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Re-examination of Hydrochemistry and Groundwater Potentials of Cross River and Imo-Kwa-Ibo Intersecting Tropical Basins of South-South Nigeria

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ABSTRACT

This review attempted a detailed description of geological and hydrogeological configurations of Cross River and Imo-Akwa Ibo basins. It presented a synthesis of hydrochemistry and a description of the hydrogeological configurations of the two basins. Hydrogeologically, most areas under Cross River and Imo-Kwa-Ibo are poor in terms of groundwater potentials. Based on the hydrochemistry, the basins hold water of excellent quality. Groundwater sources fall in soft to moderately hard classes. The entire sources groundwater has a TDS concentration of less than 500 mg/l. Groundwater classification based on electrical conductivity (EC) showed EC levels were less than 500 µS/cm. Most of the examined cations and anions are within WHO reference guidelines for drinking water quality. However, no broad analysis of water quality based on water quality indices. Also, studies modeling pollution or the impact of land use changes on groundwater quality are wanting. Thus, further analysis of the hydrochemistry of groundwater aquifers is recommended.

1. Introduction

Groundwater is under stress in the tropical basins consequent of climate change, pollution, population growth, urbanization, and industrialization, as well as land use, all of which are changed by anthropogenic activities [1-6]. These pressures are expected to have great environmental concerns. Therefore, understanding hydrogeological and hydrochemical configurations plays an important role in the functioning of the tropical basins under the current era of human impact on the entire components of the natural environment [7]. Hydrogeochemical processes that operate within the tropical basins are anticipated to accelerate as land use changes and the capacity of the aquifers to regulate natural geological process (including rock weathering and ion exchange process) and increased anthropogenic activities (such as overexploitation of aquifers, application of agrochemicals, municipal
and industrial wastes), with its consequent depletion of groundwater [8-11]. Groundwater is polluted in many ways as illustrated in Figure 1.

**Figure 1. Sources of groundwater contamination** [12]

Understanding the major hydrogeochemical interactions at basin scale is constrained geographically and relies on limited filed observations [13-18]. Improved understanding of interactions within the basins is required for the stakeholders to actively focus on mitigation and adaptation strategies for anthropogenic pollution and land use changes. Of special concern are the interactions among pollutants and groundwater near-surface and subsurface water table (including shallow aquifers), and solutes transport, streamflow, and sediments [19-22]. The current state of awareness underlines the need for a detailed review of hydrogeology and hydrochemistry of tropical basins and indicates research approaches that would aid the interpretation of hydrogeochemical processes in the tropical basins within the context of precipitously changing ecological environments, and it affects groundwater quality.

There is need for three focal research areas related to (1) nutrient cycling - additional explicit consideration to cohesive modeling, measuring and understanding of nutrients fluxes between surface and groundwater [7,23-25]; (2) basin processes- highlighted the necessity for a vibrant understanding of how anthropological land modifications affect chemical transport and flow to streams and aquifers [7,26-30]; and (3) acquisition of long-term hydrogeochemical data- there is a need for consolidative field studies that concurrently evaluate nutrients contents in streams and aquifers [7,31-36]. This review seeks to identify the groundwater potentials and hydrochemistry of groundwater in the humid tropical basins of South-South Nigeria.

2. Cross River and Imo-Kwa-Ibo Basins

2.1 Cross River Basin

Cross River Basin (CRB) is located in the eastern part of Nigeria. It occupies most parts of Cross River State [37-42]. The basin is characterized by poor groundwater potentials. This attributed to low permeability shale bedrock which underlain the basin [37,43]. In most remote communities, accessibility to potable water from groundwater sources is very difficult. Besides, the water supply in most of these rural communities is almost exclusively through shallow wells and surface water. The basin is bounded to the north by the Lower Benue Basin covering most of Otukpo and Igumale areas to the north, down to Calabar in the south (Figure 2). The basin covers an area of about 68,000 km² and is drained by the Cross River and its tributaries [44].

The climate type is tropical (Am) based on The Köppen-Geiger climate classification. Throughout the year, there is considerable precipitation and a brief dry season. The basin has a mean yearly temperature of 26.2 °C. The annual precipitation is about 2741 mm [39]. The drainage pattern is dendritic and discharges its headwaters into the Atlantic Ocean. The longer tributaries which include the Onwu, Konshisha, and Aboine rises from the Enugu escarpment [44]. The River Calabar which is smaller arises from the Oban Massif in the east of the basin [45-48]. In terms of topography, the CRB is gently sloping, the surface rises at a low gradient from less than 200 meters above sea level, in the west and the southwest, to the uppermost points above 350 meters in the south-eastern parts, at the Oban hills and the northeast, at the Boji hills [44].

**Figure 2. Geological map of Cross River Basin** [43]
2.2 General Hydrogeological Characteristics

The age of the geological formations of Cross River Basin (CRB) ranged from Precambrian through Cretaceous to Tertiary with an unconformity from Upper Coniacian to Lower Campanian \[37,43,49\]. The catchment is composed of sandstone, limestone, shale, and marl, or marlstone, which is a calcium carbonate or lime-rich mud or mudstone, containing largely variable amounts of clays and silt. The dominant carbonate mineral in most marls is calcite, but other carbonate minerals such as aragonite, dolomite, and siderite may be present. The Abakaliki Shale is the oldest formation and lies unconformably on the Basement Complex, notably Oban massif and Obudu plateau \[46,47,50-53\]. It is characterized by bluish-grey black and black shales, sandy shales, fine micaceous and calcareous sandstone, and siltstone with limestone interbedding \[43,54-56\]. The Cenomanian Odukpani Formation overlies the Asu River Group and is made of black shales with slight interbeddings of limestone and sandstone \[57,58\]. The Turonian to early Santonian Eze-Aku Formation \[59\] contains black shales separated within sandy units and shelly limestones overlies the Odukpani Formation. The Eze-Aku shale is overlain by the Conacian Agwu shale and is made up of black shale with minor separations of limestone and sandstone \[60,61\].

Superimposing the Agwu Formation is the Campanian to Maastrichtian Enugu/Nkporo Formation comprising mostly of shale, limestone, and sandstone \[62-64\]. The youngest unit (Imo Formation) is found in the Tertiary Niger Delta \[65,66\]. The black shale interbedded with clay and sandstone constitutes the major rock formation. The Cretaceous sediment was transformed by tectonics activities (folding/faulting) during the pre- and post-Turonian times \[37,43\]. The outcrop pattern of geologic formations and major structural elements in the Cross River Basin is shown in Figure 2. Tectonism was trailed by magmatism which caused the formation of volcanic rocks in the Asu River and Eze Aku Groups \[59,67-69\]. This is illustrated in Figure 3. These intrusive rocks have been detected in Obubra and Iyamet \[43\].

Cross River Basin falls into three hydrogeological assemblies of south-eastern Nigeria: lower, middle, and upper \[43\]. The lower hydrogeological group is lying beneath the Shale rocks of the Abakaliki Formation, Odukpani Shale, Eze-Aku Shale, Agwu Shale, Nkporo Shale, and Enugu Shale. The middle hydrogeological group is established in the interior of the Mamu, Ajali, and Nsukka Formations \[59,67-69\]. This is illustrated in Figure 4. The stratigraphic and hydrogeologic components of the Cross-River Basin are detailed in the literature \[43,81-84\]. The upper group consists of the Tertiary Imo Shale of Palaeocene age \[43,79,85,86\]. It is characterized by deposits of shales, clay stones, calcareous mudstones, siltstones, ironstones, and lenses of sandstones. The shales are fissile and sporadically interbedded with sandstone layers producing the confined aquifer-aquitard system \[43\]. The stratigraphic and hydrogeologic units of CRB is presented in Figure 4.
Figure 4. Hydrogeology of Cross River Basin

The hydrogeology of CRB comprises of a sequence of rocks leading from Basement (Precambrian) through Cretaceous and Tertiary sediments beds \[43,44\]. Most of CRB is underlain by Cretaceous Sediments of the Ameki, Asu River, Awgu, Ajali, Benin, Ezeaku, Imo, Nkporo, and Nsukka Formations \[43,87-89\], with the oldest (Asu River Formation) underlain by Basement Complex Formation. All these hydrogeologic units are poor aquifers except Awgu and Ezeaku Formations \[43,44,90\]. The Basement Complex is confined south-eastward, on the Oban hills and the northeast-ward along the Boji hills. Groundwater in these areas has not been fully explored, though the situation is expected to be like in the other sections of the Basement Complex areas. Groundwater condition in this area is typical of Nigeria’s Basement Complex. There are published data on the hydrogeology of the Basement Complex of Nigeria \[91-96\].

