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AQUIFER SEDIMENT COLOUR - A VIABLE GEOLOGICAL SOLUTION FOR IRON (Fe) MITIGATION IN YENAGOA AND ENVIRONS IN THE NIGER DELTA, SOUTHERN NIGERIA

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ABSTRACT

This study investigates the potentiality of aquifer sediment colour as a broad indicator of Fe concentration in the shallow alluvial aquifer in parts of the Niger Delta. Using Vertical Electrical Sounding (VES) curve types obtained from geoelectrical sounding, three boreholes were drilled in HA curve type locations, two in HK locations and seven in K locations. Aquifer sediment colours at the screen depths in these boreholes were either grey, off-white or brown. Correlation of the aquifer sediment colour and chemical characteristics of groundwater samples from the boreholes shows that the groundwater derived from the grey and off-white aquifer sediments is characterised by relatively higher concentration of dissolved Fe (> 0.3 to 12.3mg/L) and occur in a reducing environment (redox potential Eh ~107 – 128mV). The groundwater abstracted from the brown aquifer sands is characterised by low concentration of dissolved iron (Fe < 0.3mg/l) and occur in a mildly oxidizing environment (Eh ~134 – 164mV). The study shows that aquifer sediment colour is a reliable indicator of high and low iron concentration and can be used to locate low iron groundwater in the study area.

Keywords: Yenagoa, Niger Delta, aquifer, sediment colour, redox potential, iron, vertical electrical sounding, groundwater

INTRODUCTION

Clean water is an essential necessity of life and plays a significant role in the socio-economic growth of a Country. In Yenagoa city and environs in Southern Nigeria, clean water is often a scarce commodity because there is no public water supply. The lack of public water supply accounts for why water borne diseases occur and sometimes to epidemic scale (Dawoud and Raouf, 2009), compelling inhabitants to look for alternative sources of water such as streams and boreholes. Unfortunately, noxious compounds and elements are daily being discharged through leachates and effluents into surface waters. Aside, large-scale pollution from petroleum spills has rendered surface waters unusable. As a result, groundwater of the Quaternary shallow alluvial aquifer is the most important alternative source and is being exploited extensively in the study area. However, groundwater chemistry indicate that dissolved iron (Fe) concentration in the groundwater are relatively high and often exceed the acceptable limit of 0.3 mg/L (Amadi et al., 1987; Okiongbo and Douglas, 2015). While Fe is

essential for both plants and animal forms (Hem, 1989), its presence in excessive amounts can result in metallic tasting water, staining of clothes and dishes. According to the report of Brown et al. (1992), a high concentration of dissolved Fe (> 0.5 mg/L) in groundwater can lead to reduction in water pressure and flow in pipes due to accumulation of Fe oxide, for which treatment and remediation are difficult and costly (Siegel et al., 1992). Additionally, high concentration of Fe is also considered harmful to human health if such water is consumed for a long time (Liap, 1992). According to the report by Rehema et al. (1998), exposure to long term alimentary iron overload can cause a positive serum iron (Fe) balance, which in turn, results in an increased oxidative stress. For individuals who suffer Fe storage disease such as hemochromatosis, consumption of groundwater with Fe concentration of up to 2-3 mg/L in drinking water might pose a problem (Donohue et al., 2004; Franchini and Veneri, 2005).

Recently, several investigations were carried out in the study area to characterize the source, regulating processes and distribution of Fe in the aquifers (Amajor, 1991;

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Okiongbo and Douglas, 2013; Okiongbo and Douglas, 2015). These studies reported occurrence of high dissolved Fe in the groundwater abstracted from shallow aquifers (depth < 100 m). On the contrary, deep aquifers (depth > 150 m) have been reported to have relatively lower concentration of dissolved Fe and offer a possible alternative source of low Fe (< 0.3mg/l) drinking water (Ngah and Nwankwoala, 2013). However, with the local drilling techniques, drilling to depths more than 150 m is costly and may not be possible. It is thus suggested that the identification of low Fe aquifer (s) within the shallow depth is necessary to improve Fe mitigation. In recent years, one of the most highlighted aspects of Fe enrichment in the groundwater is its spatial distribution within the shallow aquifers. The distribution of Fe in the groundwater is extremely heterogeneous, both vertically and horizontally, within a scale of tens of meters. Presently, Fe heterogeneity in the area remains poorly constrained. To better understand how such heterogeneity develops, investigating aquifers over tens to hundreds of meters and in different locations would help test whether groundwater Fe heterogeneity can be explained by local variations in aquifer stratigraphy.

In the last few years, a popular perception of local drillers within Yenagoa and environs is that brown colour sediments are correlated with low-Fe groundwater whereas groundwater abstracted from an aquifer with grey or off-white colour sand has high Fe concentrations.

If the colour of the sediments provides a broad indicator of the Fe concentrations then local drillers could target this visible geological feature (brown colour sediments) while drilling. This could provide a viable geological solution for Fe mitigation in the Quaternary alluvial deposits. However, the colour perception of the local drillers has no scientific basis for targeting low Fe aquifers.

In this study, we have undertaken subsurface lithological investigation to determine whether groundwater Fe heterogeneity can be explained by local variations in aquifer stratigraphy, examine and validate the possible correlation between aquifer sediment colour, groundwater chemical characteristics and dissolved Fe concentrations in Yenagoa and environs.

Study Area
Location, Physiography and Climate
Yenagoa is the capital city of Bayelsa State and is located within the Southern Nigeria sedimentary basin. The study area consists of Yenagoa metropolis and covers an area of about 170 km^2, bounded by longitudes 006° 05´ and 00 6° 025´ East of the prime meridian and latitudes 04° 23.3´ and 04° 38.2´ North of the equator. Geographically, the study area lies within the coastal area of the recent Niger Delta Figure 1 where the ground surface is relatively flat, sloping very gently seawards (Akpokodje and Etu-Efeotor, 1987). Its mean elevation is about 8m above
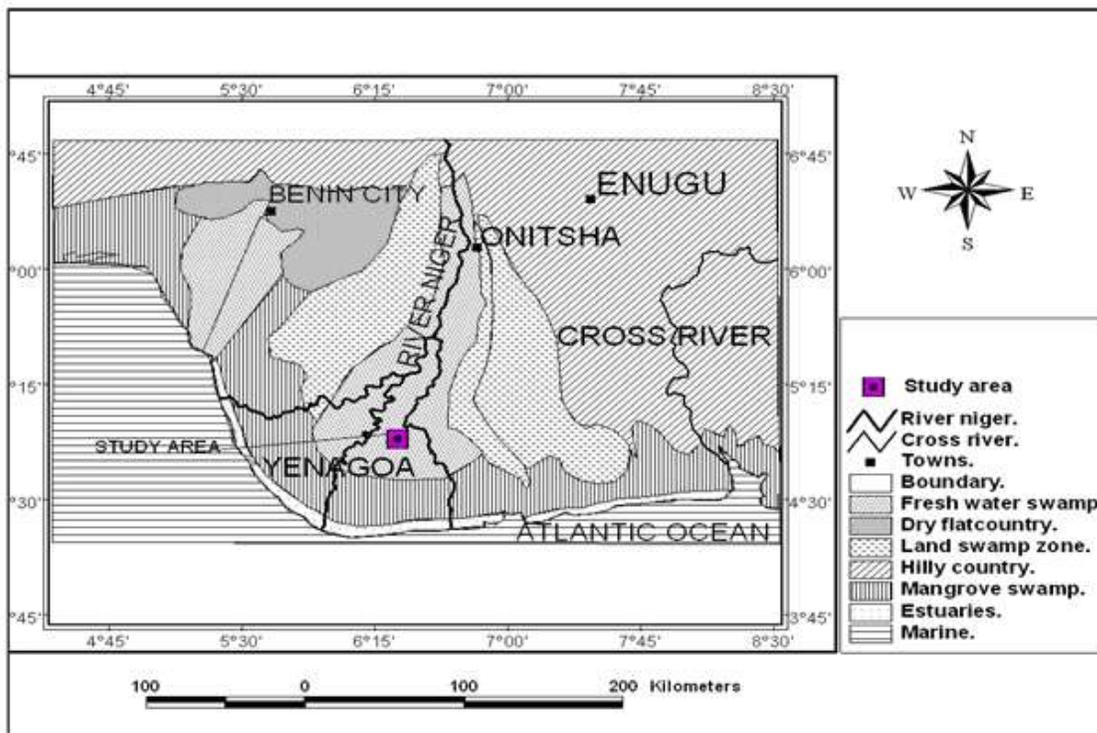
Fig. 1. Map of Niger Delta Showing the Study Area.

