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Groundwater resources of the Niger Delta: Quality implications and management considerations

H.O. Nwankwoala[1] and S.A. Ngah[2*]

[1]Department of Geology, College of Natural and Applied Sciences, University of Port Harcourt, Nigeria.
[2]Institute of Geosciences and Space Technology, Rivers State University of Science and Technology, P. M. B. 5080, Nkpolu-Oroworukwo, Port Harcourt, Nigeria.

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The Niger Delta region of Nigeria is of great socio-economic importance because of its huge and abundant reserves of crude oil and natural gas. The phenomenal increase in both industrial and social activities within the area in recent times has led to increase in groundwater abstraction rates. Groundwater development in the Niger Delta region has been carried out with little hydrogeological considerations. This is probably, due to strong political and other extraneous pressures. Consequently, borehole drilling has been indiscriminately and randomly sited and located, resulting to a myriad of problems. As a result, boreholes have failed where there are abundant groundwater storage, and many a time, have been drilled in, obviously, most unpromising locations. Salinity, bacteriological contamination, presence of undesirable iron and manganese as well as the high acidity of the groundwater and consequent corrosiveness pose serious distribution problems in the area. Efforts to solve the problems have been unsuccessful and supply of potable water remains grossly inadequate. Recent development plans proposed for the Niger Delta would call for high water demand. There is therefore an urgent need for a meaningful approach to the study of groundwater resources of the region. It is therefore hoped that many of the observations made in this paper will not only form a guideline for meaningful collection of data for quantitative analysis in future, but will also help in the understanding of the nature of groundwater resources of the region.

Key words: Groundwater resources, quality, aquifers, groundwater management, Niger Delta.

INTRODUCTION

The Niger Delta has an aerial extent of 75,000 km^2 and is located between latitude 4°30' and 5° 20' N and longitude 3° and 9°E. It is the second largest delta in the world with a coastline spanning about 450 km terminating at the Imo River entrance (Awosika, 1995). The region spans over 20,000 km^2 and it has been described as the largest wetland in Africa and consists mainly of freshwater swamps, mangrove swamps, beaches, bars and estuaries. This difficult terrain made it a region mostly forgotten by the rest of Nigeria, until the advent of petroleum in the area in the late fifties.

The pressure on water supplies and precious ecosystems in the coastal areas of the Niger Delta is very high and can increase in the future if urgent management

*Corresponding author. Email: ngahsab@yahoo.com

measures are not put in place (Nwankwoala, 2011). Groundwater is the only source of water for water supply for both domestic and industrial uses in the Niger Delta and its demand will increase astronomically within the foreseeable future with increase in population, improved standard of living and more expansion and growth of the oil and gas industry (Oteri, 1983; Akpokodje, 2005; Nwankwoala and Udom, 2011).

Though the Niger Delta produces over 80% of Nigeria's petroleum, it is still very much a neglected part of the country. Beside efforts made by oil prospecting companies in the process of oil exploration and production, the region has not been studied in many areas and respects. Groundwater resources development of the Niger Delta is one such area where no serious effort has been made to investigate its nature, distribution and occurrence. Geologic considerations are rarely or inadequately incorporated into the design of boreholes (Amajor, 1989). Generally, groundwater has not attained a high level of development in the Niger Delta partly as a result of difficult environmental condition, low level of general underdevelopment of the region, inadequate finance; and partly perhaps as a result of deliberate neglect of the area by successive governments.

The Niger Delta is a large and ecologically sensitive region in which various water species (including surface and groundwater, saline and freshwaters) are in dynamic equilibrium (Abam, 1999). Because of the very nature of the region, groundwater constitutes the predominant, if not the only source of water supply in the area and unless a determined effort is made to understand the nature of the groundwater in the region, serious problems would be encountered in the area of water needs of the region, in future. Although, detailed stratigraphic analysis of the various geologic/geomorphic and aquifer systems (Etu-Efeotor and Akpokodje, 1990) have yielded a better understanding of the groundwater potentials of the Niger Delta region, they have not addressed the important and crucial question of over-abstraction and its associated consequences, particularly the possibility of large scale saltwater intrusion and general issue of sustainable supply of potable water in the region. This paper therefore appraises groundwater resources of the Niger Delta region, the quality impairments and management considerations.

GEOMORPHOLOGIC/GEOLOGIC SETTING

The geomorphology of the Niger Delta has been described by many researchers (NEDECO, 1954, 1959, 1961; Allen, 1965; Weber, 1971). The topography of the area is essentially flat, sloping very gently seawards. The area is low lying (usually does not exceed 20 m above sea-level) and is drained and criss-crossed by network of distributaries. The Niger Delta constitutes an extensive plain exposed to periodical inundation by flooding when the rivers and creeks overflow their banks. A prominent feature of the rivers and creeks is the occurrence of natural levees on both banks, behind which occur vast areas of backswamps and lagoons/lakes where surface flow is negligible.

