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Detailed Hydrogeological and Hydro Chemical Reassessment of the Niger Delta Basin, South-South Nigeria

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Abstract:* This review presents a detailed analysis of hydrogeological and hydrochemical conditions of the Niger Delta Basin. Hydrogeologically, the specific capacities recorded from different areas within this Basin vary from 6700 lit/hr/m to 13,500 lit/ hr/m. The water table is very close to the ground surface and varies from 0 to 4 meters. Unconfined groundwater aquifers occur in shallow unconfined aquifers, sands of the coastal beach ridges and river point bars, and sandy islands within the mangrove belt. There is a stable water table fluctuation which characterised the high precipitation zone. The shallow aquifers of Benin Formation are more porous than those in the Deltaic areas. In the southern areas, along the coastal zone, an artesian condition occurs. However, the aquifers are less transmissible with increased depth of the confined aquifer, owing to its more delicate texture. Therefore, more compact, and less permeable, or that there is not enough water in storage. More than half of groundwater sources in the Basin are acidic. Based on mean TDS concentration groundwater, fall in an excellent class for drinking. Groundwater classification based on conductivity showed all the reported findings indicate conductivity ranging from 250-750 µS/cm. Based on cation and anion chemistry, the Niger Delta Basin holds water of relatively acceptable drinking quality. However, the uncontrolled groundwater development, land-use changes, pollution from industrial, municipal, and agricultural effluents pose a threat to groundwater quality protection. Thus, a policy guideline is required to protect groundwater from pollution.

***Keywords:* Niger Delta Basin, Deltaic Formations, Benin Formation, Unconfined Groundwater Aquifers, Confined Groundwater Aquifers, Groundwater Composition.**

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1. INTRODUCTION

Access to potable water is essential for good health and healthy life [1-4]. The worldhas recorded some success in improved hygiene and access to portable water in line with the Sustainable Development Goals, especially in developing countries [1]. At least 2.6 billion people worldwide have increased access to portable water of improved quality between 1990 and 2020 [1]. This success notwithstanding, access to portable of excellent quality is yet to be achieved by 663 million around the world [1]. Consequently, many developing countries such as Nigeria have to depend heavily on untreated water from personal boreholes, vulnerable shallow groundwater wells, rivers and streams [1, 2, 5-7].

Though, as 2015 only 79.75 out of 319 million (25%) of peoples in Sub Saharan Africa had access to potable water of good quality, in the Caribbean and Latin South America, North Africa, West Asia, South and East Asia had theirs varying from 65% – 94%. It is important to note that 70% of the global population that rely on surface water for drinking are in Sub Saharan Africa [1]. Accordingly, between 1990 and 2015, 723 million new users of piped borne water were documented in East Asia, a reduction from 43% to 33% was noticed in Sub Saharan Africa. Correspondingly, 67% of Nigeria's population had access to improved water supply in 2015. However, it was short of the 77% Millennium Development Goal Target and much less than the global average of 91%. Based on Nigeria's Demographic and Health Surveys of 2013, 14.4% (urban) and 50.8% (rural) households used unprotected drinking water sources [1].

Access to potable water and sustainable water resources management depends heavily on thorough analysis hydrogeological configurations of basins and hydrochemistry of aquifers [8-11]. Understanding the hydrochemical properties and aquifer hydraulic characteristics is critical for overall groundwater management in coastal areas [12-14]. Generally, groundwater hydrochemistry is strongly influenced by its flow paths and aquifer rock-mineral mineralogy [15-18]. The hydrochemistry of Groundwater is the consequential of all the reactions and processes that operate in the water from right from the condensation in the atmosphere to the time is precipitated and collected by rivers and streams, recharged into aquifers and discharged by a well [15, 19-22]. Therefore, the critical insights about aquifers' geological history and its suitability for different uses can be revealed by the groundwater chemistry [15, 23-33].

The groundwater quality is sturdily conditional on the hydrochemical processes that operate in unsaturated and saturated zones, the regional hydrogeological conditions and anthropogenic activities [34-37]. The projected changes in global groundwater reserves due to climate change and human population growth within the 21st century are enormous [38-40]. Coastal regions such as Niger Delta are heavily inhabited, because they offer the most excellent environments for both quality of life and economic development, offering freshwater to more than one billion people living there [38]. One of the most critical ecological crises in coastal regions is the salinisation of aquifers. Saltwater intrusion triggered by groundwater overuse, which upsets the delicate hydrogeological balance between freshwater and seawater, is now concerning many coastal areas worldwide [38]. Hence, to

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foresee and thwart saltwater intrusion in coastal aquifers, it is essential to study coastline aquifers' aquifer geometry and salinisation boundaries [38].

Hydrogeochemical analyses of Groundwater in different parts of the Eastern Niger Delta Edet [41] indicate that the major cations' intensities are lower than the World Health Organization (WHO) guidelines for domestic uses. The incidence of slightly saline water in some areas is ascribed to regional hydrogeological processes taking place in the region. Groundwater quality in the eastern Niger Delta's coastal aquifer is controlled by multi-chemical processes that have shaped the groundwater quality/facies and their spatial distributions [42]. The Groundwater from the coastal areas around Port Harcourt is more contaminated by heavy metals than those from the inland area. The pollution is attributed to anthropogenic activities [43]. However, evaluating hydrodynamic characteristics of hydrogeological units in parts of Niger Delta, southern Nigeria have not shown any interaction between freshwater and saltwater within the potential aquifers despite the salt water's proximity within the area [44]. It is against this background that this review seeks to present a detailed hydrogeological and hydrochemical reassessment of the Niger Delta Basin, South-south Nigeria.

The Geographical Setting

The Niger Delta Basin covers most of the Bayelsa and Rivers States areas and further south-east corner of Delta and Edo States [45]. The Basin occupies a broad riverine area through which the River Niger (the largest river in Nigeria) pass into the Atlantic Ocean, forming a Bird Foot Delta, which fans out into the ocean. The Basin also contains many tidal bays separating small islands of less than 10 meters above sea level (Figure 1). The primary drainage system comprises of the New Calabar, Andoni, St. Nicholas and Sambraino River networks. The islands are creased with sandy ridges. The vegetation cover is thick mangrove, found in the swampy environment. Annual rainfall is generally high, with a mean annual rainfall above 2600mm. The relative humidity is generally high (>80%), and the average annual temperature is less than 27°C.

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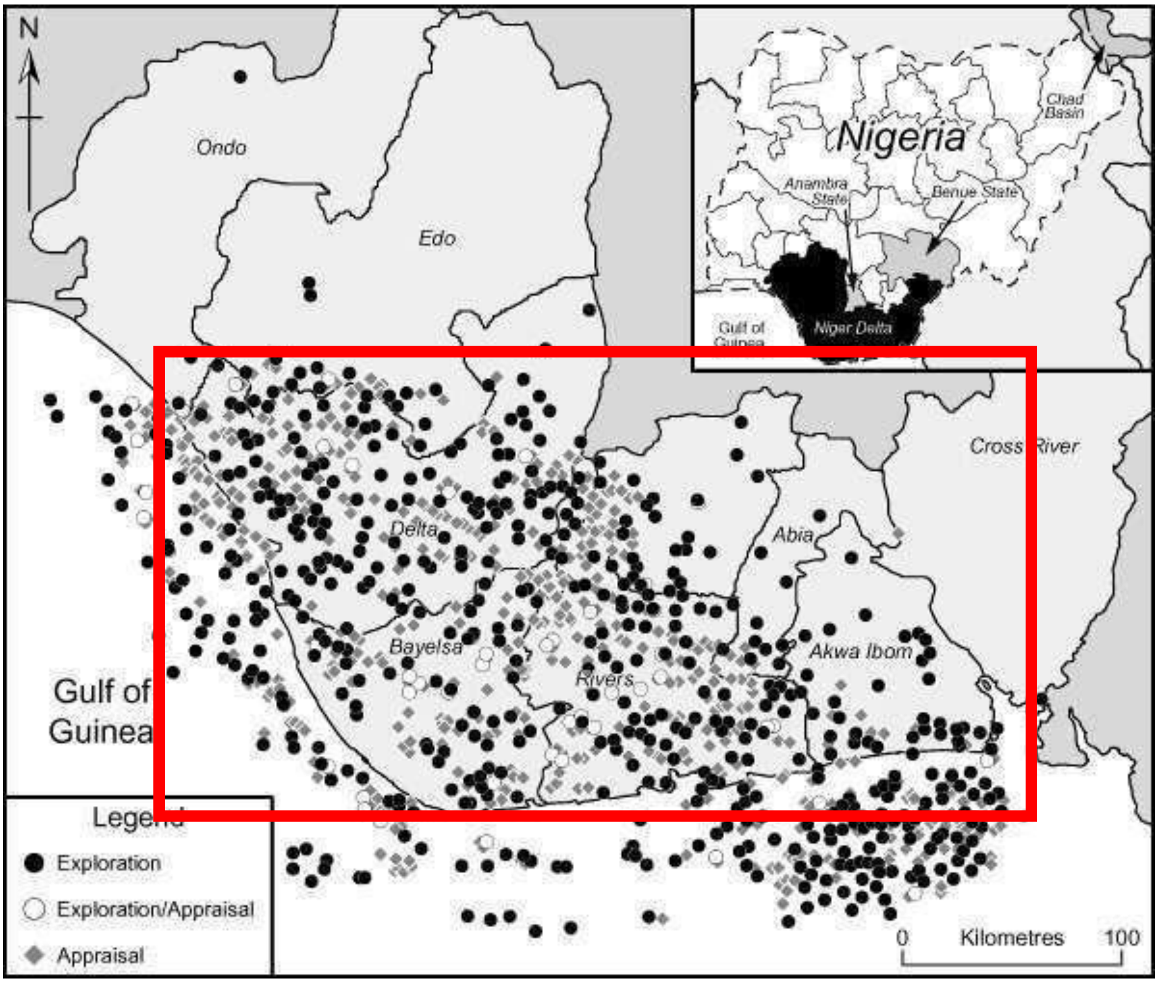

Figure 1. Map of Niger Delta Basin. After Bello and Olukolajo [46]

Geological Setting

A detailed geological account of the Niger Delta is well documented in the literature [45, 47, 48]. The effect of geology on the groundwater resources of the Niger Delta establishes the most central factor in addition to the climate in the region [49]. Regrettably, the existing knowledge of the geological setting prevailing within the groundwater province of the Niger Delta is partial. Three major formations comprise the modern Niger Delta, overlain by various Quaternary deposits (Figure 2). The first group comprises deltaic plains (including Akata Formation), predominantly shale and clay, the Agbada Formation which is largely fluviatile and fluviomarine, and the Benin Formation, creating a continental deposit of sand and gravel. The depositional form that goes together with the build-up of sediments during the delta formation produced structural traps in the Agbada Formation. This constitutes the petroleum-containing formations in the Niger Delta. While suitable for petroleum build-up, the Agbada Formation is too deep to be related to groundwater storage.