mean sea level (Akpokodje, 1987).

The study area has a tropical rain forest climate characterized by rainy season and dry season. The rainy season starts from April and ends in October with a brief dry period in August. The dry season lasts between November and March. The mean annual rainfall is about 4,500 mm (Akpokodje, 1986) and about 85% of the mean annual rain falls during the wet season. The temperature varies between 25 and 32°C. More than 70% of the inhabitants of the study area are engaged in subsistent farming and fishing.

Geology and Hydrogeology

The study area lies within the fresh water swamps, backswamps, deltaic plain, alluvium and meander belt geomorphic unit of the Niger Delta (Akpokodje, 1986). The Niger Delta is basically an alluvial plain and consists of the modern and Holocene delta top deposits. Grain-size profiles of the Holocene alluvial deposits consist of a fining-up sequence of sand capped by fine silts and clay indicating a fluvial environment of deposition (Amajor, 1991). The fine grained silts and clay overlying the basal sandy sequence is often referred to as the near surface aquitard. The thickness of the surface aquitard varies between < 5 to about 12 m, and due to the varying proportions of clay, silt and fine sands, the permeability of the aquitard is highly heterogeneous (Amajor, 1991). Where the surface aquitard is thick and less permeable, it forms a confining unit which impedes recharge to the alluvial aquifer. Akpokodje (1986) reported that groundwater flows from North to South in the region.

The Niger Delta consists of three main subsurface lithostratigraphic units (Short and Stauble, 1967). From top to bottom they are Benin, Agbada and Akata Formations. The Benin Formation which is fluvial in origin is the main aquifer in the study area. Groundwater in the Benin Formation occurs mainly under unconfined conditions. Abam (1999) observed that the sediments of the Benin Formation were deposited during the Late Tertiary – Early Quaternary period and is about 2100 m thick. The sediments are lenticular and unconsolidated and consists of coarse to medium–fine grained sands with localized intercalations of clay/shale. Gravel and pebbles are minor components. Mbonu *et al.* (1991) reported that the sands are moderately sorted and poorly cemented. The presence of thin clay beds creates discontinuities in the vertical and lateral continuity of the aquifer, resulting in the presence of local perched aquifers (Amajor, 1991). The aquifer is directly recharged through the infiltration of rain water. Water table in many areas of the Niger Delta is close to the surface but subject to seasonal variations. In the dry season, the water table is about 3 – 4 m in the study area (Ekine and Osobonye, 1996). During the rainy season, the water table rises considerably, in some cases, the ground surface is flooded. Groundwater is the main source of drinking water for over 80% of the population in the study area.

MATERIALS AND METHODS

Vertical Electrical Sounding (VES)

Vertical Electrical Soundings (VES) were acquired with a DC resistivity meter (Abem Terrameter SAS 1000) in twenty-six locations covering the entire study area (Fig. 2) utilizing the Schlumberger electrode array.

Current and potential electrodes were maintained at the
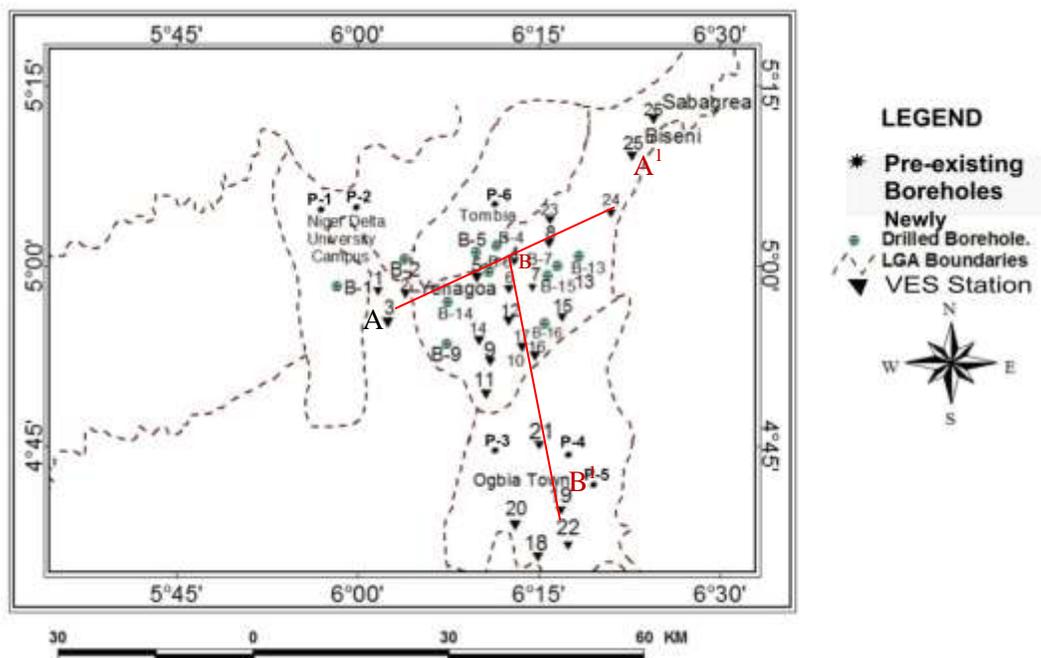
Fig. 2. Map of the Study Area Showing VES Stations and Borehole Locations.

same relative spacing and the coverage was progressively expanded around a fixed central point. Maximum current electrode spacing (AB/2) ranges between 100 and 200 m. The positions and surface elevations of VES locations were also recorded during survey with a GPS receiver. Vertical Electrical Sounding (VES) curves generated from the apparent resistivity values were interpreted qualitatively and quantitatively. The quantitative interpretation involved computer assisted I-D forward modelling using a I-D inversion software (Interpex, USA). The program iteratively compares the field data to a calculated model curve, and converts the apparent resistivities as a function of electrode spacing to true resistivities as a function of depth The resulting true resistivities represent the best average resistivity for the given layer. The results interpreted from the VES data were validated with borehole lithological logs.

