



The use of very low-frequency electromagnetic survey in the mapping of groundwater condition in oporoza-gbamaratu area of the Niger Delta

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Abstract

The use of VLF-EM in sedimentary basins has not been fully understood and has not attracted substantial usage in groundwater exploration, specifically in coastal Niger Delta. In the present study, VLF and 2D electrical resistivity imaging (ERI) surveys were combined with hydrogeochemical data to examine groundwater quality. Both interpretations of VLF and 2D ERI uncovered subsurface conductive geologic materials. Eight groundwater and one river water samples as well as static water level were analyzed to complement geophysical data (VLF-EM and ERI). The results suggested that conductive materials detected in the subsurface are unconnected with intrusion of sea water but depicted clay material typical of tidal flat deposits. Furthermore, hydraulic heads estimated from water level and land elevation measurements did suggest that groundwater flows into the Escravos River. Also, the stage of the Escravos River is above water levels in boreholes and hand-dug wells, which is not an indicative of the incursion of salt water into aquifer from the river. The slight level of nitrate loading in groundwater probably suggests contamination emanating from anthropogenic sources such as septic tanks and leachates from diffuse refuse dumps. The study has validated the effectiveness of VLF technique usage in sedimentary basins for the delineation of groundwater quality, but not without important hydrogeochemical data.

Keywords Niger delta · saltwater intrusion · groundwater · VLF · 2D ERI · Escravos river

Introduction

Most of the communities in the coastal areas of the Niger Delta usually suffered from poor and inadequate access to potable water for domestic purposes. This is adduced to deterioration of groundwater quality mostly from shallow boreholes and dug wells. The degradation may arise from anthropogenic effects, sea water intrusion and unexplainable concentration of high percentage of dissolved iron. As a result, the people depend on rainfall harnessing and packaged water from onshore areas within the Delta for drinking water. Oporoza as a community is not different in

this respect from other coastal regions of the western Niger Delta.

Aquifers in regions located in a transitional environment like Oporoza and other coastal areas adjacent to the sea have been misconstrued and poorly understood to be degraded by sea water intrusion (Ohwohere-Asuma et al. 2014; Ohwohere-Asuma and Essi 2017). For instance, Omamode et al. (2014) and Olobaniyi et al. (2007) ascribed salt water intrusion to be responsible for groundwater degradation in Burutu and Warri areas in the Delta. Their results were in variance with those of Ohwohere-Asuma et al. (2014); Ohwohere-Asuma et al. (2017); Akpoborie and Aweto (2012) for Burutu and Ughoton (near Warri). Their findings negate the hydrodynamics driving sea water intrusion. This purported misconception has persistently continued as a result of paucity of groundwater data and studies in the western Niger Delta. The reason for the scarcity of groundwater studies and hydrogeological data in the Niger Delta is due to unsafe water transport system that characterized the coastal areas; lack of support by the government on

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groundwater research; and militancy that prevailed in the coastal Niger Delta in the recent past. In spite of the above limitations, Ohwoghre-Asuma and Essi (2017); Omamode et al. (2014) have observed the presence of saltwater and brackish water at depths of 10.5 m and 4–9 m from resistivity sounding around Escravos area and poor quality groundwater that is naturally induced. The general perception that groundwater aquifer in coastal areas is either saline or brackish without hydrogeological evidence of saltwater intrusion is evidently becoming more explicitly following the works of Ohwoghre-Asuma et al. (2014); Ohwoghre-Asuma and Essi (2017); Ohwoghre-Asuma et al. (2017); Akpoborie and Aweto (2012); Atakpo (2013) in some of these coastal areas of the Niger Delta.

Like electrical resistivity technique, the very low-frequency electromagnetic (VLF-EM) is sensitive to ground water quality (Sharma and Baranwal 2005) and conductive geological materials in the subsurface (Ohwoghre-Asuma et al. 2018). It is the easiest to use of all known electromagnetic methods for subsurface exploration. VLF is conventionally used for reconnaissance survey prior to further validation by resistivity sounding and possibly by other subsurface data. In Utah County, the USA, VLF integration with electrical resistivity was used for the delineation of shallow alluvial aquifer contaminated by hydrocarbon (Alvin et al. 1997). Ohwoghre-Asuma et al. (2018) and Aizebeokhai and Oyeyemi (2015); have at different places demonstrated the effectiveness of same methodology in aquifer vulnerability study and delineation of high resistivity layers in sedimentary terrains in the Niger Delta and southwestern Nigeria, respectively.

The use of VLF-EM in sedimentary basins has not been fully understood and has not attracted substantial usage in groundwater exploration, specifically in coastal Niger Delta. To better understand how VLF-EM responds to subsurface geology and groundwater condition is needed. The present study assembled data from different geophysical surveys including VLF-EM and 2D electrical imaging of the subsurface and combined them with hydrogeochemical data for an enhanced interpretation of the geophysical data. The choice of incorporating VLF with ERI is adduced to its sensitivity to variation in the conductivity of subsurface geologic materials. Consequently, it is a good par in delineating aquifers intruded by saltwater from freshwater and can be supplemented by ERI. It is usually used as bases for selecting areas that required further investigation by the geoelectrical approach.

Description, climate and drainage of the study area

Description

The study area is located between Latitude ($5^{\circ} 35' 51.1''$ N, $5^{\circ} 35' 49.2''$ N) and Longitude ($05^{\circ} 16' 58.9''$ E, $5^{\circ} 16' 55.8''$ E) (Fig. 1). It is circumscribed in the north by the brackish River Escravos, in the south by mangrove forest and east and west by creeks/tidal inlets. Oporoza is one of the smallest communities comprising the Gbaramatu Kingdom in Warri-South West, Delta State region of the Niger Delta. It is a linear community, with the population under 1000 and settlement is concentrated along the bank of River Escravos and less than 10 km away from Escravos oil tank farm terminal on the shore of the Atlantic Ocean. The main occupation of the people is mostly fishing and collection of seafood such as periwinkles and oysters. Source of water is mainly from shallow groundwater aquifer and sometimes complemented by rainwater during the wet season.

Drainage

The area is low and flat lying, with topography ranging between 2 to 3 m above sea level and slopes toward the Escravos River. The stage of the river is very close to the surface, and at low tide it drops by receding into the rivers. The drainage is controlled by River Escravos and the creeks either side of the community. The river and creeks are tidally influenced by ocean waves situated few kilometers away. During high tide, flow is toward River Escravos from the Ocean and into the creeks, and reverse flow is at low tide.

Climate

The climate is not different from other parts of the Niger Delta and is described as a typical equatorial with rainforest vegetation. The mangrove forest is essentially supported by freshwater from rainfall. Oporoza is typically a transitional environment characterized by high rainfall that ranged from 3000 to 4000 mm per annual. Rainfall period usually lasts from April to October, and dry period lasts from November to March. Rainfall is not entirely restricted to the wet season alone, as it also rains during the dry season but with a significant amount of variations from those of the wet seasons. Temperature is within the normal range for the region, with a minimum of 24°C in the wet period to 32°C maximum in the warm season.

