

Challenges of Groundwater Development and Supply in the Niger Delta, Nigeria

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Abstract

Some problems of groundwater development in the Niger Delta ranging from negligence to geological peculiarities are examined to highlight the importance and application of geologic knowledge and research for decision making and averting failure in groundwater development for provisional use. Although the geology and hydrogeologic properties of the aquifer system in the Niger Delta immensely favors groundwater development, there are several recorded cases of failed groundwater development projects poor water quality, dry boreholes and boreholes with surprisingly low yield which could have been avoided. This is due to the perception that since groundwater is prolific, geologic and locational peculiarities can be ignored. This research has highlighted the importance of the knowledge of the hydrogeology of the different geologic units as significant factor in the success of groundwater projects through the correlation of past research of geologic units and groundwater potentials, quality and challenges with the present projects implemented in some of the locations. Cases where groundwater projects are executed with wrong exploration options and without consideration of the peculiarity of the geologic units of the project area, including engagement of incompetent contractors, and negligence to the existing regulatory framework for groundwater development in Nigeria are presented. In order to promote sustainable groundwater development and management in the Niger Delta, this research highlights and recommends the pragmatic use of geologic information including various technical, institutional, regulatory and management measures which have the capacity to avert challenges in groundwater development for provisional use.

Keywords

Groundwater Development, Niger Delta, Geological Peculiarities,

1. Introduction

According to the United Nations World Water Assessment Programme, groundwater accounts for approximately 99% of liquid freshwater on Earth. It is important for human, economic and environmental development and provides half the volume of freshwater withdrawn for domestic use by global population and 25% for irrigation. Groundwater faces challenges from climate change, management and policies across the world [1]. Especially in sedimentary basins where huge reserves of groundwater exist and contribute the greatest percentage of groundwater withdrawal in the world. Bear [2] classified these basins as permeable huge reserves for groundwater and having the largest groundwater reserves on Earth. In Sub-Saharan Africa's sedimentary basins, the huge groundwater reserve has the potential to significantly meet the region's provisional needs for water supply. And in Western Africa, the huge permeable reserve, high annual rainfall and regular recharge provide a great opportunity for groundwater development. Despite an abundance of groundwater, identified limitations to groundwater development have been attributed to the lack of investment in infrastructure, institutions, trained professionals and knowledge of the resource [1].

According to Molerio-León, [3] groundwater development is planned to satisfy a certain demand for water such as for provisional use or for the assessment of the groundwater resources of a watershed. In the Niger Delta, groundwater development projects are primarily for provisional water supply in which significant amount goes for domestic and industrial consumption. Others include regulatory services; groundwater and aquifer pollution assessment (especially due to hydrocarbon contamination) and research for sustainable management of groundwater in the Niger Delta due to its significant support to sustain the environment and the wetland ecosystem. Despite having high capacity to offer several services ranging from provisional, regulatory, cultural and support to human, ecosystem and development, including other beneficial opportunities such as support to climate balance and adaptation, the peculiarity of the Niger Delta sedimentary aquifer systems significantly influences groundwater development, methods of abstraction and challenges encountered during development. According to Nwankwoala [4], the geology of the Niger Delta sedimentary basin including the thick and extensive sediment deposits and favorable climatic factors such as high precipitation enable good aquifer recharge. Nwankwoala [4] confirmed from the hydrogeological studies conducted that the Niger Delta aquifer system has favorable groundwater resource potential.

The role played by the application of knowledge and research and technology in geosciences to groundwater development enabled large-scale groundwater

withdrawal in the Niger Delta especially for oil and gas development and related industrial activities (which required huge amounts of freshwater), including large municipal groundwater development projects. The application of geoscience enhanced methodology for groundwater investigation including the identification of the prospective zones through the assessment of geomorphologic, geophysical and specific hydrogeological characteristics of an interest area. Geoscience knowledge and expertise are not limited to the drilling and development of wells, performance of pumping tests to obtain numeric indices of groundwater potential and water quality assessment and averting potential risk and proffering solutions to challenges encountered in all these processes.

2. Some Influential Geologic Research and Efforts Which Led to the Success of Groundwater Development in the Niger Delta

Groundwater development in the Niger Delta has come a long way with greater success, challenges and lessons learned in terms of advancement in technology for exploration and development, research, challenges and management policies. At present, groundwater accounts for the most developed and preferred source of water in the Niger Delta. Despite large networks of surface water and abundance of rainfall in the region, greater than 2000 to 5000 mm/yearly average [5] [6], the ease of groundwater development, quality and reliable quantity make it more dependable than other sources. And the peculiarities of the Niger Delta aquifer system which influence groundwater development services, techniques or methods of design have been investigated extensively by several researchers in the field of geosciences. Groundwater potential, all-year water reliability due to the availability and ease of abstraction, ease of groundwater recharge, increasing economic activities and population size, and research have significantly enhanced groundwater development, especially for shallow and some deep aquifers of interest in the Niger Delta. And the characteristics of the Niger Delta groundwater aquifer systems and potential for groundwater development for water supply including ecosystem benefits have been researched extensively by researchers in the field of geosciences. These research works have high capacities to guide groundwater technical projects for infrastructure development, policies and reforms and enable management of risk and innovations in groundwater development. The studies have excellent potential to be used as a guide to resolving the groundwater development limitations identified by the UNESCO World Water Assessment Programme [1], with confidence that they can effectively enable investment in infrastructure, improve institutions, used as guide to train young and upcoming professionals and to inform and enhance knowledge of the resource.

Several aspects of the Niger Delta geology have been studied by prominent researchers to aid groundwater development projects from assessment and analysis, planning and design, and the implementation to completion phase. With

confidence that the application of this scientific geological knowledge ensures that one's expectations about the groundwater potential of the area closely match reality. While these researchers identified challenges and solutions to effective groundwater development and also presented scientific information about site specific geological characteristics as guide to important parameters which include groundwater potential and groundwater hydrochemistry.

Some of these studies which have been acknowledged in this paper are powerful tools for the understanding of the groundwater system of the Niger Delta as a guide to its development and management.

Edet [7] identified favorable conditions for groundwater development in the Niger Delta which are the hydrogeological characteristics of the shallow coastal aquifer including the sand-clay intercalations, high hydraulic conductivity and transmissivity in most parts of the Niger Delta. The study stated that the increased uncoordinated development of groundwater as economic activities has affected the availability and quality of groundwater resources in the coastal areas of the Delta.

Abam & Nwankwoala [8] reviewed and established extensive information about the hydrogeologic parameters and obtainable values in different locations within distinct geomorphologic units in their study of the Hydrogeology of Eastern Niger Delta. According to the study, groundwater development and water quality challenges in the Eastern part of the Niger Delta observed include the high levels of iron, manganese and chloride and saline water intrusion in some locations and coastal communities in the Niger Delta. Their study is an important guide to understanding the gradual change in groundwater quality in the different encountered geomorphologic units from the inland part of the basin and down to the coast. Their review also explained the dominant and localized groundwater flow directions in the region. And pointed out increasing pollution from hydrocarbon spillage and unregulated waste management as major challenges which have made groundwater increasingly sensitive. The study also explained that groundwater quality in the Niger Delta follows the sedimentation pattern resulting in three distinct groundwater zones which include the northern border corresponding to the coastal plain sands with the most desirable water quality, the transitional zone mostly encircled by the meander belt with less desirable quality dominated by iron water and the coastal zone located within the mangrove swamps with frequent challenges of saline intrusion [8].

These studies distinctly and significantly identify important geological characteristics and groundwater parameters to look out for while carrying out a groundwater development project. Some parameters such as transmissivity which are important to understand the rate of groundwater flow have been evaluated for most parts of the Niger Delta. According to Ngah & Eze [9] field experiment evaluated that the transmissivity value of the aquifer around Eleme area ranged from 1324 m²/day - 5815 m²/day, and was interpreted as having very good yield. Their study went further to identify important information about groundwater development and management challenges in the area which include the unen-

couraging success rate of drilling borehole in the area which is due to lack of planning, no hydrogeological expertise to aid technical input, data and information management. Despite the high transmissivity value and yield identified in the area, most of the boreholes drilled in these unguided conditions were abortive and unsustainable. The study recommended engagement of competent consultants with hydrogeology experience to improve success rate of drilling deep boreholes for groundwater development for water supply [9].