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The existing knowledge of the Benin Formation is limited, associated with that of the Agbada Formation. The too sandy nature of the upper Benin Formation and the abundant growth faults in the underlying Akata Formation have permitted meteoric water to infiltrate very deep into the subsurface. The controlling effect of geology on groundwater occurrence in the Niger Delta is no longer in doubt. The sedimentation outline and stratification control both the quality and quantity of water in the region. Its examination is the first step towards a meaningful groundwater study of the region. The Benin Formation, therefore, requires a comprehensive examination. The Cretaceous unit beneath the Basin has not been penetrated. The lithology of Cretaceous rocks in the Niger Delta Basin can only be inferred from the visible Cretaceous section in the north-eastern Anambra Basin, as indicated by Figure 2. From the Campanian through the Paleocene, the shoreline was concave into the Anambra, forming convergent longshore drift cells that produced tide- dominated deltaic sedimentation during transgressions and river-dominated sedimentation during regressions. Low marine classics were deposited beyond offshore and, in the Anambra Basin, are characterised by the Albian-Cenomanian Asu River shale, Cenomanian-Santonian Eze-Uku and Awgu shales, and Campanian/Maastrichtian Nkporo shale, among others. The spreading of Late Cretaceous shale underneath is well documented, see Michele, et al. [50].

During Palaeocene, a significant transgression (i.e., the Sokoto transgression) began with the Imo shale being deposited in the Anambra Basin to the northeast and the Akata shale Niger Delta Basin area to the southwest (Figure 2). During Eocene, the coastline shape became convexly curvilinear; the longshore drift cells switched to divergent, and sedimentation changed to being wave-dominated [50]. At this time, deposition of paralic sediments began in the Niger Delta Basin proper and, as the sediments prograded south, the coastline became progressively more convex seaward. At the moment, delta sedimentation is still wave-dominated and longshore drift cells divergent. However, the Niger Delta Basin's Tertiary segment is divided into three formations, representing prograding depositional facies distinguished generally based on sand-shale proportions. The Akata Formation at the delta base is of marine derivation and is composed of thick shale arrangements, turbidite sand (potential reservoirs in deep water), and minor amounts of clay and silt. Commencing during the Palaeocene and through the Recent, the Akata Formation moulded during low stands when earthly organic matter and clays were transported to deep water areas branded by low energy circumstances and oxygen deficiency. Little of the Formation has been penetrated; consequently, only a structural map of the Formation's top is available. It is projected that the Formation is up to 7,000 meters thick [50].

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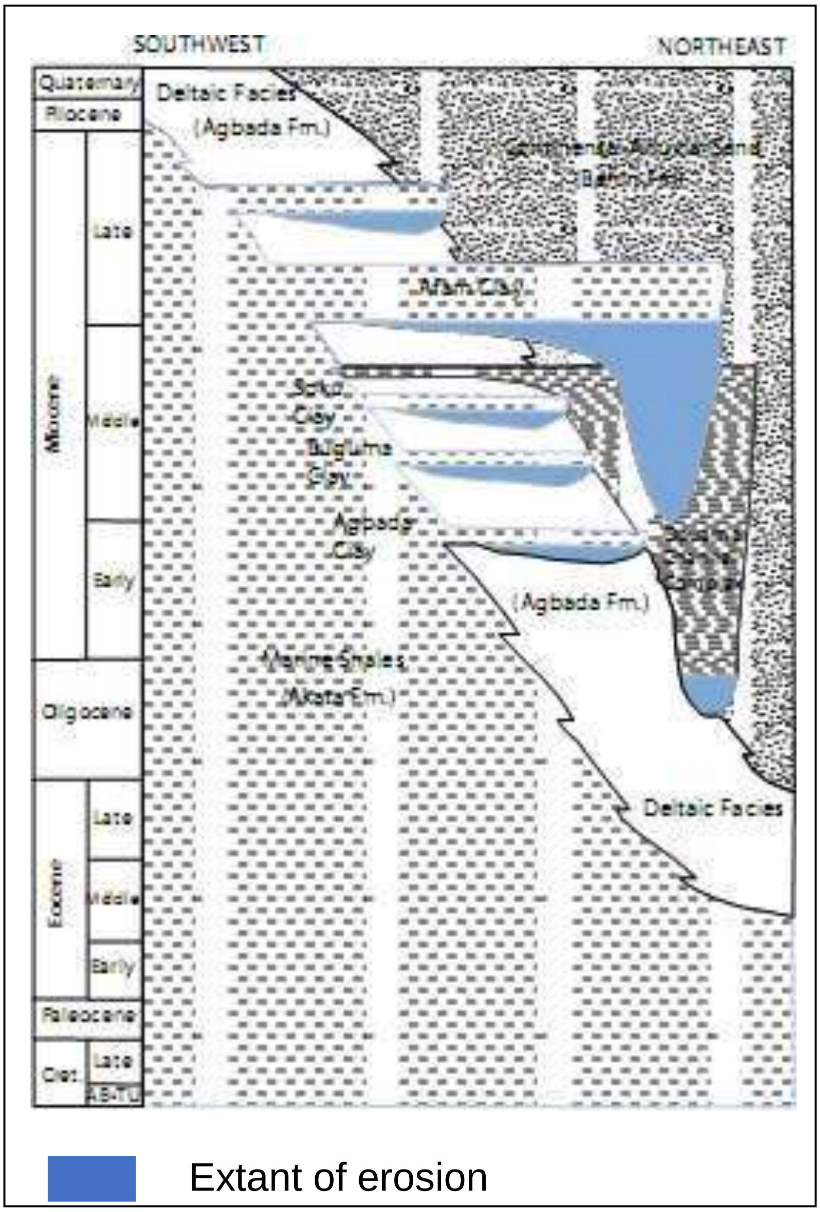

Figure 2. The stratigraphic column is showing the three formations of the Niger Delta. After Michele, et al. [50].

The superimposing Agbada Formation deposition, the central petroleum-bearing Formation, commenced during the Eocene and lingered into the Recent. The Formation contains paralic siliciclastics over 3700 meters thick and characterises the actual deltaic portion of the arrangement. The clastics accrued in delta-front, delta-top set, and fluvial- deltaic surroundings. In the lower Agbada Formation, shale and sandstone beds were placed in equal proportions, though, the upper portion is typically sand with only negligible shale interbeds. The Agbada Formation is covered by the Benin Formation (the third Formation), acontinental latest Eocene to the Recent deposit of sedimentary and upper coastal plain

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shingles that are up to 2000 meters thick. The deposition of the three formations happened in each of the five flapping siliciclastic sedimentation cycles that encompass the Niger Delta. These cycles (depobelts) are 30-60 kilometres wide, prograde south-westward 250 kilometres over oceanic crust into the Gulf of Guinea and are defined by synsedimentary faulting that befell in response to mutable rates of subsidence and sediment supply.

The interplay of subsidence and supply rates give rise to deposition of the separate depobelts-when further crustal sinking of the Basin could no longer be put up, the focus of sediment deposition shifted seaward, forming a new depobelt. Each depobelt is a discrete component that matches to a break in the delta's regional dip and is confined landward by growth faults and seaward by large counter-regional faults or the growth fault of the next seaward belt. The three depobelt provinces are categorised based on structure: the northern delta province, which overlies relatively shallow basement, has the oldest growth faults that are generally rotational, evenly spaced, and rise their steepness seaward. The central delta province has depobelts with well-defined structures such as successively deeper rollover crests that shift seaward for any given growth fault. The third province, the distal delta province is the most structurally complex due to internal gravity tectonics on the modern continental slope.

Groundwater condition

The Geological sequence in the Niger Delta comprises four types of Geological units (Figure 3.). The Ameki and Benin Formations' groundwater potentials have been described in the previous studies Igboekwe, et al. [51]; Akujieze, et al. [52]; Amadi, et al. [42]; and Adelana, et al. [53];. The Akata Formation (deltaic plains) lie unconformably on the migmatite-gneiss basement complex and form the Niger Delta stratigraphic pile [54]. This Formation consists of an open marine facies' unit dominated by high pressured carbonaceous shales. The Formation ranges in age from Palaeocene to Eocene, and its thickness could exceed 1000 meters. The Agbada Formation consists of a sequence of alternating deltaic sands and shales. It is Eocene to Oligocene in age and exceeds 3000 meters in thickness. The Benin Formation is Oligocene to Pleistocene in age. It consists of freshwater continental friable sands and gravel with outstanding aquifer properties, with occasional intercalation of shales. This Formation contains the most prolific and hence most tapped aquifer in the Niger Delta region, particularly in areas north of Warri where it is shallow. The thickness of the Benin Formation is variable but generally exceeds 2000 meters [54].

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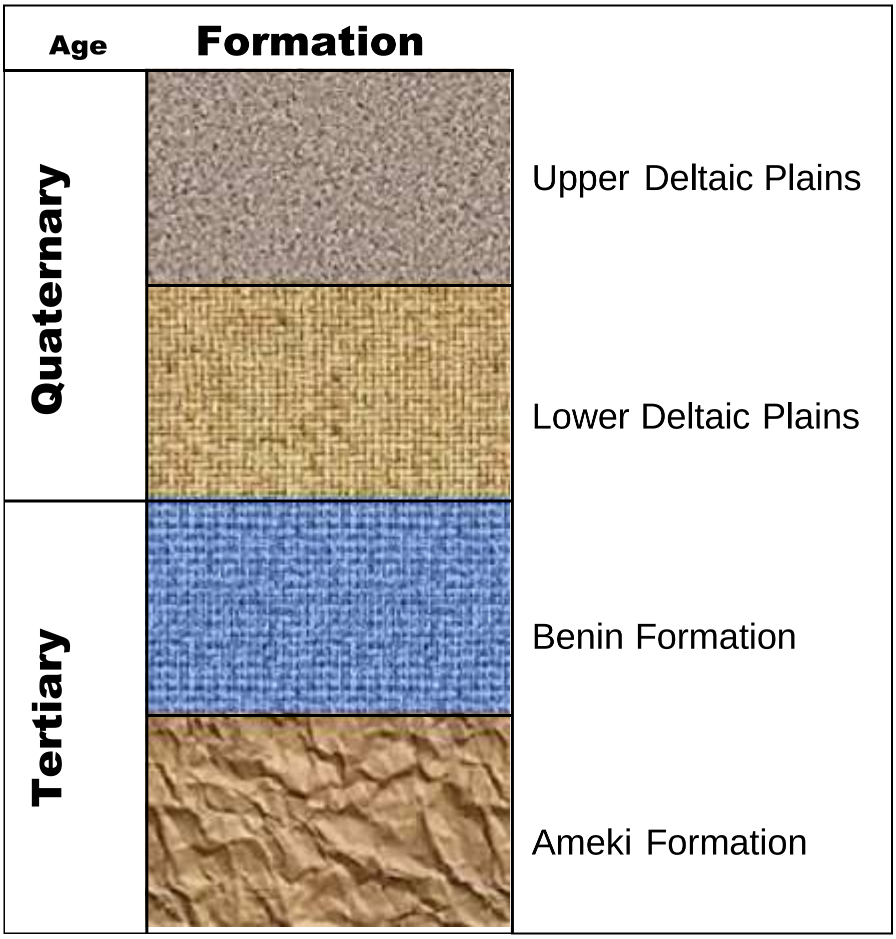

Figure 3. The geological sequence in the Niger Delta Basin. Source of data: Offodile [45].

