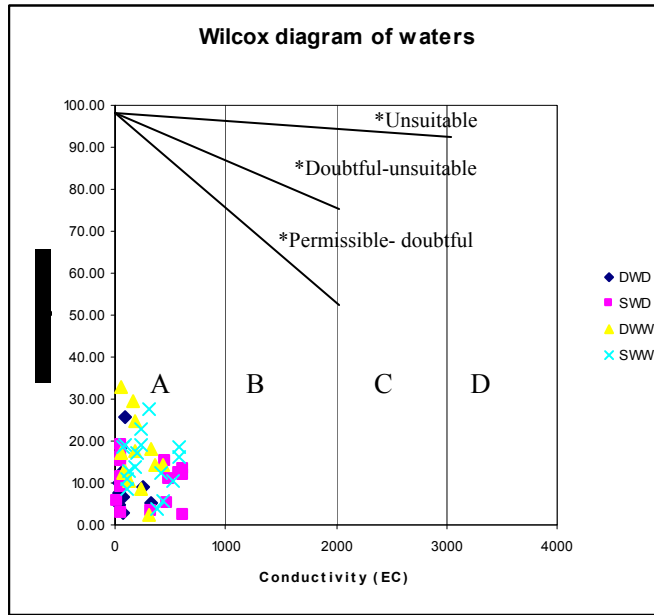


Figure 2. (a) Cross section of drilled wells (section A-A') and (b) cross section of drilled wells (section B-B')



Field: A - excellent to good, B - good to permissible, C - doubtful to unsuitable, D - unsuitable
DWD - deep groundwater / dry season; SWD - shallow groundwater / dry season
DWW - deep groundwater / wet season; SWW - shallow groundwater / wet season

Figure 3. Wilcox diagram for the groundwaters from the Oban massif