The works of Etu-Efeotor, Etu-Efeotor & Odigi, Udom, *et al.*, Edet, Olatunji, Ngah; Abimbola, *et al.* and Nwankwoala & Ngah [10]-[17]; provided resourceful information about groundwater hydrochemistry in the Niger Delta and explained significant roles played by geology and water quality on groundwater development and infrastructures. The technical information in their research work is an important guide to water quality which will help make technical decisions about project feasibility and is an important factor in the cost of groundwater development. Some of the research work advised on drinking water quality and public health which involved anthropogenic and organic influence on groundwater quality which include analysis of coliform contents in the water and test on the oxygen demands (biological or biochemical) oxygen demand, BOD and chemical oxygen demand, COD). These are important parameters because developing groundwater in areas prone to fecal coliform contamination can be health-wise expensive in terms of the danger of exposure to fecal coliform bacteria leading to diarrhoea. And high BOD or COD values indicate high level of pollution by organic matter in water. In any case and for drinking water, frequent testing and chlorination of water is required or other forms of treatment such as boiling should suffice.

Several studies have presented groundwater hydrochemistry and quality as important parameter to understand in groundwater development. Abam [18] explained the importance of understanding the chemical processes which control groundwater quality, facies, their spatial distributions including water quality indices which range from poor to excellent quality in groundwater development and management. Most of the studies showed that values of physicochemical parameters, cations and anions evaluated in the groundwater deviate from the guideline values. As a result, high values of pH, iron, cadmium, lead, nitrate, electrical conductivity, chemical oxygen demand, phosphates, manganese, chromium, nickel and zinc contribute to the deteriorating groundwater quality in the Niger Delta region. The deviations from the acceptable quality are mainly due to geogenic and anthropogenic factors which correlate to the increasing events of saltwater intrusion, chemical weathering, leaching, pollution from human activities and climate change. The study also identified over abstraction of groundwater especially in urban coastal areas as a major cause of aquifer salinity [18]. Amadi, *et al.*, [19]; Omontese, *et al.*, [20]; Udom, *et al.*, [21]; Nwankwoala, *et al.*, [22]; Amajor, [23]; Amadi, *et al.*, [24]; Udeh, *et al.*, [25] carried out studies on hydrochemical analysis, geophysical investigation and groundwater quality in the Niger Delta with results ranging from poor to acceptable due to contami-

nants such as hydrocarbon and heavy metals in the water. These studies recommended seasonal groundwater chemistry assessment for decision making on management and policy implementation.

The aforementioned shows explicitly that consultations of available resources including knowledgeable and skilled geologists, institutions (academic and government), data and use of digital technology and policy guides should be able to limit the challenges faced during groundwater project implementation. This is especially in cases where poor and objectionable water quality are encountered, or dry borehole drilled and borehole have been abandoned. Despite the availability of water in the Niger Delta, many of these kinds of failed projects implemented by government establishments, private organizations and individuals exist. This should not be the case because groundwater development projects should record greater success due to the extensive knowledge of the Niger Delta geology and hydrogeology available in published research.

This study specifically reviewed and connected important geologic research on groundwater development to the success of some implemented projects and for effective decision making in different geomorphologic units of the Niger Delta. Especially highlighting important groundwater quality issues which should be averted by the application of geological reconnaissance assessment and decisions.

3. Geologic and Hydrogeologic Settings of the Niger Delta

According to Reijers [26] the Niger Delta basin is situated on the margin of the Gulf of Guinea in the Equatorial West Africa, the Basin extends from the Calabar flank and the Atlantic Ocean in the south. And protrudes southwards into the Gulf of Guinea as an extension from the Benue Trough and Anambra Basin provinces. Westward, the Basin merges across the Okitipupa high into the Dahomey Embayment. This coastal sedimentary basin of Nigeria experienced three major depositional cycles which resulted in the regional stratigraphic units of the Niger Delta (**Figure 1**). They are upper sandy Benin Formation, a unit of alternating sandstone and shale named the Agbada Formation, and the oldest lower shaly Akata Formation [27]. These three units of about 10,000 m total thickness extend across the whole Delta and each range in age from early Tertiary to Recent, related to the present outcrops and environments of deposition, including interplay between subsidence and deposition arising from a succession of transgressions and regressions of the sea [28] [29].

The aquifer of interest for groundwater development in the Niger Delta Basin is the Benin Formation and the Quaternary deposits. According to Etu-Efeotor & Akpokodje (1990) [31] in the geologic units of the Niger Delta (**Table 1**), the upper section of the Benin Formation is the Quaternary deposits which is about 40 - 150 m thick and comprises sand and silt/clay with the later becoming increasingly more prominent seaward. The Benin Formation has significant groundwater potential consisting predominantly of freshwater continental sands and gravel with intercalations of shale and with thickness of about 2100 m at the

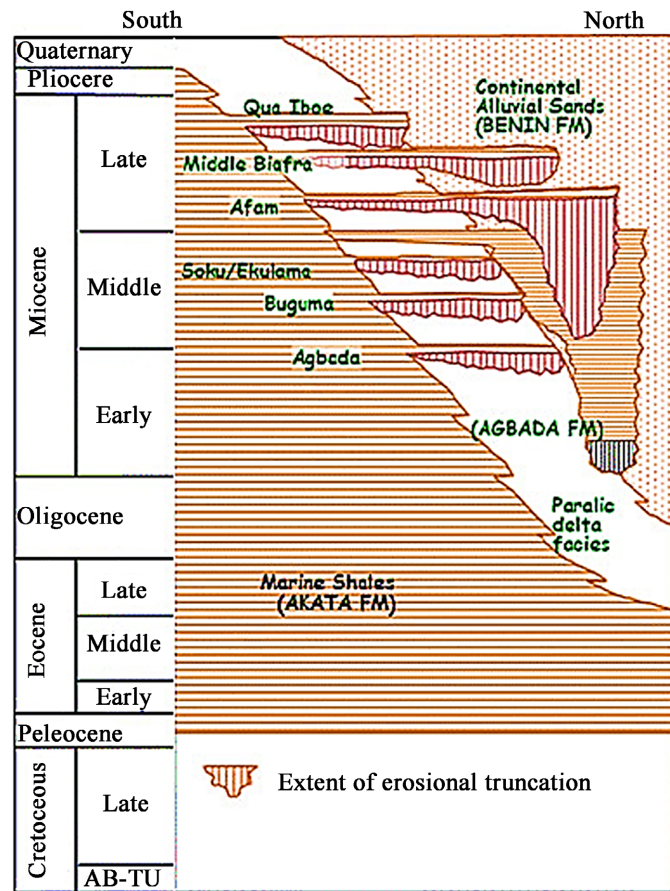


Figure 1. Regional stratigraphy of the Niger Delta showing different formations (Adopted from Ozumba). [30]

Table 1. Geologic units of the Niger Delta (Etu-Efeotor and Akpokodje, [33]).

GEOLOGIC UNIT	LITHOLOGY	AGE
Alluvium (General)	Gravel, sand, clay, silt	
Freshwater Back Swamp, Meander Belt	Sand, clay, some silt, gravel	
Mangrove and Saltwater/Back Swamps	Medium - fine sands	Quaternary
Active/Abandoned Beach Ridges	Sand, clay, and some silt	
Sombreiro-Warri Deltaic Ridges	Sand	
Benin Formation (Coastal Plain Sands)	Coarse to medium sand with subordinate silt and clay lenses	Eocene
Agbada Formation	Mixture of sand, clay and silt	Eocene
Akata Formation	Clay	Eocene

center of the Basin. Hydraulic conductivities of the Quaternary sand aquifer vary from 3.82×10^{-3} to 9.0×10^{-2} cm/sec, indicative of a potentially productive aquifer, and specific capacities recorded from different areas within this formation vary from 6700 lit/h/m to 13,500 lit/h/m drawdown [32].

The hydrostratigraphic units of the Benin Formation summarized by Akpokodje

et al. [33] consist of four well-defined aquifers of unconfined, semi-confined and confined conditions, respectively, from surface to subsurface, and of varying thickness in the upper 305 m. A major [23] presented a regional lithostratigraphic and hydraulic interpretation for the upper 0 - 300 m of the Benin Formation where groundwater is principally abstracted from across the region, Nigeria. According to the study, aquifers are predominantly sand beds with minor clays, lignite, and conglomerate intercalations. The Deposition of the aquifer materials is thought to have occurred in alluvial fans, fluvial channels, tidal channels, intertidal flats, beaches, and related microenvironments.