Geology and hydrogeology

The study area lies within the Quaternary mangrove swamps of the alluvial deposits of the Niger Delta. The subsurface

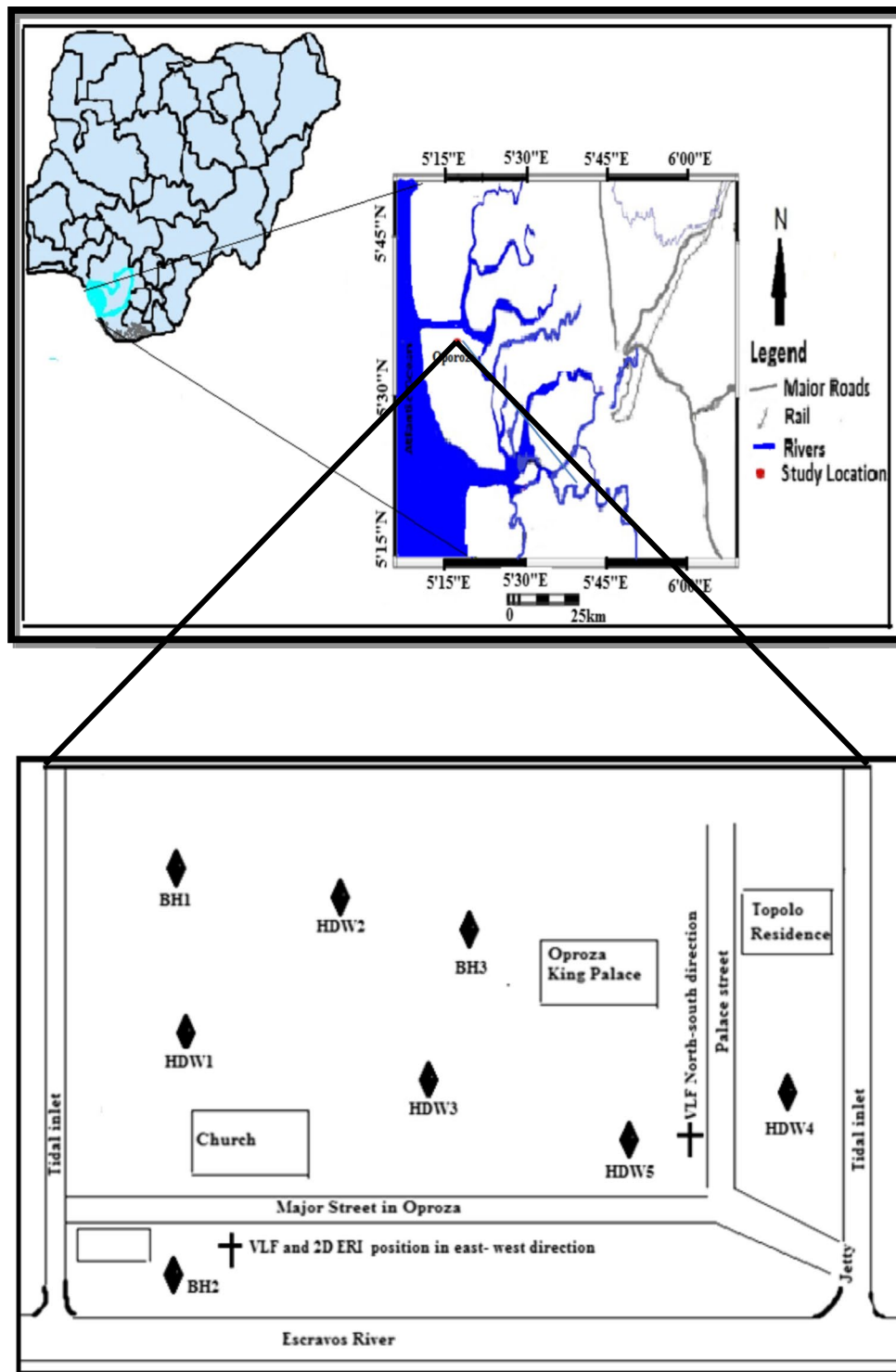


Fig. 1 Map showing study location within the coastal area of the Western Niger Delta

geology consists predominantly of tidal deposits, sand, silts and clays deposited during fluctuating flows typical of estuary environment. Deposition of terrigenous and siliciclastic fluvial sediments is probably routed through River Escravos and possibly by tidal forcing. The sediments were products

of fluvial environment and deposited by the river current, reworked by Ocean tide and wave. Prevalent on the surface is strong evidence of bioturbations reflected by the availability of burrows created by crabs and other marine organisms, which signify sediments deposited in a transitional

environment (Ohwohere-Asuma and Essi 2017). This is an indication of an environment in which the interplay of marine and terrestrial environment influences the deposition of sediments. Overlying the Quaternary alluvial deposits are three lithostratigraphic units of the Niger Delta, which were deposited during cyclic series of sea level rise and fall (Reijers 2011). Immediately below the Quaternary alluvial deposit is the Benin Formation, consisting mostly of unconsolidated sands and interbedded clays and aged Miocene. The hydrocarbon reservoir of the Niger Delta province is the Agbada Formation, with age that ranged from Eocene, and it underlies the Benin Formation. Basically, the Agbada Formation is made up of a sequence of cyclic sand and shale deposit. At the base of the Niger Delta stratigraphy is the Akata Formation, consisting of open marine shale and turbidities. Its age ranged from Miocene to Paleocene, and it is highly over-pressured.

The depth to groundwater level ranged from 0.09 to 0.8 m that seasonally fluctuates. The aquifers are characterized by grains that ranged from fine, medium, coarse sands and gravelly, which is typically of the Niger Delta. The geology of the delta is such that sequences of alternating clays and sands appear increasingly dominant toward the sea. Therefore, multiple occurrences of aquifer layers may also be common. Pumping data and subsurface information are lacking; however, hydraulic conductivity and transmissivity of aquifers may not be significantly different from others within the same region.

Materials and methods

Very low-frequency electromagnetic (VLF-EM)

VLF data were acquired with ABEM WADI instrument, which consists of two components: transmitter and computer-like-screen receiver. The instrument uses the negative part of electromagnetic field obtained from a military radio transmitter with very low frequency that varies from 15 to 30 kHz. The frequency of 27 kHz was used in the acquisition of VLF-EM data. The ABEM WADI instrument operates by inducing primary field waves into the earth subsurface and receiving weak secondary magnetic fields that emanate conductive geologic materials beneath the surface are returned. The weak secondary magnetic fields are the normal response of the EM signal to the conductive body in the subsurface. Two profiles are: one with spacing intervals of 10 m and 20 m in the east–west direction and the other with 20 m and 50 m in the north–south direction with each traverse length of 700 m and 250 m, respectively. The short profile is due to clusters of the houses that hindered lateral extent. The instrument records the real (in-Phase) and the quadrature (out-of-Phase) or imaginary constituents of the ratio of the

vertical to horizontal magnetic components. Subsequently, the computer like screen displayed both raw and filtered real and imaginary positive and negatives values. These values assisted in making preliminary inference on the existence of conductive geologic material in the subsurface in the field (Karous and Hjelt 1983). The decision made can necessitate further probing by utilization of VES and ERI for the delineation of the conductive material.

The acquired VLF data were processed by filtering with the aid of Karous–Hjelt (K–H) filter (Fraser 1969); the obtained Karous–Hjelt filtered data provided information on current density against the depth at which conductive material occurs. Microsoft Excel application package was used in plotting both the filtered real and filtered imaginary components on the vertical axis and the comparable distance on the horizontal axis. The plot produced a typical curve from which interpretation and inferences about the specific position of conductive geologic material may be situated with respect to distance. Furthermore, to achieve a better quality data with a high signal-to-noise ratio, the data were subjected to Fraser filtering (Ariyo et al. 2009), which are shown in Figs. 2, 3, 4, 5.