Although various types of morphological units and depositional environments have been recognized in the area (coastal flats, ancient/modern sea, river and lagoonal beaches, sand bars, flood plains, seasonally flooded depressions, swamps, ancient creeks and river channels), the area can be sub-divided into five major geomorphological units (Figure 1) namely:

i) Active/abandoned coastal beaches
ii) Saltwater, mangrove swamps
iii) Freshwater swamps, back-swamps, deltaic plain alluvium and meander belt
iv) Dry deltaic plain with abundant freshwater swamps (Sombreiro-Warri deltaic plain) and
v) Dry flat land and plain.

Along the coastline lies a long coastal saline belt of active and abandoned beaches built by ocean currents and tides. This area is comparatively higher than the adjacent areas and its width varies from 1 to 10 km. Parallel to, and north of the coastal saline belt of the beaches, is a stretch of mangrove swamp with an approximate width of 10 to 25 km. North of the mangrove swamp is the freshwater swamp which is in turn succeeded inland by dry areas that are not prone to periodical flood inundation.

Consequently, the present knowledge of the geology of the Niger Delta was derived from the works of the following researchers (Reyment, 1965; Short and Stauble, 1967; Murat, 1970; Merki, 1970) as well as the exploration activities of the oil and gas companies in Nigeria. The formation of the so called proto-Niger Delta occurred during the second depositional cycle (Campanian Maastrichtian) of the southern Nigerian basin. However, the modern Niger Delta was formed during the third and last depositional cycle of the southern Nigerian basin which started in the Paleocene.

The geologic sequence of the Niger Delta consists of three main tertiary subsurface lithostratigraphic units (Short and Stauble, 1967) which are overlain by various types of Quaternary deposits. From bottom to top, the tertiary units are the Akata, the Agbada and the Benin Formations (Table 1).

Hydrologic factors in the Niger Delta

The hydrologic conditions in a region are important in understanding the groundwater situation, in that they determine the availability of water input into the basin for groundwater storage, the rate of groundwater recharge, and the movement of the water in the groundwater system, for extraction purposes. The factors of precipitation, runoff, evapo-transpiration and infiltration play major role. The process of water movement in the ground is more related to the factor of geology.

The amount of rainfall that takes place in a basin would determine the water input into the basin (Gobo, 1988). The annual rainfall in the Niger Delta is high and varies from 500 mm per annum at the coasts, to about 300 mm at the northern part of the delta (Etu-Efeotor and Odigi, 1983). Evapo-transpiration is 1000 mm, leaving an effective rainfall of 2000 mm. Of this effective rainfall, 37% or 750 mm is known to recharge the subsurface aquifers while the remaining 1250 mm flows directly into the streams (Akpokodje et al., 1996). This recharge which is 75% of the total precipitation is on the high side of the range commonly reported for unconsolidated sediments (Vecchioli and Miller, 1973; Legeette and Graham, 1994). This therefore ensures that the region is adequately supplied with water. Besides, rain may fall at any time of the year, even during the peak of the dry season, further ensuring an all year round water input into the region. Basically, the Niger Delta water resources are drawn from the Eastern littoral hydrological and the Niger South hydrological zones. Infiltration and percolation processes from these broad recharge networks flow southwards into the underlying aquifers of the Benin

