BOREHOLE LOG CORRELATION AND GEOCHEMISTRY AS TOOLS IN DETERMINING RECHARGE ZONES TO THE MIDDLE ZONE AQUIFER OF THE CHAD FORMATION IN THE NIGERIAN SECTOR OF THE CHAD BASIN

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ABSTRACT

The continuous decline in hydraulic head of the Middle zone aquifer of the Nigerian sector of the Chad Basin and the increasing water demand by human and animals necessitated a study of the recharge and flow direction of the aquifer. In this work lithologic correlation and geochemistry are used as tools. The lithologic correlations of the Middle zone aquifer indicate possible linkage of the aquifer with the overlying Upper aquifer at the southwestern fringe near Damboa. The chemistry of the water samples indicates that the concentration of most of the elements increases in the direction towards the Lake hence pointing at the southwestern fringe to be a recharge zone. The pH and EC of the water samples were determined with a Combo pH/EC meter. Sodium, potassium, calcium and magnesium ions were determined using Perkin Elmer Analyst 400 Atomic Absorption Spectrometer (AAS). The anions of sulphate were experimentally determined by Lamda 35 Ultraviolet Visible Spectrometer and amount of chloride and bicarbonate ions were determined by titration. The aim and objectives of the research is to determine the recharge zones and flow direction for the Middle Aquifer using boreholes logs of 1960-2010 in addition to their water samples analysis. Different authors gave divergent views on whether recharge into the Middle aquifer is taking place or not. This issue is the main problem to be tackled. This will facilitate proffering solution to its sustainability, realizing that the Middle Aquifer is the most extensive and most exploited of all the three known aquifers in the Chad Formation to date. The major limitations of this study are that: The work relies on existing boreholes as cost of drilling new ones for this study is prohibitive and hence based on locations of existing boreholes.

Keywords: Aquifer, Chad Basin, Middle aquifer, Piezometic head, Recharge zone.
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INTRODUCTION

The Chad Basin is the largest inland drainage in Africa [1] covering an area of about 2,335,000Km^2 [2]. About one-tenth of the basin lying within Nigeria [3] is here called the Nigerian sector of the Chad Basin. This falls within the semi-arid region of Nigeria with average annual rainfall generally below 500 mm and evapo-transpiration in excess of 2000 mm [4]. The surface water resources endowment of the sector is evidently limited. The study area is the Middle zone aquifer of the Nigerian sector of the Chad Basin. The area falls within latitude 11^{o}30'N to 13^{o}30'N and longitude 12^{o}00'E to 14^{o}30'E (Figure 2). In contrast, groundwater has long been recognized as the major source of perennial water supply for the people of the region. Groundwater in the Quaternary Chad Formation in the Chad Basin occurs under both confined and unconfined conditions in three aquiferous zones i.e. Upper, Middle and Lower zones. The Upper aquifer is generally unconfined and semi-confined, while the Middle and Lower Aquifers are confined by argillaceous deposits of 100 – 150 m thick, and boreholes drilled to these zones give rise to artesian wells with piezometric head as high as 20 m above ground level (agl) in the 1960s. However, the most important hydrogeological formation in the Chad Basin is the Chad Formation and covers more than 65% of the basin [5]. It consists mainly of sands, Clays, Silty clays and gravels. Chad Formation is the youngest and the last phase of deposition in the Basin and groundwater in this deposit occurs under both confined and unconfined conditions.

The Middle zone arenaceous horizon stores water and is termed Middle zone aquifer [6]. The Middle zone aquifer is heterogeneous in nature. Because of this heterogeneity of the aquifer materials, there is variability in hydraulic properties. Miller *et al.* [7] subdivides the aquifer into six based on water yielding capability with hydraulic conductivity range from 0.0000428 – 0.000179 m /sec; transmissivity 0.000818 – 0.1141m^2/sec and storage coefficient 0.000014 – 0.00018. However, it was observed that the boreholes tapping this aquifer are of very small diameter < 10 cm in relation to their depth 182 – 365 m, resulting in considerable head loss due to friction. The small diameter is mainly due to cost and for use as piezometers.