2.3 The Asu River, Ezeaku, Awgu, Mamu and Nkporo Assemblages

Albian in age, the Asu group can be subdivided into three formations:

1. Over 200 meters bluish grey to olive-brown shales and sandy shales;
2. Fine-grained micaceous and calcareous sandstones and some patches limestones; and
3. Small dikes, sills, and several igneous intrusive rocks.

The Asu River group lies beneath greater parts of eastern Enugu, Imo, and larger parts of Ebonyi State \[43,97-100\]. The Okposi, Uburu, and Abakaliki are the main outcrop areas, which are dominated by Abakaliki anticlinorium which runs coarsely north-southwest \[43,44\]. Around Enyibai, Uburu and Okposi, the Asu Formation is highly weathered and large quantities of saliferous groundwater were pumped out during lead-zinc mining activities. In less weathered sections the Asu Formation cannot be well-thought-out for groundwater exploration \[43,74,101,102\].

Bordering the Asu River Group, and plummeting northwestward and south-west, are outcrops of the Ezeaku formation, with its facies member, the Amasiri sandstones \[105,106\]. The formation of about 100 meters thick passes laterally into sandstones and sandy limestones in some locations. Groundwater aquifers are found mainly within the coarser, less cemented sandstones, weathered limestones with solution cavities and channels \[44\]. This geological group comprises of granites and has a thin lenticular shale, layers of grits, and gravelly stones. The textural classes are mostly coarse in texture. The Awgu Formation outcrops in the southern areas close to Awgu, where it is referred to as “Awgu sandstone”. This formation reaches about 450 meters in thickness \[107,108\]. The hydrogeology of Awgu formation has been described in the literature \[107,109-111\].

The Mamu and Nkporo groups were superimposed by the Awgu Group, successively are not excellent groundwater aquifers \[44\]. Entirely these poor aquiferous formations lie beneath the CRB and have added to the hydrogeological complications of the basin \[112-114\]. Abakaliki, Enugu, and Afikpo are the Major cities affected. In contrast, the extreme southeast corner, where Cross River flows into the sea, lies beneath by more promising younger aquifers, notably, the Ajali and Benin Formations which outcrops around Utapate, Efinan, Oron and Calabar areas \[44\]. Most of the deep wells constructed in CRB seemed to be positioned on the Benin Formation, as the outcrops of the Ajali Formation is narrow. The aquifers of Benin Formation
are confined in some places producing artesian conditions \[44,115-118\]. As a result of poor groundwater conditions in CRB, people largely depend on surface water sources, waterborne diseases like guinea worm contagion, is rather widespread, especially in Abakaliki, Enyimba, and Uburu areas \[44\].

2.4 The Akwa-Ibo-Imo River Basin

This small basin covers an aerial extent of about 12000 km\(^2\), forming a rectangular basin, extended in the northwest-southeast direction \[78,119\]. The basin is bordered by the Southern Trunk of the River Niger, just south of Onitsha extending to the northwest, and Atlantic coast, to the south and southeast. The basin is drained by River Imo and River Akwa-Ibo. The two rivers run virtually parallel to each other. The River Imo had its source from the Igboukwu-Orlu-Okigwe highlands, just southeast of Umuahia. Both rivers flow southeastward directly into the Atlantic Ocean \[44\]. The River Imo is joint by its major tributary-the River Otamiri. River Orashi had its origin from Orlu-Okigwe and also runs virtually parallel to River Niger. The river appears to join the Deltaic network to the south \[44\].

The basin covers most parts of Imo State, southern Anambra State, southwestern areas of Akwa Ibom and the Cross-River States. The basin also extended to the north-eastern parts of Rivers State \[44\]. Major towns include Abak, Eket, and Opobo in the coastal areas. Towns in the hinterland include Aba, Umuahia, and Owerri. Rainfall is highly localized and is strongly influenced by the ocean factor. Mean annual rainfall ranges from 1000-2000 mm near the coast \[44\]. The relative humidity is very high with a mean potential annual evapotranspiration of less than 1400 mm. The topography of the basin is shaped by the Igboukwu-Orlu-Okigwe ridge, extending from northwest to southeast and sloping from a just over 300 meters above sea level down to about 150 meters to the northwest of Umuahia, and gradually to sea level in the extensive coastal area of the basin, proximal to the Atlantic Basin \[44\].

2.5 General Hydrogeological Characteristics

Geologically the basin is characterized by the Miocene Akata Formation (shales, intercalated sands, and Silestone) \[120\] , Miocene-Pliocene Agbada Formation (sands and sandstones, intercalated with shales) \[121-123\] and the Pliocene Benin Formation (coarse-grained sand, gravelly sands with minor inter-beddings of clays and shales), from top to bottom \[124-127\]. The middle and the upper sand units of the Benin Formation form the major aquiferous units in the area. Average boreholes depths in the area range from 42-172 meters in depth \[128-130\]. The static water level ranges from 1-55 meters, and saturated thickness ranged from 39-100 meters. On the other hand, transmissivity is about 216-5304 m\(^2\)/day. A drawdown ranging from 1.2-42.5 meters was recorded in Ikot Ekpene, and storage coefficient of 0.10-0.30 \[44\].

![Figure 5. The lithology of Southern Ukanafun, Akwa Ibom State, (a) Borehole 1, and (b) Borehole 2](image)

The water table varies from 1.3-52 meters in the area \[128-130\]. These formations are comprised of continental sand and gravel, deposited in an upper deltaic plain environment \[44\]. The grain sizes range from coarse to fine in texture and are poorly sorted. They are also thick and friable with minor intercalations of clay, silts, and sandstones. The alternate assemblage builds up multiple-aquifer systems with various thicknesses. Consequently, the aquifer systems are a combination of the different grain sizes of sand \[44\]. Figure 5 shows the lithology of Southern Ukanafun Local Government Area, Akwa Ibom State. In all the five layers within the maximum electrode, the separation was identified with each having its distinct thickness and resistivity range as shown in Figure 4. The upper layer, which is medium-grained sand, is generally very thin and it overlies medium coarse-grained sand layer \[44,77,131,132\]. This layer shows an increasing resistivity with depth. The fine sand layer overlies the very coarse-grained sand layer. This layer shows resistivity inversion with depth. The fine sand and the very coarse-grained sand layers which are sandwiched with a thin bed of clay formed the major shallow productive aquifers in the area. The bottom layer at the maximum current electrode separation is sandstone whose thickness cannot be defined within the maximum current electrode separation (Table 1).
Table 1. Resistivity and depths obtained by correlations of VES and the nearby logged boreholes at Ukanafun [131]

| Types of rocks             | Resistivity (Ωm) | Depth to Bottom of layers (m) |
|----------------------------|------------------|------------------------------|
| Medium grained sand        | 385-6860         | 0.40-3.00                    |
| Medium-coarse grained sand | 1425-8800        | 0.70-26.47                   |
| Fine Sand                  | 207-2530         | 4.40-40.00                   |
| Very coarse sand (gravelly)| 46870-30700      | 30.00-60.00                  |
| Sandstone                  | 15,700-163000    | 31.00-                        |

The depth to the first aquifer compared favorably with the static water levels, which are 20.16 and 18.32 meters, respectively. These layers have very good potential for freshwater based on their high resistivities and the aquifers may not likely to be contaminated due to their depths. The shallow aquifers are characterized by insignificant hydraulic gradients due to the slight variation in the static water levels [131]. The Imo Basin is underlain by the following geologic sequence (Figure 6). The principal water-bearing formations are the Ameki and Benin Formations. The Ameki Formation is confined by the Imo Shale in the northern edge of the basin. However, in the southern part of the basin, both the Ameki and Benin Formations, as well as the sedimentary deposits the River Niger, seem to be hydrologically connected and therefore, provide combined aquiferous horizons [44].