Directly underlying the Warri area and the topmost of the sedimentary Formation is the Quaternary to Recent alluvium, the Somebreiro-Warri Deltaic Plain Sands. This Formation contains fine to medium and coarse-grained unconsolidated sands that are often feldspathic (with 30 - 40 wt % feldspars) and occasionally gravelly. This arrangement is stratified with peat and soft and plastic clay lenses that could be sandy and shales. The Formation generally does not exceed 120 meters in thickness, and it is predominantly unconfined. The sand's hydraulic conductivities vary from 3.82 x 10^{-3} to 9.0 x 10^{-2} cm/sec, which indicates a possibly productive aquifer. Specific capacities recorded from different areas within this basin vary from 6700 lit/hr/m to 13,500 lit/ hr/m. The water table is very close to the ground surface and varies from 0 to 4 meters. This limited groundwater level fluctuation reflects the high amounts of precipitation often recorded in the Warri area over the greater part of the year. This aquifer is partly recharged from River Warri. Shallow resistivity subsoil corrosivity in Port Harcourt metropolis was evaluated by Ngah and Abam [55]. Two geoelectric resistivity layers were distinguished to a depth of 40 meters based on characteristic resistivity ranges and were interpreted in terms of soil type, water level, and lithology. The upper layer with resistivity values between 11 – 53 ohm-m has a thickness of between 5 - 13m.The lower layer has higher resistivity values; 68 – 875 ohm-m. The upper layer's resistivity values fall within corrosive – moderately corrosive, while the lower layer falls within moderately corrosive – slightly corrosive in the B.S. Soil Electrical Resistivity

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Classification. Shallow installations will suffer corrosion from aggressive subsoil if appropriate measures are not taken to protect them. Groundwater quality will be a major casualty of corrosion of unprotected buried steel pipes since the groundwater table is shallow to near-surface. The coastal basins enclose the area. The river basins falling within this regioninclude the Deltaic Basin, the Imo-Aiwa Ibo, and Cross River Basins. The region is situated between longitudes 5°30' and 8°30' and latitudes 5° and 4°15' and enclosed by two prominent geological formations, notably the Benin Formation and the Niger Delta group. The Niger Delta group consists of a network of tidal creeks, which separate small islands of less than 6 meters above sea level. The sandy ridges mark the islands, though the vegetation is dense mangrove in the very marshy setting. However, the outcrop area of Benin Formation is generally flat-lying, with the highest elevation less than 180 meters above sea level [45]. However, the groundwater table, slopes gently from the higher grounds towards the River Niger valleys, divided mostly by the Cross, Imo, KwaIbo, and Sambraino river networks. Thevegetation is characteristically tropical rainforest [45]. The geological order in the coastal areas of the Niger Delta is summarised in Table 1. The most critical water-bearing formations are the Deltaic Formations and the Benin Formation.

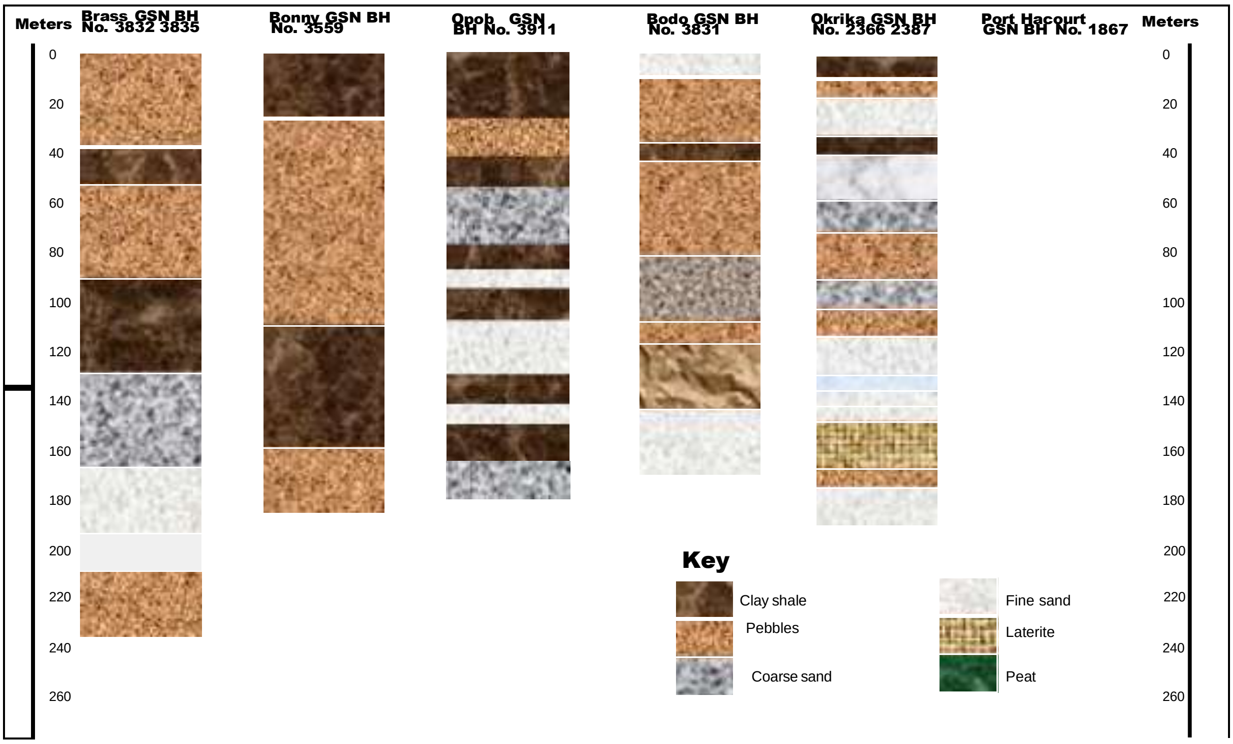

Figure 4. Section through the Deltaic Formation. Source of data: Offodile [45]

Table 1. The geological sequence of the coastal areas of Niger Delta

Formations	Age	Era
Upper Deltaic Plains	Late Pleistocene	-
Lower Deltaic Plains	Holocene	Quaternary
Benin Formation	Oligocene	-
	Pleistocene	-
Ameki Formation	Palaeocene-Eocene	-

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Deltaic Formations

These formations comprise late Holocene plains and cover most of the present Niger delta and stretch narrowly eastwards along the coastline. The sediments comprised coarse to medium-grained unconsolidated sands forming lenticular beds intercalating peaty matter and lenses of soft, silt clay and shale. A gravelly bed 9 meters thick was reported. These beds dip at varying angles towards the sea, forming units representing a sequence of old estuaries [45]. Near the surface, sediments dip at low angles and represent the delta's present phase's top set beds. For instance, in Brass, G.S.N. B.H. No. 3835, 57 meters of fine to medium sand were recorded, which is underlain by dark grey clay with sand intercalation 6 meters thick. This was lies beneath 51 meters of very coarse to pebbly sands underlain by sandy woody or peaty matter. Underneath this a 36 meters thick layer of very compacted clay bed overlies fine to very coarse sand, extending far down from the 150 meters depth of clay formation to the bottom of the hole 255 meters below the ground level (GSN. B.H. No. 3835)-Figure 4. A similar succession was run into at Bonny. Thin beds of clay, at the top, overlies a 90 meters column of coarse and pebbly sands covering dark shales 27 meters thick. These shales also confine very coarsely to pebbly sands below the 135 meters depth. At Opobo, the sequence changes slightly. The shale bed in this area occurs between 113.4 meters to 131 meters and confines an aquifer that produces pressure water.

Benin Formation

Benin formation's outcrops are found in the northeast of the coastal belt and dips at a low angle in the southwest. The sediments comprise mainly of lenticular unconsolidated, predominantly sandy formations. The pebble beds occur irregularly and have given rise to high yielding boreholes in Port Harcourt (GSN. BH. No. 8171). Other boreholes in the Benin Formation (e.g., Azumini GSN. BH. No. 2372 and Elele GSN. BH. No. 2842) show the same sequence continuous sandy pebbly formations [45]. Conversely, lenticular shales and clays occur mainly in the eastern parts where they confine small but moderately high yielding aquifers. In Oyo, Utapate, Etinan, Oron, and Calabar, many confined aquifers were run into, and most of these aquifers produced artesian conditions. The 90 to 150 meters confining clay beds run into the Niger Delta area and adjacent to the Benin Formation zone, notably, Bodo, Okrika, and Port Harcourt. The laterite beds were also run into at Okrika, Etinan, Oron, Calabar and Port Harcourt (Figure 5). These appear to mark the erosional surfaces of the offset beds of the old delta. The Benin Formation (Oligocene to Recent) is about 2100 meters thick at the centre of the Basin and comprises medium to coarse-grained sandstones, thin shales, and gravel. It is the most productive aquifer in the region [42].

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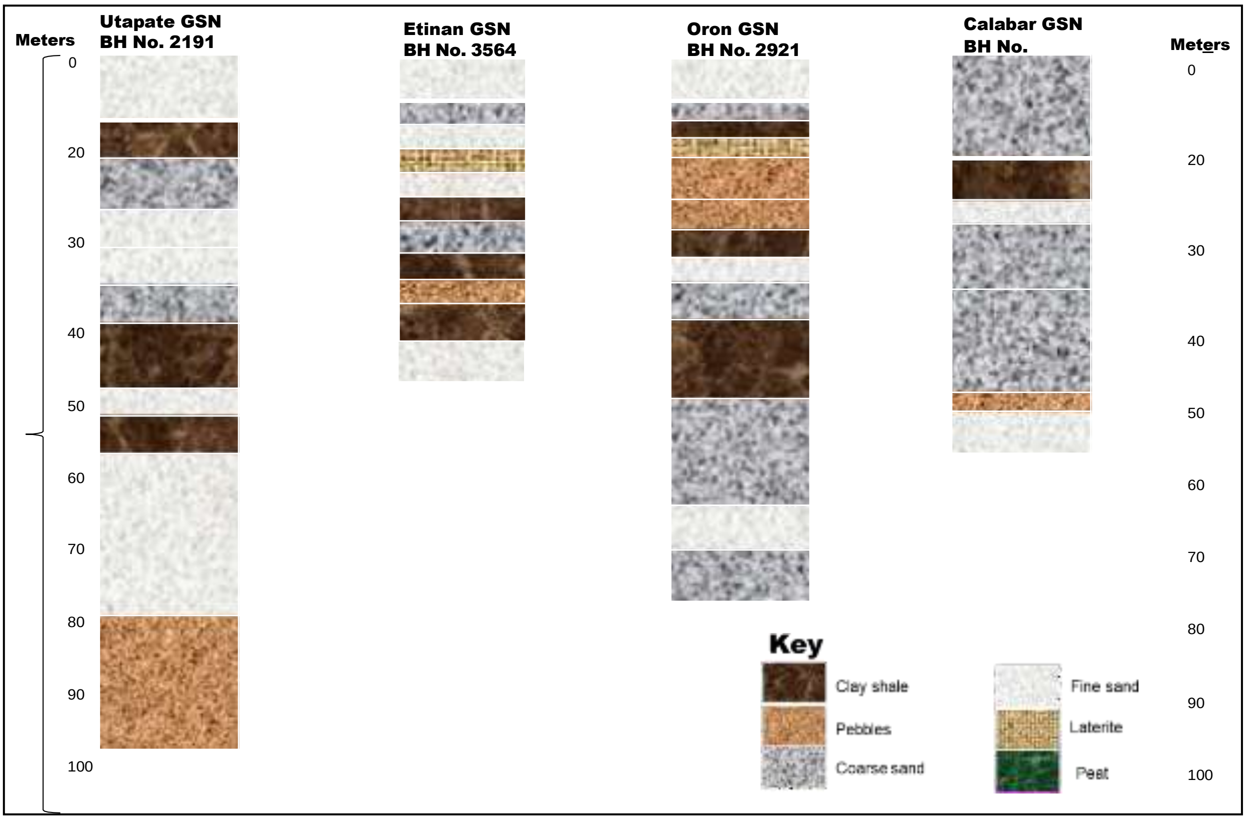

Figure 5. Confined aquifers in the Benin Formation. Source of data: Offodile [45].

