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ARTICLE

Reassessing Groundwater Potentials and Subsurface water Hydrochemistry in a Tropical Anambra Basin, Southeastern Nigeria

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ABSTRACT

This review presented a detailed re-assessment of the hydrogeology and hydrochemistry of the Tropical Anambra Basin. It identified and discussed the major geological formations and their groundwater potentials. The geological examination showed that the Ajali Formation is confined in places forming an artesian condition; the potentials of this aquifer decline in the western basin due to a decrease in thickness. The sandstone associates of the Nsukka Formation are aquiferous and have produced high-pressure artesian boreholes along the Oji River. The Imo Shale is characterized by permeability stability all over much of the intermediate unit. The Bende-Ameki aquifer has a lesser amount of groundwater when equated to other formations; the geologic characteristics do not produce favorable hydrogeological conditions for groundwater occurrence. The stratigraphical and structural framework suggested the presence of an efficient throughflow in the basin. Based on physical and chemical parameters of water quality, the basin holds water of acceptable quality. While there are considerable investigations on the hydrogeology and hydrochemistry, studies are short of analysis of the hydrogeochemical evolution of groundwater, water quality index, heavy metals pollution index as well as total hazard quotient. Suitability of groundwater based on agricultural water quality indices (e.g. SAR) is also salient. Therefore, future studies should address these owing to increasing dependence on groundwater.

1. Introduction

Groundwater is an indispensable natural resource, which supports human life, biodiversity, socio-economic development, and human health and security [1-6]. As a result of its inherent natural quality, it has become an enormously vital and dependable resource for water supply in all climatic regions [7-9], including the Tropical areas [10]. Groundwater withdrawal is on the rise in both the developed and developing countries as a consequence of growing demands by the manufacturing sector, urbanization, irrigation farming, and mining

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processes [11-15]. The origin, occurrence, and movement of groundwater are primarily influenced by the geological framework [10,16-18], i.e., depths of aquifers, type of lithology, structure, and permeability. In hard rock aquifers, groundwater is confined to weathered horizons or fractured zones. Consequently, broad hydrogeological studies are required to scientifically understand the conditions of aquifers. Typical objectives of any hydrogeological and/or hydrochemical studies are to trace, outline, and assess additional sources of groundwater [10], and their suitability for different uses.

Detailed studies of hydrogeology and hydrochemistry of basins are carried out in different parts of the world [10,19-33]. Results indicated that the cation exchange process and dissolution of soluble salts dominate the hydrochemistry groundwater and the trend of evolution followed the pattern of subsurface water movement projected using a calibrated transient groundwater model [31]. The hydrochemical variability of groundwater tends to be influenced by regional hydrogeological configurations, and excessive evaporation of effluents from irrigated fields that led to evaporites precipitation, e.g. dolomite, calcite, and gypsum. It particularly affects shallow groundwater [30]. Groundwater composition varies with natural geological formations, climate, and land use [34-39].

Nigeria is characterized by multiple geologic formations having different stratigraphy and mineralogy [40-44]. Therefore, groundwater in Nigeria is expected to vary with the natural geogenic processes and land use. Apart from Sokoto and Chad Basins, the Anambra Basin is the third most important basin in Nigeria. Its advantage is that the basin occurs within Nigeria, so it requires no international cooperation. The basin formed a triangular shape and covers about 30,000sqkm. It extends from the south of the confluence of the River Niger and River Benue to areas around Auchi, Okene, Agbo, Asaba, Anyangba, Idah, Nsukka, Onitsha, and Awka [45]. Previous hydrogeological and hydrochemical evaluations of groundwater in the basin showed two groundwater potential zones based the computed transmissivity. The sulfate mineral showed a significant difference in concentration from the Nanka Sandy Aquifers [46].

Groundwater quality is generally excellent for drinking and irrigation uses. The quality of subsurface water is good and satisfied with the World Health Organization (WHO) and the Nigerian standard for drinking water [47]. Similarly, 90% of groundwater sources are suitable for domestic uses in Ngbo and Environs. Groundwater hydrochemistry is strongly influenced by mineral dissolution within the aquifer media [48]. Based on the water quality index (WQI) deep groundwater was categorized as good to excellent in Enugu [49]. In Onitsha and Environs, the geophysical investigation showed a saturated sandstone in the area which is proficient in producing good groundwater yields [50]. The objective of this review is to identify some missing gaps in hydrogeological and hydrochemical investigations in the Anambra Basin.

2. The Anambra Basin

2.1 Location and Climate

Anambra Basin is situated in the south-eastern section of the provincially broad northeast-southwest trending Benue Trough (Figure 1a). It formed a synclinal formation comprising of over 5,000 meters thick of Upper Cretaceous to Recent Deposits signifying the third stage of marine deposition in the Benue Trough [51]. Studies have indicated that the basin was formed as a result of the Late Jurassic to Cretaceous basement breakup, block faulting, subsidence, rifting and drifting apart of the South American and African plates and so symbolizing a part of the West African Rift Systems (WARS). The basin shares a boundary with the Benue Trough system. The two basins are described as a set of pull-apart basins generated by sinistral wrenching along pre-existing Northeast-Southwest transcurrent faults [51]. The topography of the basin is marked by the Udi, Idah, and Kabba cliffs. The Udi and Idah cliffs rise to about 300 meters above sea level [45]. It is drained by the Anambra River and its tributaries, notably the Mamu and Adada. The Anambra River joined the River Niger at an acute angle. Besides, some smaller rivers including Rivers Edion and Osara joined the Niger from the west-eastern axis. The Ankpa escarpment which comprises Idah and Udi cliffs formed a divide that separates the Anambra Basin from the Cross-river Basin.

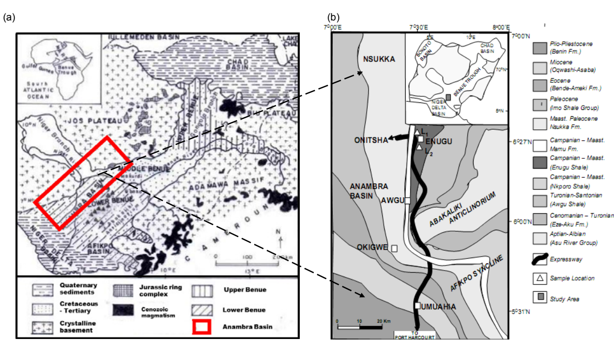

Figure 1. (a) Map of Nigeria Showing Anambra Basin [52] and (b) Anambra Basin [51]

2.2 Geological Setting

The stratigraphic sequence of the Anambra Basin encompasses of the Campanian to Maastrichtian Enugu/Nkporo/

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Owelli Formations (lateral equivalents). This is succeeded by the Maastrichtian Mamu and Ajali Formations [51]. The series is covered by the Tertiary Nsukka Formation and Imo Shale (Figure 1b). The detailed stratigraphic account is presented in several publications [47,51-55]. The paleoenvironments, biostratigraphy, and petroleum geology of the Anambra Basin have engrossed the consideration of numerous writers [51]. The Awgu and Nkporo shales create the major source and seal rocks in the basin. The Nkporo Shale as an example of a sea source rock comprised of type II/III kerogens with minimal but consistent input from marine organic material [51].

However, some reports showed that the organofacies of the Nkporo Shale are regional with the Calabar Flank having the ultimate oil possibility whereas those in the Anambra Basin and Afikpo Syncline are gas prone [56-62]. Besides, the lower Maastrichtian Coals of the Mamu Formation are characterized by moderate to high concentrations of huminite and some minor amounts of inertinites and liptinites [51]. Figure 2 shows the steady-state groundwater flow net across south-eastern Nigeria, which indicates that the escarpments of south-eastern Nigeria are both surface and regional groundwater divides. The figure also shows the steady-state regional groundwater flow net diagram synthesized from hydraulic head values in several smaller drainage basins of south-eastern Nigeria [63].

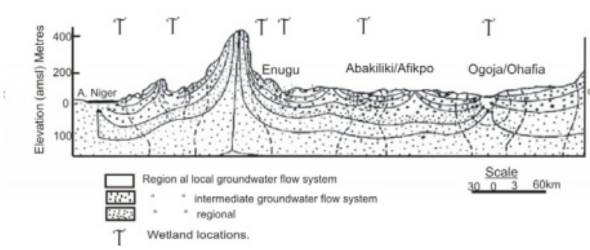

Figure 2. The steady-state groundwater flow net across south-eastern Nigeria [63]

The regions of local, intermediate, and regional systems of groundwater flow as indicated correspond to three distinct hydraulic systems in the basin, viz.:

An upper system with hydrostatic formation pressures;

A middle system with pressures moderately higher than hydrostatic; and

A relatively deep system of abnormally high formation pressures.

The regional flow systems discharge into the rivers Niger, Anambra, and Cross River, while the intermediate flow systems empty into their minor tributaries. Local groundwater flow systems are associated with minor and usually seasonal streams. Towards the center of the basin and coastal areas, local relief is negligible; hence, regional flow systems dominate these areas. The distribution of fluid potentials in the upper and middle hydrostratigraphic units are presented to illustrate that the hydraulic heads and fluid energies are highest at the basin edge to the east where the major aquifers of the unit are exposed and much lower in the basin center to the southwest where the aquifer is kerbed [63].

Hydrostratigraphically, the basin is underlain by the Nkporo, Mamu, Ajali, and Nsukka Formations as well as the Imo and Bende-Ameki Formations (Figure 3). The aquifer units are characterized by two distinct ionic regimes: Ca-HCO_3 and Na-SO_4. The latter is associated with the deeper groundwater flow system within the Mamu Formation while the former occurs in the upper shallow flow system within the Ajali Sandstone [63]. The basin seems to represent an inverted triangular depression with its base along the River Benue axis, and its summit pointing in the direction of Onitsha, along with the River Niger. It lies beneath the geological sequence shown in Figure 3. The Ajali Formation is the most important aquifer in the basin. The aquifer is underlain by Mamu Formation and Nkoporo Shale, 585 meters thick [45]. These formations are comprised of clay, shale, and coal seams, resulting in very poor groundwater potentials. These types of geological formations tend to form aquifers which are either aquicludes or aquitard. The formations also edge the outcrops of the Anambra Basin and incline gently to the southwest beneath the Ajali and the younger formations.