Figure 6. Geologic progressions in Imo Basin

Groundwater is chiefly found under water-table conditions. However, the water table is very deep in some places including Akata, Orlu-Ezima, Umuahia, Atta, Awomama Umuma circle where the depth of water table varies from less than 50 meters along the Awomama Umuma circle to over 75 meters towards the center of the Orlu ridge [44]. Along the area south of Owerri and Abba, closer to the lower plains, the water table depth increases to between 6 meters close to the coast to 30 meters inward. Groundwater recharge is primarily by precipitation in most parts of the basin, through the profuse porous sands of the Benin Formation [133-136]. Groundwater is assumed to be flowing from the northern highland areas of the basin towards the coastal areas in the south and beyond under the sea. The alluvial deposits and deltaic formation is formed by the Imo River [137,138], it’s tributary the Otamiri River, the River Kwa Ibo and the extensive valley of the Niger River and its tributary, the Orashi River are marked by wide sedimentary deposits which store large quantities of groundwater [136-141]. The groundwater potential of the areas is high and can be utilized for irrigation farming. The thickness of the alluvium range from a few meters to 20 meters, along with the river courses [44]. Along the coastal margin, are the deltaic formations of the Imo Basin, where the River Imo and River Kwa Ibo empty their flows into the sea.

3. General Hydrochemical Characteristics

The two basins are hydrochemically and geographically comparable, thus are treated jointly in this section. Physical parameters of groundwater (pH, temperature, EC, TDS, alkalinity, TSS, DO, turbidity, and salinity) were synthesized from the literature and were used to characterize the physical chemistry of groundwater. The cation and anion chemistry was depicted using chemical parameters including Al, Ba, Ca, Mg, Mn, Cd, Pb, Cu, Fe, Zn, NO3, NO2, PO4, and SO4. The concentrations of heavy metals in the harbor or estuarine deposits within the study area are generally high owing to substantial anthropogenic metal loadings carried by upstream of the tributary [142]. The alluvium serves as a metal pool that can release metals to the overlying water through natural or anthropogenic processes, which may impact the ecosystem. Besides, marine biota can take up metals, which in turn increases the potential of some metals entering into the food chain [142]. Evaluation of chemical parameters of water quality is important due to their deviating sources. At a level above the recommended limits, these elements may render groundwater sources unfit for human use. Chemical elements such as Ca, Mg, Cu, Cd, B, Al, and As, are primarily derived from rocks. But elements such as Cl, NO3, and SO4 are added to groundwater from anthropogenic sources. Thus, under-
standing the origin and concentration level of chemical elements in groundwater is very important for groundwater management.

3.1 Physical Chemistry of Groundwater

Groundwater is expected to meet all the physical requirements for drinking: tasteless, colorless and odorless \(^{[143]}\). In assessing the physical quality of drinking-water, consumers rely largely on their senses \(^{[144,145]}\). It is important to note that, the microbial, chemical and physical characteristics of water may impact its appearance, odor, or taste \(^{[146]}\), and the water users tend to measure the quality and acceptability of the water-based on these principles. Even if these rudiments may not impact human health, very turbid groundwater is usually colored and may have an objectionable taste or odor. Consequently, it is important to be aware of considering both health-related guideline values and aesthetic criteria when assessing groundwater sources and develop-

![Graphs showing physical characteristics of groundwater](image)

**Figure 7.** a-k physical characteristics of groundwater

*Note:* Ikot=Ikot Effanga, Ebo=Ebonyi, Idu=Idu Uruan, Oko= Okorette, Iko Town, Umu=Umuahia North

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Dissolved calcium hydroxide forms soda and hydrogen gas. It typically occurs when CO₂ is freed, resulting in the development of carbonic acid, affecting Ca compounds. The carbon weathering reaction and the total reaction are defined in equations 2 and 3, respectively.

\[ \text{H}_2\text{O} + \text{CO}_2 \rightarrow \text{H}_2\text{CO}_3 \quad \text{and} \quad \text{CaCO}_3 + \text{H}_2\text{CO}_3 \rightarrow \text{CaH}(_2\text{CO}_3)_2 \]

(2)

\[ \text{CaCO}_3(s) + \text{CO}_2(g) + 2\text{H}_2(g) \rightarrow \text{Ca}^{2+} + 2\text{HCO}_3^{-} \]

(3)

Consequently, calcium hydrogen carbonate is produced. Groundwater aquifers can be affected by changes in temperature since Mg is a relatively low reducing element. Thus, rising oxygen can increase the reduction process. Additionally, Mg can react with water vapor to produce hydrogen gas or magnesium hydroxide as defined in Eq. 4.

\[ \text{Mg}(s) + 2\text{H}_2\text{O}(g) \rightarrow \text{Mg(OH)}_{2(aq)} + \text{H}_2(g) \]

(4)
Magnesium (Mg) ranged from 0-52.6 mg/l with an average value of 16.57 mg/l. Like Ca, Mg is also profuse in natural waters and an important nutritional prerequisite for humans - 0.3-0.5 g/day. It is the second major constituent of hardness and it generally comprises 15-20% of the total hardness. Its absorption is very important when measured in combination with that of sulfate. The significance of Mg is that it constitutes a second major component of hardness (CaCO₃). Dolomite and magnesium carbonate are primary sources of Mg in aquifers. The concentration of manganese (Mn) in drinking water is above 0.1 mg/l, which may cause an unwanted taste in drinks and stains sanitary ware and laundry. The existence of Mn in drinking water may cause the accumulation of deposits in the distribution system. At levels, less than 0.1 mg/l is generally satisfactory to consumers. However, under some environments, Mn can be at levels above 0.1 mg/l and may go on in solution for a longer period compared with its usual solubility in most drinking water. Mn ranged from 0-20.4 mg/l, with an average value of 3.17 mg/l.

Figure 8. a-j the cation chemistry of groundwater

Note: Ebo=Ebonyi, Idu=Idu Uruan, Oko=Okorette, Iko Town, Umu=Umuahia North.

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Mean sodium (Na) was 18.46 mg/l and ranged from 13-24.1 mg/l. Na concentrations are very low at some locations. The taste verge concentration of Na in water rests on the accompanying anion and the temperature of the solution. At room temperature, the average taste threshold for Na is about 200 mg/l. Potassium (K) ranged from 0.04-0.2 mg/l with an average value of 0.09 mg/l. Potassium occurs widely in the environment, including all-natural waters. But K occurs in natural waters at levels far below those of health concern. The recommended daily requirement is above 3000 mg/l. Cadmium (Cd) ranged from 0-4966 mg/l with an average value of ~591.77 mg/l. The WHO, 1963 standards for drinking water quality recommended 0.01mg/l Cd, as a maximum permissible limit based on health concerns. In 1971 this value was as a tentative higher concentration limit, based on the lowest concentration that could be appropriately measured. In 1984, a guideline value of 0.005mg/l was recommended for Cd in drinking water, which was further reduced to 0.003 mg/l in the 1993 Guidelines. Fluoride (F) was not widely reported. Fluoride (F) concentration was 0.01 mg/l at Uyo. Lead (Pb) ranged from -0.032 to 10 mg/l with an average value of 1.98 mg/l. In drinking water, Pb is generally less than 5mg/l.

Nickel (Ni) ranged from -0.032 to 0.011 mg/l with an average value of -0.019 mg/l in Abakaliki. Like F, Ni was not widely reported. Nickel is another metallic element that is limited in drinking water because of possible carcinogenicity as far as humans are concerned; it also has variable detrimental effects on aquatic life. Nickel is toxic to plant life and is a danger to fish. Copper (Cu) ranged from 0.001-15 mg/l, with an average value of 2.26 mg/l. The threshold for the effects of Cu in drinking water on the gastrointestinal tract occurs, but then there is still some hesitation concerning the long-term effects of Cu on sensitive populations, such as carriers of the gene for Wilson Disease and other metabolic disorders of copper homeostasis. Iron (Fe) ranged from 0-28 mg/l with an average value of 3.98 mg/l. Iron is available in natural freshwaters at levels ranging from 0.5 to 50mg/l. At levels above 0.3 mg/l, Fe stains laundry, and plumbing fixtures. There is generally no obvious taste at iron concentrations below 0.3 mg/l, although turbidity and color may form. Zinc (Zn) ranged from 0-75.5 mg/l with an average value of 7.92 mg/l. Water containing Zn at concentrations more than the range of 3 to 5 mg/l may look opalescent and form an oily film on boiling. Natural waters seldom contain Zn at levels above 0.1 mg/l.