Sediment sampling
The VES curve types obtained are mainly HA, HK and K. Based on the VES results, twelve boreholes were drilled in the study area within the shallow depth (≤30 m) at different sites using rotary drilling method. Three boreholes were drilled in HA locations, two in HK locations and seven in K locations. The boreholes were lithologically logged and sampled at 3.0 m or more often when characteristics of the sediment changed based on their grain size and colour. Sediments were classified into four major lithotypes of top soil (alluvium), clay, silty sand and sand. Sand and clay represents aquifer and aquitard respectively, while silty sand represents and aquitard though having higher permeability. The colours (grey, off-white and brown) of the sediments were determined after recovery, prior to atmospheric oxidation. Each sample was assigned to one of the three colours – grey, off-white and brown by virtual inspection of the sediments. About 100 g of the drill cuttings from the aquiferous horizon were dried and used for particle size analysis using mechanical sieving technique using Ro-tap shaker (Alyamani and Sen, 1993). The Fe concentration of about 3g of the wet sediments was measured by AAS after extraction with hydroxylamine hydrochloride ($NH_2OH.HCl$) in 25% acetic acid, and filtering using a 0.45μm cellulose acetate filter. The boreholes were screened at depth intervals of either oxidized brownish sand aquifers, off-white or greyish reduced sediments. The depth of these boreholes varied between 8 and 30 m.

Groundwater sampling
The twelve drilled boreholes mentioned above (Fig. 2) were developed and groundwater samples were collected in clean 500 ml polyethylene bottles. The boreholes were handed over to the villagers soon after collecting the groundwater samples. Groundwater samples were also collected from six pre-existing boreholes in which aquifer sand colour was known making a total of eighteen groundwater samples. A global positioning system (GPS)

was used for location and elevation reading. Prior to sample collection, the boreholes were pumped continuously for about 20 minutes. In these groundwater samples, in situ measurements of temperature, redox potential (Eh) and pH were carried out using precalibrated portable pH/ORP meter at the time of groundwater sampling. Major ions such as Na, K, Ca, Mg, Fe, HCO_3, Cl, and SO_4 were determined including total dissolved solids (TDS) in the laboratory using standard procedures (APHA, 1998). Major ions like sulphate (SO_4^{-2}) were determined by spectrophotometric turbidimetry. Using EDTA, calcium (Ca^{2+}) and magnesium (Mg^{2+}) were determined titrimetrically; chloride (Cl^-) was determined by standard $AgNO_3$ titration and bicarbonate (HCO_3^-) was determined using titration with HCl. Sodium (Na^+) and potassium (K^+) was measured using flame photometry; nitrate (NO_3^-) was determined by colourimetry with a UV-visible spectrophotometer (brucine method) while iron was measured using colourimeter with a UV-visible spectrophotometer at 520 nm. Subsequently the groundwater composition was correlated with the colour characteristics of the sediments.

RESULTS AND DISCUSSION

Electrical resistivity of the subsurface geological sequence
The resistivity curves identified in the study area are predominantly HA, HK and K curve types. Model results are presented in Table 1. Table 1 shows a lateral and vertically varying succession of high-and low-resistivity geoelectric layers. In the alluvial formation, the wet soils and clays show lower resistivities than sands which form the aquifer. Based on the correlation of VES 1 interpretation results and the stratigraphic section from the nearby borehole (B-1) three subsurface layers were delineated (Fig. 3).

The top most layer consists of calcareous loam mixed with organic matter (Amajor, 1991) with variable moisture content. The thickness and resistivity of this layer were 0.6 m and 46 Ωm respectively (Table 1). The thickness and resistivity of the second geoelectric layer were 4.2 m and 12 Ωm, respectively. This layer corresponds to the near surface wet clay unit (aquitard).

The third layer has resistivity of 250 Ωm and consists of either fine-medium light to dark grey or off-white non-oxidized/reduced freshwater sand aquifer (Fig. 4). This layer extends continuously beneath the near surface aquitard to a depth of about 25 m, where drilling was stopped.

Table 1. Geoelectrical Layer Parameters (Resistivity and Thickness) obtained from the Interpretation of the Geoelectrical Soundings.

VES No	Thickness of Layers (m)				Resistivity of Layers (Ohm-m)					RMS Error (%)	Curve Type
	h_1	h_2	h_3	h_4	ρ_1	ρ_2	ρ_3	ρ_4	ρ_5		
1	0.6	4.2	22.7		46	12	250	492		2.4354	HA
2	1.5	13.6	8.1		90	12	161	873		3.6721	HA
3	0.92	3.2	12.5		36	7	559	53		2.9083	HK
4	0.93	1.2	11		21	222	1596	45		2.4470	K
5	0.7	0.8	9.1		22	237	2144	30		2.1380	K
6	0.4	1.5	7.8		30	26	342	83		4.9617	HK
7	0.5	1.0	15.3		41	1113	1683	80		3.4463	K
8	2.6	1.4	10.4		15	83	680	20		2.6181	K
9	0.6	5.7	9.8		52	27	189	266		1.9559	HA
10	0.6	5.4	11.4		46	36	77	400		2.8962	HA
11	1.0	4.6	16		34	6	871	14		4.3442	HK
12	0.6	1.5	8.3		208	115	511	70		1.9836	HK
13	0.9	1.8	10		44	70	801	14		4.3366	K
14	1.0	5.6	27.7		13	10	69	94		2.4581	HA
15	0.83	2.9	19.3		53	16	133	134		2.9936	HA
16	0.83	6.9	17.7		33	8	274	2093		3.9026	HA
17	1.5	7.2	3.1		12	10	41	2024		3.0955	HA
18	1.5	4.1	15.8		62	47	457	50		1.7395	HK
19	0.4	1.5	7.4		64	115	258	91		2.0262	K
20	0.5	2.1	8.6		30	15	63	4		1.8558	HK
21	0.9	2.9	7.3	30.8	94	6	52	8	343	2.3838	HKH
22	0.5	11	12.6		41	20	287	1036		4.2417	HA
23	0.62	9.5	14.4		43	10	182	64		2.7128	HK
24	0.5	2.9	14		58	56	200	110		1.9097	HK
25	0.7	7.3	19.1		96	63	221	235		2.4452	HA
26	0.44	1.5	11		54	10	567	46		3.4494	HK