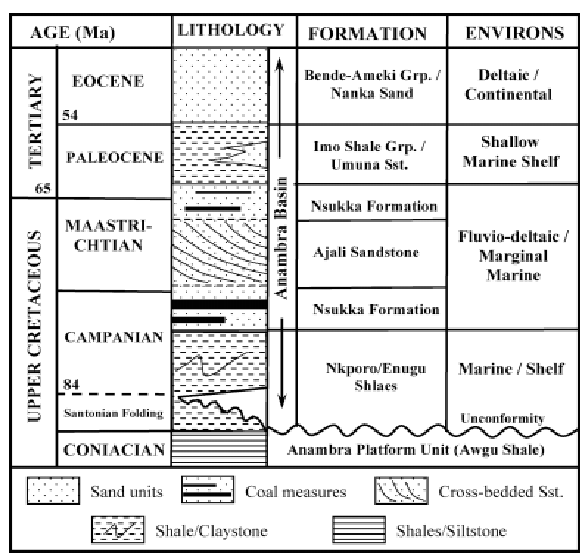

Figure 3. Stratigraphic outlines and depositional environment of the sedimentary formations in the Anambra Basin [64]

3. General Hydrogeological Characteristics

3.1 The Ajali Formation

The Ajali formation, which is over 300 meters thick, is comprised of cross-bedded fine-coarse sands, friable, and very porous sandstone. The formation outcrops at the Idah-Ankpa, and Nsukka Highlands, forming the Enugu cliffs which cover most parts of Ankpa, Idah, and Nsukka axis [54,64,65]. Around Ezimo and Orokam a thickness of about 420 meters was recorded and the older formations incline steadily under the younger formations toward the southwest axis. It is overlain by the Nsukka, Ameki, and Dende Formations as well as the Imo shales, clays, and a thin sandstone layer in Awka, Onitsha, and Asaba [45]. Like the Ajali Formation, the thickness of the Nsukka Formation is over 300 meters. The Nsukka Formation also has the effect confining the aquifers of Ajali Formation. The sandstone beds of the Ajali Formation are confined in places and as a result, formed an artesian condition in some places.

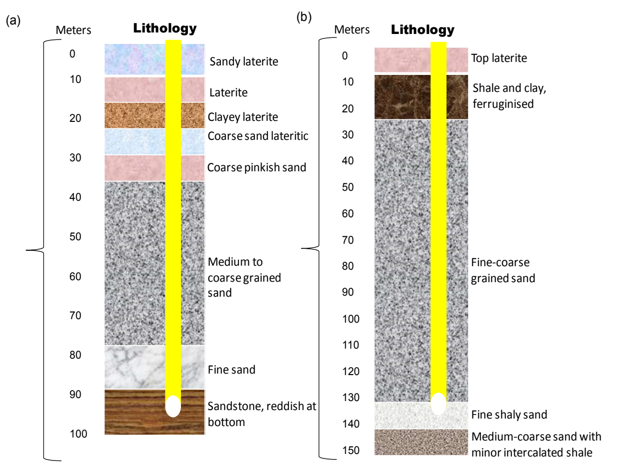

Figure 4. The lithology of the Ajali Formation (a) Borehole No. 3 Ngwo and (b) Umana Ndiuno RCC Borehole, Ezeagu LGC

The aquifer is primarily recharged in the outcrop area by the abundant rainfall and surface flows. Groundwater builds up and moves down under hydrostatic pressure, underneath the confining Nsukka and Imo Formations [45]. Figure 4 shows a typical lithologic section of boreholes penetrating the Ajali Formation. A comparison of the two boreholes showed that the lithology of the Ajali Formation is mainly dominated by fine to coarse-grained sands. Table 61 further summarised data on total depth, borehole diameter, the yield of borehole, static water level, drawdown, and specific capacity of boreholes drilled under the Ajali Formation. The data presented not only showed the groundwater potentials of the Ajali aquifer, but also the heterogeneity and the relativity of water table conditions of the formation. Also important is the generally very deep-water table levels ranging from 30-170 meters across the area of its occurrence [45]. Similar water table conditions can be found in other locations including Ankpa, Idah, Ukehe, and Okpatu areas. Towards the center of the basin, the Ajali aquifer becomes confined resulting in artesian conditions. At Umumbo, some 50 km west of Enugu, a borehole drilled to about 513 meters deep gave a free flow of seven liters per second, with an artesian head of about 15 meters below the ground [45].

Table 1. Total depth, borehole diameter, the yield of borehole, static water level, drawdown, and specific capacity of boreholes drilled under the Ajali Formation [45]

Pumping Station	Date completed	Total depth (m)	Borehole diameter	The yield of Borehole	Static Water Table (m)	Drawdown (m)	Specific capacity ($m^3/hr/m$)
BH No. 3 Ngwo	29/10/75	96.9	17.5 inch	26.3 lit/sec	32.1	47.4	-
BH 5 Awgu	22/11/75	96.6	17.5 inch	13.0 lit/sec	33.5	26.4	-
Umana Ndiuno BH RCC (Ezeagu LGC)	-	234	300mm	$48m^3/hr$	142.5	3.5	13.71
Ibinofia Ndiuno (Ezeagu LGC)	-	200	347mm	$105m^3/hr$	87.85	25.8	-
Olo Amagu/Amadin (Ezeagu LGC)	-	234	-	$162m^3/hr$	9.72	6.0	27.0
Umulumgbe (Udi LGC)	-	247	-	$24m^3/hr$	181.6	1.89	12.7
Awhum	-	330	437.5mm	$169m^3/hr$	159.55	0.38	16.37
Awha Imezi	-	270	437.5mm	$60m^3/hr$	136.0	5.1	11.76
Ubelagu Umuna (Ezeagu LGC)	-	234	437.5mm	$108m^3/hr$	91.23	24.13	4.48
Umaida (Igboeze LGC)	-	190	437.5mm	$72m^3/hr$	102.85	5.52	13.04
Ozalla II	-	250	442.5	$66.8m^3hr$	197.9	9.09	7.33
Nguru (Nsuka LGC)	-	270	347.5mm	$60m^3/hr$	209	13.48	4.45
Ogurute II (Igboeze (LGC)	-	241	347.5mm	$67.2m^3/hr$	140.63	4.77	14.08
Imufu (Igboeze (LGC)	-	216	437.5mm	$792.2m^3/hr$	133.4	7.05	11.23
Obimo (Nsukka LGC)	-	240	347.5mm	$120m^3/hr$	66	15.9	7.55
Iheakpu Awka (Iboeze LGC)	-	200	437.5mm	$68.4m^3hr$	129.45	6.9	9.9
Ekwebe (Iboeze LGC)	-	234	437.5mm	$60m^3/hr$	163.69	12.02	44.99
Itchi (Ibo-eze LGC)	-	200	347.5mm	$110.3m^3/hr$	118.63	7.0	15.7
Ede-Oballa (Nsukka LGC)	-	275	347.5mm	$51.6m^3/hr$	221	4.05	12.74
Amufie Umuitudo (Igbo-eze LGC)	-	255	437.5mm	162.44/hr	157	4.84	33.5
Ohebe-Dim II (Igbo Ekiti LGC)	-	256	437.5mm	$60m^3/hr$	169.12	7.49	8.01

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Hydrogeologically, the cross-bedded Ajali Formation presents a wider local aquiferous stratigraphic unit. It is comprised of the Maastrichtian sand unit, which serves as a vital supplier of water in the Anambra Basin [54]. The formation conformably covers the Mamu Disposition and is partially covered by the Late Maastrichtian Nsukka Formation, which is characterized by irregular sandy and shaly units (Tijani and Nton, 2009). The Ajali Formation outcrops and spreads from Fugar/Agenebode area in the west and extends eastward along the Enugu-Udi escarpment where groundwater is recharged. It further narrows southwards towards the Okigwe area (Figure 1b). The thickness of the Ajali Formation ranges from 350 to 450 meters. The formation thins southward to a few tens of meters around Okigwe. Studies have shown that the higher section of the Ajali Formation is ferruginized in some areas [54,64,66-69]. This condition, joint with the clay/shale unit of the overlying Nsukka Formation and the basal Mamu Formation favors the progression of a confined/semi-confined aquifer system [54]. The following geological succession as illustrated in Figure 5 was reported at the location, some 24 km north of Umumbo.

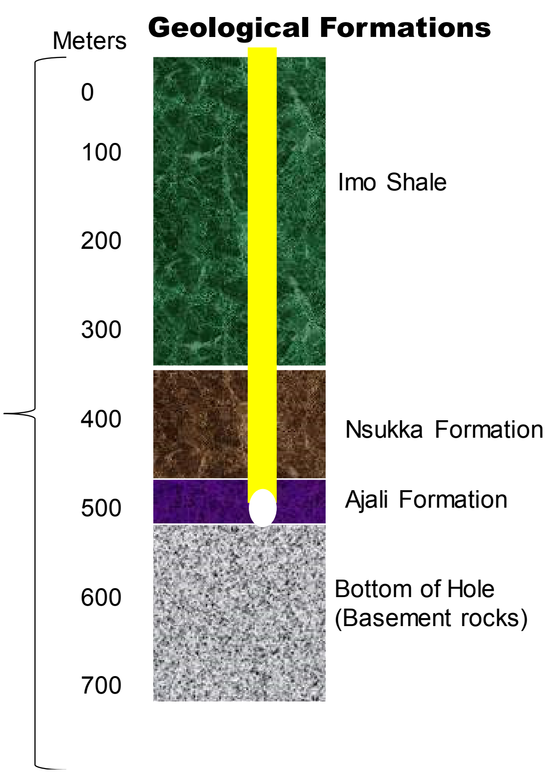

Figure 5. Geological successions in the Anambra Basin

At Uzouwani, the Ajali Formation halted at 180 meters beneath the surface, resulting in a high yield of boreholes (7-9 liters per second). At Agba Umuna the yield was very high (69 liters per second) and a free-flowing head of 30 meters. A yield of about 111 liters per second was also recorded at Mgbagbuowa [45]. The most important hydrogeologic feature of the Ajali Formation is the existence of a cavernous and thick confined and semi-confined aquifer, particularly in places covered by the Nsukka Formation [54]. Though unconfined conditions occur mainly in the outcrop areas of the formation. Also, the existence of a confined floating aquifer network is well pronounced in areas where the lateritised Nsukka Formation arises as outliers on the Ajali Formation. Most of the wells exploiting this profound aquifer have depths ranging from 120 to 200 meters and saturated width ranging from 42-150 meters. However, the yield varies from 10 to 100 m^3/hr. Transmissivity values of 1.0 x 10^{-2} to 1.7 x 10^{-2} m^2/s and storativity of about 0.02 suggest the prolific nature of the Ajali aquifer [54]. Summary of the data of some artesian boreholes drilled in the area is presented in Figures 6-8.