It is evident therefore that the Niger Delta geology favours groundwater development because of the prolific aquifers which exist in the region. In this region, many wells both deep and shallow abound and with very low to high expertise required for borehole drilling and development, and depending on the hydrogeologic conditions, hence the importance of understanding the geology and hydrogeology for groundwater development for water supply cannot be overstressed. The regional geologic setting and stratigraphy, sedimentation processes, age and maturity of the deposition, major geologic units and aquifers where abstraction and development occur, including the influence of localized geology on development techniques and expertise to be implemented are important for Successful groundwater development in the Niger Delta.

According to Nwankwoala & Ngah [34], the influence of geology on the groundwater resources of the Niger Delta is the most important factor besides that of climate in the region. While Abam & Nwankwoala [8] emphasized that geology has been observed to be responsible for the complex groundwater distribution, extractability and quality in the Niger Delta.

According to Offodile [35], the hydrogeological data from the sand units of the Benin Formation estimated the values of hydraulic conductivity as a range from 3.82×10^{-3} to 9.0×10^{-2} cm/sec, showing that the aquifer is highly productive. And estimated transmissivity values for the aquifers across the Niger Delta region range from 1.05×10^{-3} to 11.3×10^{-2} m²/sec, coefficient of storage varies between 1.07×10^{-4} and 3.53×10^{-4} , while the specific capacity values range from 19.01 and 139.8 m³/h/m of drawdown [35] The annual water storage and recharge of the aquifer have been estimated to be 6.163×10^8 m³ [36].

According to Abam & Nwankwoala [8] on the aquifer hydraulic parameters of some selected boreholes in the Niger Delta, the hydrogeologic data showed significant variation in the average specific capacity values of the upper and lower aquifers of the Benin Formation. The mean value of specific capacity for the upper aquifer is 19.4 m³/h/m and maximum value of 75.1 m³/h/m. Observed specific capacity maximum value for deeper aquifer evaluated from fewer boreholes was 139.7 m³/h/m of drawdown. The study also emphasized the good quality of the groundwater from the Benin Formation compared to the WHO standards for drinking water. Although high iron and chloride values have been observed at different locations and times.

The study also showed that values of static water level (SWL) are influenced by proximity to coastline or drainage rivers and artesian conditions exist in areas with well confined aquifers. While the depth to static water level varies across the region, decreasing from north to south of the study area from 18.2 m at Ulakwo in the northern part of the study area, 0 - 5 m in the flood plain areas, 0 - 1.5 in the Beach ridges, 0 - 0.5 m in the mangrove swamp, 0.34 near coast at Abissa, 0.69 m at Brass and zero at Akassa. And areas close to rivers such as in Omoku, Bodo and Abonema experienced low SWL values [8].

Important challenge observed is that due to mismanagement, indiscriminate and unsustainable development of groundwater because of the belief in the abundance and availability of groundwater resource in the Niger Delta. This challenge which is largely experienced in borehole drilling projects was discussed by Amajor [37], Nwankwoala & Udom [38] and Ngah & Eze [9] who identified that the design of boreholes does not usually consider geologic characteristics and involvement of geologist, and quacks have taken over in the business of groundwater development.

The application of geologic knowledge and research in preparation for groundwater development project serves as a powerful tool in preventing project failure such as dry and abandoned borehole or poor water quality and abandoned borehole, very low yielding borehole. It also helps to maximize yield and make decisions for exploring alternatives in situations of predicted water quality issues. The involvement of competent geologists with good professional knowledge and expertise provides the essential requirements relied upon during groundwater development projects. Especially in the planning and design phase (desk and reconnaissance study, field technical investigation), and the field implementation aspects which involve supervising the drilling work, logging of samples, conducting pumping tests, borehole development procedures, and the casing and gravel packing selection, installation and completion works and ensuring sustainability of the service. The abundance of published and open-source research work about the geology, hydrogeology and groundwater potentials of the Niger Delta has sufficient and excellent capacity to guide any groundwater development project when consulted. And the engagement of competent contractors with the right qualifications and understanding is important for a successful groundwater development project. It is also important to upscale research for groundwater development in the Niger Delta to improve the availability of data and information especially with the recent and evolving cases of climate change impacts and other environmental issues that affect groundwater resources.

4. Method and Material

This study reviewed literatures, geologic map of the project locations, available data and information from some completed groundwater development projects implemented in the Niger Delta; they include the project technical details, water

quality, implementation procedures, groundwater development challenges encountered due to the geology and hydrogeology of the project area, the level of geological considerations and input to the project. **Figure 2** and **Table 2** are maps and tables, respectively, showing the evaluated project locations and their geomorphologic units in the Niger Delta. Included is **Figure 3** which is the geologic map of the Niger Delta showing the Quaternary sedimentary deposits which

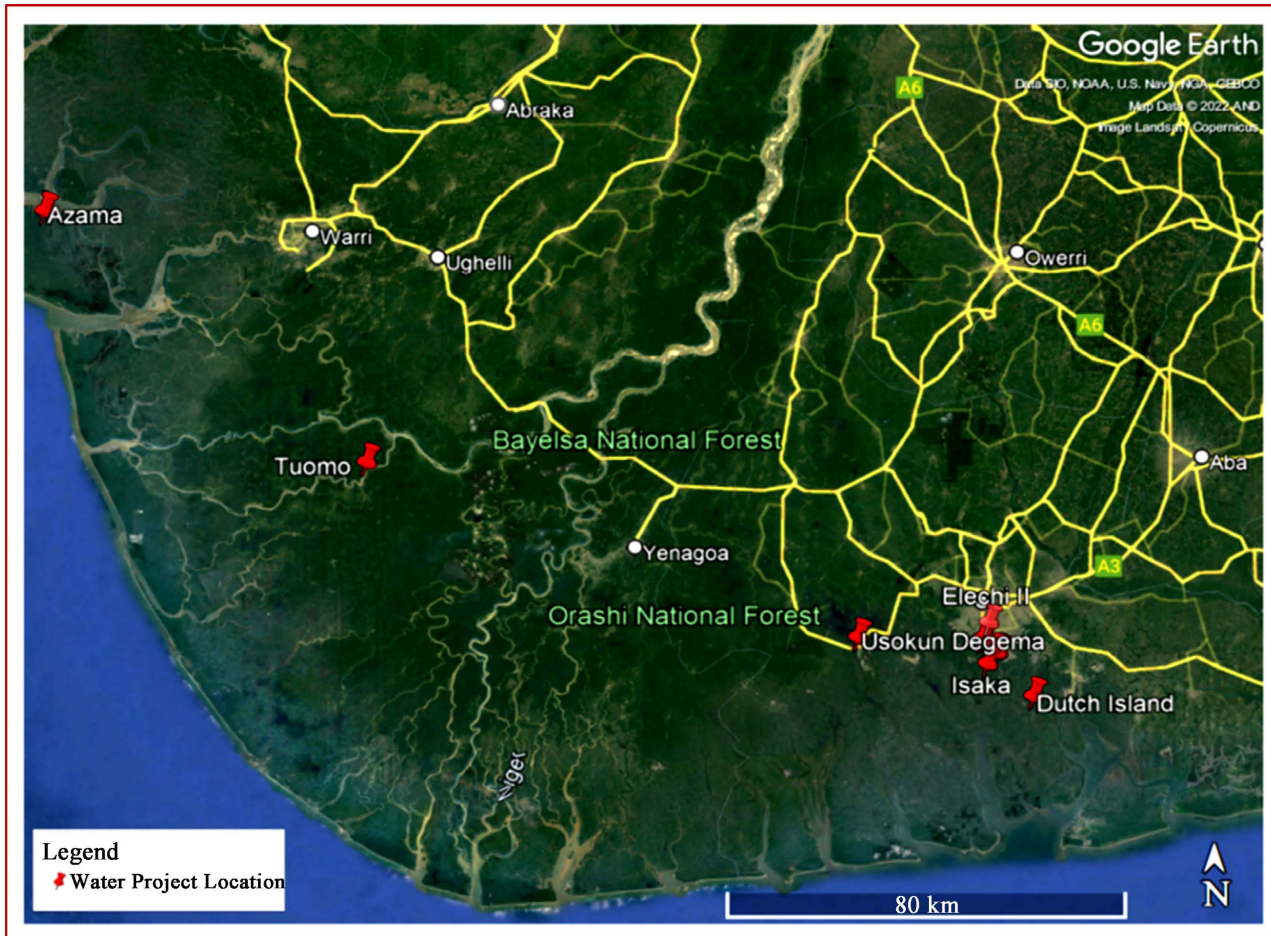


Figure 2. Google earth pro Map showing project locations in the Niger Delta.