Figure 5 shows correlation between the VES 5 interpretation results and the lithological information from the nearest borehole (B-5). The topmost layer is represented in the geoelectrical column by two units of which the upper one has a thickness of 0.7 m and a resistivity of 22 Ωm, this is the top soil. The underlying layer has a thickness of about 0.8 m with resistivity of 273 Ωm and consists of unsaturated brown silty sand. The increase in the resistivity value from the surface downwards is attributed to the increase in grain size. Locations that exhibit this curve type do not have the clay unit or is thin (< 2 m). The second layer thickness and resistivity are 9.1 m and 2144 Ωm respectively which was interpreted to be the freshwater saturated alluvial sand aquifer. The borehole lithology log shows that this aquifer is composed of fine-medium grained oxidized brownish sand (Fig. 4) and extends beneath the silty sand to about 10 m. At greater depths, though the sediment texture remains the same, the brown colour of the sand was noticed to decrease, and change to light grey and subsequently dark grey. The change in colour from brown to dark grey sand corresponds to a decrease in the apparent resistivity values (Fig. 5) and reflects a change in redox conditions resulting in the reduction of iron oxide coatings (Kelly, 1997). The thickness of the grey sandy layer is not known since drilling was stopped at about 12m.
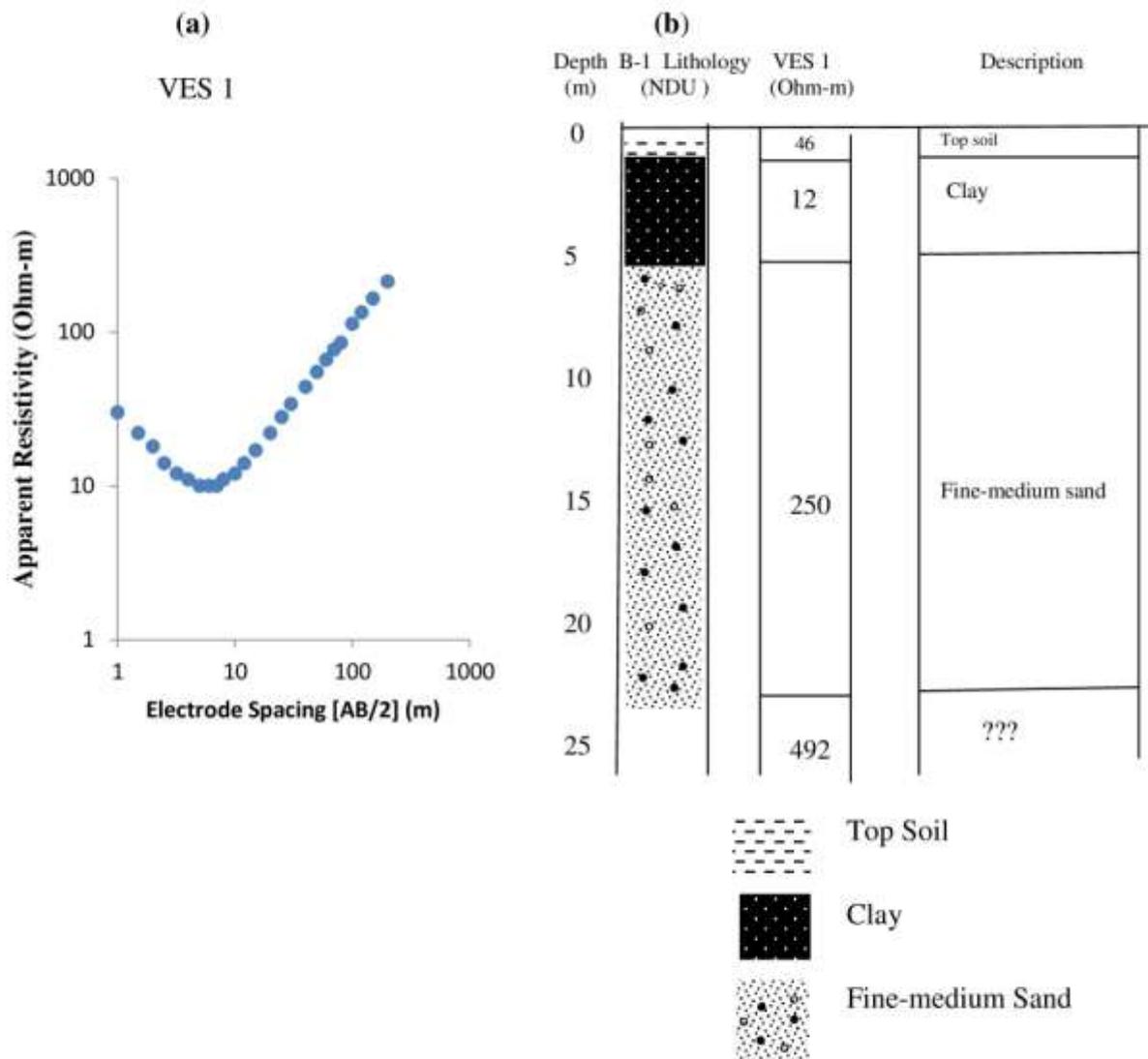
Fig. 3. (a) VES 1 Curve and (b) Correlation of the VES 1 Interpretation Results with the Lithology of the nearest Borehole

Shallow hydrostratigraphic framework in the study area

Figures 6 and 7 show the geoelectric section constructed from the interpreted VES data to reveal the lateral and vertical lithological variations in the study area. These cross-sections show that the imaged subsurface section is composed mainly of three geologic layers. The investigation shows a relatively thin surface layer of fine grained material (top soil) and is well correlated with the agricultural soil used in the cultivation of cassava, plaintain, corn etc in the area. The thickness and resistivity of this layer varies from 0.4-2.6 m and 12-208 Ωm respectively. Of greater interest with respect to the hydrogeology and Fe mobilization is the second layer, (the near surface aquitard), represented by low resistivity values ranging between 7-115 Ωm.

The thickness of this clay layer varies between 0.4-13.6 m. The study area is covered mostly by this aquitard but it is thin or absent in some locations e.g VES 4, 5 and 8 (Fig. 6) and VES 6 and 19 (Fig. 7). Because this layer is composed mostly of media of low permeability, and forms a confining layer over much of the aquifer, it plays a significant role in the development of low redox conditions in the aquifer that drives Fe release to the groundwater. Its lateral extend explains in part why the occurrence of high groundwater Fe is pervasive in the study area. In locations where the clay layer is thin or is absent, silty sand outcrop at or near the surface. Due to the spatial distribution of varying proportion of clay and silt sand in this lithological unit, the spatial distribution of porosity and permeability varies significantly. Underlying the near surface aquitard is a layer of sand.