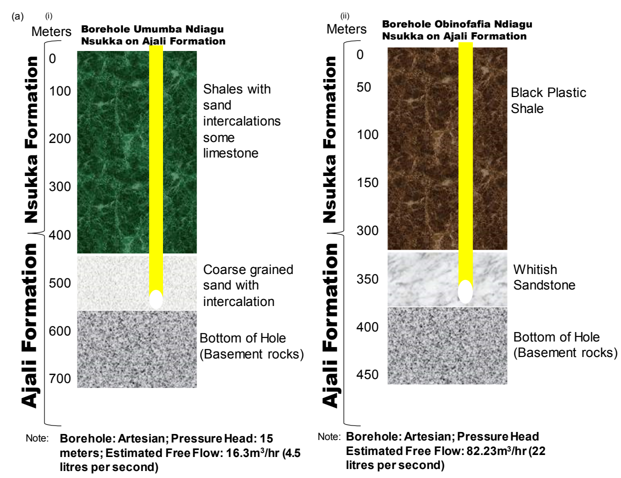

Figure 6. Lithology, Pressure Head, and Estimated Yields of Artesian Boreholes in (1) Umumba and (2) Abinofafia (Ndiagu Local Government Council) in Ajali Formation

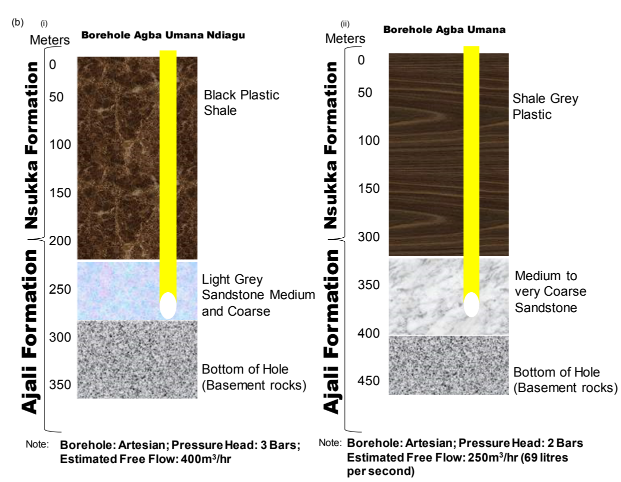

Figure 7. Lithology, Pressure Head, and Estimated Yields of Artesian Boreholes in (1) Agba Umana Ndiagu (2) Agba Umana in Ajali Formation

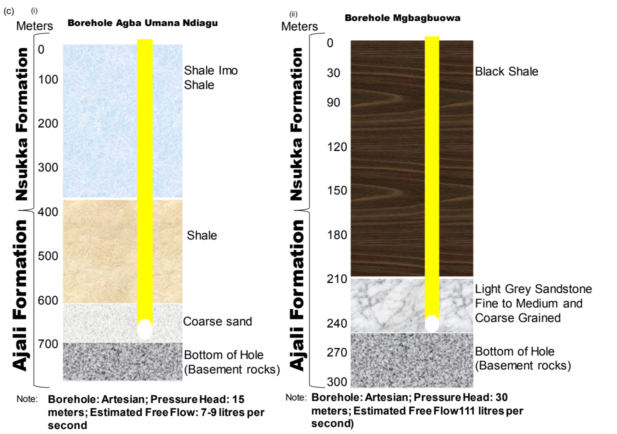

Figure 8. Lithology, Pressure Head, and Estimated Yields of Artesian Boreholes in (1)Agba Umana and (2) Agbagbuowa (Udiagu Local Government Council) in Ajali Formation

However, the potentials of this aquifer, seem to decline westwards due to a drop in thickness [54]. Even so, it should be acknowledged that the friable and porous nature of the Ajali Formation is as a result of environmental/ land degradation, notably, gully erosions in some areas. This also suggests problems in terms of the occurrence of shallow aquifers, as a result of its comparatively high perviousness that lets the whole seeping of water to the cavernous unit of the formation [54]. An Exploratory borehole drilled by the Federal Department of Water Resources at Umulokpa, Uzo Uwani revealed an artesian condition in the area. The well passed through 195 meters of bluish-grey shales of the Nsukka Formation into the sands and sandstones of the Ajali Formation (Figure 9).

The piezometric surface of the Ajali Formation was derived from a general inclination from a depth of about 100 meters near the edge of the cliff, to about 50 meters near the boundary of the Nsukka Formation, where the sub-artesian conditions are attained (20-30 meters) to artesian (+15 - 50 meters) above the ground level, further west [45]. Though within the outcrop sections the aquifer appears to be relatively less porous, as a result of ferruginisation and lateritisation, westwards the perviousness gradually increases as the sands become less cemented, loose, and whitish, suggesting minimal induration with it consequent high yield. This condition is confirmed by the flow net analyses, which indicates a closer cluster of the piezometric contours closer to the cliff, than westwards in the confined artesian areas of the basin, where the contours are spread out, suggesting greater porosity in that direction [45]. The groundwater regime appears to separate into two: a flow trend towards Umumbo, Ndiagu, Mgbagbuowa; and Ndiagu Obinofia, the area that has registered prolific artesian flows.

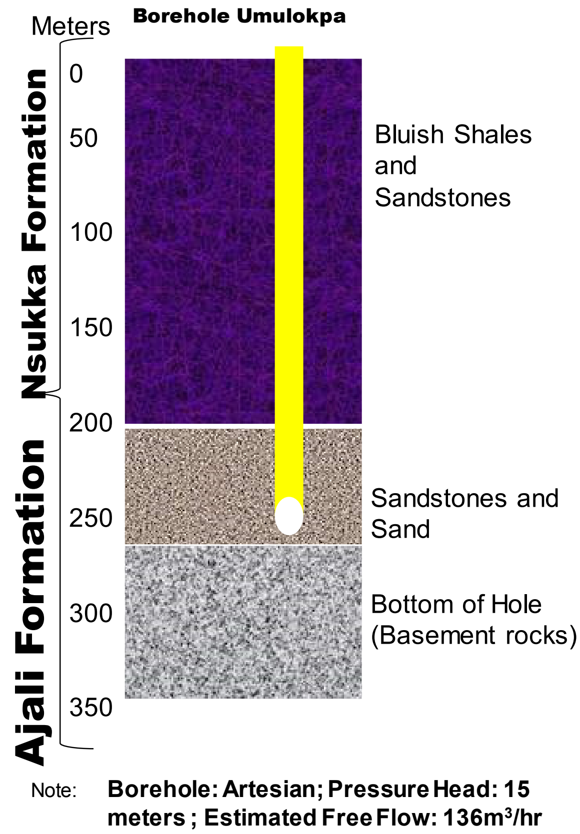

Figure 9. Artesian borehole drilled by the Federal Department of Water Resources in Umulokpa, Uzo Uwani

3.2 Nsukka Formation

The Nsukka Formation covers a wide area in the eastern part of Nigeria, overlying the Ajali Formation. The formation is made up of dark shale, sandy shale, and carbonaceous shales having tinny coal layers [70-72]. Sandstone 15 meters thick occurred at the basal section in the Nsukka area. Along the Oji River, a comparable sandstone layer occurred forming the artesian conditions, at the transition zone between the Nsukka and Imo Formations. The two formations are essentially aquiclude confining the Ajali aquifer westward of the Anambra Basin [45]. The sandstone associates of the Nsukka Formation are aquiferous and have produced high-pressure artesian boreholes along the Oji River. These boreholes include the PTF borehole along Enugu-Onitsha Express Way and a borehole at Akpugo Eze (south of Oji River). These boreholes give a free flow at a depth of 27.8 and 64 meters, respectively. Other boreholes having artesian pressure are the Water Board and Leprosarium boreholes, and Old Oji River borehole constructed in 1913. At Akpgo, flowing layers were run into as indicated by Figure 10.