Overlying this Formation are the Quaternary deposits, an unconfined aquifer sequence comprising rapidly alternating sand, silt and clay sequence with the silt and clay becoming very prominent seawards. The Basin extends across many ecological zones, including sandy coastal ridge barriers, brackish/saline mangrove, freshwater, and swamp forest. Recharge to aquifers is by direct infiltration of rainfall, which ranges annually from 2540 mm on the mainland to about 5010 mm towards the coast. Groundwater in the area occurs in shallow aquifers belonging to the coastal plain sand, containing sand, gravel and clay intercalations. Borehole yields are excellent, with production rates of about 20,010 l/h and the borehole success rate is generally high. The transmissivity ranges 59.00 to 6050.00 m^2/d; hydraulic conductivity varies from 0.04 to 60.00 m/d, and storage coefficient is 10^{-6} to 0.15. Surface water in the area is numerous, including streams, rivers, and creeks [42]. Most of the wells in the northern parts of the coastal belts tap the unconfined aquifers. In most of these wells, the geological sequence comprises constant sandy formations from top to the bottom of the boreholes. However, some aquifers occur under confined conditions and produced artesian wells.

Unconfined groundwater aquifers

Groundwater occurs in shallow unconfined aquifers, sands of the coastal beach ridges and river point bars, and sandy islands within the mangrove belt. It also occurs in confined aquifers at varying depths. Groundwater exploration in the coastal belt revealed brackish

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water (Table 2). Shell Petroleum Development Company of Nigeria Ltd drilled boreholes into the deep confined aquifers to obtain freshwater (samples 4 and 6), while samples 10 and 11 represent surface water in the mangrove belt area (Oteri, 1984). The water table in the Niger Delta region is very high, and well depths ranged from 0 to 9 meters below the ground surface. The aquifers in this Basin derived steady recharge from direct infiltration from rainfall. The water table's shallowness introduces the problem of saline water intrusion from the sea and pollution from chemical, petroleum and sewage effluent discharges [45]. Precipitation in the Niger Delta is very high, ranging from 2400mm to 2400mm per annum in the inland areas. Along the coast, annual rainfall reaches to 4800mm. The mean annual rainfall in the area is about 31.4 x 10^{12} litres, based on average precipitation of 2400mm per year. Some proportion of the rainfall is lost by runoff and evaporation. A range of 720mm to 960mm per year evaporation and the coastal areas, mainly dense mangrove swamps, to 1200mm in the northern parts of the Basin with low vegetation density [45].

Table 2. Chemical characteristics of water samples in the Niger Delta.

Sample	Location	Type and depth (m)	Cl (mg/l)	TDS (mg/l)	Fe (mg/l)	E.C. (µS/cm)	Classification
1	Burutu	GW 200	nd	2222	Nd	2400	B
2	Buguma	GW259	nd	2908	Nd	2300	B
3	Kula	GW151	nd	399	0.2	362	F
4	Forcados	GW548	5	90	0	180	F
5	Focados	GW6	42.5	164	5.5	263	F
6	Escravos Beach	GW457	Nd	Nd	Nd	180	F
7	Escravos Beach	GW105	551	1150	Nd	1000	B
8	Kulama	GW60	640	1540	0.2	1047	B
9	Sengana	GW3	50	410	0.3	23900	F

Note: Nd = Not detected, B= Brackish water, F = Freshwater, GW = Groundwater
After Oteri [56].

The stable water table fluctuations which characterised the high precipitation zone. There were no measurements of storage coefficients of the aquifers of the Niger Delta Basin. Pumping tests from boreholes in the Basin indicate specific capacities summarised in Table 2. Some contrasting results showed contrasting results of drawdown against yield in the Benin Formation and the Deltaic Formation. While drawdown at Opobo borehole in Deltaic Formation is steep, owing to the shallowness and extent of aquifers, the Formation is thicker and broader, coarser generally more porous, shows a gentler slope in the drawdown. Table 3 shows an average of about 7500 litres per hour per meter drawdown (500 gl/hr/ft/m drawdown) which is comparatively low. The low yields are attributed to the aquifers' fineness and thinness, mostly intercalated with clay shale and organic matter.

Table 3. Specific capacities (lit/hr/m) of some boreholes in the Deltaic Formation.

G.S.N. B.H. No.	Location	Specific yield (gph/ft)
3272	Ofoniama	700 (19500 lit/hr/m)
3684	Yenegoa I	530 (7950 lit/hr/m)
3685	Yenegoa II	902 (13530 lit/hr/m)
3476	Oloibiri	900 (13500 lit/hr/m)
2636	Nembe	900 (13500 lit/hr/m)
1864	Bonny	500 (7500 lit/hr/m)
2229	Amassoma	450 (6750 lit/hr/m)
2366	Okrika II	460 (6900 lit/hr/m)

After Offodile [45]

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The shallow aquifers of Benin Formation

As explained in preceding sections, the Benin Formation sediments are more porous than those in the Deltaic areas. Surface runoff is insignificant due to the extensive surface drainage system's paucity and a reasonably dense vegetation cover incidence. The depths of the water table in the area ranged from 3-15 meters below the surface. However, owing to the more arenaceous aquifers' character in Benin Formation, these aquifers expected to release more copiously than the Deltaic sediments. Furthermore, with little runoff and evapotranspiration, much of the precipitation will infiltrate and recharge the shallow aquifers. Table 4 summarises the specific capacities of some boreholes in Benin Formation. The mean specific capacity of the area, as indicated in Table 5 above is 10500 lit/hr/m (700gph/fit). In Port Harcourt, the borehole is exceptionally high yielding with a specific capacity of 58500 lit/hr/m (3900 gph/ft). In this respect, the well taps a gravel bed. A few studies on seasonal fluctuations obtained from the area show seasonal variabilities ranging from 2.1-3.6 meters [45].

Table 4. Specific capacities in gph/ft. (lit/hr/m) of drawdown.

Location	G.S.N. B.H. Specific (Lit/hr/m) Yield No. in Drawdown		Size of the screen (mm)	Length of Screen (m)	Water table (m)
Ahoada	1654	*	70	-	6
Azumini	2374	*	-	4.5	-
Port Harcourt	3270	9000	100	4.8	16.8
Imo River	1871	58500	190	10.8	6.9
Igrita	2845	9000	100	2.1	6.9
Eket	2025	*	80	4.2	12.9
Nkali	3577	6000	70	2.1	23.4
Umuechem	-	10500	-	-	-
Elele	947	18000	100	4.5	12.3
	2842	15000	120	16.5	11

After Offodile [45] Note: * = No data.

Confined groundwater aquifers

Apart from the shallow water table or unconfined conditions described above, confined aquifers also occur within the Deltaic Formation and Benin Formation areas and the areas of Benin Formation. In both areas, high yielding artesian flows were recorded.

The deltaic aquifer (Delta area)

In the Niger Delta's southern areas, particularly along the coastal area, boreholes constructed produced an artesian condition. In the boreholes constructed at Opobo, Bonny, and Brass, the aquifers are confined by shale or clay beds. The section along Bonny, Brass, and Opobo indicates thickening of the shale bed from Opobo in the east to Brass in the southwest. At Opobo, the depth range in thickness of aquiclude meters ranged from 113.4-131.4 with a pressure head of 19.8 meters. In Bonny, the thickness ranged from 108.0-135 meters with a pressure head of 27 meters. Lastly, in Brass, the thickness was 144.0-150 meters with a pressure head of 36 meters [45]. The depth at which the confining layer is encountered in the boreholes is approximately the same. This has also been confirmed by the resistivity survey results from the Geological Survey of Nigeria, which showed the Occurrence of a shale layer within the depth range of 144-150 meters.

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The aquifers' total depth under this shale layer has not been determined, requiring deeper test boreholes. However, at Brass, 150 meters depth of the aquifer has been evidenced.
The section passing through Brass, Bodo, Okrika, Opobo and Port Harcourt (Figure 6), indicates that the aquifers cannot be wholly said to be confined [45]. It shows a definite hydrologic connection between the confined aquifers along the coastline and the unconfined aquifer of the Benin Formation to the north, inland wards. The aquifers increase thickness towards the mainland, while the confining clays thin out, exposing the water charged medium to direct recharge, through precipitation in the surrounding area [45]. Therefore, nearer to the coastline, it is probable that the confined aquifers are recharged by the Groundwater of the Benin Formation and parts of the Deltaic Formation in its continuous seawards flows. This has been confirmed by the reported Occurrence of submarine freshwater springs near the coastline [45]. As a result, the water table from the confined aquifers is free of saline pollution. Table 5 and 6 show some of these wells that gave sub artesian to artesian conditions in the Niger Delta Basin.

The specific yield of 3750 and 4500 lit/hr/m of drawdown is the lowest recorded in Bonny and Brass correspondingly against 6480, 13500 and 1200 lit/hr/m of drawdown recorded Opobo, Bodo and Okrika, which are shallower in depth [45]. From these records, it will be difficult to conclude since there is no consistent basis for comparison. However, it would appear that the aquifers are either less transmissible with increased depth of the confined aquifer, owing to its more delicate texture and therefore more compact and less permeable, or that three is not enough water in storage. Although the hinterland's recharge volume cannot be measured, the flow direction is assumed to be regionally seawards to the south [45]. Most of the constructed boreholes, for instance, G.S.N. B.H. No 3831 at Bodo, recorded the highest-pressure head of +4.6 meters, followed by G.S.N. B.H. No. 3911 at Opobo with a pressure head of 1.125meters. The remaining boreholes at Bonny, Brass, and Okrika ranged from 0.3-0.6 meters positive head. No records of drawdown are available. However, tidal effects were recorded in Bonny [45]. At low tide G.S.N. B.H. No.3108 at Bonny was reported to have given a free flow yield of 765 lit. Hr (150 gph) with water table slightly above ground level, while at high tide it gave free flow yield of 2250 lit/hr (500gph), and increased head of +0.45 meters [45].