### 3.3 Anion Chemistry

Figure 9(a-e) summarized the anion chemistry of groundwater. Chloride (Cl) ranged from 0-105.5 mg/l with an average value of 32.8 mg/l. Elevated Cl in groundwater results in a salty taste. Taste verges for the Cl rest on the accompanying cation and is in the range of 200-300 mg/l for Na, K, and calcium chloride. At levels, above...
250 mg/l are increasingly likely to be detected by taste. Nitrate (NO₃) ranged from 0.02-35.4 mg/l with an average value of 11.44 mg/l. Nitrate occurs naturally in the environment and is a vital plant nutrient. It is found at varying levels in all plants and is a part of the nitrogen cycle.[159]. Nitrate is primarily derived from organic matter, chemical fertilizers, and oxidation of ammonia. High NO₃ levels in aquifers can be related to past pollution by anthropogenic activities. Diverse sources of NO₃ in aquifers is illustrated in Figure 10. Nitrite (NO₂) is not usually present in large quantities except in a reducing condition since nitrate is the most stable oxidation state, which can be formed by the microbial reduction of nitrate.[159]. The most important source of human exposure to NO₂ and NO₃ is through vegetables and meat in the diet. Nitrite ranged from 0.003-5.2 mg/l with an average value of 2.09 mg/l.

Phosphate (PO₄) ranged from 0-44.2 mg/l with an average value of 7.35 mg/l. The consequence of phosphorus (P) is primary concerning the phenomenon of eutrophication (over-enrichment) of lakes and, to a lesser extent, rivers. Phosphorus gaining access to such water bodies, along with nitrogen (N) as nitrate, promotes the growth of algae and other plants leading to blooms, littoral slimes, diurnal dissolved oxygen variations of great magnitude and related problems.[152]. Sulfate (SO₄) ranged from 0.03-44.2 mg/l with an average value of 8.67 mg/l. The existing data do not identify a level of SO₄ in the Cross River-Anambra Basin that is likely to cause adverse human health effects. Nevertheless, because of the gastrointestinal effects resulting from the ingestion of drinking-water containing high SO₄ levels, it is recommended that sources of drinking water that contain sulfate concentrations more than 500mg/l.[159]. With a clear picture of general physicochemical characteristics of groundwater. Based on the hydrogeological and hydrochemical analysis, the following remarks can be made:

1. The hydrogeological analysis showed most geological formations in Cross River and Imo-Kwa-Ibo are poor in terms of groundwater potentials;
2. Based on total hardness, 74% of groundwater sources fall in soft class and 26% fall in moderately hard class;
3. The entire sources groundwater have TDS concentration less than 500 mg/l;
4. Groundwater classification based on EC showed that EC levels were less than 500 µS/cm. In contrast, 78.57% of groundwater sources in the basin are acidic;
5. Studies on Al, As, Ba, and NH4 are rare, making it difficult to make an inference. Consequently, further evaluations are required;
6. Calcium ranged from 8.2-116 mg/l with an average value of 43.73mg/l. Magnesium ranged from 0-52.6 mg/l with an average value of 16.57 mg/l. Mn ranged from 0-20.4 mg/l, with an average value of 3.17 mg/l;
7. Sodium concentration is generally low. Na ranged from 0.01-0.15 mg/l with an average value ~0.062 mg/l;
8. Cadmium concentrations are above WHO reference guidelines. Lead concentration ranged from -0.032-10 mg/l with an average value of 1.98 mg/l;
9. Nickel range of -0.032 to 0.011 mg/l with an average value of -0.019 mg/l in Abakaliki. In Ebonyi, Idu Uruan, Uyo, and Iko Town indicate Cu concentration ranged from 0.001-15 mg/l. Iron (Fe) ranged from 0-28 mg/l. Zinc concentration ranged from 0-75.5 mg/l;
10. Mean chloride (32.8 mg/l ) is less than WHO reference guidelines. Nitrate ranged from 0.02-35.4 mg/l. Nitrite ranged from 0.003-5.2 mg/l. Phosphate ranged from 0-44.2 mg/l. Sulfate ranged from 0.03-44.2 mg/l.

The physicochemical composition of groundwater showed that the two basins hold water of excellent quality. However, analysis of the hydrogeochemical evolution of groundwater in lacking. No broad studies of water quality based on water quality indices. Also, studies modeling pollution or the impact of land use changes on groundwater quality are wanting. Thus, further analysis of hydrochemistry of shallow and deep aquifers is recommended.

4. Conclusion
In this reassessment, a detailed explanation of the geological and hydrogeological setting of Cross River-Akwa Ibo basins was attempted. The review also presented a summary of synthesis data on hydrochemistry of the Cross River-Akwa Ibo basins. Data on 26 physicochemical parameters were fused and presented, to provide the reader

![Figure 10. Potential sources of nitrate in groundwater](image-url)

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References
[1] Carvalho Resende, T., et al. Assessment of the im-
pacts of climate variability on total water storage across Africa: implications for groundwater resources management. Hydrogeology Journal, 2018, 27(2): 493-512.

[2] Da Silva Rangel Neto, R., L.D. Luz, T.R. Aguiar Junior. Springs’ Water Quality Assessment in Areas with Different Degrees of Forest Conservation: a Study in Tropical Climate Basins. Water, Air, & Soil Pollution, 2020, 231(227): 1-16.

[3] Dovie, D.B.K., R.A. Kasei. Hydro-climatic stress, shallow groundwater wells and coping in Ghana's White Volta basin. Sci Total Environ, 2018, 636: 1268-1278.

[4] Owusu, G., et al. Analyses of freshwater stress with a couple ground and surface water model in the Pra Basin, Ghana. Applied Water Science, 2015, 7(1): 137-153.

[5] Sharma, P.J., P.L. Patel, V. Jothiprakash. Impact of rainfall variability and anthropogenic activities on streamflow changes and water stress conditions across Tapi Basin in India. Sci Total Environ, 2019, 687: 885-897.

[6] Tenorio-Fernandez, L., A. Valle-Levinson, J. Gomez-Valdes. Subtidal hydrodynamics in a tropical lagoon: A dimensionless numbers approach. Estuarine, Coastal, and Shelf Science, 2018, 200: 449-459.

[7] Wohl, E., et al. The hydrology of the humid tropics. Nature Climate Change, 2012, 2(9): 655-662.

[8] Ayogu, C.N., et al. Hydro-geochemical analysis and quality evaluation of surface water in the Mamu River basin, southeastern Nigeria. Applied Water Science, 2020, 10(159): 1-24.

[9] Pant, R.R., et al. Spatiotemporal variations of hydro-geochemistry and its controlling factors in the Gandaki River Basin, Central Himalaya Nepal. Sci Total Environ, 2018, 622-623: 770-782.

[10] Sefie, A., et al. Hydrogeochemistry and groundwater quality assessment of the multilayered aquifer in Lower Kelantan Basin, Kelantan, Malaysia. Environmental Earth Sciences, 2018, 77(10).

[11] Wagh, V.M., et al. Influence of hydro-geochemical processes on groundwater quality through geostatistical techniques in Kadava River basin, Western India. Arabian Journal of Geosciences, 2018, 12(1).

[12] Andrade, L., et al. Surface water flooding, groundwater contamination, and enteric disease in developed countries: A scoping review of connections and consequences. Environmental Pollution, 2018, 236: 540-549.

[13] Argamasilla, M., J.A. Barbera, B. Andreo. Factors controlling groundwater salinization and hydrogeochemical processes in coastal aquifers from southern Spain. Sci Total Environ, 2017, 580: 50-68.

[14] Bao, C., et al. Understanding watershed hydrogeochemistry: 1. Development of RT-Flux-PIHM. Water Resources Research, 2017, 53(3): 2328-2345.

[15] Coomar, P., et al. Contrasting controls on hydrogeochemistry of arsenic-enriched groundwater in the homologous tectonic settings of Andean and Himalayan basin aquifers, Latin America and South Asia. Sci Total Environ, 2019, 689: 1370-1387.

[16] Hamutoko, J.T., et al. Hydrogeochemical and isotope study of perched aquifers in the Cuvelai-Etosha Basin, Namibia. Isotopes Environ Health Stud, 2017, 53(4): 382-399.

[17] Ordens, C.M., et al. Preface: Advances in hydrogeologic understanding of Australia’s Great Artesian Basin. Hydrogeology Journal, 2020, 28(1): 11-11.

[18] Rajendiran, T., et al. Influence of variations in rainfall pattern on the hydrogeochemistry of coastal groundwater—an outcome of periodic observation. Environ Sci Pollut Res Int, 2019, 26(28): 29173-29190.

[19] Lamb, K.J., et al. Hydrogeophysical monitoring reveals primarily vertical movement of an applied tracer across a shallow, sloping low-permeability till interface: Implications for agricultural nitrate transport. Journal of Hydrology, 2019, 573: 616-630.

[20] Marcais, J., et al. Dating groundwater with dissolved silica and CFC concentrations in crystalline aquifers. Sci Total Environ, 2018, 636: 260-272.