Table 2. Geomorphologic units and project location/coordinates.

S/No.	Geomorphologic Units	Project Location	Latitude (N)	Longitude (E)
1	Mangrove & Saltwater Back Swamp	Degema	4.47°	6.766°
2	Freshwater Back Swamp and Meander Belt	Tuomo	5.116667°	5.883333°
3	Mangrove & Saltwater Back Swamp	Azama	5.593231°	5.297772°
4	Coastal Alluvium, Mangrove and Freshwater Swamp	Port Harcourt Diobu	4.780725°	6.994094°
5	Saltwater Swamp	Isaka & Dutch Island	4.735091°	7.002645°
6	Coastal Plain Sand Benin Fm.	Inen	4.783277°	7.561288°
		Odoro Ikpe	5.357311°	7.753379°

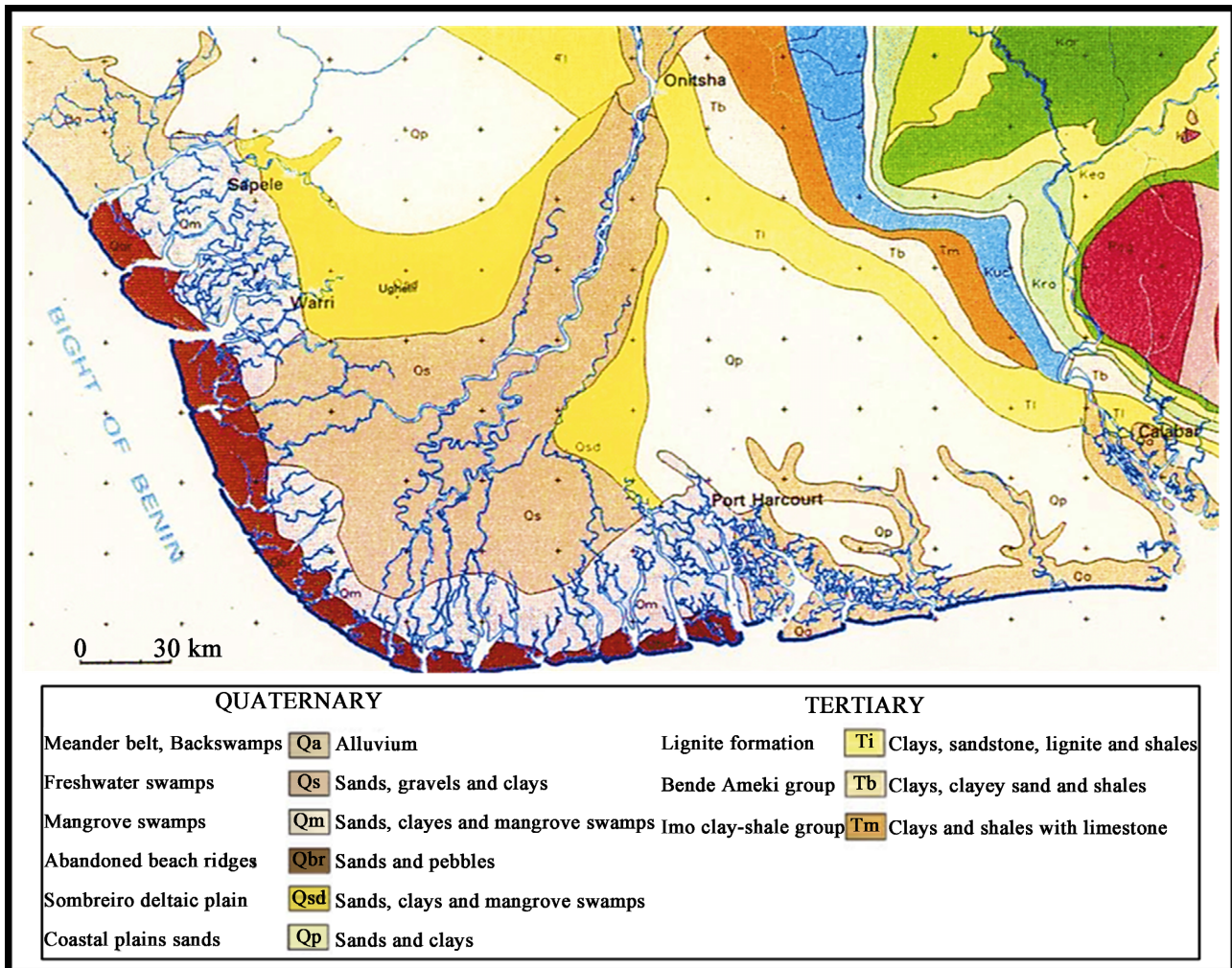


Figure 3. Geologic map of the Niger Delta (after Reijers [39]).

serves as the aquifer where groundwater is abstracted within the respective project locations.

5. Result & Discussion

The favorable geology underlying the project locations influenced the method of shallow borehole drilling, including cost and material. The common and cost-effective method of drilling shallow boreholes is the jetting (Washboring) method (**Figure 4**). This drilling method is suitable for the shallow geologic formations of the Niger Delta quaternary deposits which serve as the aquifer for groundwater development in most parts of the Niger Delta. This method is also suitable for areas with limited accessibility and reduces cost of drilling since motorized drilling rig is expensive to mobilize. The ease and low cost of drilling boreholes in the Niger Delta were identified as contributing factors to the indiscriminate groundwater development projects scattered around. Because it was observed that there are many shallow boreholes existing (both successful and unsuccessful) in remote communities which were drilled by the individual



Figure 4. Jetting (Washboring) borehole drilling in one of the project locations (Port Harcourt).

community members, local or state government, organizations or philanthropists.

Pumping test reports showed that most of the boreholes drilled in the shallow aquifers have considerably good yield to sustain a pump of above 5 m³/hour. Although unexpectedly low yielding boreholes have been observed in close locations having similar geologic and aquifer characteristics.

Water quality problem identified was basically iron, salinity and pH concentration values in highlights deviated from the WHO drinking water quality guidelines (**Table 3(a)** & **Table 3(b)**). High coliform bacteria counts were observed in some water samples analyzed (**Table 4(a)** & **Table 4(b)**). The challenge of saline and poor water quality was identified with the boreholes located in the Mangrove and Saltwater Backswamp and the Saltwater Swamp geomorphologic units. Most cases of poor water quality have been linked to lack of geologic considerations and poor technical decision making.

Borehole reports were not comprehensive and the problem of using incompetent contractors exacerbated the already existing challenges faced because most of them present erroneous, misleading and incomplete or no reports of projects implemented.

Most of the clients (public and private organizations) are not informed about the geology of the environment (especially the water quality) before proceeding to project implementation. Even with the vast research on groundwater resource development in the Niger Delta which should guide project planning and implementation, some organizations do not carry out detailed local hydrogeological study as preliminary investigation and they do not consult experts for professional guidance.

The project's technical details during implementation were not adequately documented and some completed projects were abandoned mostly due to poor water quality, dry well and very low yield.

Table 3. Result of water quality analysis showing some highlighted parameters with concentration above the WHO standards.