The aim and objectives are to determine the recharge zones and flow direction for the Middle Aquifer using boreholes logs of 1960-2010 in addition to their water samples analysis. This will facilitate proffering solution to its sustainability: From the divergent views by different authors mentioned above, the work of [1, 6, 8, 7] seem appropriate to tackle the problems. The major limitations of this study are that it relies on existing boreholes and their locations.

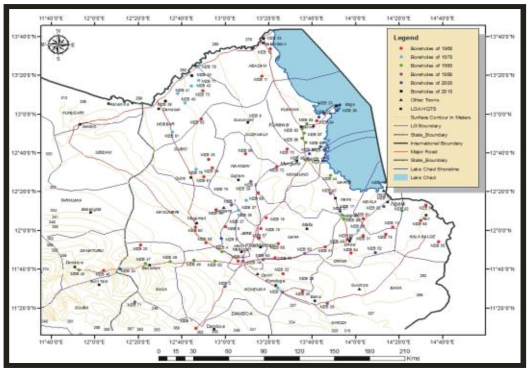

Figure 1: Study area showing distribution of Middle zone aquifer boreholes (Modified) [9].

It is the most extensive and widely exploited of all the aquifers in this region. Boreholes drilled to the confined aquifer yield artesian wells. However, these artesian heads have been declining over the last 30 years due to (a) over abstraction [10] largely because of the uncontrolled discharge from artesian wells, (b) lack of or little replenishments [11-13] and (c) poor borehole construction method [11].

Water demand has increased over the last few decades, due to increase in social and economic development in the region associated with increasing population and changes in the life style of the people due to modernization [10]. This has led to the establishment of some highly water - demanding industries such as soft drink factory, leather tannery and shoe factory etc. which have also put enormous pressure on the Middle aquifer. Many authors [2, 11, 14, 15] etc, by the use of water level indicator for some certain periods of time have attributed the decline in the Middle zone aquifer to over exploitation.

Recharge to the Middle aquifer is speculative; there were two opposing points of views. One is that recharge is not taking place; this view is supported by [16, 17]. These three authors opined that the aquifer is connate/fossil water and receives no recharge directly or indirectly from external source. In a divergent view from the above, [1, 6, 7, 8] supporting their argument with geochemical information claimed that water enters into the Middle aquifer from three distinct areas of intake: an area to the south of Maiduguri, an area in Niger Republic and an area in Cameroun Republic. While, [11- 13] reported that the Middle zone aquifer receives negligible or no recharge from meteoric source by the use of different methods.

From the above-mentioned divergent views by different authors, the works of [1, 6, 7, 8] seem particularly appealing to the focus of this research. In pursuance to this, logs correlation and geochemical techniques were considered as tools.

MATERIALS AND METHODS

A total of 252 lithologic logs of boreholes tapping the Middle Zone Aquifer were collected for correlation from both Government and Private Organizations. The depth of occurrence of Middle aquifer, textural and morphological features such as the grain size, grain morphology and grain sorting were also used in the correlation process. All the borehole logs locations were plotted on a map and correlation lines were drawn along the various directions. All the boreholes on the line were correlated based on lithology.

Geochemistry of the water samples across the correlated profiles was carried out for both major and minor elements. Ninety-six (96) water samples were collected for geochemical analysis. Temperature, electrical conductivity and the pH were measured by the use of portable digital HANNA conductivity meter (Model: H1 98129) testing kit on the field.

The water sample was collected from the main borehole outlet after rinsing the one litre plastic can. The samples were analysed for pH, electrical conductivity (EC), sodium, potassium, calcium, magnesium, bicarbonate, chloride and sulphate using standard methods for examination of water and wastewater of American Public Health Association. Sodium, potassium, calcium and magnesium ions were determined using Perkin Elmer Analyst 400 Atomic Absorption Spectrometer (AAS). The anions of sulphate were determined by Lamda 35 Ultraviolet Visible Spectrometer and amount of chloride and bicarbonate ions were determined by titration.

RESULTS

The results obtained in the measurements are presented, analysed and discussed below. The lithologic logs were used in plotting the trends. The data were used to indicate the trends of the flow direction to the Middle aquifer of the Nigerian Sector of the Chad Basin.