The interpretation of the curve is qualitative as no other curve can be compared or matched with it to aid easy interpretation. Since the values of the filtered real and imaginary are either positive or negative, an inflexion is caused by a positive and a negative maximum of the filtered real and the imaginary components, respectively, which indicates conductive geologic structures and materials. (Ariyo et al. 2009; Bayewu et al. 2012) suggested that interpretation should be concentrated on the filtered real positive component, as the imaginary part mostly appears complex to interpret and that the positive filtered real is easier, because it usually appeared positive above a conductor. However, (Wright 1988) suggested that positive behavior of the real component represents freshwater flow in a fracture, while negative of the imaginary represents saltwater zones. He stressed further that values which are closer or nearer zero and zero indicate freshwater, while values that are positive and negative indicate saltwater. Consequently, the interpretation was based on the above usage of both components of VLF in groundwater investigation. This is pertinent since the objective of the study is to evaluate the potential of saltwater intrusion compromising the quality of freshwater aquifer in an estuary environment.

2D electrical resistivity imaging (ERI)

To obtain a lateral variation of subsurface geology along the profile, a Werner array configuration was employed for ERI data acquisition. The profiling was chosen parallel to the river Escravos due to the cluster of houses and presence of mud near the bank of the river, which could not permit

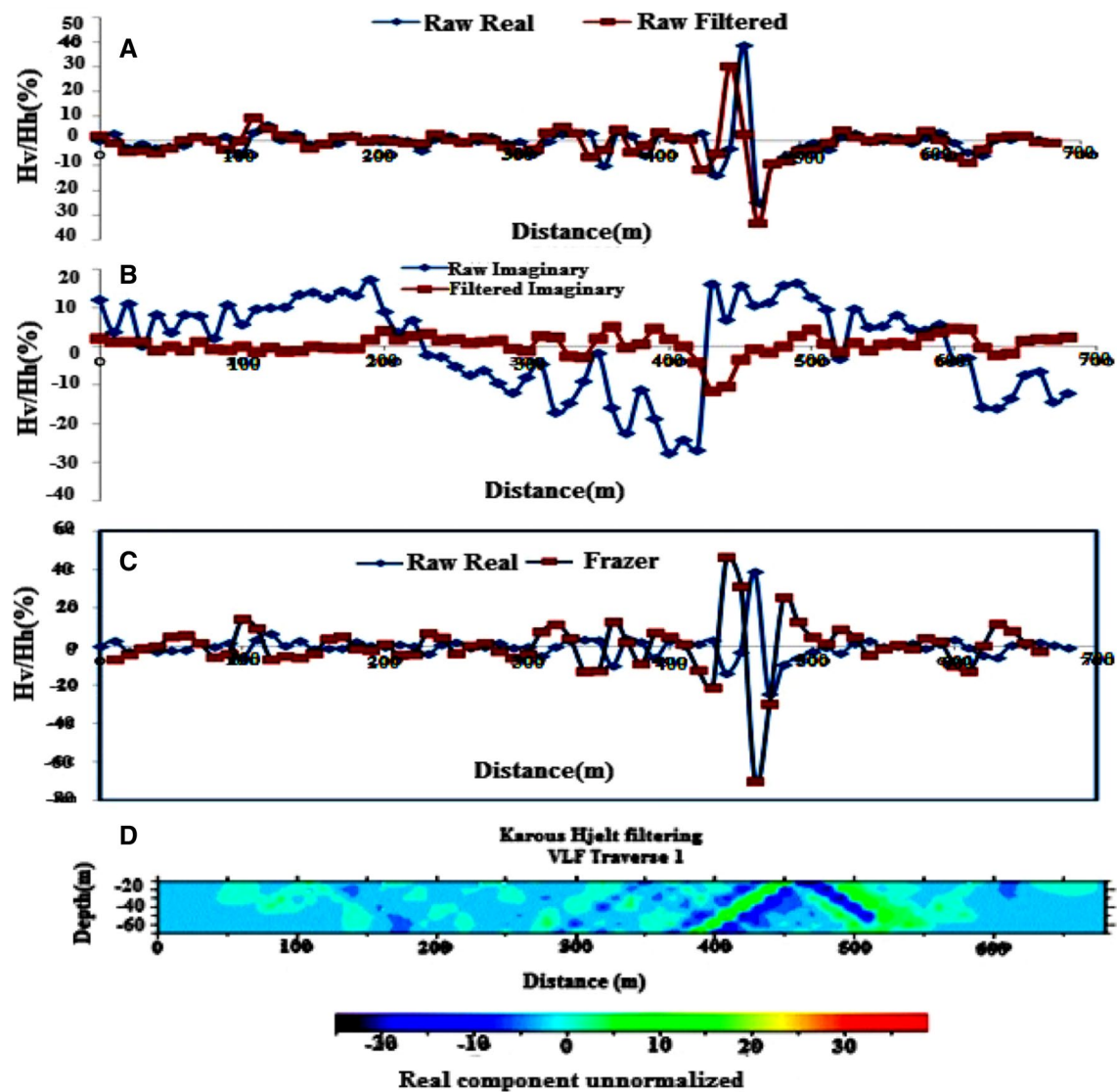


Fig. 2 VLF-EM profile 1 along east–west direction **a** Plot of raw and filtered imaginary against distance **b** Plot of imaginary raw and filtered against distance **c** Frazer filtering against distance **d** Pseudosection of the inverted real component, unnormalized

profiling perpendicular to the river. The portable chargeable 4pointLight 10w Lippmann Terrameter, with only four electrodes, was also used for the profiling, and electrodes were rolled along manually, thus subjecting the procedure for acquisition of ERI data to tedious and arduously task, but enough to unraveled subsurface information, at least as it regards groundwater quality and saltwater intrusion potential of shallow aquifers in the area. A distance of 10 m between electrodes inclusive of current and potential electrodes was used. All electrodes were rolled along with the distance of 5 m spacing, starting with the last electrode. This was done till a distance of about 700 m was covered. We moved the electrodes at 5 m spacing to ensure important subsurface geologic information is not bypassed compared to moving the electrode at 10 m. The procedure was repeated for 20 m

and 50 m with the roll-along spacing of 20 and 50 m, respectively. The apparent resistivity data acquired were inputted into RES2DINV software, for inversion of resistivity data proposed by Loke and Barker (1996). The software uses finite difference procedure for calculating apparent resistivity (Dey and Morrison 1979). Detail description of how field ERT data are acquired and processed is covered in Loke (2000).

Samples collection and water level measurement

Eight water samples were collected from hand dug-wells and boreholes, and one sample from Escravos River. To ensure that sample is representative of aquifer groundwater, boreholes were pumped for 2 min before collection, except