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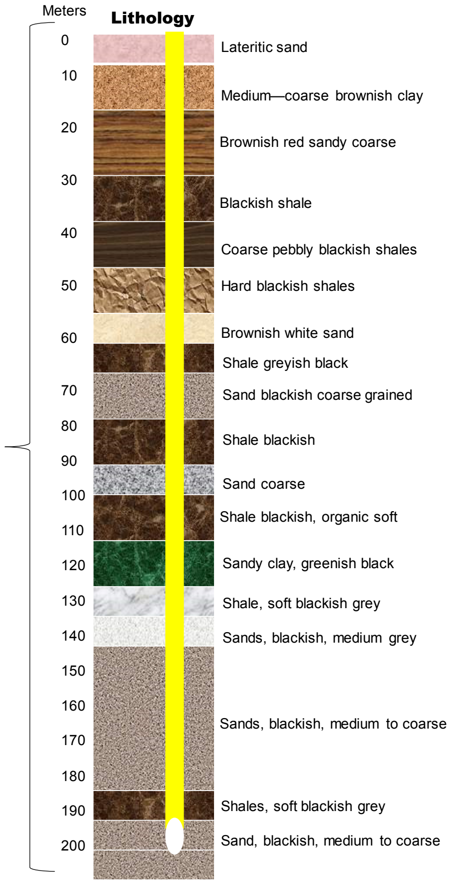

Figure 10. The borehole at Akpugo containing free-flowing aquifers

Uzoije, Onunkwo [73], assessed the groundwater potentials of Southeastern Nsukka. The study showed that the mean annual rainfall of the area is 2.09 x 108 m^3, though the rainfall intensity gives 0.15/year. Overflow for the area was 1.06 x 107 m^3/year, amounting to 5.07% of the total rainfall. Potential evapotranspiration is 1057.98mm/year giving 8.112% of the water available from precipitation. Distance to water table ranged from 106.70 to 9.15 meters from the recharge area of the watershed to the farmland discharge low lying area. Aquifer type ranges from unconfined, semiconfined to confined. The mean transmissivity values were 3.25 x 10-2m^2/s, whereas hydraulic conductivity gives 2.3 x 10^{-3}m/hr. Specific discharge is 2.24 x 10^{-4} m/yr, mean groundwater linear velocity is 4.98 x 10^{-4} m/yr.

The hydrochemistry of deep and shallow aquifers indicates that iron concentration is high. The deep groundwater shows no pathogens, whereas the superficial aquifers show a severe coliform presence. The water class for deep aquifer indicates magnesium and a no dominant anion, whereas the shallow aquifer water is magnesium-sulfate (hard water). The water meets the drinking and industrial standards, though acidic and of elevated iron concentration. The water is good for irrigation use. The study further revealed that the Nsukka aquifer contained water of good quality which is best for reference in the course of the water resources expansion in the basin.

3.3 The Imo Shale

The Imo Formation, popularly known as the Imo Shale, is comprised of blue-grey clays and shales and black shales with bands of calcareous sandstone, marl, and limestone [74-77]. Ostracode and foraminiferal biostratigraphy, and microfauna recovered from the basal limestone unit indicate a Paleocene age for the formation [78]. The basal sandstone unit reflects foreshore and shoreface or, delta front sedimentation (Figure 11). The Imo Formation is the outcrop lithofacies equivalent of the Akata Formation in the subsurface Niger Delta [78]. The three hydrostratigraphic units recognized are divided by thick (>100 meters) clay-Shale units (Imo Shale), which act as confining cots and provide efficient perpendicular seals against the discharge of fluid load [75]. The middle hydrostratigraphic section is the most productive and its surface crag shapes the hydrological frontier in the east and north [79].

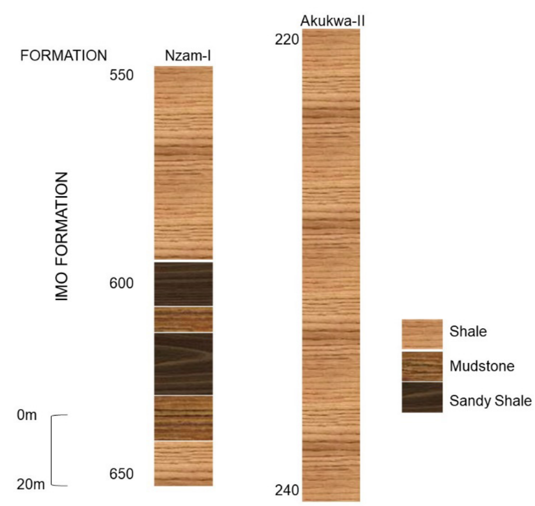

Figure 11. Lithologic section of the studied boreholes [75]

There is a continuous absorbency in much of the middle unit. On the other hand, there are rapid lateral facès changes and interfingering between sandy and Shaley units in both the upper and the middle hydrostratigraphic units [78]. The Imo shale is essential of the Selandian age. This interlude covers 59.4my-56.5my and parallels to F3100-F3500 on the Niger Delta chronostratigraphic chart as revised by the SPDC Ltd in 1998 [45]. The chronostratigraphic table indicates that the interlude comprises of 2/3-order depositional series connected with the 59.4my, 57.5my, and 56.5my first-order progression margins and

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58.1my and 56.3my maximum inundating sides. The succession stratigraphic outline of the Imo Formation is therefore based on the detection and explanation of these series frontiers and sea inundating sides or in crags, and their basin-wide relationship. Four core faces assemblies (depositional faces) which are recognized in the Imo Formation are: (1) tidally-inclined fluvial faces; (2) estuarine cove plug delta; (3) estuarine and oceanic shale faces; and (4) progradational shoreface-foreshore faces assemblies [80]. These faces collections define the reservoir crates, flow sections, and caps (Table 2).

Table 2. Major faces assemblies of the Imo Formation [80]

Faces Assembly	Physical appearance
(iv)	Fine-grained, well sorted sandstones, locally medium-grained, with interbeds of fossiliferous limestone, siltstone and shale. Hummocky cross-stratification, swaley lamination, wave ripple lamination, lenticular bedding, bioturbation, contains bivalve and gastropod shells; trace fossil suite of *Skolithos and Glossifungites.*
(iii)	Mainly bluish-grey shales and black shales with thin interbeds and nodules of coquinas, limestone and sharp-based micaceous siltstones. Hummocky cross-stratification and wave ripple laminations in the sandstones; abundant casts, moulds, and shells of bivalves, gastropods, *Skolithos and Cruziana ichnofacies.*
(ii)	Interbedded fining-upward, well-sorted, and wave rippled laminated, strongly bioturbated sandstone and crudely laminated or mottled / fissile clay and clay Shale; Skolithosichnofacies.
(i)	Profusely cross-bedded, friable sandstone characterised by tidal bundles at lower sections and large scale planar-cross strata up the section. Upper beds may be conglomeratic with distinct pebble horizons; strongly ferruginized; *Ophiomorpha* and *Arenicolites.*

In terms of groundwater potentials, the Imo aquifers have mostly less productive capacity than those of the Ameki formation [74]. Appraisal of groundwater potentials in Okigwe District revealed that the southern region is highly productive in terms of groundwater development and thus the most favorable for establishing boreholes [81]. These findings concurred with Nwankwo, Nwosu [82]'s evaluation of groundwater potentials in Imo State. Based on the longitudinal conductivity, three aquifer system was recognized. The circulation of transverse resistance yielded a comparable result. The results are dependable and coherent with the geological configuration. The north-eastern and western sections of Imo State are more sustainable for establishing productive wells [82].

3.4 Bende-Ameki Formation

Covering the Imo Shale to the west of River Niger, and directly south of the Anambra River, lies the Ameki Formation [79,83,84]. The formation extends far south reaching Okigwe where a large part of its portions was overlain by the Benin Formation [45]. The Ameki aquifer is the major source of groundwater tapped in Onitsha and Asaba. In Onitsha, the aquifer is underlain by a series of sandstones interbedded with shales and reedy limestone layers. The lateral equivalent of the Ameki Formation to the southwest of Anambra Basin is the Nanka sands better developed in Nanka and Nnobi areas. Across the Niger and in the southwest, the Nanka sands are superimposed by lenticular siltstones, clays, and shales with secondary sandstones and lignites, grouping into what is labeled as the Ogwashi-Asaba Formation [85].

The formation grades south-eastward towards the upper Orashi valley into some 270 meters of shales. The sandstones of the Ameki Formation are generally very previous. In Onitsha, a high water table (20-30 meters) was encountered. In contrast, the water table is generally very low in Nanka, Idimili, and Oko (30-300 meters in depths). Therefore, the development of the Nanka sands aquifer can only be achieved through deep wells, except in low lying areas [46,85]. In Nanka, for instance, springs issue profusely at its outcrop points, where the water table is traversed by deep erosional valleys, forming scenic lakes at the top of the hill [45].

The Bende-Ameki Formation of Eocene to Oligocene age comprises of medium-coarse-grained white sandstones. The formations are covered by late Tertiary-Early Quaternary Benin Formation with a southwestward dip [86]. The Formation is about 200 meters thick. The lithology is unconsolidated fine-medium-coarse-grained cross-bedded silts irregularly rocky with concentrated shale and clay. Hydrogeologically, the two major formations have a relative groundwater regime. They both have dependable groundwater that can maintain the local borehole system. The Bende-Ameki Formation has a lesser amount of groundwater when equated to other formations. The various lenticular sand carcasses within the Ameki Formation are not large and represent minor aquifer with tight zones of the sub-artesian condition. Specific capacities are in the range of 3 - 6 m^3,m/hr. However, the high absorptivity of Benin Formation, the overlying lateritic earth, and the weathered top of this Formation, as well as the underlying clay shale member of the Bende-Ameki series, provide the hydrogeological condition favoring the aquifer formation [87].

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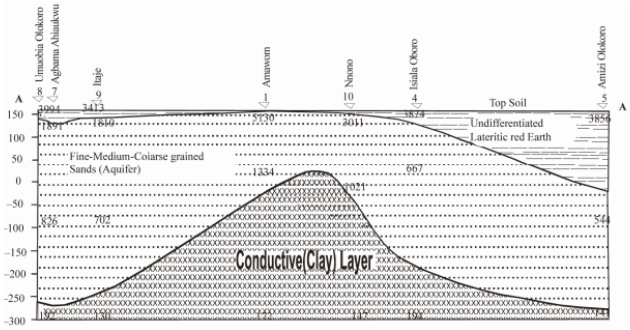

Figure 12. The geoelectrical section along section AA, showing good aquifer (Bende-Ameki) formation [87]

The geological physiognomies of Bende-Ameki Formations do not allow permeation of rainwater because of thick deposits of the lateritic layer rather the rainwater runoff to recharge the aquiferous units that are located within Imo Shale [87]. The fundamental stratigraphic layers underneath the thick surface laterite layer within the Bende-Ameki aquifer lack the hydrogeological property suitable to retain groundwater and transmit it (Figure 12). That is the reason no river drains Ekpoma and no groundwater in the area where Bende-Ameki Formation underlies in Ekpoma and some other pocket places in Irrua. However, areas in Ekpoma and Irrua that lie beneath by Ogwashi Asaba Formation are drained by rivers/streams and even characterized by lakes [87]. The existence of surface water in the area underlain by Ogwashi-Asaba Formation is as a result of the scarp fault (Figures 13a, b) and scarp fault line that is connected with Ogwashi Asaba [88]. The scarp fault forms a conduit via which groundwater moves from the underlying aquiferous unit to the surface as springs, rivers, and streams, while areas where line fault scarp is found, lakes, and artisanal wells are predominant. But, despite Imo Shale has an aquiferous unit, areas that lie beneath by Imo Shale do not have surface water due to the scarp fault and line fault scarp that occurs in Ogwashi Asaba do not cut across or spread to Imo shale [88].