Lithologic log correlation

The lithologic log correlation results of 252 boreholes tapping the Middle zone aquifer are presented in Figures 3 to 8 below. Six cross sections have been drawn for the boreholes tapping the Middle zone aquifer across the Nigerian sector of the Chad Basin in four major directions, SW-NE, W- E, S – N and SE-NW (Figure 2). The conventional [1] cross section is along the SW – NE direction (Damboa – Baga).

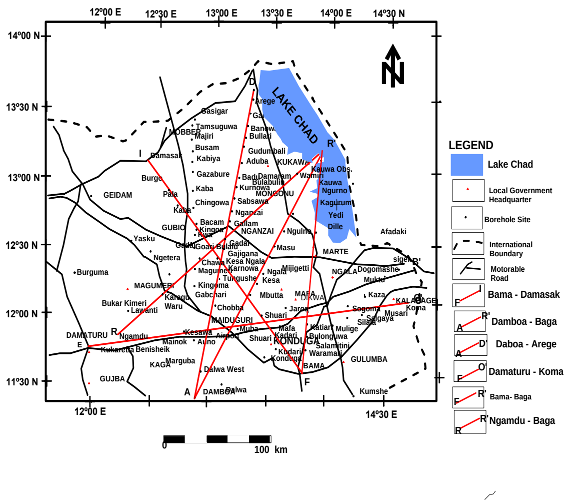

Figure 2: Map of the study area showing lines along which correlation cross sections were drawn. Profiles (Adopted) [18].

The correlations along the southwest – northeast direction are presented in Figures 3, 4 and 5. In general, in this direction the aquifer dips towards the Lake with the aquifer thickness remaining nearly constant, while the confining clay layer increases in thickness northeastwards. The increase in the thickness of the clay layer makes it difficult for water infiltrate from the surface to the aquifer.

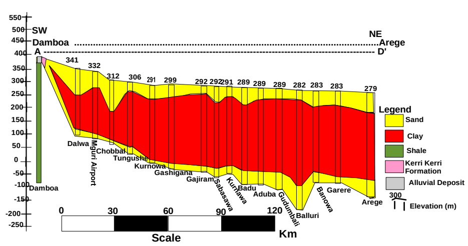

Figure 3: Cross Section from Damboa to Arege (A to D') in Southwest - Northeast direction.

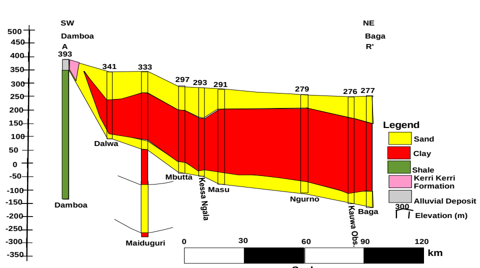

Figure 4: Cross sectional profile from Damboa to Baga (A – R') in SW - NE direction.

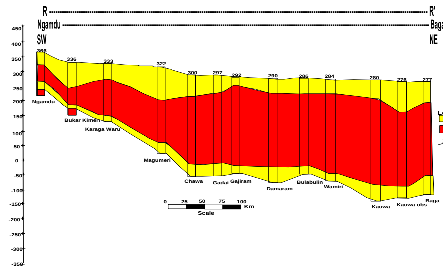

Figure 5: Lithologic correlation diagram from Ngamdu to Baga (R-R') in SW- NE direction.

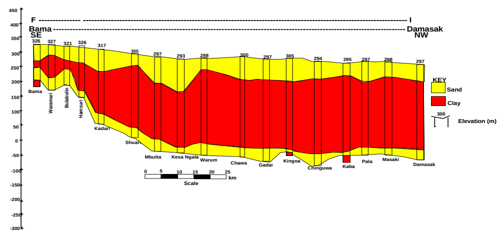

Figure 6: Correlation profile of boreholes from Bama to Damasak (F –I) in SE- NW

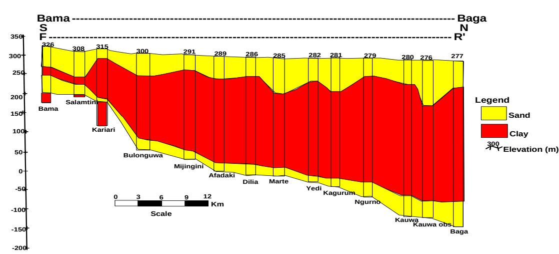

Figure 7: Lithologic correlation profile from Bama to Baga (F-R') in an S - N direction.