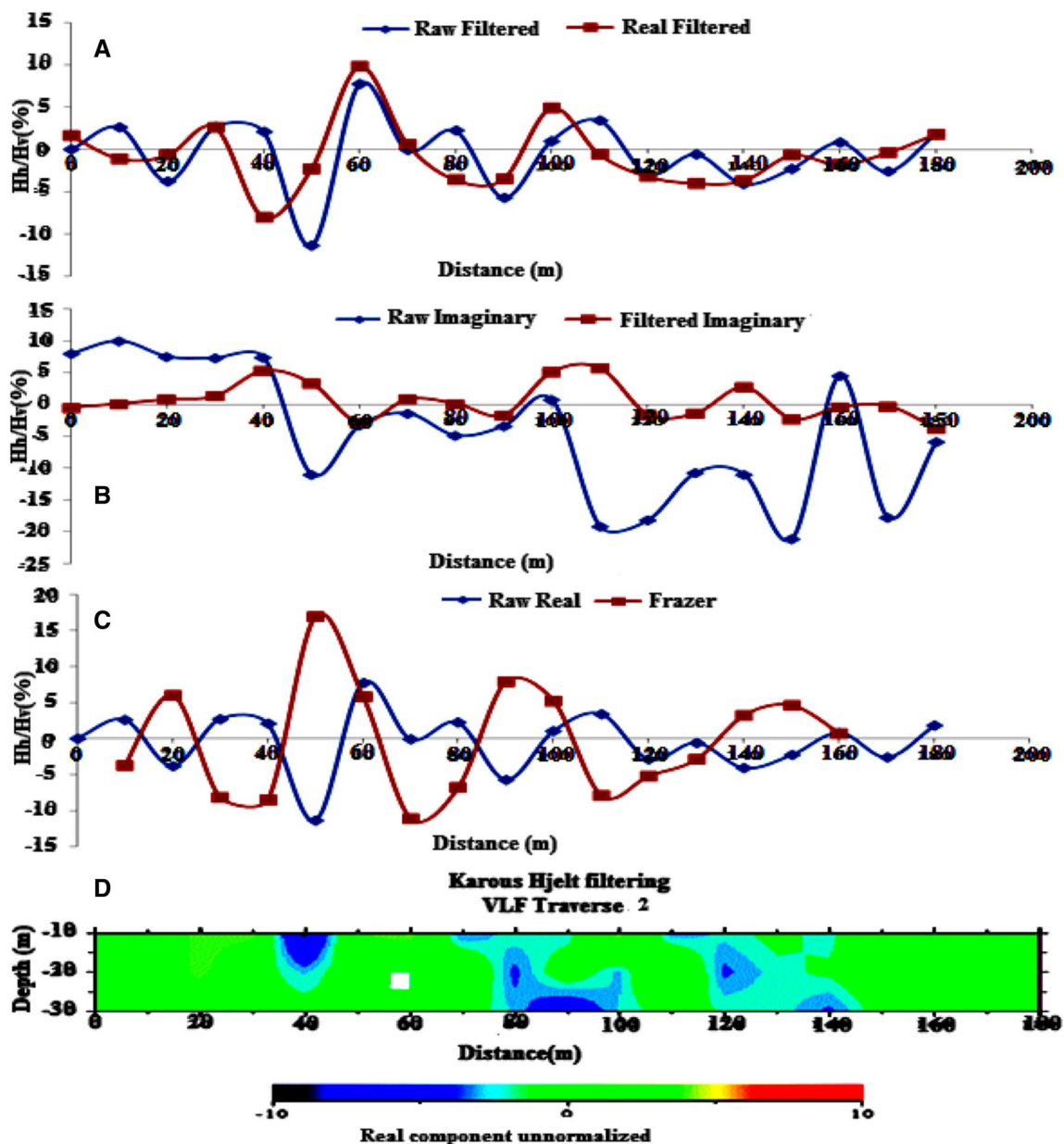


Fig. 3 VLF-EM profile 1 along east-west direction **a** Plot of raw and filtered imaginary against distance **b** Plot of imaginary raw and filtered against distance **c** Frazer filtering against distance **d**

hand-dug wells. The pH was ascertained by the Schott Gerate Model pH meter; the HACH conductivity-TDS meter was engaged to ascertain electrical conductivity and total dissolved solids (TDS) in situ. Samples for laboratory analysis were stabilized with nitric acid to pH of 2. Table 1 depicts main cations, anions and other determined by required laboratory standard in accordance with APHA (1996). The results of groundwater analysis were subsequently compared with the WHO (WHO 2011) drinking water quality guidelines.

Water levels and depths of both hand-dug wells and borehole were measured by water Solinst meter on 6th April, 2013, a day after VLF and ERI data were acquired. Depth

and water level of one of borehole were not determined due to complex nature of the wellhead. Coordinates of wellheads and elevation were determined by Ertec model GPS equipment.

Results

VLF-EM interpretation

Figures 2, 3, 4, 5 depict the results of VLF-EM Fraser filtering, plots and pseudosection of current density against the depth of conductive material in the subsurface. The

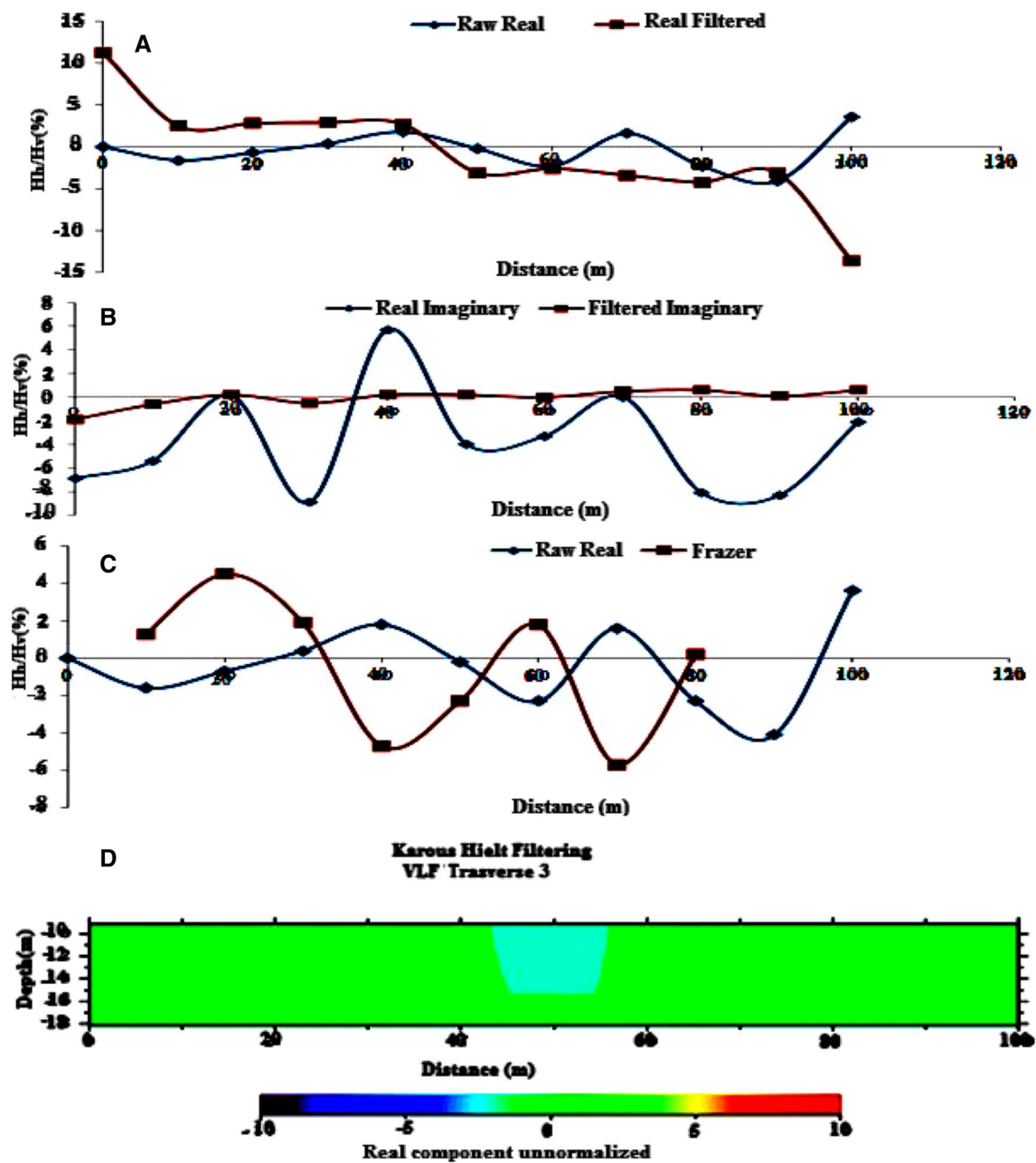


Fig. 4 VLF-EM profile 2 along north–south direction **a** Plot of raw and filtered imaginary against distance **b** Plot of imaginary raw and filtered against distance **c** Frazer filtering against distance **d** Pseudosection of the inverted real component, unnormalized

subjection of VLF data to filtering processing has enhanced deciphering and understanding behavior of the real and the imaginary components. This is discernable in all imaginary components, which are shown in Fig. 2b through Fig. 4b and Fig. 5a, respectively. The exhibition of positive high values by raw imaginary components has been enhanced to values as low as zero through filtering of noises.