Figure 13. (a) Outcrop section of Ogwashi-Asaba Formation in the boundary line of Ekpoma at Ogidakpe Exposing fault Scarp (b) Faulted portion of Ogwashi-Asaba Formation that forms spring by the fault Scarp at AAU Dam in Ekpoma [88]

The groundwater and surface water occurrence in the study area (Ekpoma and Irrua) is geologically and structurally controlled. Areas in Irrua and the pocket of places in Ekpoma that are underlain by Imo Shale and Ogwashi Asaba have groundwater since the two formations have thin aquiferous units. The aquiferous units in Ogwashi Asaba are about 3.7 meters. The aquiferous layer within Imo Shale is one. It is located at a depth of 78 meters or above depending on topographic location with a thickness of fewer than 4 meters [88]. The reedy aquiferous units that occur in Imo Shale and Ogwashi-Asaba Formations [76,89] is largely responsible for the inability of water pumping machine to sustain continuous pumping in a conventional borehole. As a result, the borehole is drilled by hands in the area to have a larger surface area of exposure to the aquifer to avoid water-cut while pumping. Ekpoma is mainly lying beneath by Bende-Ameki Formation except for some pocket of areas that are located in the extreme boundary line where there is formation transition to either Imo Shale or Ogwashi-Asaba [88].

The geologic characteristics of the Bende-Ameki Formation [86,90], do not produce favorable hydrogeological conditions for groundwater to occur, as a result, Ekpoma town does not have water and parts of Irrua that are underlain by Bende-Ameki Formation. Apart from some pockets of areas in Ekpoma that fall within the extreme boundary line, deep borehole drilled into the older formations through Bende-Ameki Formation up to Ajali Sandstone to a depth of 297 meters or over and 396 meters depending on the topographic location and aquifer depth of over 27 meters that can sustain continuous pumping [88]. The underlying aquifer can be easily exploited in Ekpoma town but at such depth, drilling of the borehole is very expensive. The water contains iron since the Ajali Sandstone that lies beneath Ekpoma is highly ferruginous. Hence water at that depth within Ajali Sandstone needs treatment for excess iron content [88]. This deep aquiferous unit which exists within Ajali Formation that underlies Bende-Ameki Formation in Ekpoma in the aquiferous unit where GT Bank's borehole and the State Government's Borehole in the Market Square get their water from. That is the reason the boreholes yielded a large amount of water without many drawdowns during continuous pumping.

The Ameki Formation is unconformably covered by the continental sandstones of the Ogwashi-Asaba and Benin Formations [89,91,92]. From the Okitipupa Ridge, this formation occurs in a flared crag pattern through Asaba, Onitsha, and Uyo to Calabar [93]. The outcrop area is at Eke-Mgbalingba in Ogwashi-Asaba. Beds are horizontal to near horizontal, as such can be termed as undeformed. The area is drained by the Otamiri, Njaba, and Oramiri-

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ukwa, the Nwaorie Stream, and the ephemeral Okitankwo Stream. Groundwater recharge is mainly from surface runoff and groundwater baseflow [93]. The absorbent and pervious sands and interfering sandy clay and gravels of the Benin Formation form a multi-aquifer system in which aquifer units are divided by semi-permeable sandy clay aquitards [93]. Three aquifer units are recognized in the area. These are; (1) an upper water-table (unconfined) aquifer, (2) a middle semi-confined aquifer, and (3) a lower confined aquifer.

The base of the upper water-table aquifer is at a maximum depth of 100 meters. The middle semi-confined aquifer has a typical width of 80 meters, and the lower confined aquifer has an approximated width of more than 600 meters. The aquifers have high storativity and transmissivity. Borehole yields range from 54.2 to 231.5 m h^{-1}. Effective hydraulic conductivity ranges from 5.6 x $l0^{-9}$ to 1.44 x 10^{-3} ms^{-1}, the higher value being in the coarse sand and gravel units. The depth to the water table is about 60 meters in the north decreasing southward to less than 20 meters; the hydraulic-head gradient is 9-22% [93]. As recharge water meets the Ajalli sandstone unit, the water obtains small concentrations of Na and Ca due to the dissolution of calcite and feldspar. On running into the shale unit, Na would be exchanged for Ca, thus resulting in a slight rise in Na concentration, and a decline in Ca.

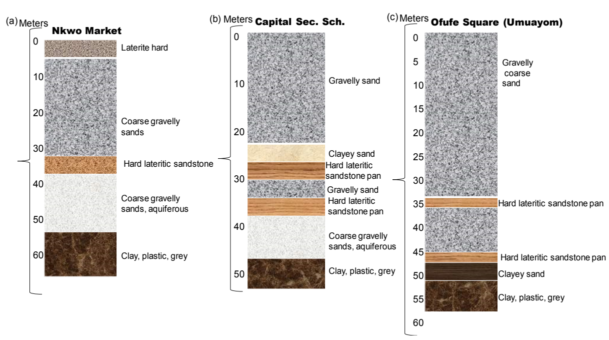

Figure 14. A typical borehole lithological log in Awka (a) Nkwo Market, (b) Capital Secondary School, and (c) Ofufe Square

However, in Awka, several hand-dug shallow wells tap the aquifer [94-97], at a depth between 15 meters in the low-lying areas, to 60 meters over the highland. The uppermost layer is marked in places by a hard-lateritic pan which confines it and separates it from the overlying clayey section of the Imo-Clay Shale. The sequence comprises of gravelly coarse sands, interbedded towards the base, by the very hard lateritic sandstone pans [45]. A typical lithology of the borehole in Awka is illustrated in Figure 14 a, b, c. The stratigraphical and structural framework, as well as the available groundwater chemistry, seem to suggest the existence of an effective throughflow across the basin. This seems to show that the water in the Mamu aquifer is much younger than would be expected based on the velocity calculations [98]. However, in Awka, several hand-dug shallow wells tap the aquifer at a depth between 15 meters in the low-lying areas, to 60 meters over the highland.

Borehole from the Ameyi sandy aquifer and Ugwuoba sandstone aquifer is likely to be more productive. The Ajali aquifer in the Awka zone is very deep to be economically viable and cannot be well-thought-of been a groundwater source in this area. In Agulu, Nanka, and Ekwulobia areas (south) the major aquifer is the Nanka sands. The water table is generally very low, with about 89 meters in Agulu, 137 meters in Nnobi to 230 meters at Igboukkwu, the town with the deepest water table. The deep-water tables are obtained in boreholes located in the lowland areas or valleys usually spreading the mainly mountainous region [45].

4. Groundwater Hydrochemistry

4.1 Physical Chemistry

Anambra Basin is endowed with innumerable abundant natural groundwater sources. Quite a lot of isolated studies of the water quality of the basin have been undertaken by several types of research. This section attempts a review of these works and offers a guide to the understanding of the physicochemical characteristics of the groundwater sources and the aquifer system in the basin for more effective groundwater quality management. Figure 15 presents a summary of the physical chemistry of aquifers in the Anambra Basin. It is assumed that groundwater should be free of predilections and fragrances that would be unacceptable to the users [99]. In evaluating the quality of drinking water, water users depend mainly on their sensations. Physical, chemical, and microbial elements of water can affect the odor, taste, or appearance, and the user will consider the acceptability and quality of the water-based on these standards. Even if these elements may have no direct health effects, highly turbid water, is exceedingly colored, or has an unpleasant odor or taste might be deemed by users as risky and rebuffed [99]. In risky circumstances, users might dodge aesthetically objectionable but then safe drinking-water in preference of more enjoyable but possibly perilous sources. Some physical constituents of groundwater are presented in Figure 15.