(a)

Geomorphologic Unit/Parameters	Mangrove & Saltwater Back Swamp-Degema		Freshwater Back Swamp and Meander Belt-Tuomo		Mangrove Saltwater Back Swamp-Azama		WHO Standard	
	WS1	WS2	WS1	WS2	WS1	WS2		
Physical/ organoleptic	Appearance	Clear	Clear	Clear	Reddish yellow		Pale yellow	Clear
	Turbidity NTU	2.86	3.03	25		4.05	12	5
	Odor	Unobj	Unobj	Obj	Obj			Unobj
	Taste	Unobj	Unobj	Obj	Obj			Unobj
	Temperature (°C)	29.8	29.8		27.1			25-30 (Ambient)
Chemical	Conductivity uscm	51	52	40.5	155.3	92.7	792	250
	pH	5.5	6	5.7		6.83	6.15	6.5-8.5
	Chlorides as NaCl			11.70 mg/l		895	278	250
	Total alkalinity as CaCO ₃			13		12	2.72	10
	Total hardness	10	5	20	60		2.88	100
	Mg Hardness as MgCO ₃ mg/l			5	33			20
	Ca hardness mg/l				17	176		150
	Total Iron as Fe mg/l			9.2	0.53	14.19	3.823	0.3
	Nitrates NO ₃ ⁻	2.3	3	2.8	0.86	Nil	0.4	10
	Sulphate SO ₄ ⁻					0.2	3	250
	Phosphate						0.31	250
	Total dissolved solids TDS	28.6	28.6	18	157	46.35	396	500
	Total suspended solids	11	10	30	10		48	25
	Salinity	4.7	3.5		26.91			250
	Cu mg/l						<0.001	1
	Ca mg/l						0.452	70
	Mg mg/l						0.671	30
	K mg/l						467	200
	Na mg/l			4.6			1 128	200
	Pb mg/l						0.081	0.05
Zn mg/l				1.01		0.275	3	
Mn mg/l						0.163	0.5	
Cd mg/l						0.683	0.003	
Cr mg/l						0.464	0.05	

(b)

Geomorphologic Unit/ Parameters	Coastal Alluvium, Mangrove and Freshwater Swamp-Port Harcourt Diobu							Saltwater Swamp-Isaka/ Dutch Island			WHO Standard
	WS1	WS2	WS3	WS4	WS5	WS6	WS7	WS1	WS2	WS3	
Appearance									Reddish yellow		Clear
Physical/ organoleptic											
Turbidity NTU	0.2	2.6	0.1	0.3	2.21	0.423		3.26	29	15	5
Odour							Unobj	Obj	Obj	Obj	Unobj
Taste							Unobj	Obj	Obj	Obj	Unobj
Temperature (°C)	25.8	28.7	25.1	25.3	29.3	28.2	25.8	28.5			25 - 30 (Ambient)
Conductivity uscm	178.1	330	38.3	218.1	12.63	482	2.79	6200	88.3	48.3	250
pH	7.2	3.7	5.6	5.9	6.8	6.18	5.75	6.2	6.27	6.1	6.5 - 8.5
Chlorides as NaCl	10.34	25.1	7.1	83.43		104	30	1709	341.6	111.6	250
Total alkalinity as CaCO ₃	12	-	8	8			38	90	10	8	10
Total hardness	148	15.3	16	58	2.08	56	20	100	161	8	100
Magnesium Hardness as MgCO ₃ mg/l					0.74		0		16	8	20
Calcium hardness mg/l					6.7		20		125	90	150
Total Iron as Fe mg/l	0.028	0.135	<0.001	<0.001	0.02	0.024	0.02	<0.001	10.9	1.09	0.3
Nitrates NO ₃ ⁻	0.5	0.82	0.9	10.8		4.1		1.2	19.3	8.5	10
Sulphate SO ₄ ⁻	1	3.3	1	9		3.2	0.672	100	33	41	250
Phosphate	0.03	<0.05	2	1.5		1.02		0.16			250
Total dissolved solids TDS	95	228	18	183.5	110	321.3	1.42	3410	57.4	24.2	500
Total suspended solids	4		4	8	4	2	-	8	33	21	25
Salinity		0.15			10		0.1	2000			250
Cu mg/l	0.217		0.055	0.049		<0.01		<0.001			1
Ca mg/l	8.112	3.8	<0.001	9.092		3.09		18.777			70
Mg mg/l	5.484	1.4	<0.001	2.675		0.12		100.00 6			30
K mg/l			7.38	36.2				38.122			200
Na mg/l			4	8				574.17			200
Pb mg/l	<0.001		0.05	<0.001		<0.01		<0.001			0.05
Zn mg/l	<0.001		0.025	0.017	0.08	0.056		<0.001			3
Mn mg/l	<0.001		<0.001	0.417		0.166		0.104			0.5
Cd mg/l	<0.001		<0.001	<0.001				<0.001			0.003
Cr mg/l	<0.001		<0.001	<0.001		<0.01		<0.001			0.05

Table 4. Result of the microbiological quality of water samples showing highlighted values above the WHO standards.

(a)

Geomorphologic Unit/ Parameters	Mangrove & Saltwater Back Swamp		Freshwater Back Swamp and Meander Belt		Mangrove Saltwater Back Swamp		WHO Standard
	WS1	WS2	WS1	WS2	WS1	WS2	
Total Bacteria count cfU/ml			20+		Nil	2.50 × 10 ¹	cfU/ml
Total Coliform MPN/100ml				18		Nil	0 MPN/100ml
<i>E. coli</i> MPN/100ml				4		0	0 MPN/100ml
<i>E. coli</i> MPN/100ml	55	172				0	0 MPN/100ml

(b)

Geomorphologic Unit/ Parameters	Coastal Alluvium, Mangrove and Freshwater Swamp-Port Harcourt Diobu							Saltwater Swamp-Isaka/ Dutch Island			WHO Standard	
	WS1	WS2	WS3	WS4	WS5	WS6	WS7	WS1	WS2	WS3		
Total Bacteria count cfU/ml	2.4 × 10 ⁴											cfU/ml _
Total Coliform MPN/100ml	160	0			0	0	8					0 MPN/100ml
<i>E. coli</i> MPN/100ml					0							0 MPN/100ml
<i>F. coli</i> MPN/100ml	18+	0										0 MPN/100ml

5.1. Water Supply Project 1

The project area is located in Tuomo Community in Burutu LGA, Delta State. It is underlain by the Fresh Water Back Swamp, Meander Belt made up of sand, clay, some silt, gravel deposits. It is drained by the Forcados River and experiences seasonal flooding from the brackish water during heavy rainfall and at high tide. The geologic information of the project (drilling and lithologic sample information, pumping test and development) was unavailable from the Rural Water Supply and Sanitation Agency (RUWASSA) or the Ministry of Water Resources. There were three abandoned boreholes and a water treatment unit identified in the location, and physical observation of the abandoned water infrastructure showed that the groundwater condition around the location of the existing has high Fe concentration level (Figure 5). The client decided to go ahead to implement the project despite limited working geologic information obtained. And no detailed geologic field study of the area was implemented to guide decision making.

The borehole report showed the depth of the borehole measured at 32 m, static water level of the borehole was 2.7 m, and pumping level became constant at 3.9 m. There was important missing information in the report which should be part of a basic, standard and comprehensive pumping test information.

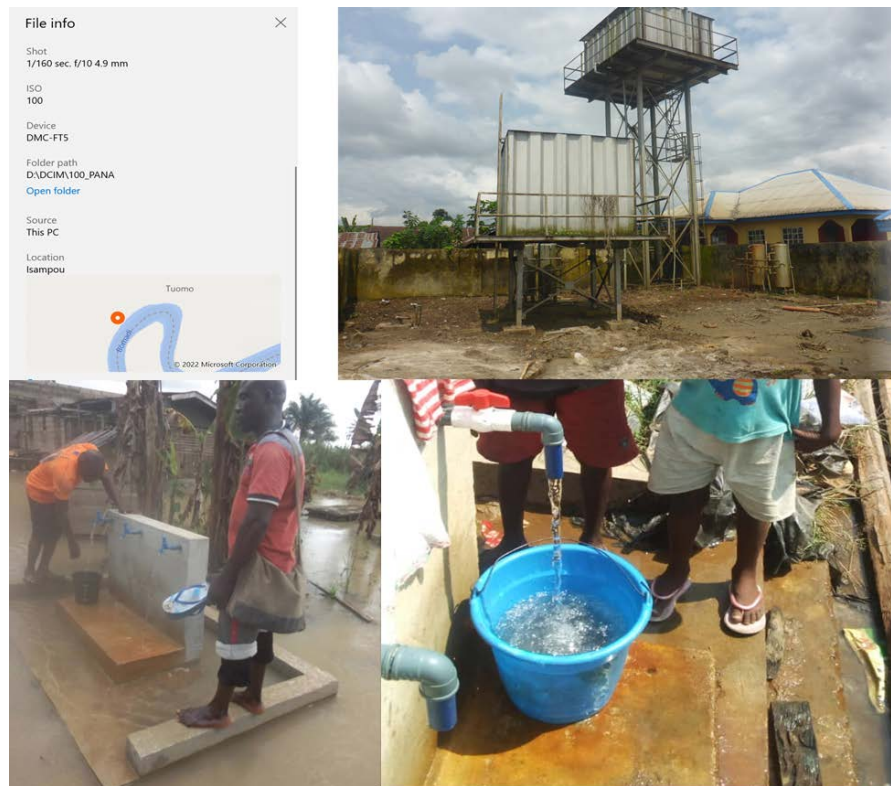


Figure 5. Flooded and Iron-stained water fetching platform due to the high Iron concentration level in the groundwater.