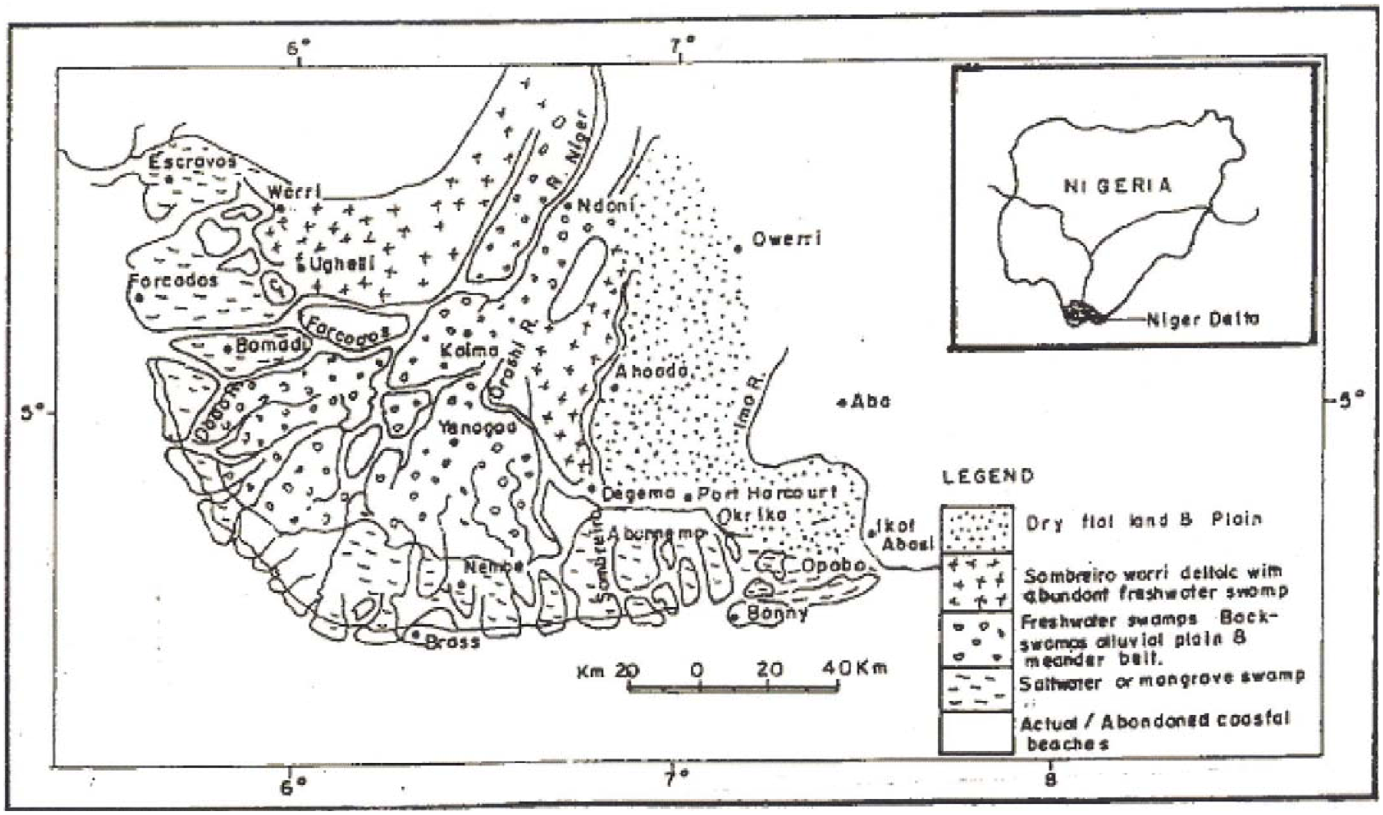

Figure 1. Major morphological units of the Niger Delta (modified after Akpokodje, 1987).

Table 1. Geological units of the Niger Delta (after Short and Stauble, 1967).

Age	Geological Unit	Lithology
Quaternary	- Alluvium (general) fresh water back swamp meander belt. - Mangrove and salt water. - Back Swamps - Active/Abandoned Beach ridges - Sombreiro Warri Delataic plain.	- Gravel, sand, clay, silt, sand, clay, some silt, gravel. - Medium-fine sands, - Clay and some silt.
Miocene	Benin Formation (coastal plain sand)	Coarse to medium grain sand with subordinate silt and clay lenses; Fluviatile marine
Eocene	Agbada Formation	Mixture of sand, clay and silt, fluviatile marine.

Formation beneath the Continental Shelf (Ngerebara and Nwankwoala, 2008). Both the structural and stratigraphic setting of the Niger Delta favour hydraulic gradient flow towards the coast, and hence into the Continental Shelf. This forms the basis of most freshwater aquifers located within the Continental Shelf. The general rainfall pattern in the Niger Delta ensures a permanent supply of water to the region.

The extent to which this rainfall reaches the ground to supplement the underground storage, greatly depend on the rate of infiltration, runoff pattern and the rate of evapo-transpiration. None of these factors had been studied quantitatively, but the following observations have been made (Ngerebara and Nwankwoala, 2008) in a more tentative way:

1) The rate of infiltration has generally been favoured by the prevailing flat nature of the Niger Delta which reduces runoff, by increasing retention time of rainwater on the land surface. Besides, the soil in most cases, except where surface clay and swamp prevail, is unconsolidated, porous and permeable, thus permitting quick infiltration of water underground.

2) The region is adequately drained by several streams and rivers. But more important is that these surface water bodies, flow through raised channels due to heavy load of sediments which settle within the channels. Consequently, the streams and rivers overlie most of the important aquifers in the area and feed them throughout the whole year. Most of the streams and rivers are therefore influent. The aquifers do not have to wait until flooding periods to be fed by

surface streams and rivers. The above prevailing conditions means that there is no period of the year when groundwater storage would have to be diminished by base flow but rather is ensured of a continuous discharge wherever the boundary with adjacent streams and rivers are continuous.

3) Evapo-transpiration measurements made on local scales by agricultural establishments indicate that water losses especially in areas of unconfined aquifers with water table near ground surface, may be high, due to high evapotranspiration during the dry season. This is in respect of the dense vegetation of the region and the dry condition that prevails during the dry season. But because of the huge reservoir prevailing under the Niger Delta, the more or less constant water supply in the region and the occurrence of clay lenses which often cut off aquifers from one another, the effect of evapotranspiration even where water is nearer the surface does not demand serious consideration in the Niger Delta.

Geological factors in the Niger Delta

The geology of the Niger Delta is well known and has been discussed by several authors (Reyment, 1965; Short and Stauble, 1967; Merki 1972; Weber and Daukoru, 1975; Avbovbo, 1978; Agagu, 1979; Whiteman, 1982; Doust and Omatsola, 1990; Owolabi et al., 1990; Koledoye et al., 2000, 2003). The influence of geology on the groundwater resources of the Niger Delta constitutes the most important factor besides that of climate in the region. Geology has been observed to be responsible for the complex groundwater distribution, extractability and quality in the Niger Delta. Unfortunately, the present knowledge of the true geological condition prevailing within the groundwater domain of the Niger Delta is limited.