The filtered imaginary component is seen at the zero mark in some figures, and in others, slightly above and

below it. Filtering has removed misinterpretation of positive high values should raw imaginary components was used directly for interpretation and delineation of subsurface geological information. Positive values of real components were interpreted as fresh water aquifers. Values of imaginary components that are slightly above zero were interpreted as freshwater, while negative and positive values of imaginary components are regarded conductive materials, in this case clay.

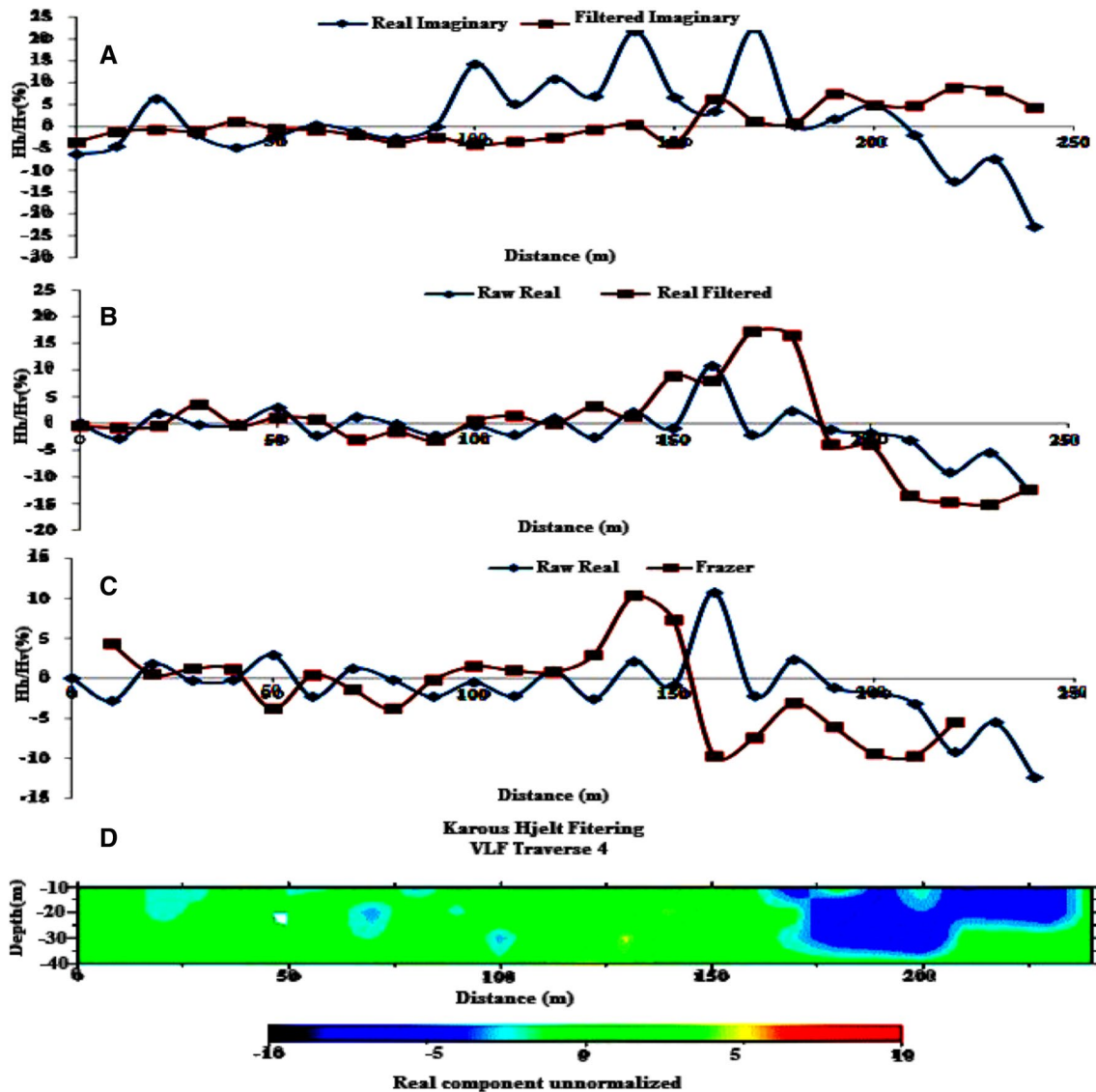


Fig. 5 VLF-EM profile 1 along north–south direction **a** Plot of raw and filtered imaginary against distance **b** Plot of imaginary raw and filtered against distance **c** Frazer filtering against distance **d** Pseudosection of the inverted real component, unnormalized

Interpretation of 2D ERI

Figure 6 presents the 2D ERI pseudosection obtained from processing of acquired field data.

The eastern section of the profile is predominantly characterized by low resistivity geologic material in the subsurface with resistivity values that range from 1.88 to 19.8 Ω m, and this low resistivity geologic material is relatively extensive; it extends from 15 to 160 m wide and also extends downward from 1.25 m to 28.7 m deep. A similar low resistivity geologic material is also obvious in the western section, which extends from 400 to 445 m and vertically from 6 to 23 m. The latter is surrounded by somewhat high resistivity geologic materials, while the former is terminated

against higher resistivity materials. A closer examination of the latter shows the existence of high resistivity body sandwiched between resistivity low materials. The low resistivity subsurface geologic materials detected in the pseudosection in Fig. 6 probably represent either saltwater intrusion into groundwater or presence of clay materials. The high resistivity on the other hand probably suggests geologic material of sandy aquifer saturated with fresh groundwater.

Hydrogeochemistry of groundwater

The results of the laboratory analysis of physiochemical parameters of groundwater samples obtained from shallow boreholes and hand-dug wells as well as river are

Table 1 Descriptive statistics of the result of laboratory analysis of physiochemical parameters of groundwater and river samples

	BH1	BH2	BH3	HDW1	HDW2	HDW3	HDW4	HDW5	MEAN	S.D	River
pH	7.4	6.9	7.3	5.6	6.7	6.5	5.8	6.2	6.55	0.66	8.4
TDS	52	152.7	58.91	643.02	599.63	762.45	945.78	887.05	512.69	370.79	8920
E/C Us/cm	78	50	102	247	219	278	323	293	198.75	99.62	15,930
Na ⁺	30.72	47.91	38.92	120.8	104.8	98.14	74.45	118.3	79.01	36.40	1871.12
K ⁺	8.72	10.85	8.99	21.44	18.52	23.72	35.72	25.77	19.21	9.44	39.32
Mg ²⁺	15.35	12.76	10.35	21.26	19.78	23.95	21.6	18.99	18.62	3.81	317.23
Ca ²⁺	19.5	17.5	21.8	23.2	29.01	24.61	39.88	27.02	25.32	6.98	99.81
Fe ³⁺	6.53	4.6	2.6	4.5	2.8	4.8	2.6	0.98	3.85	1.6	20.37
Cl ⁻	67.16	43.45	55.78	228	242	137.7	155.6	130.03	132.46	75.37	3267.4
SO ₄	60.42	86.08	72.12	126.2	146.02	152.6	165.15	108.8	115.93	40.4	935.1
HCO ₃	74.6	65.48	58.44	99.8	82.87	69.01	76.34	61.4	73.49	13.34	510
NO ₃	0.4	1.6	2.03	29.4	30.2	29.4	28.73	34.22	22.9	10.38	2.34
Cl/HCO3	0.90	0.66	0.95	2.28	2.92	1.99	2.04	2.11	1.73	0.8	6.41
Na/Ca	1.575	2.74	1.785	5.21	3.61	3.98	1.87	4.39	3.14	1.35	18.75