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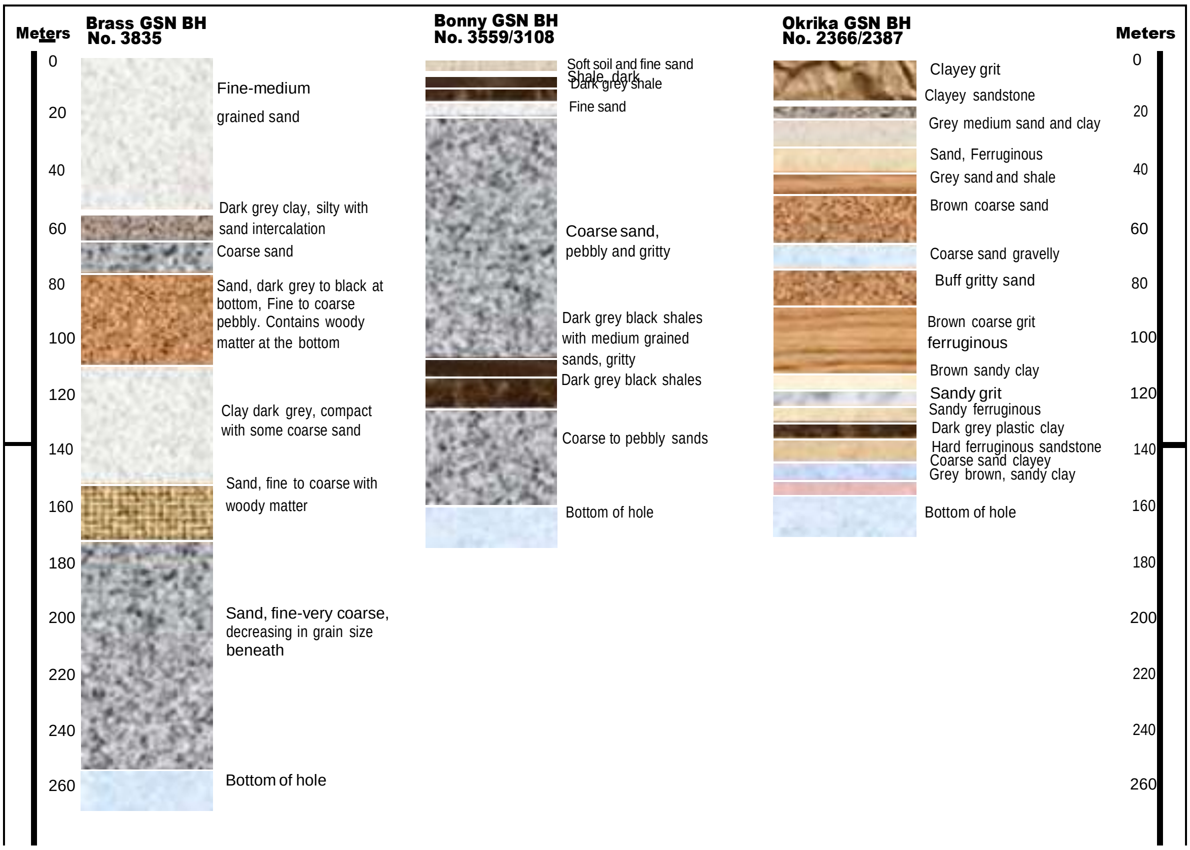

Figure 6. The lithology of boreholes in inland areas in Benin Formation at Brass, Bonny, and Okrika. After Offodile [45].

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Figure 7. The lithology of boreholes in inland areas in Benin Formation at Bodo, Opobo, and Buguma. After Offodile [45].

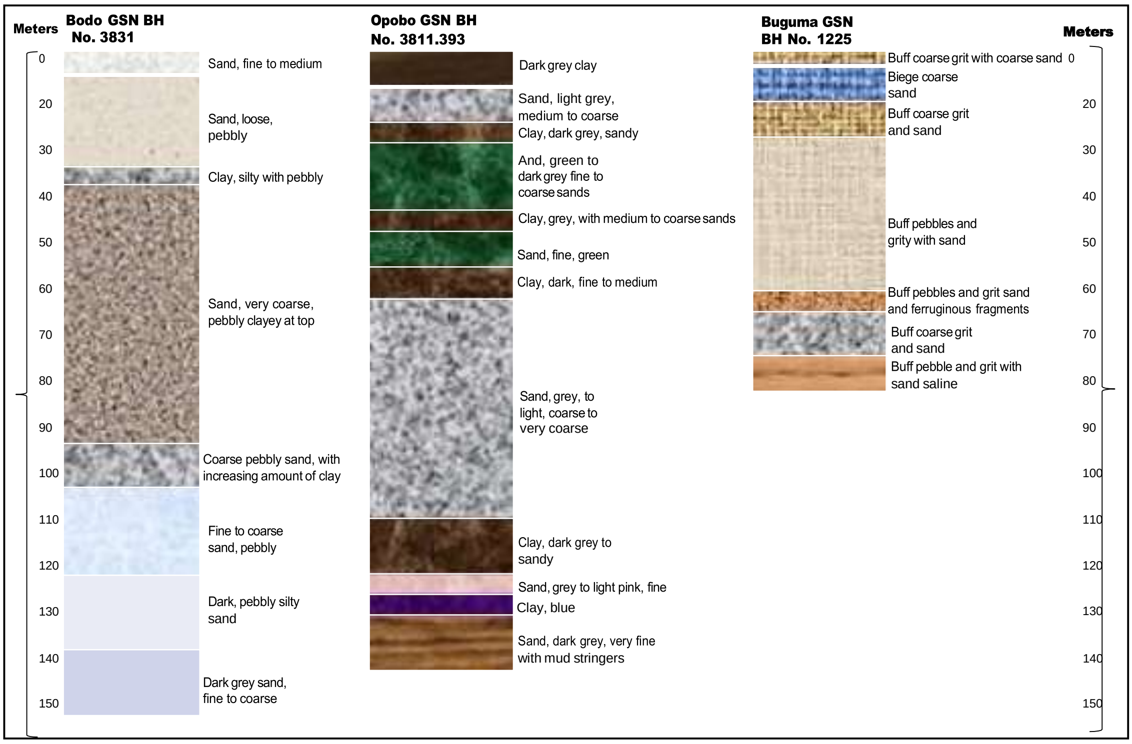

Table 5. Pressure heads in the Niger Delta.

B.H. No.	Position	Diameter	Gph/ft	Head (m)
3835 Brass	234-237	13/4”	500 (7500 lit/hr/m) (pumped)	-2m
3823 Brass	222-225m	3”	300 (4500 lit/hr/m) (pumped)	-0.5m
3559 Bonny	228-252m	6”	300 (4500 lit/hr/m) (pumped)	+40.45m
2366 Okrika	145-148m	8”	800 (12000 lit/hr/m) (pumped)	+40.3m
2387 Okrika	74.4-90.	8”	1200 (18000 lit/hr/m) (pumped)	+40.3m
3831 Bodo	71.4-87.4	55/8”	900 (13500 lit/hr/m) (pumped)	+44.6m
3911 Opobo	108?	-	432 (6480 lit/hr/m) (pumped)	+1.125m

After Offodile [45].

The inland aquifer

In places underlain by the Benin Formation, especially in the south eastern area confined aquifers occurred. Artesian conditions were evidenced at Calabar, Etinan, and Oron. Many shale and clay layers confined the aquifers in this area [45]. These aquifers contain mainly of very coarse-medium sands. The aquifers tapped by most boreholes in the area are not entirely confined. Like the Deltaic Formation, the confined aquifers in this area are recharged from the nearby inland recharge zones. Some boreholes reported have produced artesian wells of relatively good yields (Table 6). The lithology of boreholes in the Benin Formation inland area has been summarised in Figures 6-7. The overall lithological characteristics of these boreholes have shown the dominance of sandy formations in the area. Sandy aquifers are often associated with good groundwater potentials [4, 45, 57].

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Table 6. Free-flowing boreholes in inland areas.

G.S.N. BH.No.	Yield (gph) free flow	Specific yield (gph/m)	Screen size	Head
2191 Utapate	960 (4320 L/hr)	400 (6000 L/h/m)	5" (80mm)	+
3564 Etinan	*	-	8" (125mm)	+2.7m
3567 Etinan II	48000 (216000 L/hr)	-	-	+9.9m
2921 Oron	-	500 (7500 L/hr/m)	8" (125mm)	+17.4m
3578 Calabar	1300 (58501 L/hr)	500 (7500 L/hr/m)	+	+1.8m

After Offodile [45]. Note: *=Not known, +=Known to have a head but no data.

Groundwater Composition

Niger Delta Basin is blessed with countless ample natural groundwater aquifers. Many studies of the water quality of the Basin have been carried out. This section summarised some of these works and offered a guide to understanding the groundwater sources' hydrochemistry and the aquifer system for better groundwater quality management.

a. Physical chemistry

Figure 8 summarised the physical chemistry of Groundwater in the Niger Delta Basin. pH ranged from 3.77 to 10.52, with an average value of 6.17. Based on mean pH concentration, Groundwater in Niger Delta Basin is slightly acidic. The pH of drinking water may have one benefit. Some evidence shows that slightly alkaline drinking water can ease the symptoms of acid reflux. Moreover, there is limited evidence that alkaline water can slow bone loss. However, these studies have been disputed, and do not implicate acidic water as dangerous or unhealthy. About 53.78% of groundwater sources in the Basin are acidic, 43.11% are neutral, and 3.11% are alkaline. Effects of acidic water include the metallic or sour taste of drinking water, stained laundry, blue-green staining of sinks and other householdfixtures. Alkaline water is associated with scale build-up in household plumbing anddecreased the efficiency of electric water heaters.

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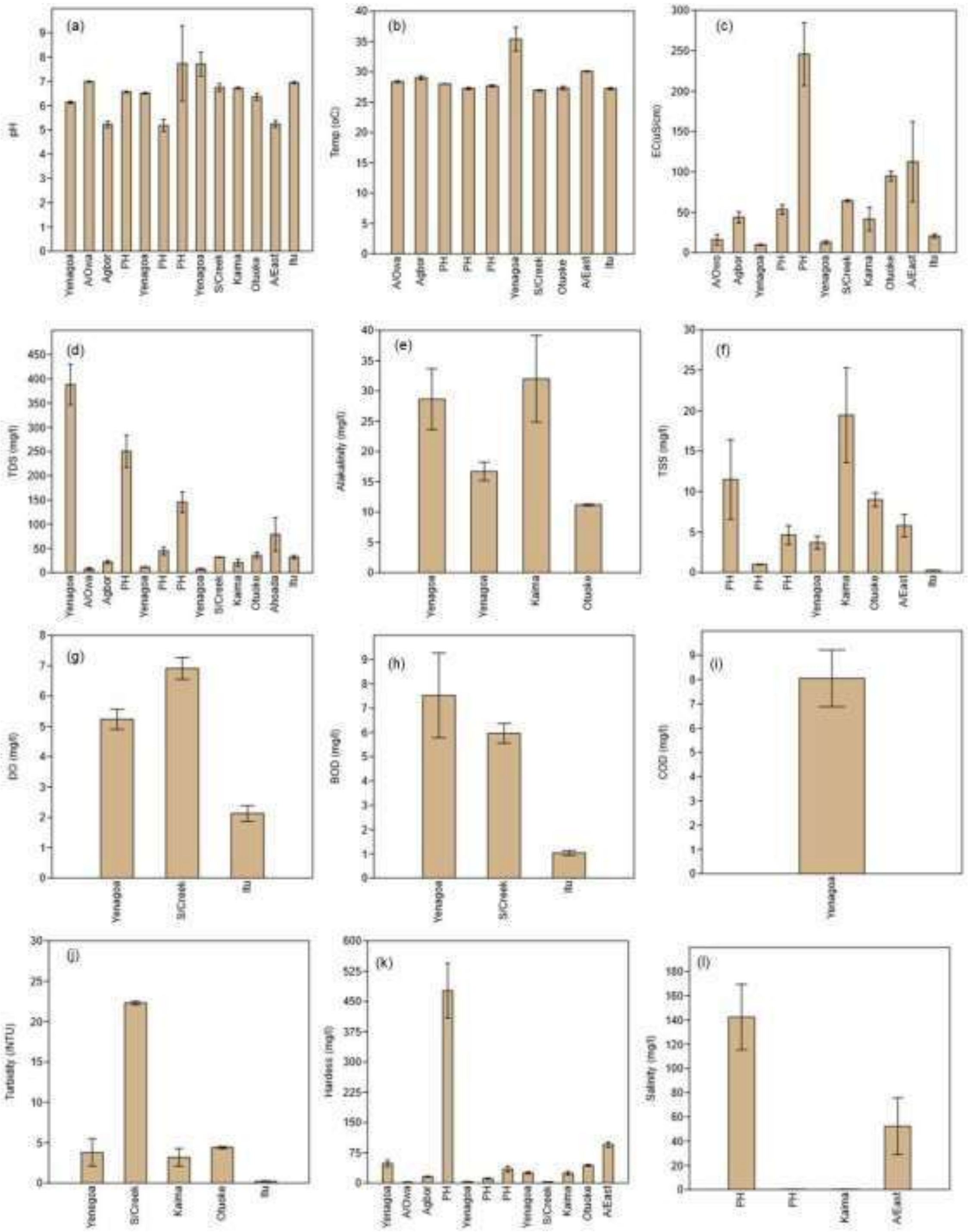
Figure 8. Physical parameters (a) pH, (b) Temperature, (c) EC, (d) TDS, (e) Alkalinity, (f) TSS, (g) DO, (h) BOD, (i) COD, (j) Turbidity, (k) Hardness, and (l) Salinity.