Three major formations comprise the modern Niger Delta overlain by various types of Quaternary deposits (Table 1, Figure 1). These are the Akata Formation, which is predominantly shale and clay; the Agbada Formation which is generally fluviatile and fluviomarine, and the Benin Formation, constituting a continental deposit of sand and gravel (Murat, 1971). The depositional pattern which accompanied the accumulation of sediments during the formation of the delta, gave rise to structural traps (growth faults and roll-over anticlines) in the Agbada Formation. This constitutes the petroleum containing reservoirs in the Niger Delta. The Agbada Formation while suitable for petroleum accummulation, is too deep to be relevant to groundwater storage. There arises therefore, the major difference between the region where the petroleum geologist is prospecting for oil, that is, the Agbada Formation, and that, where the hydrogeologist is searching for water – the Benin Formation, in the Niger Delta.

Huge financial investments by oil companies have revealed the geology of the Agbada Formation in detail. Understandably, investigating the Agbada Formation, petroleum geologists had deliberately ignored the upper lying Benin Formation. Hence, the present knowledge of the Benin Formation is limited, compared with that of the Agbada Formation. An evaluation of the hydrogeology of the Niger Delta for petroleum exploration may appear to be ill-conceived. However, there is strong evidence that meteoric water from gravity-induced flow has recharged deep enough into the subsurface to possibly play a role in the distribution of hydrocarbons. According to Dickey et al. (1987) and Amajor and Gbadebo (1992), the extremely sandy nature of the upper Benin Formation and the abundant growth faults in the underlying Akata Formation have permitted meteoric water to penetrate very deep into the subsurface.

The controlling effect of geology on groundwater occurrence in the Niger Delta is no longer in doubt. The sedimentation pattern as well as stratification determines both the quality and quantity of water in the region. Its investigation is the first step towards a meaningful groundwater study of the region. The Benin Formation therefore needs detailed investigation.

Groundwater occurrence in the Niger Delta

The main body of groundwater in the Niger Delta is contained in mainly very thick and extensive sand and gravel aquifers. Three main zones have been differentiated. These are: a northern bordering zone consisting of shallow aquifers of predominantly continental deposit, a transition zone of intermixing marine and continental materials and a coastal zone of predominantly marine deposits (Etu-Efeotor and Odigi, 1983; Amajor, 1989; Etu-Efeotor and Akpokodje, 1990). A distinct trend in aquifer properties have been observed following this division. Akpokodje et al. (1996) have summarized the hydrostratigraphic units of the Benin Formation as four well defined aquifers in the upper 305 m that vary in thickness to over 120 m. The aquifers vary from unconfined conditions at the surface through semi-confined to confined conditions at depth. The aquifers are separated by highly discontinuous layers of shales, giving a picture of an interval that consists of a complex, non-uniform, discontinuous and heterogeneous aquifer system. Although, majority of groundwater supply wells abstract water from these aquifers, there is evidence that industrial and municipal groundwater supply wells produce water from deeper aquifers in the Benin Formation.

Aquifers at the northern border of the Niger Delta are more continental in character, being composed of river loads coming from the hinter land. They are also encountered at shallower depths, so that in most cases, an average depth of 60 m had been all that was required to be drilled, to obtain very pure freshwater and in huge quantity. Clay materials, except a few metres found within the top soil, do not occur at depth. The sand is coarse to very coarse generally, and gravel layers are commonly encountered. The borehole performance in this section has generally been so good and the water quality so excellent, that sinking of wells at the northern borders of the Niger Delta has always been taken for granted. Very good examples of such regions are Port Harcourt, Ogoni, and Elele areas of Rivers State, eastern Niger Delta.

Moving coastwards from the northern borders of the Niger Delta, one comes across a transitionary zone of swamp lands. Two types of swamp lands are observed – the mangrove swamp lands and the freshwater swamp lands. The mangrove swamp lands are associated with tidal inlets and they are therefore more prominent in those areas where estuaries penetrated farther inland, such as the western and eastern zones flanking the pro delta. On the other hand, fresh swamp land persists more within the front of the delta where the dense network of streams and rivers combine to empty into the sea.

A common feature of the transition zone is the presence of clay embodiments within the aquifers. These clay lenses are erratically distributed laterally and vertically within the region. In several cases, strata logs of wells drilled less than 200 m apart, have been known to vary, and under such prevailing circumstance, prediction of aquifer performance in the region is difficult. However, the freshwater swamp lands which constitute the front of the delta, continue to indicate many features of continental environments, until very close to the coast. The aquifers are still shallow, consisting of predominantly sand and gravel materials, but clay intercalations become more prominent, than within the northern zones. Lignitic materials are also present in the aquifer and the presence of vegetative matter strongly point to sedimentation under shallow water condition.

Within the mangrove swamp lands, very strong evidences of marine conditions are indicated. Thicker lenses of marine clay are encountered and saline conditions are still well noticed. There is no doubt that these areas are protected from the dynamic zones of the deltaic front. This makes it possible for marine conditions to penetrate further inland, creating a more complex transition zone.

This is the case in the freshwater swamp lands. There is an intermixing of continental and marine sediments resulting in a very complex aquifer system. Generally, it has been necessary to drill beyond the 200 m depth before a good water yielding aquifer could be obtained and saline water intrusion problem plague the region. It is here, however, that artisan conditions, due to the interbedment of sand aquifers within clay aquicludes occur. But such confined aquifers are generally too deep seated to result in flowing wells (Ngah, 2009; Nwankwoala, 2011).