Fig. 4. Characteristics-Textural differences between (**a**) Grey Sand (**b**) Off-white Sand and (**c**) Brown Sand in Aquifers of the Study Area in the Niger Delta.
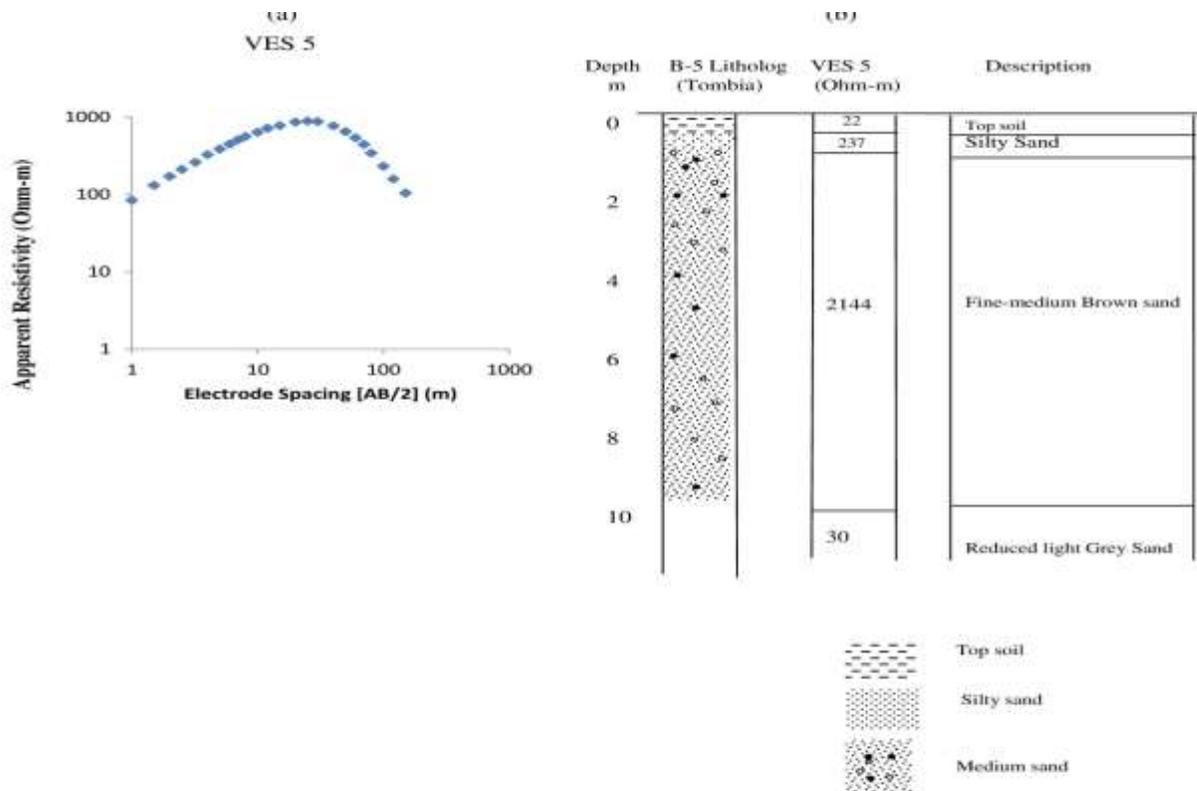
Fig. 5. (a) VES 5 Curve and (b) Correlation of the VES 5 Interpretation Results with the Lithology of the nearest Borehole

This layer comprises the shallow aquifer from which groundwater is being extracted by local drillers. Areas overlain by the near surface aquitard are characterised by non-oxidized/reduced grey or off-white aquifer sands e.g VES 3 and 24 (Fig. 6) and 10, 12, 17 and 21 (Fig. 7). Locations devoid of the near surface aquitard are interspersed in the study area (Figs. 6 and 7) and are characterised by oxidized brownish aquifer sand.

The grain-size distribution of the aquifer sediments represented by the average value of the 'graphic mean' (Folk, 1974; Masch and Denny, 1996) is 0.3 mm.

Comparison of the grain sizes of aquifer sediments from two locations B-1 (grey sand) and those from B-5 (brown sand) show no significant variations in their grain sizes.

Table 2. Aquifer lithology, sediment colour, sediment iron (Fe) and groundwater iron concentration.

Borehole No	Screen Depth (m)	Aquifer Lithology	Aquifer Sediment Colour	pH	Redox Potential (mV)	Sediment Fe conc. (mg/L)	Ground water Fe conc. (mg/L)
B-1	15.2	Fine – medium Sand	Grey	6.31	118	0.75	12.60
B-2	30	Fine – medium Sand	Grey	6.30	125	0.26	4.50
B-16	21	Fine – medium Sand	Grey	6.18	128	0.30	0.86
B-9	12	Fine – medium Sand	Off-While	6.83	120	0.9	0.50
B-10	18	Fine – medium Sand	Off-White	5.64	126	0.79	4.80
B-6	8.0	Fine – medium Sand	Brown	6.48	164	0.50	0.16
B-13	27.0	Fine-medium Sand	Brown	6.04	157	0.75	0.14
B-15	24.0	Fine – medium Sand	Brown	6.42	148	0.62	0.26
B-14	20.0	Fine – medium Sand	Brown	6.40	115	0.59	0.29
B-7	15.0	Fine – medium Sand	Brown	6.25	178	0.82	0.18
B-4	12.0	Fine – medium Sand	Brown	6.39	163	n.d	0.02
B-5	12.0	Fine – medium Sand	Brown	6.60	158	n.d	0.18