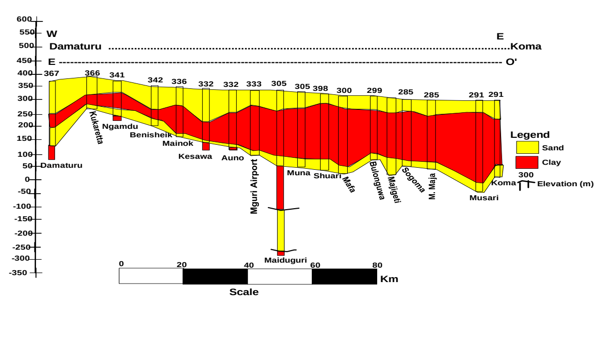

Figure 8: Correlation Section across Damaturu to Koma (E – O') in W - E direction.

Regional geochemistry

The concentration of the various ions measured in mg/L (Y axis) is plotted against the locations.

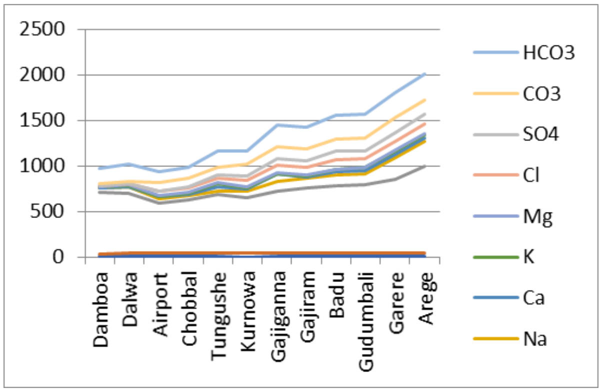

Figure 9: Geochemical analysis of water samples from Damboa- Arege (SW-NE)

DISCUSSION

The Middle aquifer is overlain by about 150 m thick clay in Dalwa west to over 250 m thick clay in Arege about a distance of about 320 km. The Middle aquifer has been expected to have merged with the Upper aquifer and outcrop to the surface near Damboa (9 km to Damboa) as seen in figure 3. Both the Middle aquifer and the overlying clay layer tilt towards the Lake Chad in a northeast direction. The expected merged Middle and Upper aquifers has a thickness of 51 m near Damboa (9 km to Damboa) while the Middle aquifer has a thickness of 63 m Arege .Figures 3, 4 & 5 shows that the depth of the aquifer increases towards the Lake Chad in conformity with the slope of the land surface and swallowing in depth as it approaches the fringes of the basin serving as a recharge zone to the aquifer. These correlation diagrams show the same trend with the conventional [1] profile showing that the three well defined arenaceous horizons within the argillaceous Chad Formation, constitute the aquifers which [6] named "Upper, Middle and Lower Aquifers". The Chad Formation directly overlies the Kerri Kerri Formation unconformably. It varies in thickness from the fringes of the basin to the shores of Lake Chad. This variation in thickness may be due to the irregular relief of the underlying Kerri Kerri Formation or / and variable degree of deposition (figs.3, 4 & 5). Within the basin, the ground slopes gently towards the lake. In the same manner the geological formation dips at about 2 m per km [1] northeast towards Lake Chad, and so the Chad Basin may be described as a "geographical and geological basin" [11]. The clays represent the deposition under less turbulent conditions away from the shore of the Lake or during period when the river flows were low [3]. The increases and decreases in the aquifer thickness might be due to few undulations which can be attributed to channel filling [19]. Also, in a similar development [9], stated that the Chad Formation was deposited on an uneven surface. This might also contribute to the undulations on the surface of the Middle aquifer. The fluctuating Middle zone aquifer and the Clay Formation overlying it become thicker and dip northeast-wards towards Lake Chad following the topography of the land surface.