All parameters are in mg/l, except EC=(us/cm) and pH
 BH borehole, HDW hand-dug well

presented in Table 1 and Fig. 7, respectively. The results are characterized by pH values that ranged from 5.6–7.4; 52 to 945.78 mg/l for TDS and 50–323 for conductivity, and these values are much higher for hand-dug wells (Fig. 7 and Fig. 8). The values of pH, TDS and conductivity are indicative of groundwater that is slightly acidic and neutral which has a high concentration of dissolved ions. For major cations, the following values were obtained: Na⁺ (30.72–120.8 mg/l), Mg²⁺ (12.76–23.95 mg/l), K⁺ (8.72–23.72 mg/l), Ca²⁺ (17.5–39.88 mg/l) and Fe³⁺ (0.98–6.53 mg/l), and hand-dug wells are generally of high magnitude than boreholes except for Fe³⁺. Furthermore, the anions depicted values for Cl⁻ (43.45–242 mg/l), SO₄ (60.42–165.15), HCO₃⁻ (58.44–99.8 mg/l) and NO₃⁻ (0.4–34.22 mg/l) again higher values are detected for hand-dug wells than boreholes. Groundwater samples were compared with river sample. The concentration of river sample was greater in magnitude than those for groundwater physical and chemical parameters (Table 1).

Discussion

The use of both VLF and 2D ERI has unraveled in the subsurface the presence of high conductivity and low resistivity geologic material underlying the profiles (Figs. 2d and 6). Ordinarily, this high conductivity and low resistivity materials were presumed to be saltwater intruding the aquifer from the eastern side of the profile on the one hand. On the other, saltwater or brackish water trapped in the western regions of the profile. The depositional setting of the study area without borehole information introduced some complications concerning the true nature of these conductive geologic

materials. Consequently, the low resistivity and high conductivity geologic materials beneath the subsurface were probably interpreted as clay materials and not brackish or saltwater on the bases of the subsurface geology. The claim is attributed to the contiguous nature of the eastern side and even the western side of the profiles to the tidal inlets; in fact, the profile is less than 2 m from the tidal inlet. The sidewalls of the tidal inlets are made up of mudflat, which is typical of a transitional depositional environment as it consists of clay or mudflat sediments. This may be the reason they appeared conductive at both the eastern and western sides, respectively. The closeness of the profile to the tidal inlets supports the claim that the low conductivities geologic material as an extension of mudflat.

Saltwater intrusion among other thing is influenced by heads of groundwater on the landward side of the coastline. When heads declined below sea level, it triggered movement of the saltwater/freshwater interface toward heavily stressed boreholes located on the landward side of the sea. Groundwater levels data obtained from boreholes and hand-dug wells in the study area ranged from 0.085 m to 0.791 m (Fig. 9), noticeably are not above the River Escravos stage. Usually, interface between freshwater and saltwater is supposed to be located at depth of 22 m below the surface in accordance with the Ghyben–Herzberg theory, which assumed that saltwater–freshwater interface should be situated at the subsurface where the product of multiply 40 by the water level in an aquifer. However, the resistivity value at this depth does indicate this, as they are lower than 0.2Ωm stipulated for saltwater. One of the reasons is that the study area is not adjacent to the ocean, as this is only applicable to aquifers connected to the sea and though it exists, but definitely not at the 22 m depth perhaps deeper. Also,

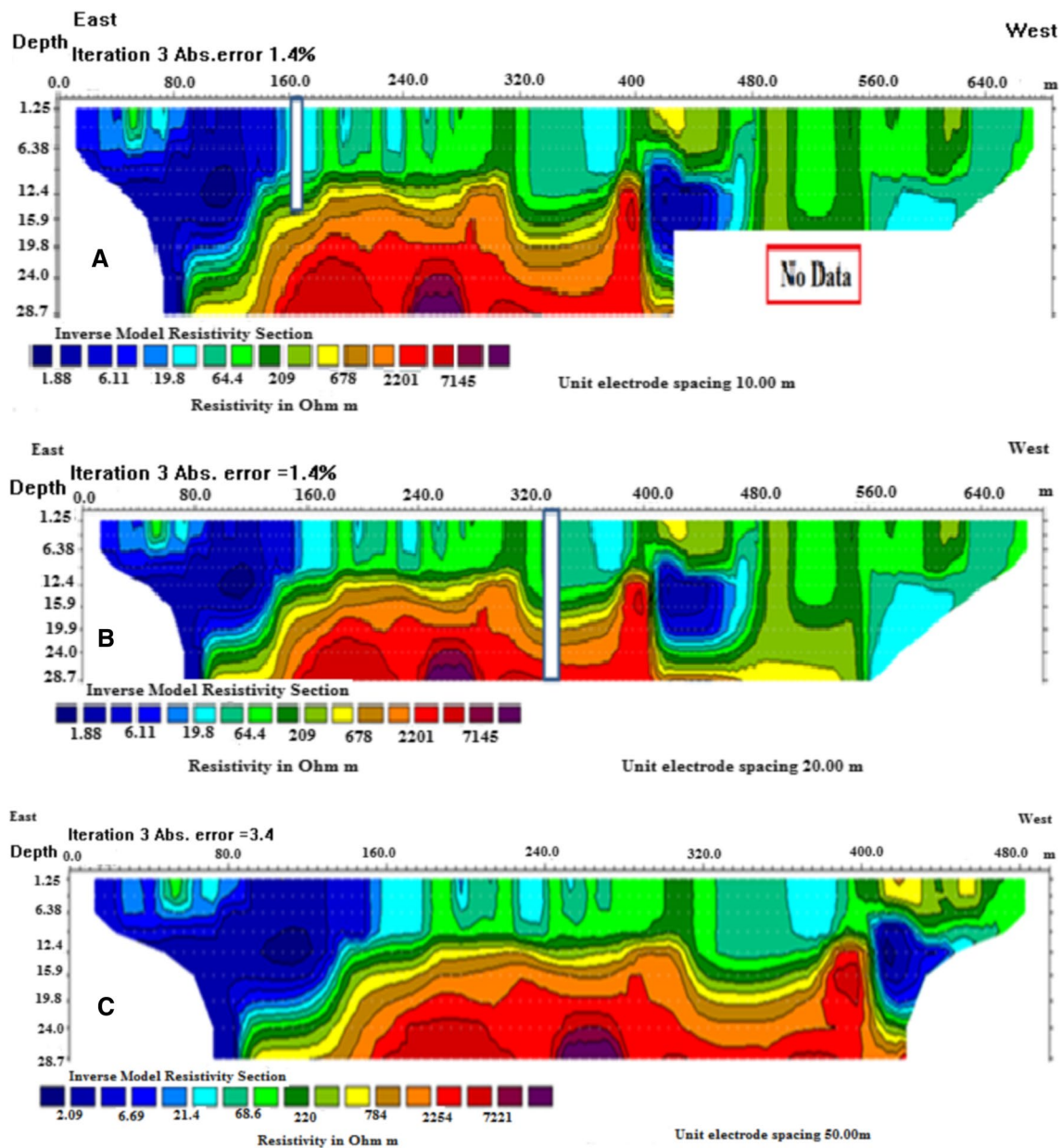


Fig. 6 2D ERT obtained from east–west profile; **a** acquired with 10 m; **b** 20 m; and **c** 50-m intervals spacing of Wenner arrays (while white rectangles in A and B are positions of vertical electrical sounding not discussed)

resistivity values of 209 Ω m at this depth were interpreted for two VES locations along the profile (white section in Fig. 6a and b), which is not discussed in this study. Another obvious reason is that the study area is not as densely populated to the extent of initiating heavy pumping of groundwater that may lead to the reversal in groundwater flow direction by causing decline in the heads is the only sure way to trigger incursion of saltwater from the brackish River. The normal direction of groundwater flow is toward the river (Fig. 7), that is north–south direction, where freshwater discharges into the river.