[21] Shultz, C.D., et al. Simulating selenium and nitrogen fate and transport in coupled stream-aquifer systems of irrigated regions. Journal of Hydrology, 2018, 560: 512-529.

[22] Tavakoly, A.A., et al. An integrated framework to model nitrate contaminants with interactions of agriculture, groundwater, and surface water at regional scales: The STICS-EauDysseé coupled models applied over the Seine River Basin. Journal of Hydrology, 2019, 568: 943-958.

[23] Sigua, G.C., et al. Nitrogen in soils, plants, surface water, and shallow groundwater in a bahiagrass pasture of Southern Florida, USA. Nutrient Cycling in Agroecosystems, 2009, 86(2): 175-187.

[24] Van Beek, C.L., et al. Emissions of N2O from fertilized and grazed grassland on organic soil in relation to groundwater level. Nutrient Cycling in Agroecosystems, 2009, 86(3): 331-340.

[25] Wilson, A.M., J.T. Morris. The influence of tidal forcing on groundwater flow and nutrient exchange in a salt marsh-dominated estuary. Biogeochemistry, 2011, 108(1-3): 27-38.

[26] Kaliraj, S., N. Chandrasekar, N.S. Magesh. Identification of potential groundwater recharge zones in
[27] Moya, C.E., et al. Hydrochemical evolution and groundwater flow processes in the Galilee and Eromanga basins, Great Artesian Basin, Australia: a multivariate statistical approach. Sci Total Environ, 2015, 508: 411-26.

[28] Sener, E., A. Davraz. Assessment of groundwater vulnerability based on a modified DRASTIC model, GIS and an analytic hierarchy process (AHP) method: the case of Egirdir Lake basin (Isparta, Turkey). Hydrogeology Journal, 2012, 21(3): 701-714.

[29] Tweed, S., et al. Arid zone groundwater recharge and salinization processes; an example from the Lake Eyre Basin, Australia. Journal of Hydrology, 2011, 408(3-4): 257-275.

[30] Zhou, Q., et al. Modeling basin- and plume-scale processes of CO2 storage for full-scale deployment. Ground Water, 2010, 48(4): 494-514.

[31] DENCHIK, N., et al. In-situ geophysical and hydro-geochemical monitoring to infer landslide dynamics (Pégairolles-de-l’Escalette landslide, France). Engineering Geology, 2019, 254: 102-112.

[32] Gasperikova, E., et al. Long-term electrical resistivity monitoring of recharge-induced contaminant plume behavior. J Contam Hydrol, 2012, 142-143: 33-49.

[33] Ingebritsen, S.E., M. Manga. Hydrogeochemical precursors. Nature Geoscience, 2014, 7(10): 697-698.

[34] Neogi, B., et al. Hydrogeochemistry of coal mine water of North Karanpura coalfields, India; implication for solute acquisition processes, dissolved fluxes and water quality assessment. Environmental Earth Sciences, 2017, 76(489): 1-17.

[35] Salas, J., C. Sena, D. Arcos. Hydrogeochemical evolution of the bentonite buffer in a KBS-3 repository for radioactive waste. Reactive transport modeling of the LOT A2 experiment. Applied Clay Science, 2014, 101: p. 521-532.

[36] Singh, V.B., A.L. Ramanathan. Assessment of solute and suspended sediments acquisition processes in the Bara Shigri glacier meltwater (Western Himalaya, India). Environmental Earth Sciences, 2015, 74(3): 2009-2018.

[37] Edet, A.E., O.E. Offiong. Evaluation of water quality pollution indices for heavy metal contamination monitoring. A study case from Akpabuyo-Odukpani area, Lower Cross River Basin (southeastern Nigeria). GeoJournal, 2002, 57: 295-304.

[38] Opara, K.N., et al. Status of forest onchocerciasis in the Lower Cross River Basin, Nigeria: Entomologic profile after five years of Ivermectin intervention. The American Journal of Tropical Medicine and Hygiene, 2005, 73(3): 371-376.

[39] Akpabio, E.M. Assessing integrated water resources management in Nigeria: insights and lessons from irrigation projects in the Cross River Basin. Water Policy, 2007, 9(2): 149-168.

[40] Akpabio, E.M. Integrated water resources management in the cross river basin, Nigeria: How can we reconcile institutional boundaries and interests? International Journal of River Basin Management, 2008, 6(3): 267-276.

[41] Akpabio, E.M., et al. Integrated Water Resources Management in the Cross River Basin, Nigeria. International Journal of Water Resources Development, 2007, 23(4): 691-708.

[42] Edet, A., A. Ukpong, T. Nganje. Hydrochemical studies of Cross River Basin (southeastern Nigeria) river systems using cross plots, statistics and water quality index. Environmental Earth Sciences, 2013, 70(7): 3043-3056.

[43] Nganje, T.N., et al. Hydrochemistry of surface water and groundwater in the shale bedrock, Cross River Basin and Niger Delta Region, Nigeria. Applied Water Science, 2017, 7(2): p. 961-985.

[44] Offodile, M.E. Groundwater study and development in Nigeria. Mecon Geological and Engineering, Ltd Ehinder O, 2nd Edition, Jos, Nigeria. 2002: 453.

[45] Ekwok, S.E., et al. Assessment of groundwater potential using geophysical data: a case study in parts of Cross River State, south-eastern Nigeria. Applied Water Science, 2020, 10(144): 1-17.

[46] Sikakwe, G.U. GIS-based model of groundwater occurrence using geological and hydrogeochemical data in Precambrian Oban Massif southeastern Nigeria. Applied Water Science, 2018, 8(79): p. 1-13.

[47] Sikakwe, G.U., A. Otele, B.N. Ozibo. Chemical speciation and complexation modeling of trace and rare earth elements in groundwater of Oban Massif and Mamfe embayment southeastern Nigeria. Chemical Speciation & Bioavailability, 2018, 30(1): 86-98.

[48] Ugba, A.N., B.E. Ephraim. Physicochemical and bacteriological parameters of surface water quality in part of Oban Massif and Mamfe embayment northeastern Nigeria. Chemical Speciation & Bioavailability, 2018, 30(1): 86-98.

[49] Akpan, A.E., A.N. Ugba, N.J. George. Integrated geophysical, geochemical and hydrogeochemical investigation of shallow groundwater resources in parts of the Ikom-Mamfe Embayment and the adjoining areas in Cross River State, Nigeria. Environmental Earth Sciences, 2013, 70: p. 1435-1456.

[50] Agumanu, A.E. The Abakaliki and the Ebonyi Formations: sub-divisions of the Albian Asu River
Group in the southern Benue Trough, Nigeria. Journal of African Earth Sciences, 1989, 9(1): 195-207.

[51] Amajor, L.C. Paleocurrent, petrography, and provenance analyses of the Ajali Sandstone (Upper Cretaceous), Southeastern Benue Trough, Nigeria. Sedimentary Geology, 1987, 54: 47-60.

[52] Effiong, C.I., et al. Magnetic basement depth re-evaluation of Abakaliki/Ikom and Environis Southeastern Nigeria, using 3-D Euler Deconvolution. Global Scientific Journal, 2017, 5(9): 120-138.

[53] Reijers, T.J.A., S.W. Pettersp. Depositional environments, and diagenesis of Albian carbonates on the Calabar Flank, SE Nigeria. Journal of Petroleum Geology, 1987, 10(3): 283-294.

[54] Aghamelu, O.P., P.N. Nnabo, H.N. Ezeh. Geotechnical and environmental problems related to shales in the Abakaliki area, Southeastern Nigeria. African Journal of Environmental Science and Technology, 2011, 5(2): 80-88.

[55] Okechukwu, P.A., O.O. Celestine. Geotechnical assessment of road failures in the Abakaliki Area, Southeastern Nigeria. International Journal of Civil & Environmental Engineering, 2011, 11(1): 1-21.

[56] Okogbue, C.O., O.P. Aghamelu. Comparison of the geotechnical properties of crushed shales from Southeastern Nigeria. Bulletin of Engineering Geology and the Environment, 2010, 69(4): 587-597.

[57] Cemil, B.C., et al. Does the corticotropin-releasing hormone system play a role in the pathogenesis of lichen planus? Postepy Dermatol Alergol, 2017, 34(4): 322-327.

[58] Odunze-Akasiugwu, S.O., G.C. Obi. Stratigraphic relations and habitat of the Bende fish teeth, southeastern Nigeria. Arabian Journal of Geosciences, 2017, 10(11).