Within the sand bars and beaches of the coastal lands, boreholes still need to go deeper to reach quality good water aquifers. Beneath the coastal sands that form the surface deposits of this last zone, marine conditions predominate, until at depth where deep seated aquifers empty into the sea. Aquifers within the Niger Delta generally produce and perform better during the rainy season. They dwindle in yield during the dry season. At the coastal lands, rains feed and maintain phreatic aquifers during the rainy season. But with the incoming of the dry season, such aquifers dry up, and wells sunk into them commonly go without water at that season.

RESULTS AND DISCUSSION

Groundwater quality status

Table 2 shows the groundwater quality in the Niger Delta. The quality of groundwater in the Niger Delta closely follows the sedimentation pattern. As a result, three distinct zones are recognized. The continental deposits of the Northern border produce the best quality water in the region – fresh, pure and commonly uncontaminated groundwater. Within the transition zones, however, the complex sedimentary environment greatly influences the water quality. Most remarkable are the freshwater swamp lands where quality degradation associated with the breakdown of organic matter derived from vegetation buried in the sediments, are encountered. These generally take the form of high carbonate acidity and introduced hydrogen sulphide, commonly identified by the bad smells of some water samples from the area.

Iron contamination is also another feature of groundwater quality within the transition zones. The intensity of its occurrence has been observed to be higher within the freshwater swamp zones (Etu-Efeotor, 1981; Etu-Efeotor and Odigi, 1983; Odigi, 1989). But in the mangrove swamp land areas, notably Buguma, Bonny and Abonnema in Rivers State, cases of iron contamination have been encountered. They are commonly in the form of ferrous iron which generally remains in solution when water samples are freshly collected. On standing the samples, the ferrous iron comes in contact with oxygen of the air and is oxidized into its ferric equivalent which is generally brownish in colour.

The source of the iron contamination is not quite known but it is suggested to have been emplaced by iron fixing bacteria associated with sedimentary environments of decaying vegetative matter. According to Allen (1965) and Oomkens (1974), the Quaternary glaciation was accompanied by eustatic lowering of the sea level such that the paleo- strandline was at the present edge of the continental shelf. This geologic event would have exposed the sediments and created paleo-soils rich in iron oxides. The subsequent rise in sea level would have incorporated the paleo-soils into the geologic record.

Salinity trends in the Niger Delta

Salinity problems are encountered in the Niger Delta. But this is a case prevalent within the mangrove swamp lands and the coastal aquifers. Because of the importance of saline problem in the groundwater development of the Niger Delta, it is necessary to know the main types of saline pollution and where they would be expected. Generally, two types of saline gradient are noticed. There is a vertical gradient which changes with respect to distance from the sea. Vertical salinity gradient develops within the estuarine areas. They arise from the penetration of saline water inland through creeks and estuaries. They are therefore saline conditions that originate from the infiltration of salt water from creeks into underlying sediments. Such saline pollution however, applies only where the aquifer is uninterrupted in depth. A thick or extensive aquiclude can and does exclude further penetration of salt water under such circumstances (Nwankwoala, 2011; Ngerebara and Nwankwoala, 2008).

The WHO (2008) appears to be silent on specifications of limit for this parameter. Salinity tends to increase in a southerly direction. Least values of salinity are more common in the hinterland. The salinity values of groundwater in the study area appear to be generally tolerable. The salinity depths in deep boreholes in Bonny Island suggest saltwater intrusion into submarine freshwater aquifers (Ngah and Nwankwoala, 2013b). Naturally, the coastal aquifers drain into the ocean and are in contact with the ocean at the coastline where under natural conditions fresh water is discharged into the ocean. Excessive abstraction of groundwater appears to have resulted in a decreased seaward flow of fresh groundwater causing saline water to enter and penetrate inland through submarine outcrops. This phenomenon will progressively displace the freshwater thereby increasing the salinity depth (Ngah, 2009). Figure 2 is the map of the Niger Delta showing salinity limits/vegetation of the coastal zones of the Niger Delta.

Human activities at times enhance such saline intrusion in the area. This was the case at Isaka near Port Harcourt where the dredging of the Port Harcourt harbor admitted saline water into the aquifer in the area. Also, influence of land reclamation in Borokiri area of Port Harcourt induced saline water (Nwankwoala and Udom, 2008). It requires further deep drilling beyond a thick lens of clay before an uncontaminated aquifer will be encountered. Within sands on islands and beach ridges at the coast, a unique condition of salinity prevails in which a cone of freshwater overlies a saline layer. Saline

Table 2. Groundwater quality data in parts of the Eastern Niger Delta (Ngah and Nwankwoala, 2013a).