The physiochemical constituent of groundwater usually provides significant information on its healthiness for drinking and quality for other purposes. In order to establish whether the groundwater from the study area is constituent of the subsurface conductive geologic materials revealed from the interpretation of the VLF and 2D ERI data, few saltwater parameter indicators were analyzed. The conductivity of groundwater is often related to the total dissolved solids in the groundwater and use in ascertaining the salinity of groundwater. The samples from the study area are characterized by the somewhat

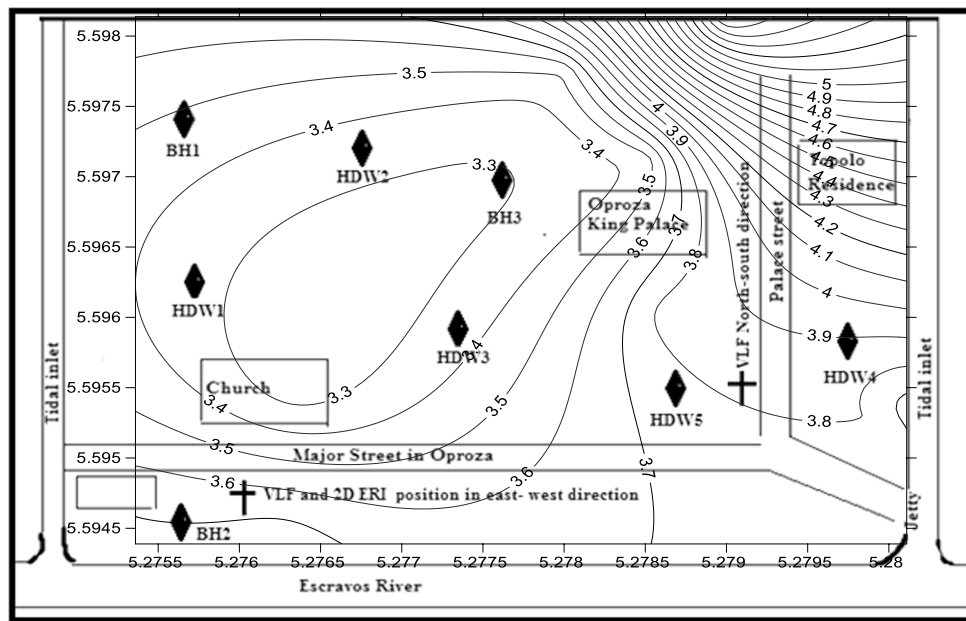


Fig. 7 Hydraulic heads showing groundwater flow direction

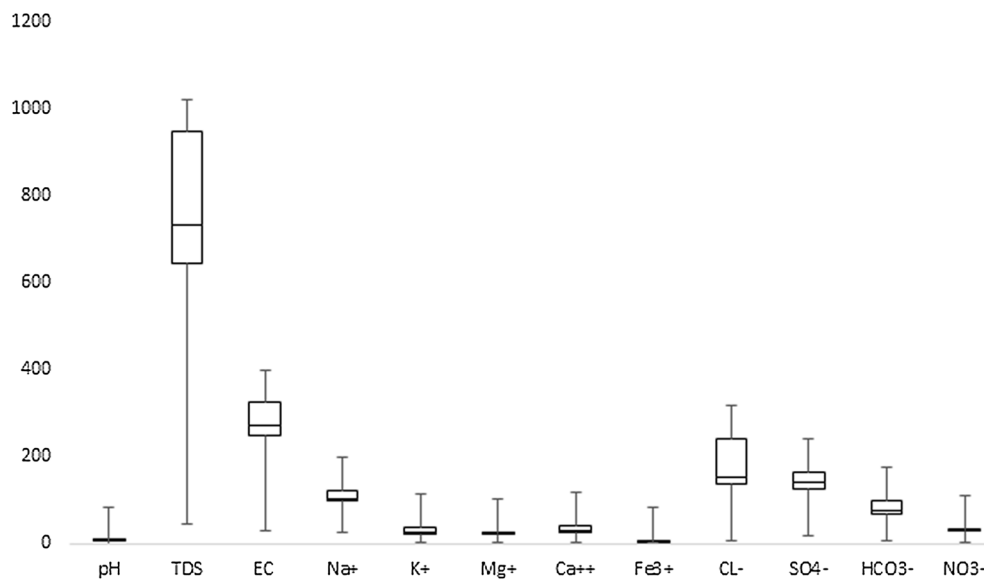


Fig. 8 Boxplot for physiochemical parameters for hand-dug wells

high magnitude of electrical conductivity and TDS values, especially among hand-dug wells with values higher than required drinking water standard (Table 1). These values are significantly lesser than those obtained for Burutu estuary by Ohwohere-Asuma et al. (2014, 2017) and lesser for Ughoton mangrove swamps in the western Niger Delta region (Akpoborie and Aweto 2012). The high magnitudes recorded for the hand-dug wells did suggest the influence anthropogenic has on the quality of groundwater than

saltwater incursion. This is because the hand-dug wells are too shallow; the deepest rarely exceed 4 m. The enhanced TDS and conductivity values were probably caused by transport of contaminants by direct runoff, and infiltration of leachates from surface dumpsites and septic tanks as most lack concrete walls.

The boreholes samples, on the other hand, possess Na^+ concentrations lesser than hand-dug wells. Among the major cation constituent of seawater, Na^+ consists of a greater