[59] Igwe, E.O., A.U. Okoro. Field and lithostratigraphic studies of the Eze-Aku Group in the Afikpo Synclinorium, southern Benue Trough, Nigeria. Journal of African Earth Sciences, 2016, 119: 38-51.

[60] Alani, O.A., K.W. Yaki. Structural Composition, and Significance of Sedimentary Formations in Nigeria. International Journal of Advanced Studies in Ecology, Development and Sustainability, 2016, 4(1): 1-17.

[61] Ola-Buraimo, A.O., I.M. Akaegbobi. Palynology, an important tool in evaluating sea-level changes, paleoenvironment and paleoclimatic conditions in geologic time. International Journal of Engineering Research & Technology, 2013, 2(3): 1-30.

[62] Chiadikobi, K.C., O.I. Chiaghanam. Visual Kerogen Study of the Campano-Maastrichtian Nkporo Group of Anambra Basin, Southeastern Nigeria. World News of Natural Sciences, 2018. 19: 142-154.

[63] Ayorinde, J., O. Adeigbe, S. Emmanuel. Petrography, and Biostratigraphic Studies of Campano-Maastrichtian Sequences of Anambra Basin Southeastern Nigeria. Current Journal of Applied Science and Technology, 2018, 27(2): 1-24.

[64] Bolarinwa, A.T., S.O. Idakwo, D.L. Bish. Rare-earth, and trace elements and hydrogen and oxygen isotopic compositions of Cretaceous kaolinitic sediments from the Lower Benue Trough, Nigeria: provenance and paleoclimatic significance. Acta Geochimica, 2019, 38(3): 350-363.

[65] Ikekwo, O.N., O.P. Umeji. Palynological age and palaeoenvironment of deposition of Mid-Cenozoic sediments around Umuahia, Niger delta basin, southeastern Nigeria. Journal of African Earth Sciences, 2016, 117: 160-170.

[66] Okeke, K.K., O.P. Umeji. Palynostratigraphy, palynofacies and palaeoenvironment of deposition of Selandian to Aquitanian sediments, southeastern Nigeria. Journal of African Earth Sciences, 2016, 120: 102-124.

[67] Eze, M.O., L.I. Mamah, A.I. Oha. Integration of in situ measurement of radiometric signatures and aeroradiometric data in geologic mapping of parts of southern Benue Trough and Anambra Basin. Arabian Journal of Geosciences, 2019. 12(150): 1-12.

[68] Igwe, E.O. Composition, provenance, and tectonic setting of Eze-Aku Sandstone facies in the Afikpo Synclinorium, Southern Benue Trough, Nigeria. Environmental Earth Sciences, 2017, 76(420): 1-12.

[69] Obasi, A.I., A.O.I. Selemo. Density, and reservoir properties of Cretaceous rocks in southern Benue Trough, Nigeria: implications for hydrocarbon exploration. Arabian Journal of Geosciences, 2018, 11(307): 1-14.

[70] Tijani, M.N., M.E. Nton. Hydraulic, textural and geochemical characteristics of the Ajali Formation, Anambra Basin, Nigeria: implication for groundwater quality. Environmental Geology, 2008, 56(5): 935-951.

[71] Uzoegbu, U.M. Lithostratigraphy of the Maastrichtian Nsukka Formation in the Anambra Basin, S.E Nigeria. IOSR Journal Of Environmental Science, Toxicology, and Food Technology, 2013. 5(5): p. 96-102.

[72] Edet, A. Seasonal and spatio-temporal patterns, evolution and quality of groundwater in Cross River State, Nigeria: implications for groundwater management. Sustainable Water Resources Management, 2018, 5(2): 667-687.

[73] Odey, M.O., et al. Drinking water quality and risk implications for community health: A case study of...
shallow water wells and boreholes in three major communities in Northern Cross-River, Southern Nigeria. Human and Ecological Risk Assessment: An International Journal, 2017, 24(2): 427-444.

[74] Stephen, U.N., O.O. Celestine, O.O. Solomon. Analysis of hydrogeochemical facies in groundwater of upper part of Cross River Basin, southeastern Nigeria. Journal of African Earth Sciences, 2017. 131: p. 145-155.

[75] Ebong, E.D., et al. Groundwater quality assessment using geoelectrical and geochemical approaches: case study of Abi area, southeastern Nigeria. Applied Water Science, 2016, 7(5): 2463-2478.

[76] Ekwe, A.C., et al. Determination of aquifer parameters from geosounding data in parts of Afikpo Sub-basin, southeastern Nigeria. Arabian Journal of Geosciences, 2020, 13(189): 1-15.

[77] Obiora, D.N., J.C. Ibuot, N.J. George. Evaluation of aquifer potential, geolectric and hydraulic parameters in Ezza North, southeastern Nigeria, using geoelectric sounding. International Journal of Environmental Science and Technology, 2015, 13(2): 435-444.

[78] Ibanga, J.I., N.J. George. Estimating geohydraulic parameters, protective strength, and corrosivity of hydrogeological units: a case study of ALSCON, Ikot Abasi, southern Nigeria. Arabian Journal of Geosciences, 2016, 9(363): 1-16.

[79] Chukwura, U.O., et al. Evaluation of hydrochemical characteristics and flow directions of groundwater quality in Udi Local Government Area Enugu State, Nigeria. Environmental Earth Sciences, 2014, 73(8): 4541-4555.

[80] Eze, M.O., I.B. Ijeh. Integration of in-situ susceptibility and petrographic data in study of the magnetic properties of some rocks of parts of Anambra Basin and Southern Benue Trough, Nigeria. The Pacific Journal of Science and Technology, 2019, 20(2): 387-395.

[81] Chukwudi, C.E., Z.U. Gabriel. Geoelectrical sounding for estimating groundwater potential in Nsukka L.G.A. Enugu State, Nigeria. International Journal of the Physical Sciences, 2010, 5(5): 415-420.

[82] Onyekuru, S.O., G.I. Nwankwor, C.Z. Akaoisa. Chemical Characteristics of Groundwater Systems in the Southern Anambra Basin, Nigeria. Journal of Applied Sciences Research, 2010, 6(12): 2164-2172.

[83] Boniface, C.E.E., O.U. Kalu. Comparative analysis of transmissivity and hydraulic conductivity values from the Ajali aquifer system of Nigeria. Journal of Hydrology, 1986, 83: 185-196.

[84] Ejeh, O.I. The Maastrichtian sedimentary successions of the Anambra basin recently exposed around Okpekpe and Imiegbua: Part of the Mamu or Ajali Formation? Nigerian Journal of Science and Environment, 2016, 14(1): 38-48.

[85] Adesina, A.M., A.V. Adeola, O.A. Oladayo. Aspects of hydrocarbon potential of the Tertiary Imo Shale Formation in Anambra Basin, Southeastern Nigeria. IOSR Journal of Applied Geology and Geophysics, 2017, 5(5): 74-83.

[86] Ekwenye, O.C., et al. A paleogeographic model for the sandstone members of the Imo Shale, south-eastern Nigeria. Journal of African Earth Sciences, 2014, 96: 190-211.

[87] Nfior, B.N., S.B. Olobaniyi, J.E. Ogala. Extent and Distribution of Groundwater Resources in Parts of Anambra State, Southeastern, Nigeria. Journal of Applied Sciences and Environmental Management, 2007. 11(2): p. 215 - 221.

[88] Igwe, E.O. Palynomorph Taxa Distribution in the Eze-Aku and Nkporo Shales within the Eastern Flank of Abakaliki Anticlinorium, Southeastern Nigeria. American Journal of Environmental Engineering and Science, 2017, 4(2): 8-19.

[89] Chiaghanam, O.I., et al. Sedimentology and Sequence Stratigraphy of the Eocene Nanka Formation (Ameki Group): An Evaluation of Ogbunike Reference Locality in Anambra Basin, South-Eastern Nigeria. IOSR Journal of Applied Geology and Geophysics, 2014, 2(3): 01-10.

[90] Ukpai, S.N., C.O. Okogbue, I.A. Oha. Investigation of hydrologic influence of geologic lineaments in areas of the Lower Benue Trough, Southeastern Nigeria. Journal of Earth System Science, 2019, 129(12): 1-18.

[91] Adanu, E.A. Source, and recharge of groundwater in the basement terrain in the Zaria-Kaduna area, Nigeria: applying stable isotopes. Journal of African Earth Sciences, 1991, 13(2): 229-234.