In Bama the Middle aquifer occurs at a depth of 72 m and clay layer of about 30 m in Damasak (Figure 6). The confining clay layer in Bama prevents the aquifer from outcropping to the surface but by extrapolation the aquifer might outcrop to the surface beyond Bama (22 km) and serve as a recharge zone to the aquifer. Cross- sections along southeast to northwest (Figure 6) shows some variation in thickness of the aquifer, which might be due to the deposition of the Chad Formation unconformably during the Pliestocene and probably Pliocene on the Kerri- Kerri Formation and Older beds. Furthermore, in a related development [10] stated that the Chad Formation dips east and northeast towards Lake Chad in conformity with the slope of the topography and land surface. A subtle trend of increases and decreases in thickness is also observed that vaguely could be associated with high supply of sediments and reduction in energy of the transporting medium (Figure 6). This indicates that thicker deposits would have tended to accumulate in some depression areas along the profile. Also, the Lake must have stood at a high level for a considerable period after the deposition of the zone to allow for the accumulation of the overlying beds of clay [1].

The cross-sectional profile in a south to north direction across the Nigerian sector of the Chad Basin is presented in fig.7. The Middle aquifer occurs at a depth of 72 m and 362 m in Bama and Baga respectively (Figure 7). The Chad Formation indicates a gentle dip and increase in thickness northeastwards towards the centre of the Chad Basin [3]. The changes in thickness observed in figure 7 might be attributable to the deposition of the Chad Formation in or near a large ancestral Lake Chad during late Tertiary and Quaternary times on an uneven surface [10]. Turker [20] also explains such an observation as resulting from channel filling and / or changes in depositional environment.

The Middle zone aquifer is thought [1] to compose of Lake Margin deposits and alluvial fan and delta deposits laid down at the mouths of the rivers which flowed into the Lake ; the sand beds are thought also to occur as lenses of varying thickness and extent [1], while the thickness of the aquifer fluctuates and slopes towards the lake following the topography (Figure 7).

The correlation profile in the west to east direction in the Chad Basin is depicted in Figure 8. Due to the lateral extent of the Middle aquifer there is a major fluctuation in the extent of the Lake during the period that these deposits were accumulating, i.e. advancing or retreating shorelines [1]. Furthermore, apart from minor flexures due to localized subsidence in the underlying sediments, there is no other evidence for the existence of major tectonic structures in the Chad Formation. The structure is therefore thought to be that of a simple shallow basin with little or subdued complicated geological features [11]. In Damaturu the thickness of the Middle aquifer is 70 m and the overlying clay layer of 50 m. By extrapolation, the aquifer might outcrop to the surface beyond Damaturu about 34 km away and receive recharge from rainwater hence making it a recharge zone. The Middle aquifer consists mainly of sands and clays or shales in nature. But of interest, is the fact that most of Nigerian sandstone aquifers give high carbonate / bicarbonate chemical characteristics. du Preez and Barber in 1965 [7] made a similar observation about groundwater from Northern Nigeria. The observation could be attributed to the environment of deposition of the sands, and the matrix binding the sands being calcareous.

The regional geochemistry of other components in the groundwater may then also be used to interpret the reactions between water and rock which have taken place in this aquifer. Some ions / elements are mainly found in surface water / rainwater there by used in tracing the source of recharge to the groundwater. The chemical characteristics of the groundwater show important changes along flow path in the Chad Basin due to geological facies variations in the aquifer system. The cross section from Damboa to Arege is used in discussing the chemistry of the groundwater along the flow path (Figure 3). This path is chosen because all the six profiles in different directions show similar character. The groundwater mineralization expressed in EC (µS/cm) shows increasing values towards the northeast fringe of the basin as seen in Figure 9. The evolution trend gradually increases towards the northeast fringe from 670 – 952 µS/cm which shows mineralization .In terms of low mineralization observed across the flow path could suggest the significance of permeable nature of the Middle aquifer deposits which allows for rapid infiltration of rainwater from the recharge source and subsequently dilution of the groundwater. While on the other hand, the Chad Formation consists of argillaceous sediments; flow through these materials could be very slow and possibly lead to accumulation of salts that may leached to the groundwater, accounting for high EC in Maiduguri (Figure 9) which are above 1000 µS/cm. The chemistry of the porous medium including the matrix of the aquifer, the rate and time of the groundwater flow in the aquifer plays a vital role in the overall chemistry of the groundwater [11].