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Water with low pH levels can corrode plumbing and leach metal. Iron, manganese, copper, lead, and zinc are commonly found in acidic water. High levels of lead in drinking water is a primary concern of pH. It places adults at risk for health problems such as cancer, stroke, kidney disease, memory problems, and high blood pressure. Children are at a greater risk because their rapidly growing bodies absorb the contaminant more quickly. Copper, Fe, Zn, and Mn are also classified as secondary drinking water contaminants. These contaminantsare likely to cause hard water and staining problems at home. However, if found in elevated levels, they could cause a variety of health issues. That includes nausea, vomiting, diarrhoea, stomach cramps, kidney disease, liver disease, and nervous system problems. TDS ranged from <0.001 to 1410 mg/l with an average value of 136.91. Based on mean TDS concentration groundwater in the Basin, fall in an excellent class for drinking (Figure 9d). About 93.33% of groundwater sources in Niger Delta Have TDS concentration less than 500 mg/l. Salts are leached from the body under the influence of drinking water with a low TDS. Because adverse effects such as altered water-salt balance were observed in wholly desalinated water and water with TDS between 50 and 75 mg/l, the team that prepared 1980 WHO report (3) recommended that the minimum TDS in drinking water should be 100 mg/l. The team also recommended that the optimum TDS be about 200-400 mg/l for chloride-sulfate waters and 250-500 mg/l for bicarbonate waters [58]. The recommendations were based on extensive experimental studies conducted in rats, dogs, and human volunteers. Several health outcomes were investigated including dynamics of body weight, basal and nitrogen metabolism, enzyme activity, water-salt homeostasis, and its regulatory system, the mineral content of body tissues and fluids, haematocrit, and ADH activity.

The optimal TDS was associated with the lowest incidence of adverse effect, negative changes to the human, dog, or rat, good organoleptic characteristics and thirst-quenching properties, and reduced water corrosivity. Hardness ranged from <0.001 to 717 mg/l with an average value of 45.68 mg/l. About 87.56% of groundwater sources in the Basin have a hardness between 0-75 mg/l, indicating soft water (Figure 9b). Most studies reported the relationship between drinking water hardness and mortality from cardiovascular diseases, arteriosclerotic and degenerative heart disease, hypertensive disease, and stroke [59]. Relationships were reported for both men and women but were often statistically significant for one sex only. An indispensable effect of hardness was found in most studies involving large geographical areas, but studies in smaller areas tended to be inconclusive or insignificant. Electrical conductivity ranged from <0.001 to 717.40 µS/cm with an average value of 85.77 µS/cm.

Groundwater classification based on conductivity showed all the reported findings indicate conductivity ranging from 250-750 µS/cm. Conductivity is a parameter of general importance in water analysis, as it shows the range in which the dissolved elements are likely to fall. It is a measure of salinity in water. The lower E.C. values reported from this Basin are further indicated by lower salinity values (Figure 8i). Alkalinity ranged from 2 to 260 mg/l, with an average value of 26.42 mg/l. There is little known sanitary significance attaching to alkalinity (even up to 400 mg/l $CaCO_3$), though unpalatability may result in highly alkaline waters. Total suspended solids ranged from <0.001 to 35 mg/l with an average value of 5.43 mg/l. The matter which is suspended in quiescent water consists of finely divided light solids

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which may never settle or do so only very slowly [60]. Indeed, the net effect may be one of apparent turbidity without any discernible solids.

On the other hand, in flowing water, the solids that are kept in suspension by the turbulence may be settleable if the water is let stand. While the later would be determinable as 'Solids, Settleable,' and the former could be assessed as 'Turbidity,' there will be those solids of intermediate grading requiring estimation. To determine as much as possible of the solids present (not in solution), the determination of TSS is carried out. Turbidity ranged from 0.10 to 23.51 NTU, with an average value of 5.51 NTU (Figure 8j). Turbidity is mainly derived from clay particles, sewage solids, silt and sand washings, organic and biological sludges etc. There is not much reporting of DO, BOD, and COD from Niger Delta Basin. Dissolved oxygen ranged from 1.1 to 8.01 mg/l with an average value of 4.61 mg/l (Figure 8j).

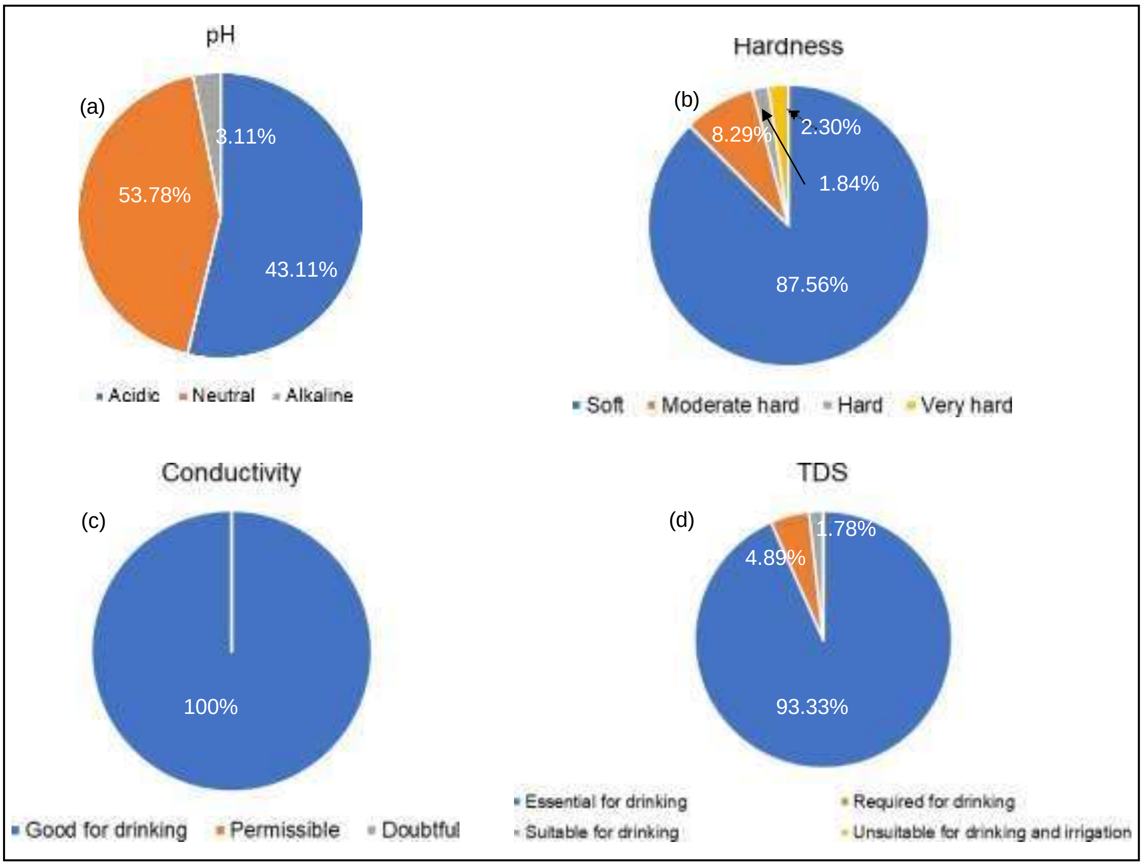

Figure 9. Groundwater classification in Niger Delta Basin (a) pH, (b) Hardness, (c) Conductivity and (d) TDS.

The dissolved oxygen level in water is influenced by the source, water temperature, treatment and chemical or biological processes in the distribution system. Depletion of dissolved oxygen in water supplies can encourage the microbial reduction of nitrate to nitrite and sulfate to sulfide [61]. It can also cause an increase in the concentration of ferrous iron in solution, with subsequent discolouration at the tap when the water is aerated. No health guideline value is recommended. However, very high levels of dissolved oxygen may

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exacerbate corrosion of metal pipes. Biological oxygen demand (BOD) ranged from 0.74 to 21.04 mg/l, with an average value of 5.69 mg/l (Figure 8h). Groundwater Quality Assessment of Yenagoa and Environs Bayelsa State, Nigeria between 2010 and 2011 by Amangabara and Ejenma [62], showed COD ranged from 3.2 to 19.37 mg/l with an average value of 7.72 mg/l. Overall, Groundwater's physical composition in the Niger Delta Basin is good and can be used for drinking with little or no potential for health hazard. Figure 9 further summarised groundwater classification base on pH, TDS, total hardness and conductivity.

b. Cation chemistry

Figure 10 summarised the cation chemistry of coastal aquifers of Niger Delta. Thechemical parameters of water quality are imperative as a result of their opposing bases. Once their concentration is above recommended limits, these essentials may render Groundwater useless. Chemical elements including Ca, Mg, Cu, Cd, B, Al, and As, are primarily derived from rocks. Nonetheless, elements like NO_3 and SO_4 are increased in groundwater consequent of anthropogenic activities [63-65]. Understanding the derivation and absorption level of these chemical elements in Groundwater is needed for effective groundwater management. Aluminium (Al), is commonly found in minerals, rocks, and clay, is the most abundant metal in the earth's crust [66-68]. It usually occurs at low levels in most natural waters. It has a secondary standard range of 50-200 µg/l; levels above this range pose water discolouration problems. Excessive concentrations may cause gastrointestinal irritation.