The borehole yield given was outrageous therefore erroneous in comparison with average yield of shallow boreholes abstracting water from the quaternary deposit aquifers (while observation from rapid pumping test conducted showed that the borehole can sustain a yield of $5 \text{ m}^3/\text{h}$).

Pumping test was conducted for just 3 hours, no standard sheet was used and type of test and measurement method was not given. Record of drawdown, residual drawdown, analysis of pumping test data to obtain the specific drawdown, specific capacity and transmissivity was not carried out. The water quality result showed high Iron content, salinity, and bacterial (heterotrophic and *E. coli*) were above the WHO standard and colour (reddish to yellowish brown) and odour were objectionable. Ammonia concentration level in the water was found to be the same as the WHO value of 0.05 mg/l . This result is expected for an unconfined borehole considering also the frequent inundation of the area by the brackish water and high rate of organic activities.

The poor water quality and frequent flooding were observed in the location. This was confirmed in a study by Ohwoghere-Asuma, *et al.* [40] on saltwater intrusion appraisal of shallow aquifers in Burutu area of the western Niger Delta using 2D electrical resistivity tomography. The study reported that the degradation of groundwater quality in Burutu area is not influenced by saltwater intrusion but by other processes which could not be distinguished by electrical resistivity technique used. It was observed that most boreholes in the area have been

abandoned to be used for other purposes, unacceptable for drinking due to high concentration of iron especially for the boreholes with depths exceeding 40 m, and wells shallower than 15 m were sometimes less affected but potentially contaminated by surface runoff.

Most abandoned borehole water in the area had issues with poor water quality which required treatment before the water could be potable. This situation could have been prevented in the planning phase if there was a hydrogeology/geophysical study conducted to guide decision making. Several useful information to guide the project could have prevented the predicament. Important information about the project area (hydrogeology) or existing water infrastructure is sometimes available from the Rural Water Supply and Sanitation Agency (RUWASSA) or the Ministry of Water Resources. All technical information and desk study are important to guide decisions regarding planning and implementation or to abort the project. Most times, aborting water supply project implementation is the best decision, especially in situations where the project beneficiaries may not have the financial capacity to manage the project if fitted with a water treatment unit requiring periodic maintenance.

5.2. Water Supply Project 2

The project is located within the Mangrove/Saltwater Back Swamp of the Lower Deltaic Plain [41] in Degema LGA, Rivers State. High Fe concentration was observed from one of the boreholes abandoned in the location and the water quality analysis showed that the water is acidic. The taste and odour were objectionable. Static water level was reported as 4.5 m bgl, depth of borehole was 45 m, and no yield information available. The water quality analysis report showed that the pH values of the water were not within the WHO standard for drinking water and contained fecal coliform bacteria which made the water not suitable for drinking unless it is treated by chlorination. Most geologic information for the completed borehole (drilling data and lithology, pumping test and development data) were not available. Information about other existing boreholes were also unavailable from state authorities responsible. This also confirms the study of Ngah & Eze [9] about the incompetence of some contractors in delivering groundwater development projects leading to frequent abortive and less productive boreholes in the Niger Delta and lack of documentation of borehole information.

5.3. Water Supply Project 3

Geologically, the community lies on the Mangrove and Saltwater/Back Swamp in Azama community in Warri South-West LGA in Delta State. The study area is less than 5 m above the mean sea level and has frequent interaction with the saline sea water which makes shallow borehole water in the vicinity brackish. Information about the groundwater situation in the area showed that the shallow boreholes in the area have poor water quality (usually issues with salinity, iron

and bacteria contamination) because the aquifer is not protected from surface contamination and interference from saline sea water. Exploring deep borehole of above 500 - 600 m to the Benin Formation is an alternative to the installation of reverse osmosis unit for removal of dissolved solutes such as salts in the brackish groundwater.

The geophysical investigation and drilling/pumping test reports of the project implemented lacked integrity, hence unreliable because they did not give a true representation of the location in terms of depth to freshwater and expected yield (The reported yield was 1.2 L/s (4.32 m³/h) which cannot even sustain a hand pump). The estimated yield of shallow boreholes in the area was above 5 m³/h based on rapid pumping test (**Figure 6**) conducted on one of the boreholes and yield of other boreholes observed. While it is expected that for a 24-hour pumping test, 90 percent recovery occurs within two to three hours after the pumping is stopped according to the Ministry of Environment, British Columbia [42]. The borehole pumping test report of recovery time after the step-drawdown test was 6 hrs, and 16 hrs for the constant rate test. This showed a contradicting result about the borehole which is interpreted as being inefficient and having low yield.

The reported static water level data of the drilled borehole (18 m) did not show credibility when compared with SWL data of boreholes measured in the location. According to Abam & Nwankwoala [8] proximity to either the coastline or drainage rivers influences values of static water level. The project location is similar in characteristics (drained by network of creeks, less than 5m above mean sea level, good tidal influence and frequently inundated by the saline sea water) and has the same geomorphology with some locations mentioned in the study of Abam & Nwankwoala [8] is expected to have static water level of about 5 - 6 m or less as seen from the static water level map of their study.

Water quality analysis showed that the salinity and Fe concentration levels were unacceptable for drinking purposes (based on WHO standards). Surprisingly,



Figure 6. Observed high borehole yield in Azama Community during rapid pumping test.

the bacteriological analysis did not report the presence of coliform in the water. Expectation about the presence of coliform bacteria in the water stems from the fact that the borehole is unconfined and sanitation situation in the community is poor. There are public overhung latrines built on the water bodies and wastes were disposed into water bodies and surrounding land.

The water quality analysis also showed that total heterotrophic bacteria (THB) concentration value of 2.5×10^4 was higher than the WHO limit of <100 cfu/ml for one of the boreholes. The high value of THB showed high organic activity presence and organic compound in water. This could unpleasantly change the aesthetics of the water (taste, odour) and be a breeding ground for some dangerous bacteria such as the *E. coli*.

5.4. Water Supply Project 4

The project site is located on the Coastal Alluvium, Mangrove and Freshwater Swamps environment around Port Harcourt area in Rivers State. The hydrogeology of the location has excellent groundwater potential, and most of the boreholes abstract water from shallow aquifers (confined and unconfined). Most of the borehole range in depth between 45 m to 70 m, with static water levels as high as 2 m to 6 m in some locations.

Conducted pumping tests showed that the boreholes have the capacity to yield water above $5 \text{ m}^3/\text{h}$ without appreciable decline in head (usually few units of meter below ground level). The water quality analysis conducted for the six boreholes in the location (one borehole had duplicate analysis) showed that the pH level of some of the boreholes was not within the WHO guideline, and two boreholes had high conductivity values above WHO standard. One of the borehole samples had total heterotrophic bacteria (THB) concentration value of 2.4×10^4 which is higher than the WHO limit of <100 cfu/ml. The high value of THB showed high organic activity presence and organic compound in water. This could unpleasantly change the aesthetics of the water (taste, odour) and be a breeding ground for some dangerous bacteria such as the *E. coli*.

Coliform bacteria (fecal and *E. coli*) as high as 8, 20 and 160 MPN was found in three of the boreholes (shown in the water quality report). Although this is not astonishing because of the unsanitary conditions of the environment around the borehole and proximity to the creek where most of the wastes from the Port Harcourt town runoff and sewage are discharged illegally.