[92] Adiatt, K.A.N., et al. Prediction of groundwater level in basement complex terrain using artificial neural network: a case of Ijebu-Jesa, southwestern Nigeria. Applied Water Science, 2019, 10(8): 1-14.

[93] Aizebeokhai, A.P., K.D. Oyeeemi. Geoelectrical characterization of basement aquifers: the case of Iberekodo, southwestern Nigeria. Hydrogeology Journal, 2017, 26(2): 651-664.

[94] Akinwunmiyu, A.S., M.O. Olornufemi. Development of a conceptual groundwater model for a complex basement aquifer system: The case OF OSUN drainage basin in southwestern Nigeria. Journal of African Earth Sciences, 2019, 159(103574): 1-19.

[95] Ashaolu, E.D., et al. Spatial and temporal recharge
estimation of the basement complex in Nigeria, West Africa. Journal of Hydrology: Regional Studies, 2020, 27(100658).

[96] Bayewu, O.O., et al. Geophysical evaluation of groundwater potential in part of southwestern basement complex terrain of Nigeria. Applied Water Science, 2017, 7(8): 4615-4632.

[97] Igwe, O., S.I. Ifediegwu, O.S. Onwuka. Determining the occurrence of potential groundwater zones using integrated hydro-geomorphic parameters, GIS, and remote sensing in Enugu State, Southeastern, Nigeria. Sustainable Water Resources Management, 2020. 6(39): p. 1-14.

[98] Nwankwoala, H.O. Localizing the strategy for achieving rural water supply and sanitation in Nigeria. African Journal of Environmental Science and Technology, 2012, 5(13).

[99] Omaka, O.N., et al. Assessment of the quality of groundwater from different parts of southeastern Nigeria for potable use. Environmental Earth Sciences, 2017, 76(344): 1-24.

[100] Udokporo, E. Assessment and Mapping of the Vulnerability of Soils in Imo State, Nigeria to Erosion Hazard Using Geographic Information System. International Journal of Environmental Monitoring and Analysis, 2015, 3(5): 245.

[101] Adamu, C.I., T.N. Nganje, A. Edet. Heavy metal contamination and health risk assessment associated with abandoned barite mines in Cross River State, southeastern Nigeria. Environmental Nanotechnology, Monitoring & Management, 2015, 3: 10-21.

[102] Ukpai, S.N., P.N. Nnabo, H.N. Eze. Groundwater facie analysis in the upper Cross River basin, southeast Nigeria. Environmental Earth Sciences, 2016, 75(1345): 1-10.

[103] Ebokaiwe, A.P., et al. Assessment of heavy metals around Abakaliki metropolis and potential bioaccumulation and biochemical effects on the liver, kidney, and erythrocyte of rats. Human and Ecological Risk Assessment: An International Journal, 2018, 24(5): 1233-1255.

[104] Eze, C.L., L.I. Mamah, C. Israel-Cookey. Very low frequency electromagnetic (VLF-EM) response from a lead sulfide lode in the Abakaliki lead/zinc field, Nigeria. International Journal of Applied Earth Observation and Geoinformation, 2004, 5(2): 159-163.

[105] Okoro, A.U., E.O. Igwe. Lithofacies and depositional environment of the Amasiri Sandstone, southern Benue Trough, Nigeria. Journal of African Earth Sciences, 2014, 100: 179-190.

[106] Okoro, A.U., E.O. Igwe, C.S. Nwajide. Sedimentary and petrofacies analyses of the Amasiri Sandstone, southern Benue Trough, Nigeria: Implications for depositional environment and tectonic provenance. Journal of African Earth Sciences, 2016, 123: 258-271.

[107] Onwe-Moses, F.D., et al. Organic geochemical evaluation and hydrocarbon prospects of the Coniacian Awgu Formation, southern Benue Trough, Nigeria. Arabian Journal of Geosciences, 2019, 12(3).

[108] Umar, et al. Groundwater Level Fluctuation in Response to Climatic Variation and its Geotechnical Implication in Part of Awgu Shale, Central Benue Trough, Nigeria. International Journal of Advanced Geosciences, 2018, 6(2): 178-183.

[109] Edegbai, A.J., L. Schwark, F.E. Oboh-Ikuenobe. A review of the latest Cenomanian to Maastrichtian geological evolution of Nigeria and its stratigraphic and paleogeographic implications. Journal of African Earth Sciences, 2019, 150: 823-837.

[110] Umar, N.D., O. Igwe. Geo-electric method applied to groundwater protection of a granular sandstone aquifer. Applied Water Science, 2019, 9(12): 1-14.

[111] Umar, N.D., O. Igwe, I.G. Idris. Evaluation and characterization of groundwater of the Maastrichtian Lafia formation, Central Benue trough, Nigeria. Journal of Earth System Science, 2019, 128(168): 1-12.

[112] Bankole, S.A., A.O. Ola-Buraimo. Biostratigraphy, and palaeoenvironment of deposition of Nsukka Formation, Anambra Basin, southeastern Nigeria. Journal of Palaeogeography, 2017, 6(2): 178-183.

[113] Bello, R., C. Ofoha, N. Wehiuzo. Geothermal Gradient, Curie Point Depth and Heat Flow Determination of Some Parts of Lower Benue Trough and Anambra Basin, Nigeria, Using High-Resolution Aeromagnetic Data. Physical Science International Journal, 2017, 15(2): 1-11.

[114] Daniel, N.O., et al. Investigation of magnetic anomalies of Abakaliki area, Southeastern Nigeria, using high-resolution aeromagnetic data. Journal of Geology and Mining Research, 2018, 10(6): 57-71.

[115] Anakwuba, E.K., et al. Sequence stratigraphic interpretation of parts of Anambra Basin, Nigeria using geophysical well logs and biostratigraphic data. Journal of African Earth Sciences, 2018, 139: 330-340.

[116] Edegbai, A.J., L. Schwark, F.E. Oboh-Ikuenobe. Nature of dispersed organic matter and paleoxygenation of the Campano-Maastrichtian dark mudstone unit, Benin flank, western Anambra Basin: Implications for Maastrichtian Trans-Saharan seaway paleoceanographic conditions. Journal of African Earth
[117] Ocheri, A., et al. Granulometric and pebble morphometric applications to Benin Flank sediments in western Anamba Basin, Nigeria: proxies for paleoenvironmental reconstruction. Environ Monit Assess, 2018, 190(286): 1-17.

[118] Ogungbesan, G.O., T.A. Adedosu. Geochemical record for the depositional condition and petroleum potential of the Late Cretaceous Mamu Formation in the western flank of Anamba Basin, Nigeria. Green Energy & Environment, 2020, 5(1): 83-96.

[119] Edet, A., et al. Numerical Groundwater Flow Modeling of the Coastal Plain Sand Aquifer, Akwa Ibom State, SE Nigeria. Journal of Water Resource and Protection, 2014, 06(04): 193-201.

[120] Ezeh, S.C., et al. Ichnological characteristics and variability of Miocene deposits in the Cenozoic Niger Delta: Examples from cores in the Coastal Swamp and Offshore depolits. Paleogeography, Palaeoclimatology, Palaeoecology, 2016, 454: 189-201.

[121] Asadu, A.N., W.N. Ofuyah. Miospore Biozonation and age characterization of Upper Miocene - Pliocene sediments in well X, deep offshore Niger delta. IOSR Journal of Applied Geology and Geophysics, 2017, 05(03): 06-13.

[122] Ola-Buraimo, A.O., I.M. Akabgbobi. Neogene dinoflagellate cyst assemblages of the late Miocene-Pliocene Ogwashi-Asaba sediment in umuna-1 well, Anambra basin, southeastern Nigeria. Journal of Petroleum and Gas Exploration Research, 2012, 2(6): 115-124.

[123] Olayiwola, M.A., M.K. Bamford. Petroleum of the Deep: Palynological proxies for paleoenvironment of deep offshore upper Miocene-Pliocene sediments from Niger Delta, Nigeria. Palaeoentology Africana, 2016, 50: 31-47.

[124] Amadi, A.N., P.I. Olasehinde, H.O. Nwankwoala. Hydrogeochemistry, and Statistical Analysis of Benin Formation in Eastern Niger Delta, Nigeria. International Research Journal of Pure & Applied Chemistry, 2014, 4(3): 327-338.

[125] Amadi, A.N., et al. Controlling Factors of Groundwater Chemistry in the Benin Formation of Southern Nigeria. International Journal of Engineering Sciences, 2020, 162: 103654.