n.d is not determined.
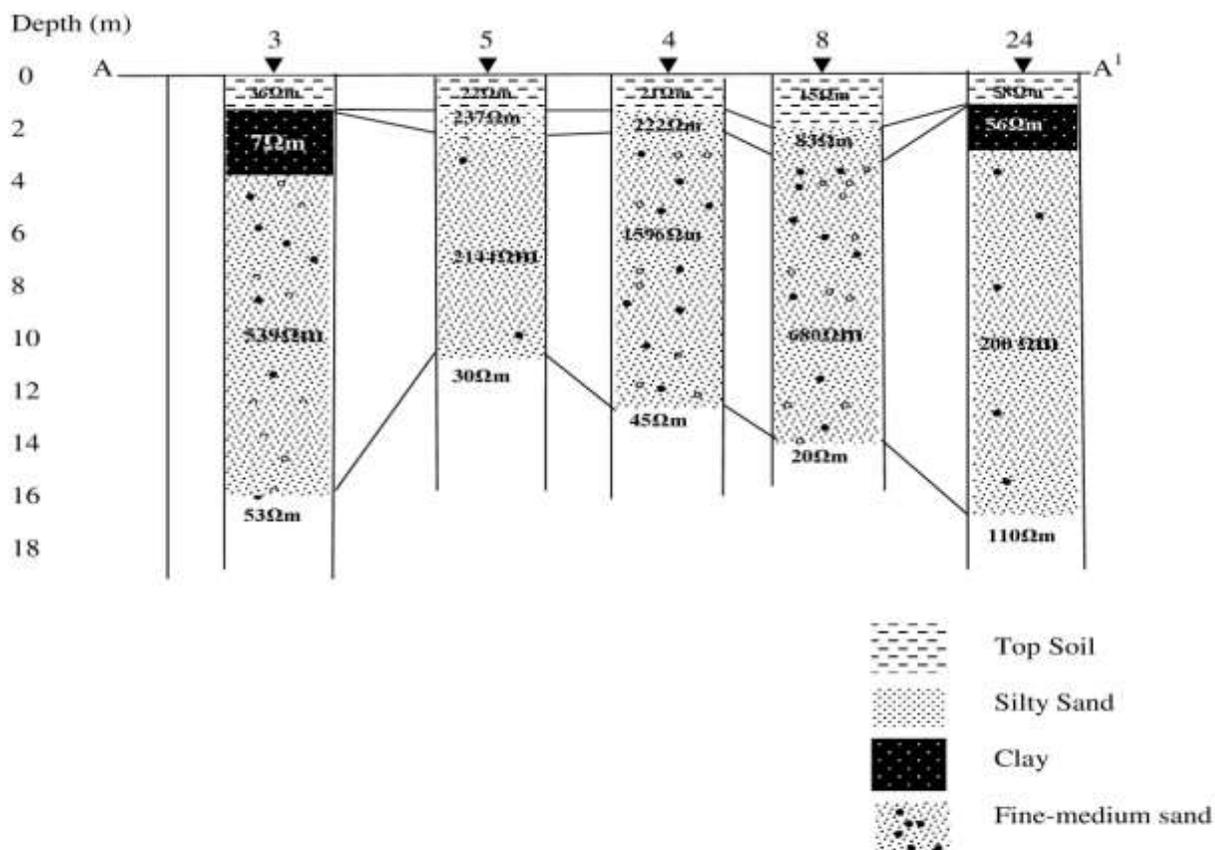
Fig. 6. Geoelectric Section along Profile AA^1
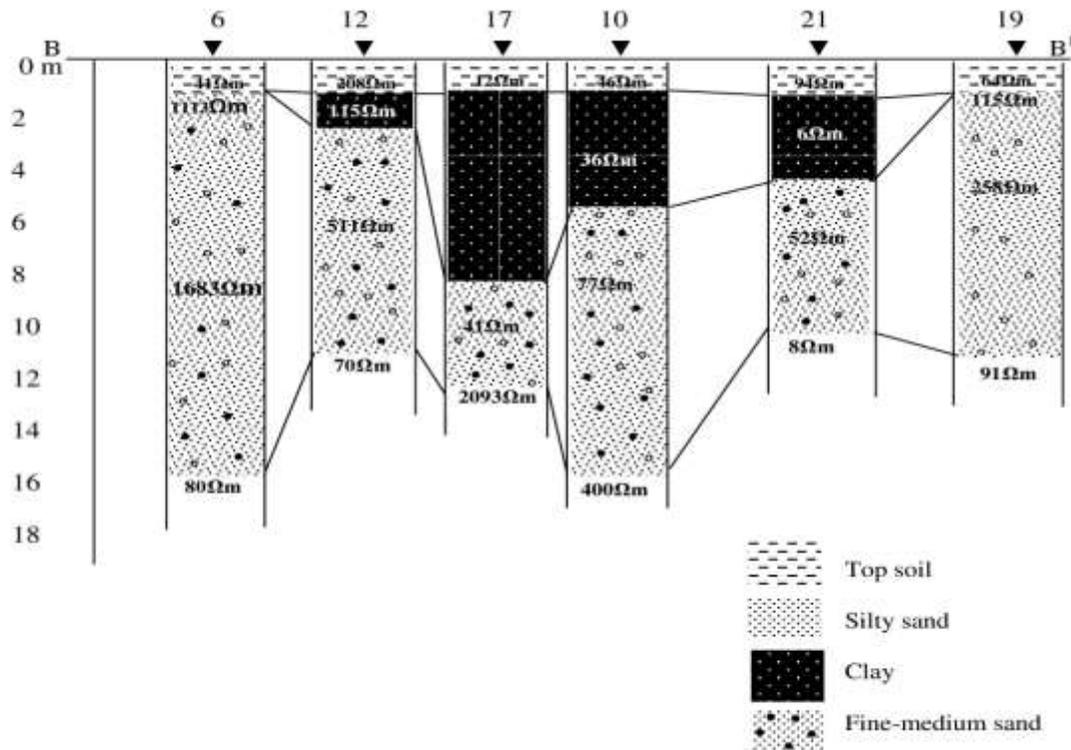
Fig. 7. Geoelectric Section along Profile BB[1]

Correlation of Fe concentration in groundwater and aquifers sediments

Table 2 shows comparison of aquifer sediment colour, Fe concentrations extracted from the aquifer sediments and groundwater samples from boreholes. The extracted Fe concentration in the sediments in the grey and off-white sand aquifers generally range from 0.26-0.90 mg/L (average 0.6 mg/L), but range from 0.5-0.82 mg/L, average 0.66 in the brown sand aquifers.

There is no significant overall difference in the amount of extractable Fe in the aquifer sediments. The similar amount of extractable Fe in the aquifer sediments implies that Fe is present in the grey, off-white and brown aquifermaterials in sufficient amounts. Thus upon transfer to the dissolved phase can cause a large increase in groundwater Fe. Also presented in Table 2 are the pH and redox potential values determined from the groundwater samples. Generally, the pH values of the groundwater samples collected from the grey, off-white and brown sediments are in the range 5.64-6.83 (Table 2). Though the pH values are in the same range, the redox conditions are different resulting in different groundwater composition in terms of the dissolved Fe concentration (Table 2). Table 2 shows that the redox potential values of the groundwaters abstracted from the grey and off-white aquifer sediments are relatively lower than those of the brown aquifer sediments. The Eh varies between +109 to 143 mV in the grey and off-white colour aquifer sediments and indicates a moderate reducing environment (Hasan *et al*., 2007), and varies between 115 and 178 mV in the brown aquifer sediments and indicates a mild oxidizing environment (Hasan *et al*., 2007). The groundwater abstracted from the grey and off-white sediments had relatively high concentrations of dissolved Fe, ranging between 0.5-12.26 mg/L. Considering the Fe-enrichment in water abstracted from grey and off-white coloured sediments, these aquifers are assigned as 'high risk' aquifers. In contrast, groundwater extracted from the brownish colour sediments had relatively low Fe concentrations, ranging between 0.02-0.29 mg/L. We infer therefore that the spatial distribution of groundwater Fe is as a result of the variation of redox conditions in the host aquifer.

The chemical composition of the groundwater from the aquifer sediments is presented in Table 3 and there is close similarity in major ion composition in the groundwater samples. The variations of major ion concentrations in the groundwater samples are also

Table 3. Chemical Composition of the Groundwater Screened at three different Colour Groups of the Aquifer Sediments.