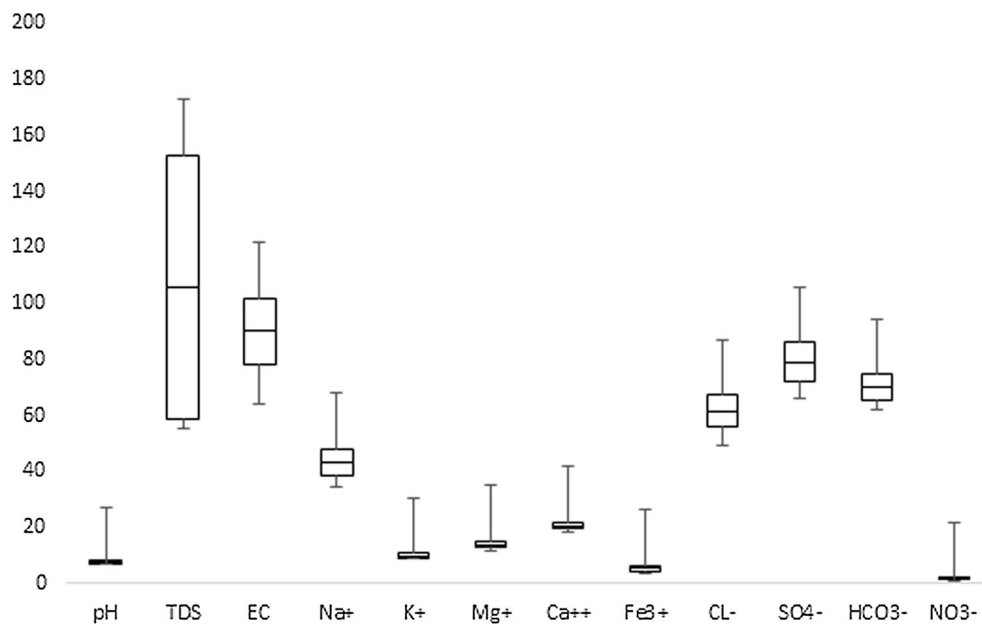


Fig. 9 Boxplot of groundwater samples collected from boreholes

percentage of it, and they are common in coastal groundwater aquifers. Enhanced Na^+ in coastal groundwater aquifer is usually attributed to saltwater intrusion. However, several sources of Na^+ are known to be responsible for the enriched level of it in groundwater. Cations exchange, silicate weathering and refreshing of groundwater aquifer do contribute to the enrichment of Na^+ in groundwater (Ohwohere-Asuma et al. 2014). The ratios of Na^+ to Ca^{2+} in groundwater samples are drastically lower than 18.768 calculated for river a sample which is brackish (Table 1). This increase in the amount of Na^+ suggests that other process may be responsible of its presence in the groundwater. Cation exchange and silicate weathering in groundwater have already been demonstrated by Ohwohere-Asuma et al. (2014) to be responsible for increased in Na^+ from a similar environment.

It is submitted here that the elevated value of Na^+ in the groundwater from the study area is probably released by clay materials in the aquifer under recharge condition enriched in Ca^{2+} .

Ca^{2+} and HCO_3^- are major constituents of freshwater contributed by filtration of precipitation through the unsaturated zone to the aquifer. However, it has been demonstrated that aquifers experiencing saltwater intrusion are characterized by the decrease in concentration of Ca^{2+} , especially the saltwater-freshwater front of the intruding saltwater. The concentrations of Ca^{2+} obtained in this study are relatively higher than those from inland aquifers and obviously do not reflect depletion on comparison with those obtained from onshore areas by Akpoborie and Aweto (2012; WHO 2011). The increase in Ca^{2+} may have been contributed from the

abundance of calcareous shells in sediment and infiltration of precipitation through the unsaturated soil zones.

Chloride is usually used along with Na^+ and electrical conductivity to determine the salinity of aquifers intruded by saltwater. The Cl^- and TDS concentrations for both boreholes and hand-dug wells in Table 1 are below 250 mg/l and 1000 mg/l for groundwater to be considered brackish. The higher values of Cl^- , which are greater than Na^+ clearly indicate that other processes other than saltwater intrusion is responsible for groundwater quality degradation. Shallow groundwater aquifer has been demonstrated to be enriched with Cl^- , and the probable source was linked to hydraulic connection with septic tank to aquifer (Ohwohere-Asuma et al. 2014, 2017; Akpoborie and Aweto 2012; Ohwohere-Asuma & Adaikpoh 2012). Considering the groundwater level that is almost at the ground surface, there is the likely tendency that effluents from septic tanks and leachates seeping from dumpsites are mixing with groundwater. In addition, the ratio of $\text{Cl}^- / \text{HCO}_3^-$ is often used to explain the source of saltwater intrusion in groundwater aquifer. Saltwater may be identified to have intruded freshwater aquifers when chloride-to-bicarbonate ratio is > 2 . The ratios of $\text{Cl}^- / \text{HCO}_3^-$ obtained for boreholes are obviously < 2 , while those of hand-dug wells are even more slightly higher > 2 . Having values lesser than 2 for the boreholes could be attributed to the freshness of the groundwater as evident by a high proportion of HCO_3^- (Table 1), which is the main constituent of freshwater. This is an indication of the fact that degradation of the aquifer quality is not related to saltwater intrusion but more of anthropogenic effects. This is reflected in the values

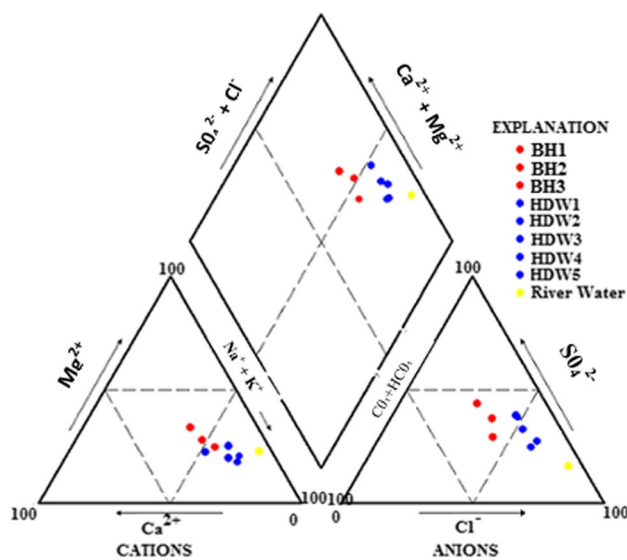


Fig. 10 Piper diagram of the groundwater samples and River Escravos sample

observed for the hand-dug wells, which are superficial in nature. This can further be supported by the elevated values observed for NO_3^- loading in groundwater samples, though lesser than the 50 mg/l required standard, but higher among the hand-dug wells. The concentration of NO_3^- groundwater is relative to human effects, especially from septic tanks which contribute to recharging of groundwater as return flow.

The Piper plot in Fig. 10 reveals heterogeneous groundwater facies types without a dominant type. For the cations, Na + K and Ca + Mg facies types can be identified, while the anions are characterized by Cl– SO_4 and Cl– HCO_3 facies types. The absence of dominant facies is suggestive of quality compromised by the mixing of two different water types, which is not related to saltwater intrusion. Significantly, the cations and anions of the groundwater samples plotted above the river sample with Na–Cl facies, a salinized river water. The river sample invariably connotes saltwater intrusion of surface saltwater and freshwater from the ocean and river, respectively.

Conclusion

The acquired filtered real and imaginary components of the electromagnetic signal of VLF-EM data were successfully used in the delineation of the subsurface conductivity of geologic materials in a sedimentary basin for assessment of groundwater quality. The recorded success is dependent on its ability to distinguish conductivity zones underneath the subsurface which was essentially not different from those obtained from 2D ERI technique.

However, the weakness of both techniques to distinguished conductive clay from saline water was unveiled by groundwater geochemistry. The study has demonstrated that the VLF-EM geophysical technique like electrical resistivity methods can be used separately for the mapping of subsurface geology in a sedimentary environment and without using the former as a baseline survey for further probing by geoelectrical electricity technique as applicable to basement terrain. Based on the result of the study, successful and efficient application of any of VLF-EM or ERI must be essentially complemented by borehole lithology and groundwater chemistry information.

The physiochemical parameters presented in the study did not suggest salinization by salt water intrusion from the salinized Escravos River at Oporoza. The salinity of groundwater as compared to the saline river water is not sufficient to be detected by both geophysical methods used. The slightly elevated chloride, TDS and nitrate loading are more of leachates and septic tank failure influence on groundwater quality than sea water intrusion. The groundwater quality analysis revealed that low resistivity values were not characteristics of sea water intrusion but of tidal flat clays of an estuary depositional environment.

Finally, computed hydraulic heads are close to the ground surface and stage of the river is not below water levels, which are indications that salinized Escravos River water does not flows into aquifers. Consequently, this hydraulic process prevailing in the study area does not suggest sea water intrusion from the saline river into the adjacent aquifers.

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Compliance with ethical standards

Conflict of interest The authors declare that they have no conflict of interest.

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