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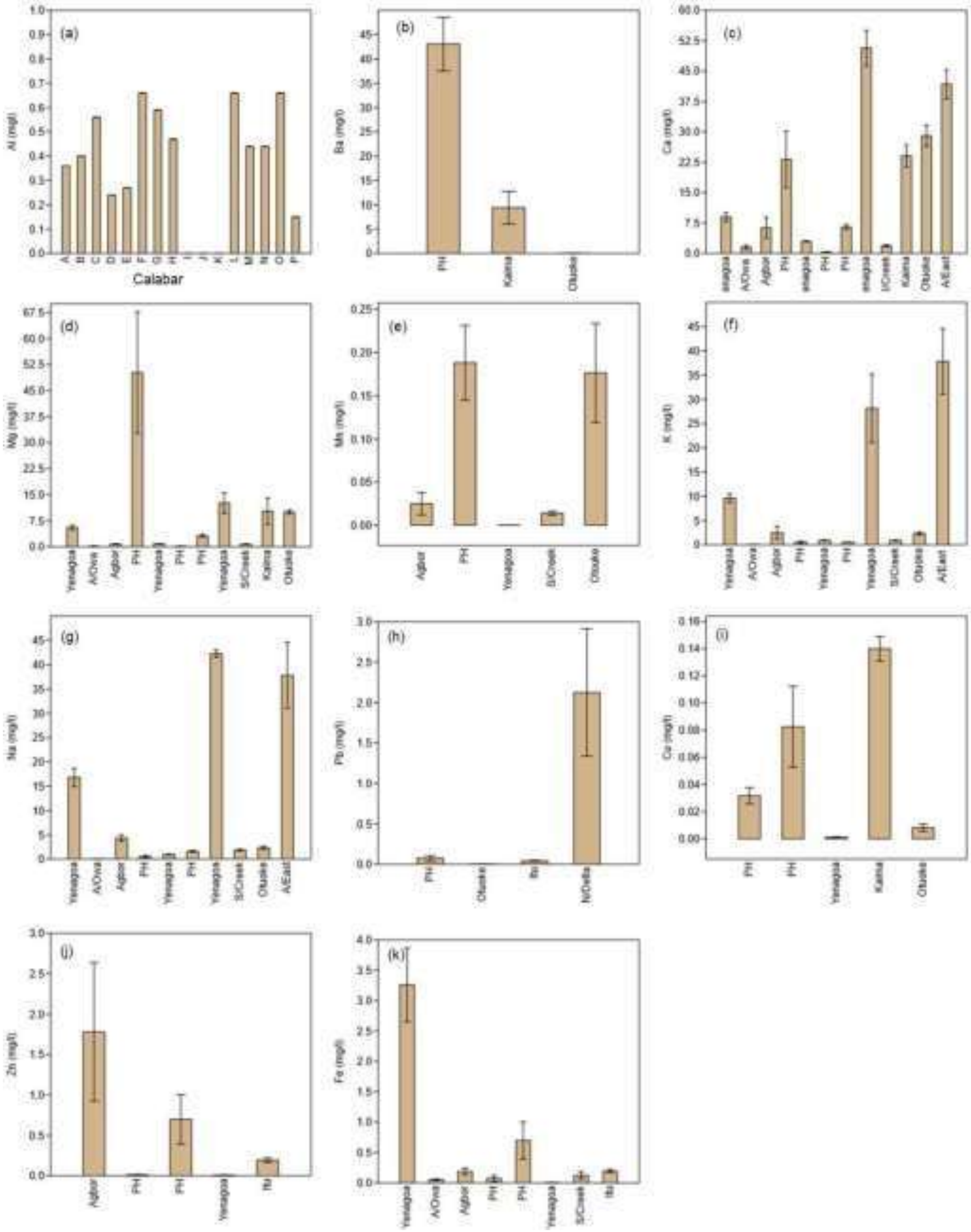

Figure 10. Cation chemistry (a) Al, (b) Ba, (c) Ca, (d) Mg, (e) Mn, (f) K, (g) Na, (h) Pb, (i) Cu, (j) Zn, and (k) Fe.

Few studies are reporting Al from Niger Delta Basin. For instance, chemical composition analysis of soil from selected oil-producing communities in the Niger Delta region of Nigeria by Idzi, et al. [69], showed Al concentration ranging from 0.08 to 22.97 mg/l with an average value of 6.45 mg/l. Additional studies assess the spatial distribution of contaminants and their levels in soil and water resources of Calabar, Nigeria using geophysical and geological data by Akpan, et al. [70], showed that Al ranged from 0 to 0.66 with an average value of 0.36 mg/l. Aluminium is a considerable metal in the earth's crust

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and is often found in the form of silicates such as feldspar. The oxide of aluminium known as bauxite provides a convenient source of uncontaminated ore. Aluminium can be selectively leached from rock and soil to enter groundwater aquifers. Al is known to exist in Groundwater in concentrations ranging from 0.1 ppm to 8.0 ppm. Like Al, Arsenic reporting from Niger Delta Basin is not much.

Arsenic is not well reported from Niger Delta Basin. Geostatistical assessment of groundwater quality from coastal aquifers of eastern Niger Delta, by Amadi, et al. [42], showed that As ranged from 0.001 to 0.016 mg/l with an average value of 0.007 mg/l. The circumstances that favour arsenic dissolution depends on the environments. What is known is that it takes more than just high arsenic concentrations in the soil or rocks of a region. As the pH is raised, the compounds will become more and more negatively charged as the arsenic, and arsenious acid loses H+ groups. So, the charge of these arsenic compounds depends on the pH. There is a general trend between pH and arsenic concentration in Groundwater. The increases in pH tend to be accompanied by a rise in arsenic concentration. The other major factor that affects the form of arsenic in solution is the redox state of the environment. The barium concentration in the Basin ranged from <0.001 to 93.01 mg/l with an average value of 39.02 mg/l.

Evaluation of Ca from 217 locations showed a range between 0 to 84 mg/l with an average value of 12.91mg/l. Magnesium ranged from 0.01 to 106 mg/l, with an average value of 5.78 mg/l. Calcium and magnesium are indispensable elements of human health. Insufficient intake of either nutrient can weaken health. Indorsed daily intakes of each element should be set at national and international levels, but no numerical guidelines for most countries drinking water quality exist for calcium or magnesium. As for Nigeria, 0.2 mg/l of Mg is recommended as the maximum permissible limits in drinking water. No guidelines value was recommended; see NSDWQ [71]. The manganese concentration ranged from <0.001 to 0.91 mg/l, with an average value of 0.10 mg/l. The Standard Organization of Nigeria (SON) defined 0.2 mg/l as the maximum permissible Mn limits in drinking water. Drinking water with Mn concentration over this value may be associated with the neurological disorder [71]. Manganese is a naturally occurring and abundant element indispensable in biological systems [72, 73].

The chemical behaviour of Mn is strongly influenced by pH, reduction and oxidation reactions. As a naturally occurring element, manganese is also ubiquitous in the environment, and so is found in soils, sediments, surface water, and groundwater [74-77]. Reference point ranges of Mn concentrations vary both within aquifers and between different aquifers over several orders of magnitude, controlled largely by prevailing Eh (reducing conditions) and pH, which respond to seasonal water table fluctuations in the aquifer. The environmental risks connected with Mn in Groundwater are relatively few and may occur most significantly only when manganese-rich Groundwater substantially feeds surface waters. Mean Mn concentration (0.10 mg/l) in Niger Delta Basin follows SON reference guidelines (0.2 mg/l). At levels above 0.1 mg/l, Mn in drinking water may cause an undesirable taste in beverages and stains sanitary ware and laundry [61].

The effects of manganese in drinking-water, like iron, may lead to the build-up of deposits in the pipe network [74-77]. At a level below 0.1 mg/l are usually acceptable to consumers. Even at a concentration of 0.2 mg/l, manganese will often form a coating on pipes, which may slough off as a black precipitate. The health-based value of 0.4 mg/l for

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manganese is higher than this acceptability threshold of 0.1 mg/l [61]. Though, under some conditions, manganese can be at concentrations above 0.1 mg/l and may remain in solution for a more extended period than its usual solubility in most drinking water. Potassium concentration ranged from 89.75 to 89.75 mg/l, with an average value of 8.11 mg/l. No reference guideline value was recommended [71]. Potassium is an indispensable element and is existing in all animal and plant tissues. The primary source of K for humans is the diet, as K exist in all foods, chiefly vegetables, and fruits. Some food seasonings are also K salts (e.g., potassium iodide). Some individuals require K supplements, which are given under medical supervision; others take K supplements without supervision, although this is not recommended [78-80]. Although potassium concentrations typically found in drinking water are generally low and do not pose health concerns, potassium chloride's high solubility and its use in treatment devices such as water softeners can significantly increase exposure.

All Groundwater comprises some sodium since most rocks and soils hold sodium compounds from which sodium is easily dissolved [81-83]. In the Niger Delta Basin, Na ranged from 0.01 to 89.75 mg/l with an average value of 11.03 mg/l. The SON defined 200 mg/l of Na as the maximum permissible limit in drinking water [71]. In Groundwater, sodium has no smell, but most people can be tested at 200 mg/l and above concentrations [84, 85]. High concentrations of Na in Groundwater occur naturally in some areas [86, 87]. For example, along with the Coastal Islands and Arid Regions, Na levels rich up to thousands of mg/l depending upon the well's location and depth. An increase in Na in Groundwater above ambient or natural levels may indicate pollution from the point or non-point sources or saltwater intrusion [88].

Studies, including Aweto and Akpoborie [89] showed that Cd ranged from <0.001 to <0.001 mg/l. Asia, et al. [90] 's analysis showed that mean Cd was <0.005 mg/l. No concentration of Cd in Benin Formation. However, mean Cd concentration above SON reference limits (0.13 mg/l) in Sombreiro- Warri was detected. People who drink water containing high cadmium above the maximum contaminant level (MCL) for many years could experience kidney damage [91, 92]. However, this health effects language is not intended to catalogue all possible health effects for Cd. Instead, it is intended to inform consumers of some of the possible health effects associated with cadmium in drinking water when the rule was finalised. Generally, Cd is found in low concentration in the Niger Delta Basin. Assessment of the water quality and prevalence of water-borne diseases in Amassoma, Niger Delta, Nigeria by Nwidu, et al. [93], did not detect Cd in the area.

Geostatistical assessment of groundwater quality from coastal aquifers of eastern Niger Delta, Nigeria by Amadi, et al. [42], showed that fluoride ranged from 0.01 to 2.33 mg/l with an average value of 0.85 mg/l. Effects of gas flaring on surface and groundwaters in Delta State Nigeria by Nwankwo and Ogagarue [94], showed that F was detected (0.03) only in one location eight studied locations. Exposure to excessive consumption of F over a lifetime may lead to an increased likelihood of bone fractures in adults and may affect bone leading to pain and tenderness. Children aged 8 years and younger exposed to excessive fluoride have an increased chance of developing pits in the tooth enamel and a range of cosmetic effects to teeth. This revelation is not intended to catalogue all possible health effects for F. Instead, it is intended to inform water users of some of the probable health effects of high fluoride in drinking water.