S/N	Bore-hole No	Colour[1]	Depth (m)	pH	Eh	EC	TDS	TA	Na^+	K^+	Ca^{2+}	Mg^{2+}	Fe	Cl^-	SO_4^{2-}	NO_3^-	HCO_3
1	B-1	Grey	15.2	6.31	118	2250	1125	42	38.9	14.0	15.0	5.7	12.26	18.50	12.40	4.60	40.00
2	B-2	Grey	30	6.30	125	250	125	17	7.5	2.4	14.9	3.7	4.50	20.00	5.50	0.42	2.00
3	B-16	Grey	21	6.18	128	495	248	18	13.8	6.5	3.5	1.8	0.86	14.20	4.70	1.60	5.90
4	P-1	Grey	20	6.06	116	910	455	23	12.4	7.6	13.5	3.8	10.10	12.50	2.30	6.74	8.40
5	P-2	Grey	15	5.80	133	890	450	17	10.6	5.8	14.8	12.6	2.08	28.40	1.20	1.68	6.20
6	B-9	Off-white	12	6.83	120	212	1060	55	52.2	24.7	30.4	10.7	0.50	31.80	7.20	0.13	10.80
7	B-10	Off-white	18	5.64	126	119	60	3	3.8	4.0	3.5	2.9	4.80	16.50	9.54	0.12	3.80
8	P-3	Off-white	12	5.78	143	201	100	14	7.5	6.1	5.4	4.8	4.60	18.20	13.60	0.15	5.80
9	P-4	Off-white	20	5.70	112	323	162	14	26.5	14.3	12.7	3.2	5.20	22.20	16.50	0.13	6.90
10	P-5	Off-white	18	5.71	109	335	168	12	7.8	7.8	4.1	4.7	3.40	17.70	15.30	0.20	6.70
11	B-6	Brown	8	6.48	164	197	99	98	5.3	1.7	9.6	3.4	0.16	10.00	6.54	0.32	1.80
12	B-13	Brown	27	6.04	157	148	74	6	2.7	4.2	7.3	3.1	0.14	19.00	3.60	0.11	0.50
13	B-15	Brown	24	6.42	148	167	84	10	2.3	6.3	10.2	6.5	0.26	16.00	4.80	0.18	0.70
14	B-14	Brown	20	6.40	115	274	137	15	5.4	1.3	12.5	2.8	0.20	17.00	3.20	0.22	1.80
15	B-7	Brown	15	6.25	178	75	37	1	1.2	0.3	1.3	0.5	0.18	1.10	0.48	0.12	1.80
16	B-4	Brown	12	6.39	163	190	96	12	6.8	2.4	13.5	4.4	0.02	23.00	2.30	0.21	1.50
17	B-5	Brown	12	6.60	158	118	59	7	7.3	2.6	14.7	4.5	0.18	23.00	4.88	0.18	0.70
18	P-6	Brown	12	6.58	142	32	160	4	9.8	4.6	21.5	5.5	0.22	30.00	10.70	0.14	0.50

[1]Colour of the sediment, at the depth of the borehole screen from where the water was abstracted. B- are newly drilled boreholes; P- are pre-existing boreholes. All parameters have been expressed as mg/L except pH, EC and Eh. The unit of EC is µS/cm and Eh is mV

presented in Box and Whisker plots (Fig. 8). Figure 8 shows that Cl^- and Ca^{2+} are the dominant ions followed by Na^+. Figure 9 shows Box and Whisker Plot showing the range of concentrations for dissolved Fe in groundwater samples abstracted from aquifer sediments with different colours. Plots of major ions on a Piper diagram are presented in Figure 10. Groundwater abstracted from the grey and off-white sediments are characterized mainly by $Na-Cl-HCO_3$ to $Ca-Cl-HCO_3$ type, while samples collected from the brown sediments are predominantly $Ca-Cl-HCO_3$ type.

Implications for Fe mitigation
The chemical characteristics of high Fe ground waters and the spatial distribution of dissolved Fe in the study area indicate that mobilization of Fe from the solid phase to solution takes place under moderate reducing conditions (Eh ~ +109 to 143 mV). Investigations of the sediment stratigraphy and lithology across the study area show a near surface aquitard composed of argillaceous materials widely occur in the upper most subsurface sediments (< 14 m). This near surface aquitard heterogeneity and variation in thickness leads to variation in vertical recharge, localized dilution, and confinement, resulting in varying redox conditions in the aquifer affecting Fe

release. Areas having the near surface aquitard greater than 1.5 m, the geoelectrical sounding curve type is HA or HK, the underlying sandy aquifer is composed of reduced off-white, or grey to dark grey fine-medium sand, relatively low redox potential values and elevated Fe levels in the groundwater. Areas that have the clay layer less than 1.5 m, the geoelectric sounding curve type is K, the aquifer is composed of oxidized brownish fine-medium sand, relatively higher redox potential values and low Fe concentrations in the groundwater. The variation in the near surface aquitard lithology and thickness explains in part why low Fe groundwater and aquifer are found in areas were high Fe occurrence prevails (Zheng, 2010).

The geoelectrical sounding approach described in this study which is quick and cost effective could be applied as a reconnaissance tool to explore the near surface lithological attributes of an aquifer before drilling. This pre-drilling information is vital to avoid wastage of scarce resources. The brown colour sands could then be easily targeted during drilling for the extraction of low Fe groundwater. This will reduce the number of abandoned boreholes due to high concentrations of dissolved Fe.
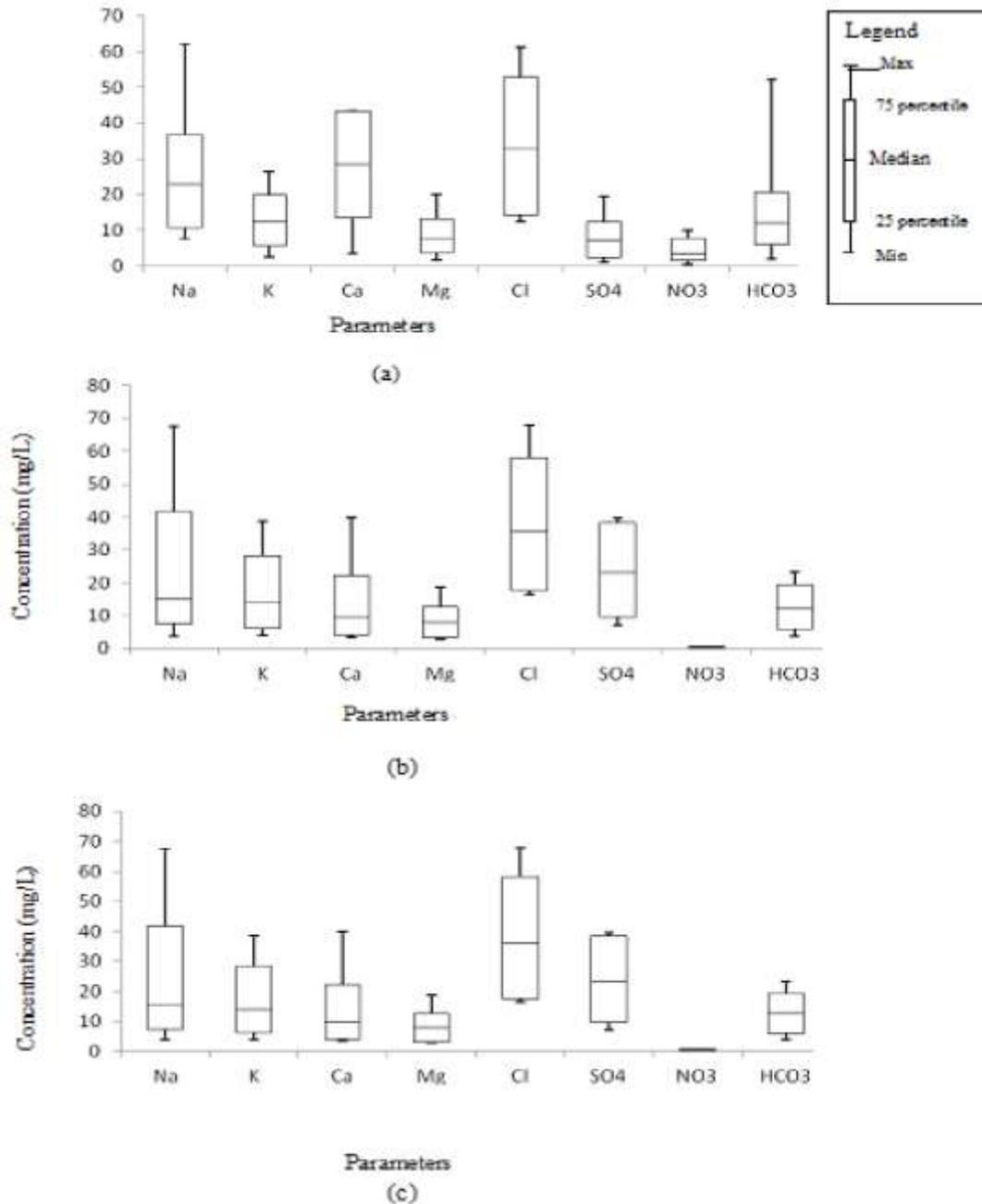
Fig. 8. Box and Whisker Plots Showing variations of the Major ion Concentrations in the Shallow Groundwater within the Studied Aquifer Sediment Colours (**a**) Grey Sand (**b**) Off-white Sand (**c**) Brown Sand.