Data on pH, temperature, EC, TDS, alkalinity, TSS, DO, turbidity, and salinity were synthesized from the literature and the result showed water of excellent quality for drinking and domestic uses. The water of low salinity is generally composed of higher proportions of calcium, magnesium, and bicarbonate ions [100,101]. Moderately sa-

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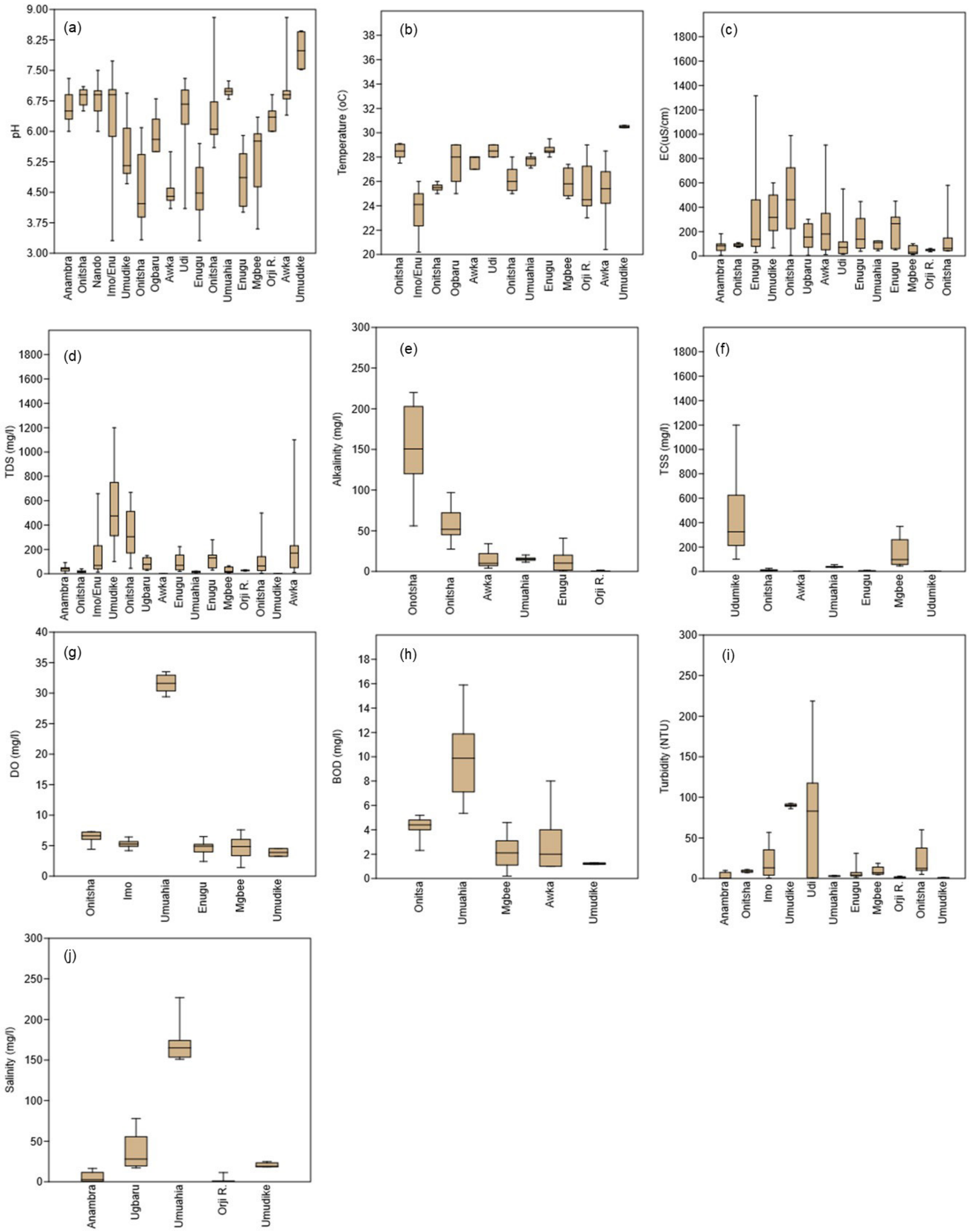

Figure 15. Physical parameters of water quality (a) pH, (b) Temperature, (c) Electrical conductivity, (d) TDS, (e) Alkalinity, (f) TSS, (g) DO, (h) BOD, (i) Turbidity, and (j) Salinity

line water have varying ionic concentrations. High saline waters consist of mostly sodium and chloride ions [102,103]. Groundwater containing a high concentration of sodium, bicarbonate, and carbonate ions tend to have a high pH level [104]. Groundwater classification based on pH showed that 54.03 % of groundwater sources in Anambra Basin have pH less than 6.5 (acidic), 35.07 % have pH ranging from 6.5 to 7.0 (neutral) and 10.90 % have pH greater than 7.0 (alkaline), as contained in Table 3d. Based on basic physical constituents (pH, TDS, EC, and Hardness), groundwater in the Anambra Basin is suitable for drinking.

Table 3. Groundwater classification based on hardness, TDS, Conductivity, and pH

(a) Hardness (CaCO3) mg/l	No. sites	Percentage (%)	Classification
0 - 75	108	80	Soft
75 - 150	27	20	Moderate Hard
150 - 300	0	0	Hard
>300	0	0	Very Hard
Total	135	100	
(b) TDS (mg/l)			
Less than 500	182	94.79	Essential for drinking
500-1000	8	4.17	Required for drinking
1000-3000	2	1.04	Suitable for drinking
Greater 3000	0	0.00	Unsuitable for drinking and irrigation
Total	192	100	
(c) Conductivity (μS/cm)			
250-750	179	98.35	Good for drinking
750-2250	3	1.65	Permissible
Greater than 2250	0	0.00	Doubtful
Total	182	100	
(d) pH			
Less than 6.5	114	54.03	Acidic
6.5-8.5	74	35.07	Neutral
Greater than 8.5	23	10.90	Alkaline
Total	211	100	

Based on total hardness, 80 % of sources of groundwater in the Anambra Basin are soft and 20 % moderately hard as indicated in Table 3. Total hardness in Anambra Basin ranged from 0-195.12 mg/l. Hardness less than 75 mg/l is especially required for drinking. TDS ranged from 0.001-1200.00 mg/l. Based on TDS 94.79 % of sources of groundwater are essential for drinking. Also, 4.17 % have TDS ranging from 500-1000 mg/l and 1.04 % have TDS ranging from 1000-3000 mg/l as contained in Table 3. Electrical conductivity ranged from 5.30-1315.00 μS/cm in the Anambra Basin. Based on conductivity 98.35 % have EC varying from 250-750 μS/cm and 1.65 % have EC ranging from 750 2250 μS/cm (Table 3c).

4.2 Cation Chemistry

Figures 16 and 17 summarized the cation chemistry of groundwater in the Anambra Basin. There are few reports on Aluminum (Al). Hydrogeochemical analysis in Nando and Environs by Egbunike [53] showed that Al ranged from 0.58-2.9 mg/l. Arsenic (As) ranged from 0.00025 to 0.80 mg/l. Low As concentration in drinking water is required owing to its adverse effects on human health (cancer). Based on WHO [105], provisional guideline 0.01mg/liter value was proposed. The guideline value is designated as provisional given the scientific uncertainties. Arsenic levels in natural waters generally range between 1 and 2mg/ liter, although concentrations may be elevated (up to 12mg/ liter) in areas containing natural sources. There remained large ambiguity over the definite risks at low intensities and existing data on mode of action do not present a biological source for utilizing either linear or non-linear extrapolation. Given the significant ambiguities bordering the risk estimation for arsenic carcinogenicity, the rational quantification limit of 1-10mg/ liter, and the practical difficulties in eliminating arsenic from aquifers, the guideline value of 10 mg/l is maintained. However, given the scientific doubts, the guideline value is defined as interim [105].

Barium (Ba) in the ranged from 0.02-186.9 mg/l. Barium concentrations in drinking water are generally below 100 mg/l, though concentrations above 1mg/l have been measured in drinking water derived from groundwater [105]. The guideline value for Ba is based on an epidemiological study in which no adverse effects were reported, though the study population was relatively small, and the power of the study was limited. As a result, an uncertainty factor of 10 was applied to the level of Ba in the drinking water of the study population. Nevertheless, the level at which effects would be seen maybe significantly greater than this concentration, therefore, the guideline value for Ba may be highly conservative and the margin of safety is likely to be high.

At a moderate concentration in drinking water Ca is beneficial. But high concentrations Ca in conjunction with Mg form carbonate hardness [106,107]. Calcium ranged from <0.001 to 240 mg/l. High levels of Ca in drinking water may be beneficial and aquifers that are rich in calcium are very tasty. There is some proof to indicate that the incidence of heart disease is lessened in areas acquiring water from aquifers with an elevated level of hardness, the major ingredient of which is calcium so that the occurrence of the element in a water supply is advantageous to health

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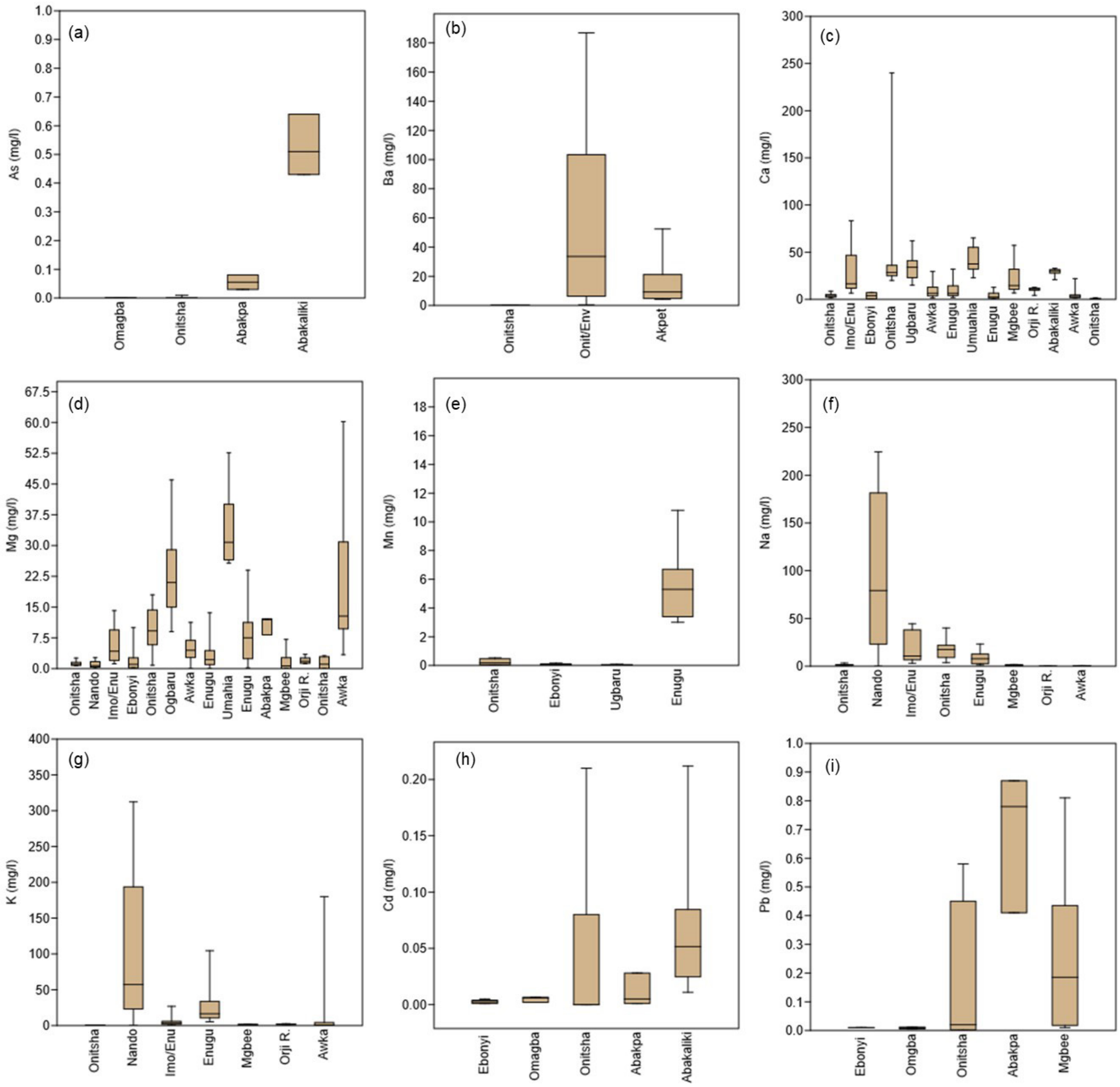