S/No.	Borehole Location	Geomorphic zone	Depth (m)	Iron (mg/l)	Chloride (mg/l)	Salinity (mg/l)	Conductivity (us/cm)	pH	Alkalinity (mg/l)	Total hardness (mg/l)
1.	Kanana	SWS	186	0.0	34	500	125	6.7	0.12	38
2.	Kala Degema	"	40.96	0.0	18	150.0	-	7.3	0.38	6
3.	Krakrama	"	75	2.5	48	700	100	6.8	-	16
4.	Abalama	"	60.96	2.0	36	10.74	35	6.7	30	11
5.	Buguma	"	60.96	0.0	10.64	17.55	-	6.2	6.5	17.0
6.	Okrika Mainland	"	320	0.0	35.5	58.5	19	6.2	10.40	20
7.	Ibuluya-Dikibo	"	180	0.0	32.0	18.00	20.00	4.5	10	21
8.	Bolo I	"	91.44	0.0	99	14.00	16.00	7.0	0.12	31
9.	Bolo II	"	91.44	0.0	97	16.00	40	6.8	0.1	35
10.	Kalio-Ama	"	82.88	0.5	10	331	58.0	6.4	0.1	61
11.	Abam-Ama	"	128.02	0.0	6.38	100	23.0	5.9	21	Artesian
12.	Okujagu	"	30.0	0.8	62	100	-	4.5	2	30
13.	George-Ama	"	109.73	1.8	31.5	60.25	29	5.1	-	22
14.	Isiokpo	CPS	70.1	2.0	38.94	64.4	20	5.6	15	10
15.	Aluu	"	60.96	0.2	10	50	23.00	6.1	2	6
16.	Umuoji	"	81	10.0	32	80	-	8.2	-	68
17.	Ogbakiri	"	78.03	0.01	24.2	51.9	4.5	6.2	0.5	60
18.	Ndele	"	72.5	0	10.6	100	13.5	7.5	19.0	9
19.	Omerelu	"	70.1	0.4	20	20	20	6.5	0.6	8
20.	Ubima	"	70.1	0.0	18	50	18	5.2	2	4
21.	Elele	CPS	60.96	0.0	29.8	49	15	6.0	3.0	5.0
22.	Ibaa	"	60.96	0.0	40	68.25	12	6.2	-	2.0
23.	Obelle	"	81.0	0.0	48	63	6.7	6.1	-	0
24.	Rumuewho	"	54.86	0.3	10	50	-	6.2	-	38
25.	Egwi	"	61.28	0.15	3.4	65	-	6.5	-	28
26.	Rumuoyo	"	57.3	0.30	24	73	-	6.4	-	8
27.	Ulakwo	"	67.06	0.0	13	60.2	100	7.4	-	34
28.	Opiro	"	138	0.0	16	100	12.5	6.2	6.0	10
29.	Rumuokochi	"	91	10	12	60	100	6.2	-	20
30.	Umuechem	"	132	0.30	11	100	36	6.7	3.0	6.0
31.	Kalibiama	CBR	281	0.0	10	202.0	440.0	8.4	-	488
32.	Bonny	"	304	0.8	5	186	140	5.9	-	78
33.	Oloma I	"	91.46	0.8	810	210.0	600	6.5	90	72
34.	Oloma II	"	82.88	0.0	250	220.0	380.0	6.2	20	454
35.	Illoma Opobo	"	19.8	0.6	330	60	280	7.2	-	84
36.	Gbokokiri	"	176.8	0.40	300	192.0	-	6.6	-	18
37.	Ikuru	"	190	0.38	351	242.0	-	6.7	-	70
38.	G.R.A. P.H.	“	170	0.00	26	50	7	5.3	2	6
39.	Creek Road	"	170.0	0.02	390.5	643.5	150.0	5.8	35	135
40.	Potts Johnson	"	180.0	0.02	401	661	160.0	5.8	18	135

CPS = coastal plain sands, FWS = freshwater swamp, SWS = saltwater swamp, CBR = coastal beaches and ridges, SWP = sombreirowarri deltaic plain.

water pollution becomes imminent, if such pool of freshwater is not intelligently extracted.

Aquifer vulnerability to contamination

Groundwater contamination may be defined as the induced degradation of natural water quality by the introduction of inorganic and/or organic compounds. It is usually more serious than surface water contamination because it is more difficult to detect in a timely manner, moves more slowly and requires special expertise to predict the path and rate of contaminant movement. Aquifers can be polluted by a combination of the following factors: agricultural activities, petroleum leakage and