CONCLUSION

Results from a geoelectric survey combined with lithological data were used to investigate the potentiality of sediment colour as a broad indicator of Fe concentrations in the shallow alluvial aquifer. The results show that the study area is underlain by an extensive near surface aquitard of varying thickness (0.4-13.6 m) which forms a confining layer over much of the aquifer in the

area, and plays a significant role in the development of low redox conditions in the aquifer that drives Fe release to the groundwater. The results indicate that though the major ion composition is similar in the groundwater samples abstracted from the different aquifer sediment colours, the redox conditions in the different sediment colours were different. In locations having clay layer greater than 1.5 m, aquifer sediments consist of reduced off-white, or grey to dark grey fine-medium colour sand,
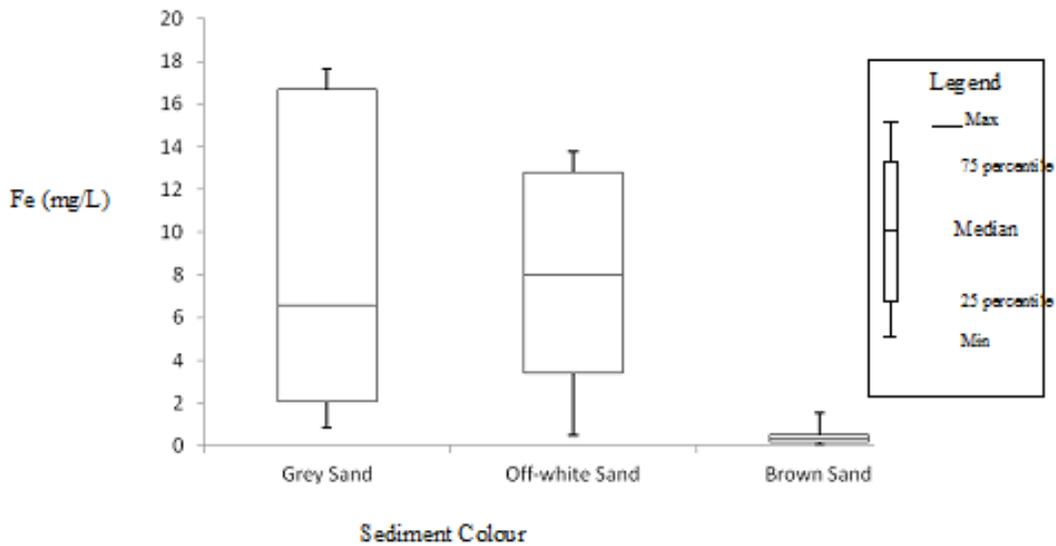
Fig. 9. Box and Whisker Plot Showing the range of Concentrations for dissolved Fe in Groundwater samples abstracted from Sediments with the three different Colour Groups.
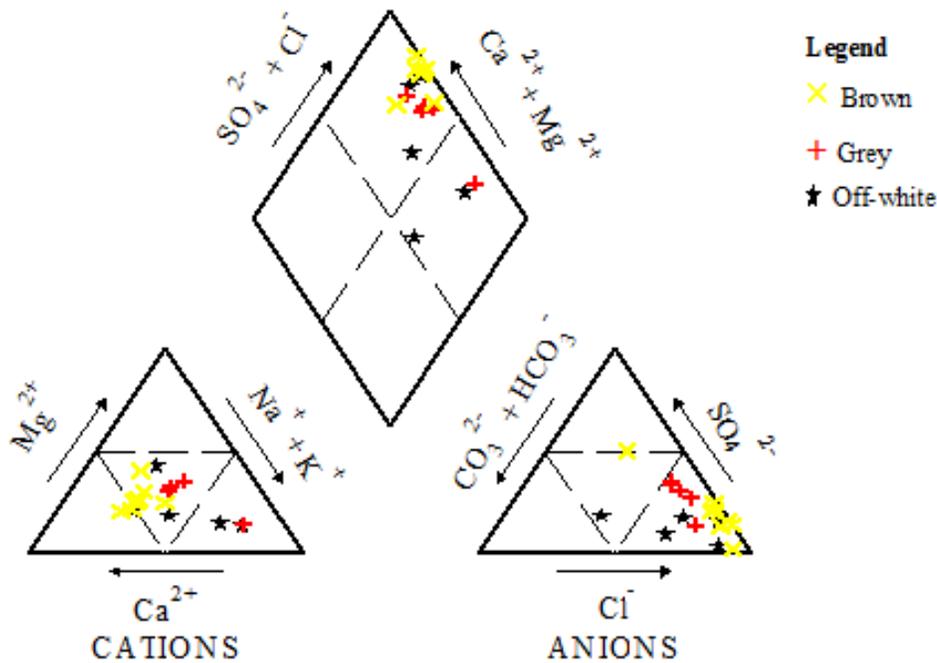
Fig. 10. Figure 10: Major ion composition of groundwater derived from the sediments of the three colour groups plotted on a Piper diagram.

elevated Fe levels in the groundwater (0.5-12.26 mg/L) and occur in a mildly reducing environment (Eh ~ 109-143 mV). In areas where the clay layer thickness is less than 1.5 m or is absent, the aquifer is composed of oxidized brownish fine-medium sand, low Fe concentrations (0.02-0.26 mg/L) in the groundwater and occur in a mildly oxidizing (Eh ~115 – 178mV). The spatial variability of recharge due variation in thickness and lithology of the near surface layer acts as a mechanism that control the variation of the redox state of the aquifer hence dissolved Fe concentration in the very shallow aquifer zone. Aquifers of fine-medium off-white, grey colour sand yield high Fe groundwater and thus are 'high risk aquifers' whereas, brown colour sand aquifers yield low Fe groundwater. This means that off-white and grey colour aquifer sands must be avoided as they are

high risk aquifers. Since off-white and grey colour aquifer sands (high risk aquifers) give HA or HK type geoelectrical signal and brown sand aquifers (low Fe aquifers) give K type, geoelectrical sounding could be used to explore the near surface soil attributes at the reconnaissance stage to determine locations of brown aquifer sand. The delineation of aquifers having iron (Fe) concentration within acceptable limits on the basis of sediment colour appears as a sustainable mitigation option.

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