Figure 16. Chemical parameters (a) Arsenic, (b) Barium, (c) calcium, (d) Magnesium, (e) manganese, (f) Sodium, (g) Potassium, (h) Cadmium, and (i) Lead

[108-114]. Magnesium ranged from <0.001-60.2 mg/l.

Magnesium is copious and a key nutritional prerequisite for a human being - 0.3-0.5 g/day (EPA, 2001). It is the second foremost component of hardness and it commonly consists of 15-20 percent of the total hardness stated as $CaCO_3$. Its intensity is very substantial when measured in combination with that of sulfate [115]. Manganese ranged from <0.001-10.8. No specific toxicological undertones; the concerns to manganese, like Fe, are aesthetic. Toxicity is not a factor, as groundwater with elevated manganese concentrations will be rebuffed by the user long before any risk threshold is attained.

Sodium Ranged from <0.001-224.4 mg/l is regulated in drinking water because of the joint effects it exercises with sulfate. High consumption is associated with hypertension. Na absorption in the aquifer is dependent on the temperature of the solution and the associated anion. No firm conclusions can be drawn regarding the probable relationship between Na in drinking water and the incidence of hypertension [116-119]. Therefore, no health-based guideline value is proposed. However, concentrations above 200 mg/l may give rise to undesirable taste. Potassium ranged from <0.001-312.4 mg/l. Higher K concentration in groundwater is associated with toxicity [120,121]. Potassi-

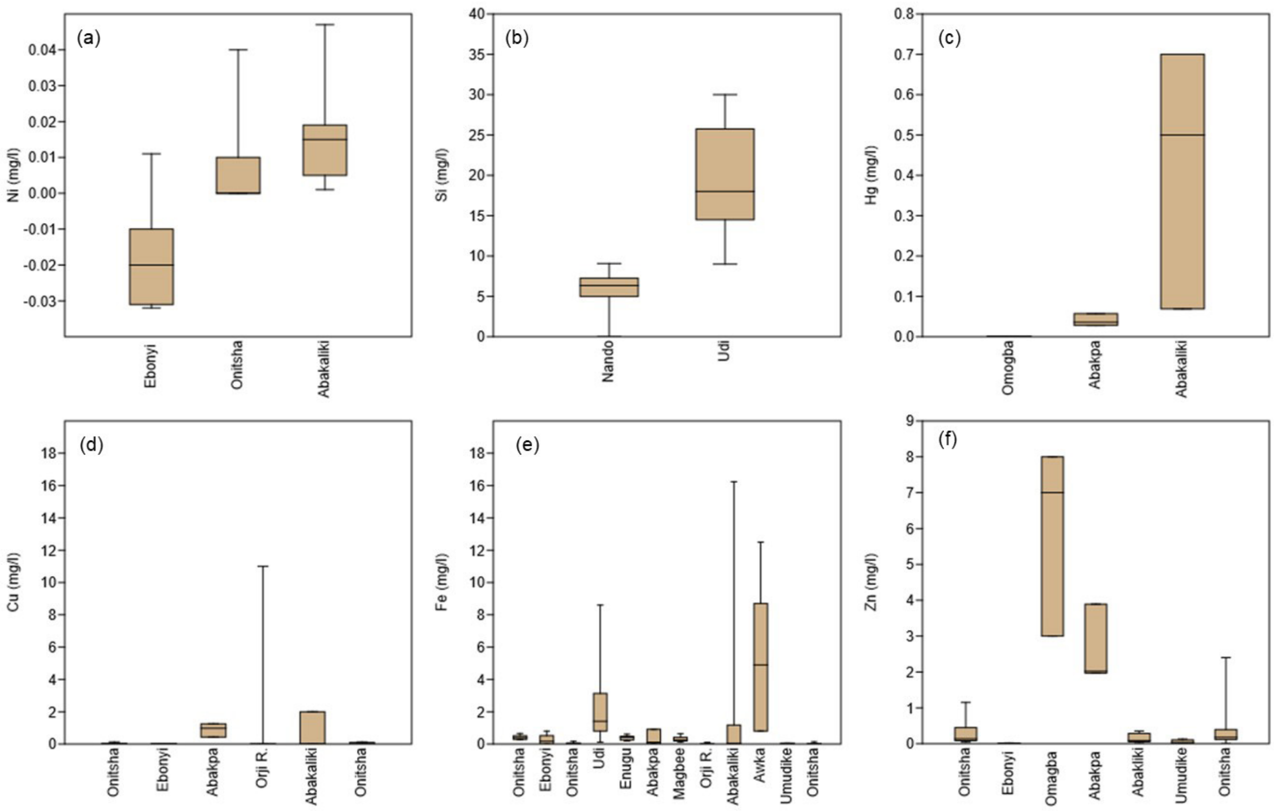

Figure 17. Chemical parameters (a) Nickel, (b) Silica, (d) Mercury, (e) Copper, (f) Iron, and (e) Zinc

um is most aquifers are found in low concentrations and excessive intake is not associated with any health hazard.

Cadmium was derived from 35 locations. Concentrations ranged from <0.001-0.08 mg/l. The 1963 International Standards for drinking water quality recommended 0.01mg/l, as a maximum permissible concentration of Cd established on health fears. This value was held in the 1971 International Standards as a tentative higher concentration limit, based on the smallest intensity that might be appropriately calculated. In the first version of the Guidelines for Drinking-water Quality, issued in 1984, a guideline value of 0.005mg/l was proposed for Cd. This value was reduced to 0.003 mg/l in the 1993 Guidelines [122]. Lead (Pb) ranged from <0.001-0.87 mg/l. Lead concentrations in drinking water are generally below 5mg/l, even though much higher concentrations (>100mg/l) have been measured where lead fittings are present [122]. Lead is exceptional since Pb in drinking water is mainly derived from the plumbing in houses and the solution comprises mainly of eliminating plumbing and fittings having Pb. This needs ample money and time, and it is acknowledged that not all water will meet the guideline instantly. Therefore, all other feasible actions to lessen total exposure to Pb, involving corrosion control, should be applied.

Nickel ranged from 0.032-0.047 mg/l. Nickel is one more metallic element which is restrained in drinking water since probable carcinogenicity as far as people are apprehensive; it also has varying toxic consequences on aquatic life [123]. Nickel is toxic to plant life and is a danger to fish [124-126]. There are few studies on Fluoride, Mercury, and Silica in Anambra Basin. Oghenenyoreme and Njoku [127] reported a fluoride range of <0.001-2.5 mg/l from the Orji River. Fluoride exists spontaneously in moderately unusual cases; appears virtually entirely from fluoridation of municipal water deliveries and industrial releases [124-126]. Health findings have revealed that the accumulation of fluoride into water supplies at levels above 0.6 mg/l, can lead to a decrease in tooth decay in growing children and that the ideal useful outcome appears around 1.0 mg/l [115].

Silica analysis in Nando and Udi by Egbunike [53] and Aniebone [128], showed that it ranged from <0.001 to 30 mg/l (Figure 18). Silica is the most plentiful element found in rocks and it is constantly present in natural waters [129-131]. The element is a foremost constituent of the structure of diatoms (*Bacillariophyta*), one of the major groups of the algae, and when algal growth takes place in a water silica levels drop as the diatom population increases. The subsequent renewal of silica is primarily