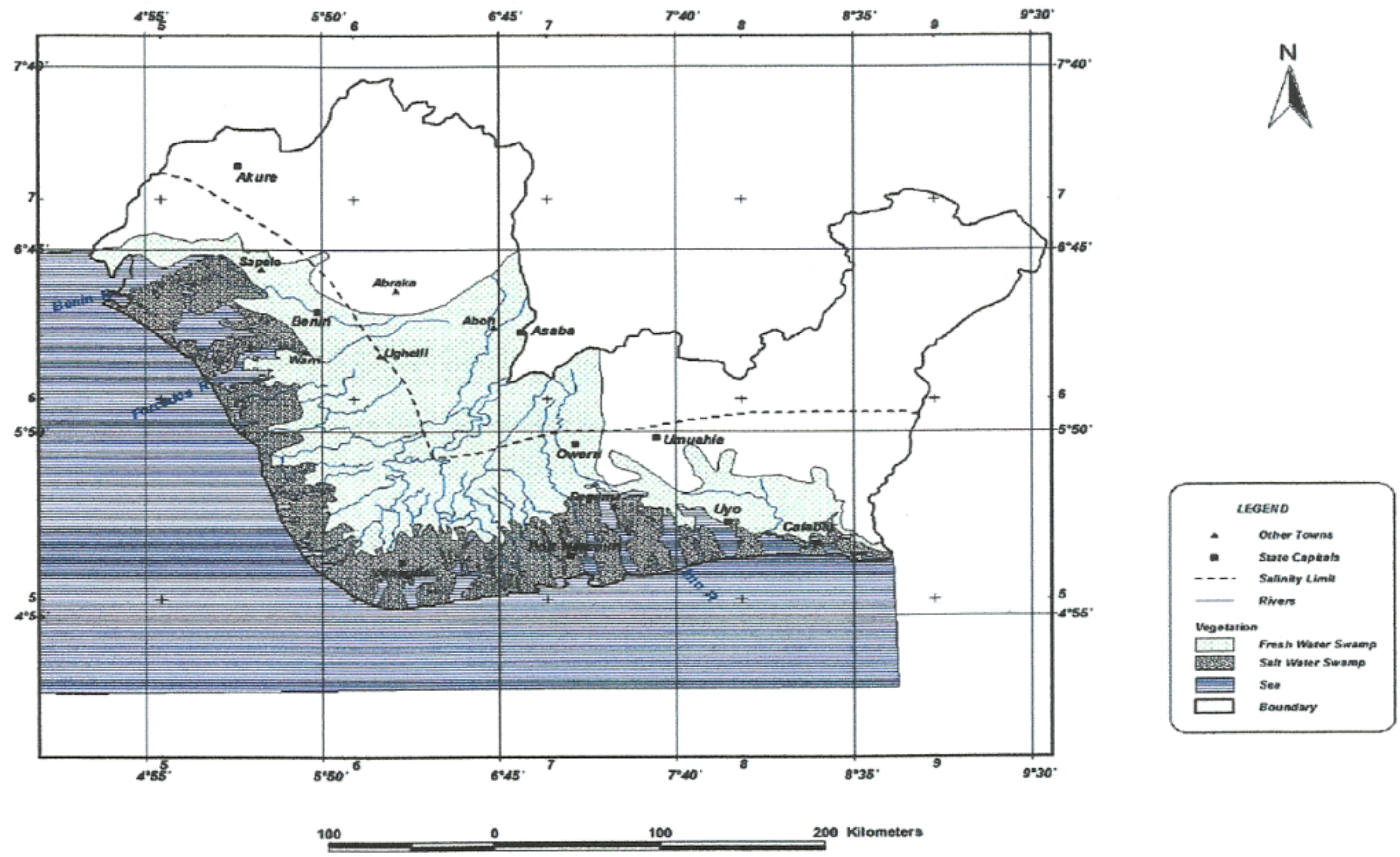

Figure 2. Map of the Niger Delta showing salinity limits/vegetation of the coastal zone (after Ogba and Utang, 2010).

spills, land disposal of solid wastes, sewage disposal on land, saltwater encroachment, deep well disposal of liquid wastes, mining activities, spread of urbanization to recharge areas, and seepage from industrial waste. Aquifers are vulnerable to pollution from these sources to the extent they are in proximity with such activities.

The first aquifer system is extremely vulnerable to pollution from surface sources. Consisting essentially of loose to poorly consolidated sandy materials, this aquifer is capped by laterized soil especially in the northern part of the study area. The laterite thins out in a southern direction and has become non-existent from the fresh water swamp to the coastline (Ngah, 2009). Where the laterite is thin or nonexistent, poor land use practices including use of fertilizers in farming and land disposal of solid wastes including refuse dump can result in the contamination of groundwater sources. For instance, the decomposition of refuse produces leachate, a highly polluting substance which can seriously degrade groundwater quality if allowed access to it. Moreover, the network of pipelines that convey petroleum products in the Niger Delta are buried in the first aquifer. Undetected leakage of hydrocarbon from the pipelines over a long period of time can pollute the aquifer.

Aquifer systems in the Niger Delta are separated by fairly thick clay/shale layer which by their nature, are impermeable, serving as a barrier to vertical (down-ward) percolation of contaminants from the first aquifer. The attenuation properties of clay also lead to an overall reduction of potency of contaminants and possible elimination through cation exchange. For this reason, it can be assumed that the aquifer systems below the first are shielded from pollution from surface sources.

Pollution of second aquifer system by surface sources can only be possible through vertical leakage if the overlying layer is an aquitard. Poor borehole completion practices may also lead to contamination of second aquifer system by the first if the well design does not exclude the first aquifer from contributing to the yield of the second.

In the coast, the shallow aquifer systems are unprotected from the dynamic coastal activities. Saltwater is likely to have mixed with shallow fresh water rendering it unfit for human use. Moreover, exploitation of the shallow freshwater aquifers will reduce the thickness and effective head of the freshwater wedge leading to saltwater intrusion into fresh water aquifers. The deeper aquifer systems are fed by recharge from distant (up-country) outcrops of the aquifers and through vertical leakage from the overlying aquitards. The deeper

Table 3. Activities that could contaminate groundwater aquifer and the likely aquifer to be affected in the Niger Delta (Ngah and Nwankwoala, 2013b).