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Some studies reporting lead concentration in the Niger Delta Basin are Figure 10h. Lead concentrations ranged from 0 to 7 mg/l with an average value of 0.53 mg/l. The SON defined the maximum permissible limits for Pb as 0.01 mg/l in drinking water. Mean lead concentrations built on these studies is above SON limit. Infants and children who drink water containing lead above the permissible limit could experience physical or mental development delays. Children could show slight deficits in attention span and learning abilities. Similarly, adults who drink this water over many years could develop kidney problems or high blood pressure. Hydrochemical facies classification and groundwater quality studies in eastern Niger Delta, by Amadi, et al. [95], showed that Hg ranged from 0.002 to 0.004 mg/l with an average value of 0.003 mg/l. Similarly, heavy metal determination and assessment in a petroleum impacted river in Nigeria's Niger Delta region by Owamah [25] revealed an average value of less than 0.35 mg/l Hg. People who drink water containing Hg above the maximum permissible level for extended periods could experience kidney damage.

There are no detailed studies on Nickel from Groundwater in Niger Delta Basin. Few studies reporting Ni include Owamah [96] 's heavy metals determination and assessment in a petroleum impacted river in Nigeria's Niger Delta region. It showed that Ni concentration was generally less than 1.5 mg/l. Asia, et al. [90] 's analysis also showed that Ni concentration was less than 0.005 mg/l. The SON has defined 0.02 mg/l as maximum permissible limits for Ni in drinking water due to its possible carcinogenicity. Like Ni, there are few studies on Silica from Niger Delta. Abadom and Nwankwoala [97] 's analysis showed that silica ranged from 0.38 to 60.02 mg/l, with an average value of 6.98 mg/l. The concentration of Cu in the Niger Delta Basin is highly variable. Evaluation of Cu from Groundwater over 70 locations in the Basin has shown that the element ranged from 0 to 0.75 mg/l with an average value of 0.06 mg/l. There is no reference value defined by the SON. Similarly, the Zn evaluation in 92 locations in the Basin showed that Zn ranged from less than 0.001to 20 mg/l. The mean Zn concentration (1.10 mg/l) in Niger Delta Basin is above SON reference limits (3 mg/l).

There was substantial reporting of Fe from the Niger Delta Basin (Figure 10k). The degree to which Fe and Mn dissolve in groundwater hinge on the amount of oxygen in the water and, to a lesser extent, upon its degree of acidity [98, 99]. Iron, for instance, can occur in two forms: as Fe^{2+} and as Fe^{3+}. When the level of dissolved oxygen in Groundwater is greater than 2 mg/l, Fe occurs as Fe^{3+}, while at lesser dissolved oxygen levels, the iron occurs as Fe^{2+}. Although Fe^{2+} is very soluble, Fe^{3+} will not dissolve significantly. If the Groundwater is oxygen-deprived, iron (and manganese) will dissolve more readily, predominantly if the water's pH is on the low side [100, 101]. Dissolved oxygen content is characteristically low in deep aquifers, mostly if the aquifer comprises organic matter [102-104]. The decay of the organic matter reduces the water's oxygen, and the iron dissolves as Fe^{2+}. Under these environments, the dissolved iron is often going together with by dissolved Mn or hydrogen. When this water is pumped to the surface, the dissolved iron reacts with the oxygen in the atmosphere, changes to Fe^{3+} and forms rust-coloured iron minerals.

c. Anion chemistry

Assessment of Groundwater in parts of the Niger Delta, by Amadi, et al. [105], showed no carbonate ions were detected, and all carbonates exist as the bicarbonate. The

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HCO_3 range from 106 to 550 mg/l with an average value of 242.94 mg/l as reported from Okpoma and Environs [106]. Okiongbo and Douglas [29] also reported bicarbonate; Udom, et al. [107]; Fashola, et al. [108]; Nwankwoala, et al. [109]; Nwankwoala and Udom [110]; Nwankwoala and Udom [111]; Amangabara and Ejenma [62]; Nwankwoala, et al. [112]; Abadom and Nwankwoala [97]; and Udom, et al. [107]. Results from these studies showed that HCO_3 ranged from 0 to 300.8 mg/l with an average value of 23.50 mg/l (Figure 11a). Bicarbonate is typically assumed to enter the groundwater system due to the uptake of CO_2 either from soil zone gases or direct atmospheric inputs [27-29, 31-33]. Additional sources can come from carbonate dissolution. Bicarbonate concentrations tend to be high in shallow aquifers.

Chloride has been substantially studied in the Niger Delta Basin (Figure 11b). Analysis of Cl concentrations from 217 sites showed that the element ranged from <0.001 to 710 mg/l. The mean Cl (43.71 mg/l) has fallen within SON reference guidelines (250 mg/l). Although there are some locations with Cl concentrations above 250 mg/l, there is no serious health hazard associated with water drinking with high Cl concentration. Nitrate in Niger Delta Basin ranged from 0 to 34 mg/l with an average value of 1.70 mg/l. Nitrate level in Groundwater is generally low in the Basin (Figure 11c). Groundwater nitrate is primarily erived from anthropogenic sources, especially inorganic fertilisers, industrial and municipal sewage [32, 113, 114]. The mean NO_3 in the Basin is within SON reference guidelines (50 mg/l).

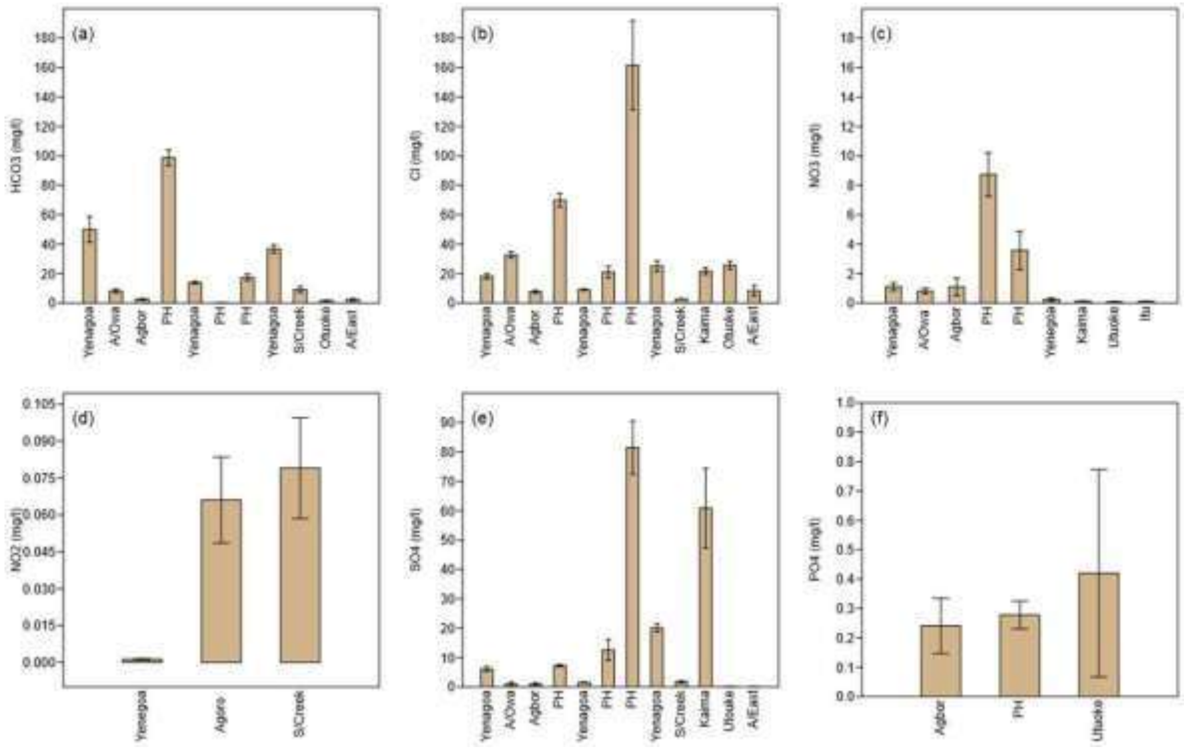

Figure 11. Anion Chemistry (a) HCO_3, (b) Cl, (c) NO_3, (d) NO_2, (e) SO_4, and (f) PO_4.

Drinking water of high NO_3 can cause Cyanosis, and asphyxia (blue-baby syndrome) in infants under 3 months [32, 33]. Studies reporting NO_2 from Niger Delta Basin are comparatively low (Figure 11c). Nitrite concentrations ranged from <0.001 to 0.151 mg/l with an average value of 0.03 mg/l. The mean NO_2 concentration in the Basin is within SON

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reference guideline (0.2 mg/l). Like the NO_3, high NO_2 in drinking water can cause the blue baby syndrome. However, the concentration of SO_4 in the Niger Delta Basin ranged from <0.001 to 230.11 mg/l, with an average value of 18.49 mg/l. Based on SON reference guidelines, the mean SO_4 in the Basin is within SON reference guidelines (100 mg/l). Likewise, PO_4 concentration ranged from 0 to 5.01mg/l with an average value of 0.34 mg/l. There were not many studies reporting PO_4 from Niger Delta Basin (Figure 11f). Besides, there is no reference value set by the SON.

2. CONCLUSION

In this review, an attempt was made to present a detailed description of the Niger Delta Basin's hydrogeological setting by discussing the basin's significant aquifers. These comprised of Upper and Lower Deltaic Plains, the Ameki Formation and the Benin Formation. The Niger Delta Basin has many things familiar with the Cross River and Imo-Kwa-Ibo Basins based on the geological setting. Based on the reviewed literature, the following remarks can be made:

i. The Niger Delta Basin's Tertiary segment is divided into three formations, representing prograding depositional facies distinguished generally based on sand-shale proportions.
ii. In terms of groundwater potentials, the specific capacities recorded from different areas within this Basin vary from 6700 lit/hr/m to 13,500 lit/ hr/m. The water table is very close to the ground surface and varies from 0 to 4 meters.
iii. The deltaic formations comprise late Holocene plains and cover most of the present Niger delta and stretch narrowly eastwards along the coastline.
iv. Benin formation's outcrops are found in the northeast of the coastal belt and dips at a low angle in the southwest. The sediments comprise mainly of lenticular unconsolidated, predominantly sandy formations.
v. Unconfined groundwater aquifers occur in shallow unconfined aquifers, sands of the coastal beach ridges and river point bars, and sandy islands within the mangrove belt. It also occurs in confined aquifers at varying depths. There is a stable water table fluctuation which characterised the high precipitation zone.
vi. The shallow aquifers of Benin Formation contained sediments which are more porous than those in the Deltaic areas. In the Niger Delta's southern areas, particularly along the coastal area, boreholes constructed produced an artesian condition.
vii. However, the aquifers are less transmissible with increased depth of the confined aquifer. It is due to its more delicate texture and therefore more compact and less permeable, or that three is not enough water in storage.
viii. About 53.78% of groundwater sources in the Basin are acidic, 43.11% are neutral, and 3.11% are alkaline. Based on mean TDS concentration groundwater in the Basin, fall in an excellent class for drinking.
ix. Groundwater classification based on conductivity showed all the reported findings indicate conductivity ranging from 250-750 µS/cm. There is not much reporting of DO, BOD, and COD from Niger Delta Basin.
x. Based on cation and anion chemistry, the Niger Delta Basin holds water of relatively

acceptable drinking quality. Overall, the basin contained Groundwater of good quality based on physical and chemical parameters.

However, the major challenge to groundwater management in theNiger Delta Basin include the uncontrolled groundwater development, changes in land use, pollution from industrial, municipal and agricultural effluents. Thus, a policy guideline is required to protect Groundwater from pollution.

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