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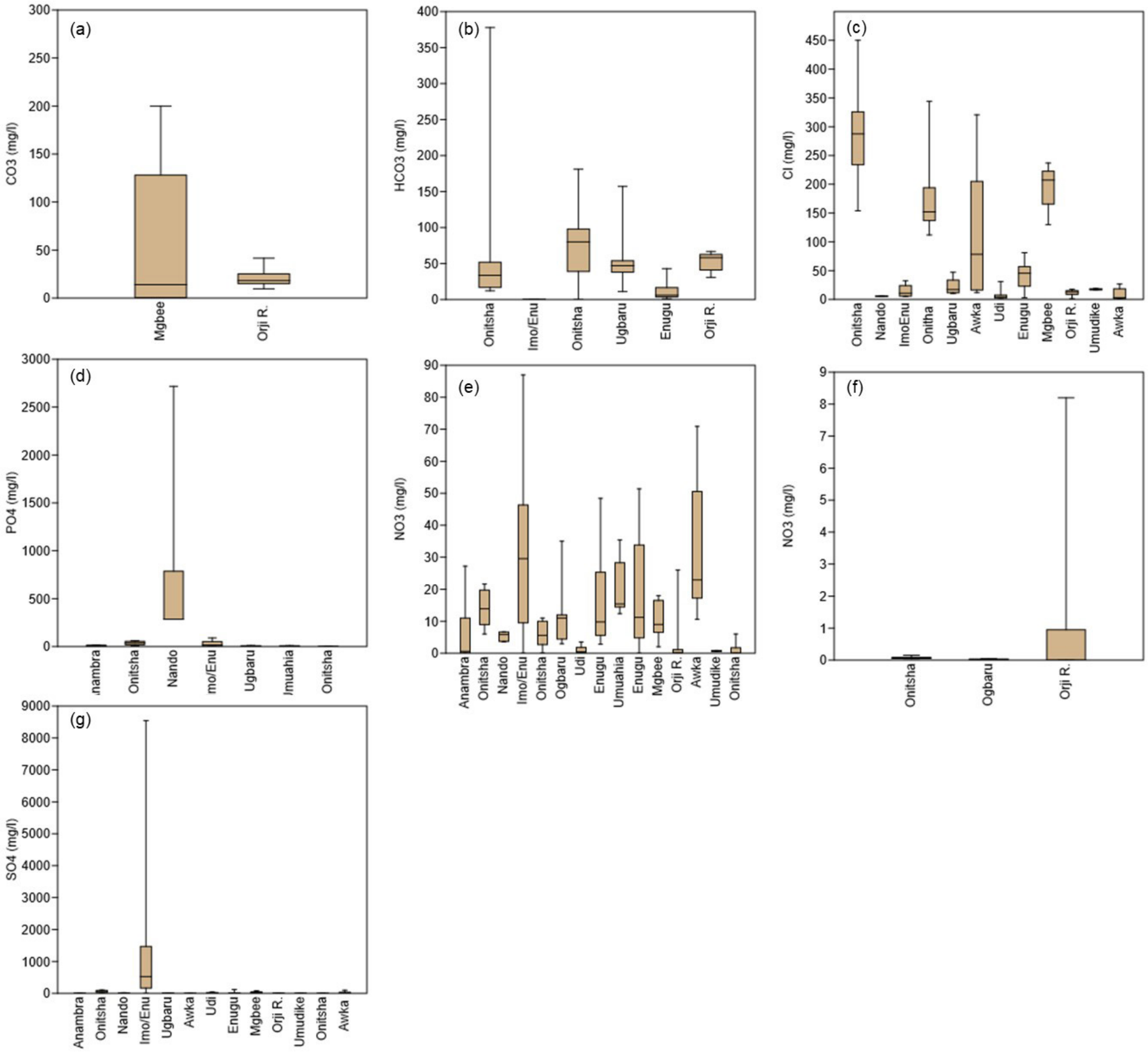

Figure 18. (a) Carbonate, (b) Bicarbonate, (c) Chloride, (d) Phosphate, (e) Nitrate, (f) Nitrite, and (g) Sulphate

from run-off [115]. The concentration of Mercury ranged from 0.00035-0.7 mg/l. Mercury is present in the mineral form in surface water and groundwater [132-135]. Concentrations are usually below 0.5 µg/l, although local mineral deposits may produce higher levels in groundwater. A guideline value of 0.006 mg/l (0.6 mg/l) for inorganic mercury was recommended in drinking water [122].

Copper concentrations ranged from <0.00-11mg/l Cu. There is increasing copper contamination in the environment [136-139]. Current studies have defined the threshold for the effects of Cu in drinking water on the gastrointestinal tract [140-142], but there is still some doubt regarding the long-term effects of copper on sensitive populations such as carriers of the gene for Wilson disease and other metabolic disorders of copper homeostasis [122]. Iron (Fe) is mainly derived from rock mineral [143,144]. Numerous studies evaluated iron (Fe) concentrations in groundwater across Anambra Basin. Iron is found in natural freshwaters at levels ranging from 0.5 to 50mg/l. Anaerobic groundwater may contain ferrous iron at concentrations up to several milligrams per liter without discoloration or turbidity in the water when directly pumped from a well. On exposure to the atmosphere, however, the ferrous iron oxidizes is converted to ferric iron, giving an objectionable reddish-brown color to the water [145]. No guideline value for iron in drinking water is proposed. At levels above 0.3 mg/l, iron stains laundry, and plumbing fixtures. There is usually no obvious taste at iron concentrations below 0.3 mg/l, although turbidity and color may develop [145].

Zinc is also derived from rock materials [146,147]. Zinc concentrations ranged from <0.001-8 mg/l. Water containing Zn at concentrations above 3-5 mg/l may appear opalescent and develop a greasy film on boiling. Natural waters rarely contain Zn at concentrations above 0.1 mg/l [145]. Chloride (Cl) ranged from <0.001-450 mg/l. High concentrations of Cl in groundwater sources give a salty taste to water and beverages [99]. Taste thresholds for the Cl anion hinge on the accompanying cation and are in the range of 200-300 mg/l for Na, K, and calcium chloride. Intensities above 250 mg/l are increasingly expected to be noticed by taste. Chloride is increasingly added to groundwater from anthropogenic activities [148-151].

4.3 Anion Chemistry

Figure 18 summarized the anionic characteristics of groundwater. Bicarbonate ranged from <0.01-377.8. Carbonate, on the other hand, ranged from 9.6-200 mg/l. Aquifers having a high concentration of sodium, bicarbonate, and carbonate ions tend to have a high pH level [152]. Nitrate ranged from <0.001-86.96 mg/l. Nitrate (NO_3) occurs naturally in the environment and is an essential plant nutrient. It is available in varying intensities in all plants and is a component of the nitrogen cycle [122]. Nitrate pollution is on the rise as NO_3 is added into aquifers from human sources [153-156]. However, nitrite (NO_2) is not usually present in significant concentrations except in a reducing environment since nitrate is the most stable oxidation state. It can be formed by the microbial reduction of NO_3.

The most important source of human exposure to NO_3 and NO_2 is through vegetables and meat in the diet [157-159]. However, groundwater can make a significant contribution to NO_3 and, sporadically, NO_2 consumption [160,161]. In the case of bottle-fed infants, drinking water can be the major external source of exposure to these elements. Guideline value for 50 mg/l NO_3 is recommended to protect against methemoglobinemia in bottle-fed infants [122]. Nitrite ranged from 0.01-0.15 mg/l. This is especially required for drinking. Guidelines values of 0.2 mg/l (provisional) (long-term exposure) was proposed [122]. The guideline value for chronic consequences of nitrite is considered temporary due to ambiguity bordering the propensity of individuals compared with animals. Sulfate ranged from <0.001- 8542.8 mg/l. The existing data do not identify a level of SO_4 in the Anambra Basin that is likely to cause adverse human health effects. No health-based guideline is recommended for SO_4. Owing to the gastrointestinal impacts stemming from the consumption of drinking-water comprising elevated SO_4 levels, it is suggested that sources of drinking water should not contain sulfate concentrations of more than 500 mg/l [122]. Sulfate in added into aquifers from different sources [162-164].

5. Conclusion

This paper presents a thorough description of the hydrogeological and hydrochemical configurations of the Tropical Anambra Basin. It identified the major geological formations and groundwater aquifers, notably Ajali, Nsukka, and Mamu formations. The hydrochemistry of the aquifers was also discussed, to provide a full picture of the general physicochemical characteristics of aquifers. However, based on the identified hydrogeological and hydrochemical data, the following remarks can be made:

(1) The Ajali formation, which is over 300 meters thick, is confined in places and as a result, formed an artesian condition. The potentials of this aquifer, seem to decline in the western basin due to drop in thickness;

(2) The Nsukka Formation overlain the Ajali Formation. The sandstone associates are aquiferous and have produced high-pressure artesian boreholes along the Oji River;

(3) The Imo Formation is comprised of blue-grey clays and shales and black shales with bands of calcareous sandstone, marl, and limestone. There is a permeability continuity throughout much of the middle unit;

(4) The sandstones of the Ameki Formation are generally very previous. The Bende-Ameki Formation has less groundwater when compared to other formations;

(5) The geological faces of Bende-Ameki Formations do not allow permeation of rainwater because of thick deposits of the lateritic layer rather the rainwater runoff to recharge the aquiferous units that are located within Imo Shale;

(6) The geologic characteristics of Bende-Ameki Formation do not produce favorable hydrogeological condition for groundwater to occur;

(7) The stratigraphical and structural framework, as well as the available groundwater chemistry, seem to suggest the existence of an effective throughflow across the basin;

(8) Based on physical parameters the basin holds water of acceptable quality. Hardness ranged from 0-195.12 mg/l. TDS ranged from 0.001-1200.00 mg/l. Electrical conductivity varied between 5.30-1315.00 µS/cm. 54.03 % of groundwater sources have pH less than 6.5 indicative of slight acidity;

(9) Ammonia ranged from 0.19-0.52 mg/l. Arsenic ranged from 0.00025 to 0.80 mg/l. Bicarbonate ranged from <0.01-377.8 mg/l. Calcium ranged from <0.001 to

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240 mg/l. Sodium ranged from <0.001-224.4 mg/l. Also lead ranged from <0.001-0.87 mg/l. Zinc ranged from <0.001-8 mg/l.

(10) Chloride ranged from <0.001-450 mg/l. NO_3 ranged from <0.001-86.96 mg/l. SO_4 ranged of <0.001-8542.8 mg/l.

(11) Based on anionic and cationic chemistry, aquifers of Anambra Basin contained water of acceptable quality for different uses.

Thus, this study presented a comprehensive review of the hydrochemistry and hydrogeology of the Anambra Basin. While there was a considerable investigation on the hydrogeology and hydrochemistry of groundwater, studies are short of analysis of the hydrogeochemical evolution of groundwater. Besides, reports on water quality index and heavy metals pollution index as well as total hazard quotient are lacking. Therefore, the suitability of groundwater for drinking remained unestablished. Also, modeling of pollutant flow from surface to groundwater is lacking despite the established hydraulic conductivity between streams and aquifers. Suitability of groundwater based on agricultural water quality indices (e.g. SAR) is required. Therefore, future studies should address these owing to increasing dependence on groundwater under changing climate and land uses.

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