S/No	Activity	Aquifer system				
		1	2	3	4	>4
1	Agricultural activities	x				
2	Petroleum leakage and spills	x				
3	Sewage disposal on land	x				
4	Saltwater encroachment	x	x	x	x	x
5	Deep well disposal of liquid wastes	x	x	x	x	
6	Mining activities	x				
7	Spread of urbanization to recharge areas	x				
8	Seepage from industrial waste lagoons	x				

aquifers are considered safe and free from pollution with zero vulnerability everywhere except in the coastal areas. Here, unplanned exploitation and/or over-pumping of groundwater could increase the already deep salinity depth thereby reducing the effective column of fresh water. Boreholes will therefore need to go even deeper to exploit freshwater. Table 3 outlines the activities and practices that could lead to the degradation of groundwater quality in the Niger Delta.

From the Table 3, it is evident that the first aquifer system is highly vulnerable to contamination and many activities of man impact directly on this aquifer. Where the lateritized soil cover or clayey overburden is thin or completely absent and the water table is shallow, the risk of contamination is much higher. Awareness of this situation amongst the stakeholders needs to be emphasized.

Groundwater management options in the Niger Delta

Groundwater deserves serious attention in the Niger Delta. This is because there are no alternative sources of water supply in many parts of the Niger Delta. This is particularly the case in those regions where estuaries penetrate very far inland, leaving many areas surrounded by saline creeks and inlets. Moreso, the network of deltaic tributaries create problem of isolation in the region. Such a condition has not favoured the growth of towns and cities. Little riverine communities scatter all over the delta and there is no likelihood that this situation would change in the very near future. The need therefore for the establishment of huge water development schemes would not arise for a very long time in the area. What would be needed would be water development projects tailored to expansion through increase in boreholes.

Furthermore, with particular reference to irrigation, waterlog problem prevalent in the Niger Delta, could be further aggravated through pumpage from the surface streams. Irrigation schemes, if planned in the area, would therefore be better served by boreholes through which groundwater levels are lowered, rather than raised in order to improve the waterlog condition in the area.

Whether for domestic, industrial or irrigational purposes, it appears evident that groundwater constitutes the most economical, practical and sensible source of water supply in the Niger Delta. It would have to be harnessed in order to meet the water needs of the several development projects now planned for the region. Important steps need to be taken in order to utilize the groundwater resources of the region more efficiently and usefully in future. Among the steps are:

(1) A deliberate effort to promote more understanding in the profession of hydrogeology. Several practicing Engineers today in Nigeria's water industry dismiss hydrogeology as irrelevant in the process of supplying the nation with more water. Consequently, wells are drilled haphazardly and are pumped without regard to the characteristics of the producing aquifer. While such a state of affair may constitute no problem under our present level of development, there is no doubt however that things might not continue in a similar way for long.
(2) The need for a Water Resources research body, specifically created to coordinate studies on both ground and surface water resources of the region. It is only such a body that can absorb the demand in money, material and men that such a complex region as the Niger Delta demands.
(3) There should be laws governing the abstraction of groundwater in the region. Today, no laws prohibiting individuals from drilling water wells anyhow, anywhere and at anytime exists. Over-pumpage in coastal aquifers can be dangerous where no regulation exists. This should be addressed with all seriousness.
(4) There is a need for accurate data collection, monitoring and on longer time scale to be able to detect and document effects of water degradation and conversely show the effects of remedial activities, despite the superimposition on natural climatic variability. Documentation, storage and dissemination of knowledge

are important. Through the development of awareness, knowledge and capacity at the national and local level, it is envisioned that the overall knowledge gap will diminish- a step towards sustainable development and management of water resources.

THE WAY FORWARD

Quite unfortunately, in spite of the fundamental role groundwater plays in human well being, as well as that of many ecosystems, groundwater basins are difficult to govern and manage, partly because of poor information, and also because of poor visibility of the resource, the need for reliable data and information in support of water resource planning is central to any strategy. Technology, knowledge transfer and sound research cooperation should receive sufficient attention at the regional scale for any meaningful solution of regional groundwater problems.

More importantly, any sustainable suggestion towards the improvement of water resources management in the Niger Delta must include but not limited to the following:

i) Re-introduction of long-term hydrological observations and investigation of new data collection on water use, irrigation and agriculture lands, water sediment deposits, industrial demands, urban development, recharge, hydraulic properties as well as groundwater/surface water interaction;

ii) Protection of groundwater resources to safeguard long-term use and balance the demands of economic development with ecosystem conservation;

iii) Regional studies of hydrogeology, hydraulic properties, regional flow system and water quality that cross state boundaries;

iv) Greater integration of the relevant information systems, e.g hydrology, hydrogeology, water quality, land use, sediment transport etc;

v) Since the responsibility of protecting our groundwater resources is a collective responsibility with everybody as a major stake holder, an aggressive public awareness programme comparable to that for HIV/AIDS is recommended for water users, planners and policy decision makers at all levels.

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