5.5. Water Supply Project 5

The project is located in Belema-Ama and Dutch Island communities in Okrika LGA in Rivers State, the communities are underlain by Saltwater Swamp which serves as the shallow aquifer system for groundwater supply. Common problems of acidity, high salinity and high Iron concentration level affecting groundwater quality were observed in this area as reported by Nwankwoala & Ngah [34] in their study about the groundwater resources of the Niger Delta. In agreement

with their study, the aquifer is intruded by the saline coastal water, hence, making the groundwater around the area unfit for human consumption due to very high salinity, Fe, and objectionable quality. High Fe is widely evidenced by reddish stains as indicated in **Figure 7**. The boreholes are high yielding borehole of above 5.9 m³/h observed. The water is being used for other purposes other than drinking because of the poor water quality.

5.6. Water Supply Project 6

Inen

The project is located in Inen in Oruk Anam LGA in Akwa Ibom State. The area is underlain by the Coastal Plain Sand of the Benin Formation. The borehole was drilled to a depth of about 90 m and the lithology is predominantly fine to coarse sand (**Figure 8**) with extensive aquifer thickness. The lithostratigraphy and hydraulic properties are similar to the description of Amajor [23] in the study on the aquifers in the Benin Formation, Eastern Niger Delta.

High yield of above 6 m³/h was observed during pumping test (**Figure 8**), excellent and unobjectionable (physical/organoleptic parameters) water quality, the pH of the water is 6.8, Fe was not detected, Chloride, EC, Nitrate, Salinity



Figure 7. Reddish-brown color stain on water fetching platform showing high Fe content in the water.



Figure 8. Fine to coarse grained Coastal Plain Sand (left) and borehole yield estimation during pumping test.

concentration levels were within the WHO standard.

Odoro Ikpe

Similar water quality standard was observed in another location in eastern Akwa Ibom State (Ini LGA). Although the aquifer (Coastal Plain Sand of the Benin Formation) in the location is not extensive and thick, pinching out in some locations because there were some dry and abandoned boreholes existing in the location. The Imo Shale is prominent in this location and was observed during the borehole drilling as thick bluish-grey shale overlain by the Bende Ameki Formation which was encountered during the drilling and known to have unfavorable hydrogeologic conditions for groundwater development.

Borehole depths evaluated in this location did not exceed 50 m. The Coastal Plain Sand aquifer thickness in this area is less than 20 m, this very coarse sand is underlain by intercalations of fine to medium coarse sand with sandy-silty clay, greyish fine sand, silt with fissile shale, and thick bluish grey fissile Imo Shale which is difficult to penetrate. In one of the failed and abandoned boreholes drilled, the Imo Shale lithology extended approximately from 70 m to 119 m where the drilling was aborted.

The groundwater supply potential is adequate for small community water supply. And estimated borehole yield from pumping test was 4.5 m³/h, and transmissivity value of 3.05×10^{-3} m²/s. Specific capacity was 61 m³/h/m.

There were several abandoned dry wells existing in the location, therefore, groundwater development in this location requires the expertise of a hydrogeologist. It is important that a reconnaissance assessment which includes a hydrogeophysical study be conducted prior to developing groundwater in the Northern part of Akwa Ibom, especially in Ini, Itu and Ikpe Ikot Nkon, Oko Ita, Ntok Okpo area. This is because of the existence of a lithostratigraphic boundary which from field experience in the two locations in Ini LGA, is characterized by the pinching out of the Coastal Plain Benin Formation, the Bende Ameki Formation and the underlying Imo shale became gradually pronounced in the area (**Figure 9**).

The extensive review and hydro geophysical investigation of the geology and hydrogeologic characteristics in Ibiono Ewuro in Ini LGA, Northern Akwa Ibom informed the decision to abort the planned groundwater development project in the location. This is because of the known possibility of encountering dry well, as seen in [43] the geological map of Northern Akwa Ibom (**Figure 9**) that the location is underlain by Bende Ameki Formation of unfavorable hydraulic properties for groundwater development and confirmed by the hydrogeophysical investigation.

6. Discussion

Groundwater development projects for water supply in most parts of the Niger Delta are implemented by private individuals, government and companies or organizations operating in the location. Review of some of these projects to get

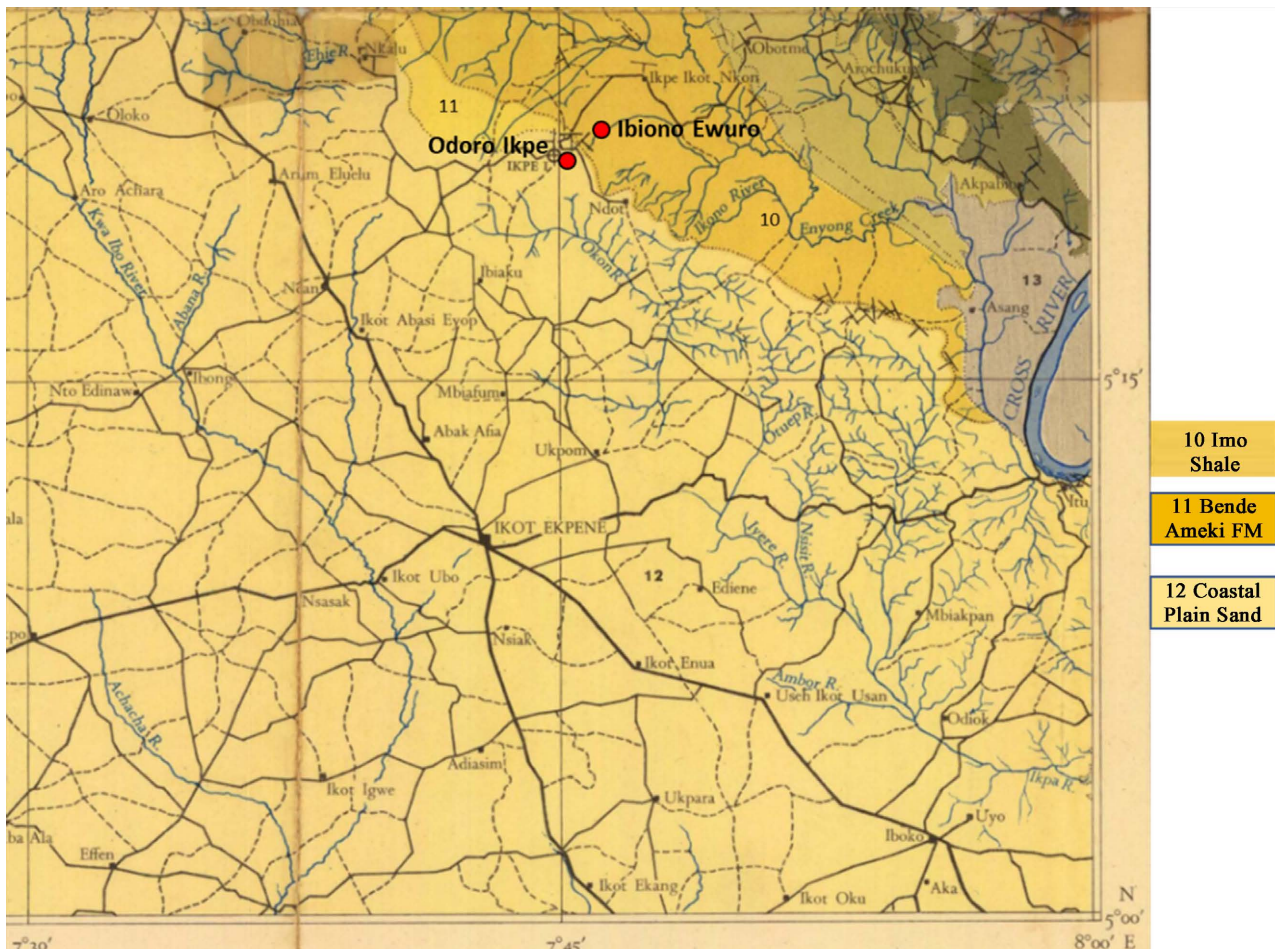


Figure 9. Northern Akwa Ibom geology (After Shell [43]).

technical information in other to support new groundwater development project or a rehabilitation project showed that most geologic information about the existing borehole is unavailable or not properly documented. And in other cases, hydrogeological field procedures such as the geophysical investigation, logging of borehole lithology samples, pumping test, development and well completion design (selection of gravel pack size, casing and installation intervals and depths) and water quality are incomplete or omitted from the project completion report. Sometimes, efforts to assess the information have proven abortive and this is the case with some of the large water projects constructed by the government and organizations. The problem of poor documentation of project technical information frustrates efforts where borehole rehabilitation is required because of the lack of technical details of the borehole or existing ones around. This adds to the cases of abandoned water supply projects, including projects which were poorly implemented due to low technical capacity in places with the potential of high yield, despite high yields observed in many parts of the Niger Delta.