[126] Major, L.C. Aquifers in the Benin Formation (Miocene Recent), Eastern Niger Delta, Nigeria: Lithostratigraphy, hydraulics, and water quality. Environmental Geology and Water Sciences, 1991, 17(2): 85-101.

[127] Irwin, A.A., E. Oghenevwede. Groundwater conditions and hydrogeochemistry of the shallow Benin Formation aquifer in the vicinity of Abraka, Nigeria. International Journal of Water Resources and Environmental Engineering, 2014, 6(1): 19-31.

[128] Inim, I.J., et al. Hydrogeochemical evaluation of groundwater in coastal alluvial aquifer of Akwa Ibom, Southeastern Nigeria. Journal of Coastal Sciences, 2017, 4(2): 1-8.

[129] George, N.J., J.I. Ibanga, A.I. Ubom. Geoelectro-hydrogeological indices of evidence of ingress of saline water into fresh water in parts of coastal aquifers of Ikot Abasi, southern Nigeria. Journal of African Earth Sciences, 2015, 109: 37-46.

[130] George, N.J., et al. Estimating the indices of inter-transmissibility magnitude of active surficial hydrogeologic units in Itu, Akwa Ibom State, southeastern Nigeria. Arabian Journal of Geosciences, 2018, 11(134): 1-16.

[131] George, N.J., A.E. Akpan, B. Obot. Resistivity Study of Shallow Aquifers in the Parts of Southern Ukana Local Government Area, Akwa Ibom State, Nigeria. E-Journal of Chemistry, 2010, 7(3): 693-700.

[132] Uwa, U.E., G.T. Akpabio, N.J. George. Geohydodynamic Parameters and Their Implications on the Coastal Conservation: A Case Study of Abak Local Government Area (LGA), Akwa Ibom State, Southern Nigeria. National Resources Research, 2018, 28(2): 349-367.

[133] Ajayi, O., O. Umoh. Quality of groundwater in the Coastal Plain Sands Aquifer of the Akwa Ibom State, Nigeria. Journal of African Earth Sciences, 1998, 27(2): 259-275.

[134] Edet, A. An aquifer vulnerability assessment of the Benin Formation aquifer, Calabar, southeastern Nigeria, using DRASTIC and GIS approach. Environmental Earth Sciences, 2013, 71(4): 1747-1765.

[135] Ibe Sr., K., A. Sowa. Hydrology of part of the Oramiriukwa River basin, southeast of Owerri, Imo State, Nigeria. Hydrogeology Journal, 2002, 10(4): 509-521.

[136] Igboeke, M.U., V.V.S. Gurunadha Rao, E.E. Okweze. Groundwater flow modeling of Kwa Ibo River watershed, southeastern Nigeria. Hydrological Processes, 2008, 22(10): 1523-1531.

[137] Aisuebeogun, A.O., I.C. Ezekwe. Channel dynamics and hydraulic geometry of two tropical deltaic catchments in Southern Nigeria. Landform Analysis, 2014, 27: 3-13.

[138] Ola-Buraimo, A.O., I.M. Akaegbobi. Neogene dinoflagellate cyst assemblages of the late Miocene-Pliocene Ogwashi-Asaba sediment in umuna-1 well, Anambra basin, southeastern Nigeria. Journal of Petroleum and Gas Exploration Research, 2012, 2(6): 115-124.
17(7): 85-101.

[139] Ibeneme, S.I., et al. Vertical electrical sounding for aquifer characterization around the Lower Orashi River Sub-Basin Southeastern Nigeria. Communications in Applied Sciences, 2014, 2(1): 36-51.

[140] Enetimi, I.S., C.N.A. Tarwari, C.O. Blessing. Physicochemical quality assessment of River Orashi in Eastern Niger Delta of Nigeria. Journal of Environmental Treatment Techniques, 2016, 4(4): 143-148.

[141] Amangabara, G. Drainage Morphology of Imo Basin in the Anambra - Imo River Basin Area, of Imo State, Southern Nigeria. Journal of Geography, Environment and Earth Science International, 2015, 3(1): 1-11.

[142] Essien, J.P., S.P. Antai, A.A. Olajire. Distribution, Seasonal Variations and Ecotoxicological Significance of Heavy Metals in Sediments of Cross River Estuary Mangrove Swamp. Water, Air, and Soil Pollution, 2009, 197(1-4): 91-105.

[143] WHO. Guidelines for drinking-water quality: Fourth edition incorporating the first addendum. WHO Library Cataloguing-in-Publication Data. World Health Organization Geneva. 2018: 631.

[144] Zoeteman, B.C.J., G.J. Piet, L. Postma. Taste as an indicator quality. Research and Technology Journal AWWA, 1980: 537-540.

[145] De França Doria, M. Factors influencing public perception of drinking water quality. Water Policy, 2010, 12(1): 1-19.

[146] Olumuyiwa, I.O. Groundwater: Characteristics, qualities, pollutions and treatments: An overview. International Journal of Water Resources and Environmental Engineering, 2012, 4(6): 162-170

[147] Edima-Nyah, A.P., S.P. Ukwo. Physicochemical, bacteriological and risk-to-health analysis of drinking water quality in some oil-producing areas of Akwa Ibom State, Nigeria. Internet Journal of Food Safety, 2013. 15: p. 109-114.

[148] Essien, O.E., E.D. Bassey. Spatial Variation of Borehole Water Quality with Depth in Uyo Municipality, Nigeria. International Journal of Environmental Science, Management, and Engineering Research, 2012. 1(1): 1-9.

[149] Barnes, L., et al. Geochemistry of highly basic calcium hydroxide groundwater in Jordan. Chemical Geology, 1982, 35: 147-154.

[150] Gu, B., et al. Geochemical reactions and dynamics during titration of a contaminated groundwater with high uranium, aluminum, and calcium. Geochimica et Cosmochimica Acta, 2003, 67(15): 2749-2761.

[151] Schot, P.P., M.J. Wassen. Calcium concentrations in wetland groundwater in relation to water sources and soil conditions in the recharge area. Journal of hydrology, 1993, 141: 197-217.

[152] EPA, Parameters of water quality: Interpretation and Standards. An Ghniomhaireacht um Chaomhnu Comhshaoil. Ireland. 2001, 132.

[153] Wali, S.U., et al. Evaluation of shallow groundwater in cretaceous and tertiary aquifers of northern Kebbi State, Nigeria. SF Journal of Environmental and Earth Sciences, 2018, 1(1): 1-11.

[154] Chapman, P.J., B. Reynolds, H.S. Wheater, Sources and controls of calcium and magnesium in storm runoff: the role of groundwater and ion exchange reactions along water flowpaths. Hydrology and Earth System Sciences, 1997, 1(3): 671-685.

[155] Magaritz, M. and U. Kafri, Concentration of magnesium in carbonate nodules of soils: an indication of fresh groundwater contamination by intruding seawater. Chemical Geology, 1979, 27: 143-155.

[156] Rapant, S., et al. Impact of Calcium and Magnesium in Groundwater and Drinking Water on the Health of Inhabitants of the Slovak Republic. International Journal of Environmental Research and Public Health, 2017, 14(278): 1-22.

[157] Ukpong, E., et al. Assessment of water quality from boreholes in Ikot Akpaden and some surrounding villages of Mkpat Enin Local Government Area of Akwa Ibom State, Nigeria. Chemistry and Materials Research, 2017, 9(2): 24-29.

[158] Essien, O.E., A.E. Abasifreke. Spatial distribution and variability of groundwater quality in state capital and contiguous local government areas under urbanization expansion. American Journal of Water Resources, 2014. 2(2): 1-9.

[159] WHO. Guidelines for Drinking-water Quality. Third Edition Incorporating The First And Second Addendum: Recommendations. World Health Organization Geneva, 2008, 1: 668.

[160] Afiukwa, J., A. Eboatu. Analysis of spring water quality in Ebonyi South Zone and its health impact. American Journal of Scientific and Industrial Research, 2013, 4(2): 231-237.

[161] Adeedji, A., A. Babatunde, A. Aderemi. Hydrochemical investigation of Groundwater quality in selected locations in Uyo, Akwa-Ibom state of Nigeria. New York Science Journal, 2010: 117-122.

[162] WHO. Guidelines for Drinking-water Quality: Fourth Edition. World Health Organization Geneva, 2011: 564.

[163] McAllee, E.B., et al. Groundwater nitrate reduction versus dissolved gas production: A tale of two catchments. Sci Total Environ, 2017, 586: 372-389.