The low mineralization in the aquifer is supported by the concentration of Cl < 100 mgL^{-1} over the whole aquifer extends (fig.9). If the outcrop part is considered then Cl concentration of about 10 mg/L is observed. The Cl concentration in rain water is < 2 mg/L^{-1} in the Chad Basin area [17] while the average Cl concentration in groundwater at the outcrop area is 10 mg/L. The Cl in the Middle aquifer is contributed by rainfall and enhanced by evaporation. The concentration of Cl that is accounted for by these (rain and evaporation) is from leaching of sediments; explaining the increases along flow line. Generally, the Na concentration increases from 50 mgL^{-1} (Figure 9) in the outcrop area of Damboa to over 250 mg/L in the northeast fringe of the basin at Baga. There are some sporadic increases in concentration of Na in some places about 100 km (Maiduguri) from the SW fringe which is probably contributed to localized deposits of mineral- rich in Na in the area. A third phase of reaction occurs with clay and shales layers inducing high Na concentration to over 260 mg L^{-1} at the shores of Lake Chad. The concentration of Ca is further increased in the water along the flow line by the dissolution of carbonate rocks. Furthermore, the concentration of Ca in the groundwater is low because divalent ions are held more strongly than monovalent ions at surface charge sites [21]. But there is some slight enrichment of Ca in some places around Maiduguri due to localized mineral deposits rich in Ca in the area. The groundwater of the Middle aquifer has Ca concentration increasing from an average of < 10 mg/L^{-1} to < 40 mg/L^{-1} (Figure 9).

The SO_4 concentration generally increases over the whole aquifer with a range from < 10 mg/L^{-1} to > 100 mg/L^{-1} in the study area (Figure 9). The SO_4 content in rainfall is <10mg/L^{-1} in most countries [21]. The relative increase in concentration of SO_4 not accounted for by rain occur as a result of igneous rock minerals of the feldspathoid and further increased its concentration when it comes in contact with a localized evaporite rock sequences around Maidguri along the flow path. The low level of SO_4 as observed could be due to SO_4 reduction that is likely taking place in the aquifer system (Figure 9). The SO_4 reduction process is associated with organic matter [22] and strong enrichment of HCO_3 over Cl (Figure 9) supports the presence of organic matter in the groundwater of the basin and hence the SO_4 reduction in the evolutionary trend.

The K deficiency might be related to the high degree of stability of potassium bearing alumino silicate minerals [21]. Furthermore, the potassium ion is substantially larger than the Na ion, and it would normally be expected to be adsorbed less strongly than Na in ion exchange reaction. The potassium is incorporated in a special way into some clay – mineral structure and they cannot be removed by further ion exchange reactions [21] and thus its lower concentration in the water of the Middle zone aquifer (Figure 9). The concentration of HCO_3 increases along the flow path of the Middle zone aquifer across the study area from 150 – 300 mgL^{-1} (Figure 9). The silicate sediments of the Chad Basin aquifers weather, consuming biogenic CO_2 and producing HCO_3 base metal cations in the recharge zone [18] this further supports the weathering of feldspar.

CONCLUSION

The Middle zone aquifer sediments in the Chad Basin show a unidirectional flow characteristic, with the flow from the fringes to the centre. The recharge zone to the Middle aquifer is the southwestern axis of the basin around Damboa area (9 km to Damboa). Geochemical analysis of the water samples in the correlation profiles points at the direction of increase in ion concentrations from the fringes of the basin to the Lake Chad area. The clay layer between the Middle and Upper aquifer might have pinched out while the two aquifers have merged together around Damboa and outcrop to the surface with a lateral extent of 2 km revealing probably a recharge zone to the Middle aquifer.

RECOMMENDATIONS

The established SW recharge zone to the Middle aquifer (7 – 9 km to Damboa) with a lateral extent of 2 km should be demarcated and protected from constructions of permanent structures to allow for easy recharge to the Middle aquifer. Remote sensing tools to be implored to confirm the recharge zone to the Middle aquifer and possibility of artificial recharge.

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