For groundwater development for provisional use, there is code of practice that provides the framework for water well construction in Nigeria which is contained in the National Code of Practice for Water Well Construction [44].

And it is known that legal and technical requirements embodied in the code of practice for water well construction are not monitored for compliance in most of the water supply projects. Information and reports reviewed from well drillers and well owners in the Niger Delta indicate that due procedures are usually neglected with the reason being that groundwater is abundant in the Niger Delta, backing up the conception that there is no need for hydrogeological procedures such as geophysical investigation, pumping test and logging. These kinds of ideology usually lead to an unsatisfactory or failed project where a borehole may have low yield or poor water quality because due processes and best practices were neglected. And can incur additional unbudgeted costs to the project, such as for the provision of water treatment facility and operation and maintenance costs.

This code of practice for water well construction in Nigeria is to ensure that borehole drilling projects pass through the legal requirements in terms of registration and permit, duly documented by the regulatory body, and that the project report authenticated by the Council of Nigerian Mining Engineer and Geoscientist (COMEG) registered hydrogeologist is submitted, therefore eliminating data and information gap with respect to the project.

Usually in such reports, it is expected that the complete borehole information, geology and hydrogeology of the location are discussed, as borehole completion and development data, pumping test containing the geographic coordinates information, casing type and diameter, screen position, yield, etc., and the aquifer hydraulic parameters evaluated from the pumping test, and picture of the actual field work should be available. And water quality analysis should be reported and detailed to the understanding of non-technical users especially if there are parameters that pose risks to human health and environment. Missing and uncoordinated data and information in such reports could be misleading and not suitable for decision making.

Technical reports should be exhaustive in any case, especially in situations where public health and the environment are at risk, and for the purpose of knowledge and information management including research and reference purposes. And groundwater development project does not only aim at implementing the technical aspect of the work, but good reporting which captures important aspects of the project from the planning to completion phase should contain detailed information which can support and improve future research, decision making and aid policy development.

The availability of geological data of a groundwater project for water supply can comfortably complemented groundwater development for other purposes (ecosystem, regulatory, pollution study, etc.) and research. The aforementioned can be explained by the nexus between oil and gas exploration and groundwater development which is in the geologic data and information. Because most of the geologic data acquired for oil and gas exploration in the Niger Delta evaluated the encountered geomorphology, stratigraphy, hydrogeology and aquifer cha-

racteristics which have also been used for groundwater development assessment studies.

Despite the existence and availability of information in research on groundwater development in the Niger Delta, quality and management problems of groundwater development still persists due to the lack of technical capacity and understanding for implementation and negligence to hydrogeology which is the same challenge reported by Nwankwoala & Ngah, [34].

The review of existing and available research about the hydrogeology of the Niger Delta has proven relevant to the understanding and prediction of the groundwater potential and quality of a region prior to the implementation of any reconnaissance field assessment. This approach to groundwater development eliminates project failure because it guides decision making whether to implement or not, prevents unbudgeted cost implication or abandonment of partially completed project, and aids the planning for addendum to the project (in the case of water treatment installation) or future development.

If hydrogeologic properties are not considered prior to project implementation, developing groundwater of low yield or poor quality can increase the cost of the project to about 50% to 100% or more of the committed cost. This can happen in a situation where the water quality is objectionable and a decision to install a water treatment unit is made. And a low yielding borehole will not serve its full purpose in terms of the availability and quantity of water, hence, the decision to drill another borehole. As explained, challenges related to groundwater quality can be appraised from available research and during the field reconnaissance assessment where some important parameters can easily be measured directly and *in situ* using a multiparameter probe which gives one good information about what to expect prior to implementation. It is also good to note that water quality plays a critical role in terms of the cost of the project, acceptability of the project and safety for human health.

7. Conclusion

The availability of literatures on the hydrogeology and groundwater studies of the Niger Delta should significantly reduce the risk of failure in groundwater development projects. And these studies have been carried out in the different geomorphologic units of the Niger Delta with the results contributing to the existing geologic information to avert failure and to guide any groundwater development projects in the Niger Delta. And one can make good predictions regarding the hydrogeologic properties and the decision to drill a borehole in a location with good expectations. This has also guided the technology to use to get the anticipated aquifer depth for optimum yield and zone of good water quality, or find alternative means of getting freshwater if the hydrogeologic conditions are not favorable. While having these privileges extensively available in research, some implemented groundwater projects still experience failure usually because of incompetence and negligence which majorly lead to the abandonment of sev-

eral projects in the Niger Delta as a result of objectionable water quality or unexpected low yield which cannot sustain a simple hand pump.

8. Recommendation

1) The acknowledgement and applications of geologic and hydrogeologic technical expertise are essential requirements and important to the success of groundwater development projects. The abundance of groundwater is not disputed but the right skills and professional expertise are essential requirements for the achievement of successful water supply project where poor water quality and other technical related borehole problems can be avoided, and to efficiently maximize aquifer potential;

2) And it is important that government revive and strengthen the established legal and institutional framework for groundwater development in the Niger Delta;

3) It is important that standards are set with regards to the management and implementation of groundwater development projects, including defining the roles and responsibilities of any profession needed at each stage of the project, and how to limit and eliminate quacks from polluting the standard practices. Therefore, it is recommended to use competent consultants to enable the data collection, analytics and informatic process, including the interpretation and recommendations and the documentation of information for future reference;

4) Detailed hydrogeological assessment and effective work supervision are recommended for drilling projects implemented in the Niger Delta with complex hydrogeology. Employing the services of a hydrogeologist is important for the success of the project;

5) It is recommended that the regulatory body responsible for enforcing the Code of Practice for Water Well Construction should proactively monitor the planning, implementation and completion of borehole water supply and rehabilitation projects. Give the responsibility to COMEG as the body responsible for the endorsement of groundwater project. Reprimand offenders carrying out indiscriminate or unlicensed borehole drilling. The Council of Nigerian Mining Engineers and Geoscientists could revoke licenses of members not dedicated and complying professionally to set standards in similar projects. All reports of borehole drilling, rehabilitation and related activities could be submitted for review and approval. Information including technical details of groundwater development projects that cut across drilling, development, design and completion works should be requested for review, proper documentation and future reference. And follow-up programme can be organized for monitoring and evaluation purpose, and lessons learned from individual project documented;

6) From this study, it is evident that the academic and research institutions have contributed impressively to groundwater development and management in the Niger Delta through active research work in the field of geology and hydrogeology. It can be recommended that government and interested stakehold-

ers should collaborate with academic and research institutions, provide grants and funding to their research and training programme to expand groundwater data and analytics, knowledge and information management.

7) Groundwater in the Niger Delta supports vast and important ecosystem including the wetland and the distinct geomorphology. In this region, many oil and gas companies abound and extensive industrial activities with influence on the groundwater system exist. It is important to establish a center for groundwater research in the Niger Delta, develop groundwater data, analytics and information management platforms for the Niger Delta where researchers can contribute reliable groundwater information. And leverage digital technology for groundwater data and analytics, knowledge and information management for the Niger Delta. Including establishment of a working group for groundwater management in the Niger Delta with stakeholders from various institutions, organizations and regulatory bodies in active participation;

8) It is important to create awareness, collaborate and engage with stakeholders and interested groups on groundwater through the planning and organization of an annual conference recognizing groundwater in the Niger Delta and its long services. This will be a platform where scientific information, collaborations and research work can be presented and deliberated upon for decision making and policy development. This idea stems from the importance and emphasis given to groundwater by the United Nations which include its delicate and invisible nature, the support to human demand and development to the role it plays in climate change adaptation.

Conflicts of Interest

The authors declare no conflicts of interest regarding the publication of this paper.

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