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ORIGINAL ARTICLE

Assessment of saltwater–freshwater interactions using water samples and borehole logging information in the Lagos coastal region, Nigeria

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Abstract

An analysis of borehole logs with hydrophysical data from the Lagos coastal belt, Southwestern Nigeria, was carried out to evaluate the subsurface lithological units and geo-environmental impact of seawater intrusion into coastal freshwater. Forty-five (45) borehole logs, consisting of natural gamma, electrical resistivity log and hydrophysical parameters were integrated to delineate saline and fresh aquifer zones and propose simplified conceptual models for adequate groundwater characterisation and development. The qualitative interpretation of the borehole logs revealed a complex lithology of alternating sequences of sand and clay layers. The study also showed that the subsurface was variably intruded by saline water indicated by low resistivity values with freshwater/saline water boundaries occurrence at depths ranging between 14 and 157 m from west to east. The variation in depths of occurrence of freshwater/saline water interface is dependent principally on the proximity to saline/brackish water source as well as variation in lithology. Complementarily, the average electrical conductivity (EC) of 1770 µS/cm (GW1–7) and 1676 µS/cm (GW8–13) recorded in groundwater at Apapa in the west and Island at the central part, respectively, further confirmed saline incursion of the coastal aquifers in the region. This study demonstrates versatility of geophysical borehole logs in identification and differentiation of the subsurface lithology and its fluid content.

Keywords Natural gamma ray · Electrical resistivity log · Conceptual models · Fresh/saline water interface · Hydrophysical parameters

Introduction

Groundwater, a precious resource, is one of the main water resources on the earth (Villeneuve et al. 1990; Sinha et al. 2016), especially for the arid and semi-arid countries. According to Raghunath (2006), about 97.2% of the global water resources is salt water, mainly in the oceans, and 2.8% is available as fresh water at any time on the earth. Out of 2.8% freshwater occurrence on the earth, about 2.2% is available as groundwater. Groundwater contributes about 95% of the readily utilised fresh water of the world (Nace 1971; Leopold 1974). In recent times, the scarce and limited water resources of the world are under increasing pressure due to pollution, urbanisation, increased per capita water use and irrigation. Hence, the management of water resources, especially groundwater, has become an increasingly pressing issue globally (Ghazavi et al. 2010). In addition, about 80% of all wastes is generated from the cities and about 60% of greenhouse gas emissions that cause global climate change emanates from cities (El-Sioufi 2010). Therefore, there is no doubt that climate change aggravates existing socio-economic and environmental problems, especially by exerting pressure on water supply and many other new challenges (Arnell 1999, 2004; United Nations 2009). Climate change will, therefore, affect the water resource base, especially in terms of water availability, quantity, quality, timing, and distribution, and other watershed services in as much as availability of potable water is a critical issue for most people in the world (Ringler 2008; USDA 2008).

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Lagos is a coastal metropolitan city and the industrial hub of the nation (Fig. 1). According to the United Nations Development Programme (2006), the annual population increase due to rural–urban migration in the study area is 3%. Consequently, groundwater is often overdrafted to meet the ever-increasing demand for water by the populace. Groundwater overdrafting can lead to a number of unsavoury consequences such as saltwater intrusion or groundwater quality degradation, environmental degradation and land subsidence (Saber et al. 2017). Potable water supply to inhabitants of the Lagos coastal belt has been a major problem resulting from saltwater intrusion (Yusuf and Abiye 2019). Due to inadequate supply of water to the populace, the residents had to result to indiscriminate sinking of boreholes for various activities and with attendant disturbance of the existing hydrogeological balance between freshwater and seawater. The problem is worsened when many boreholes which were producing freshwater after drilling become salty after a few months

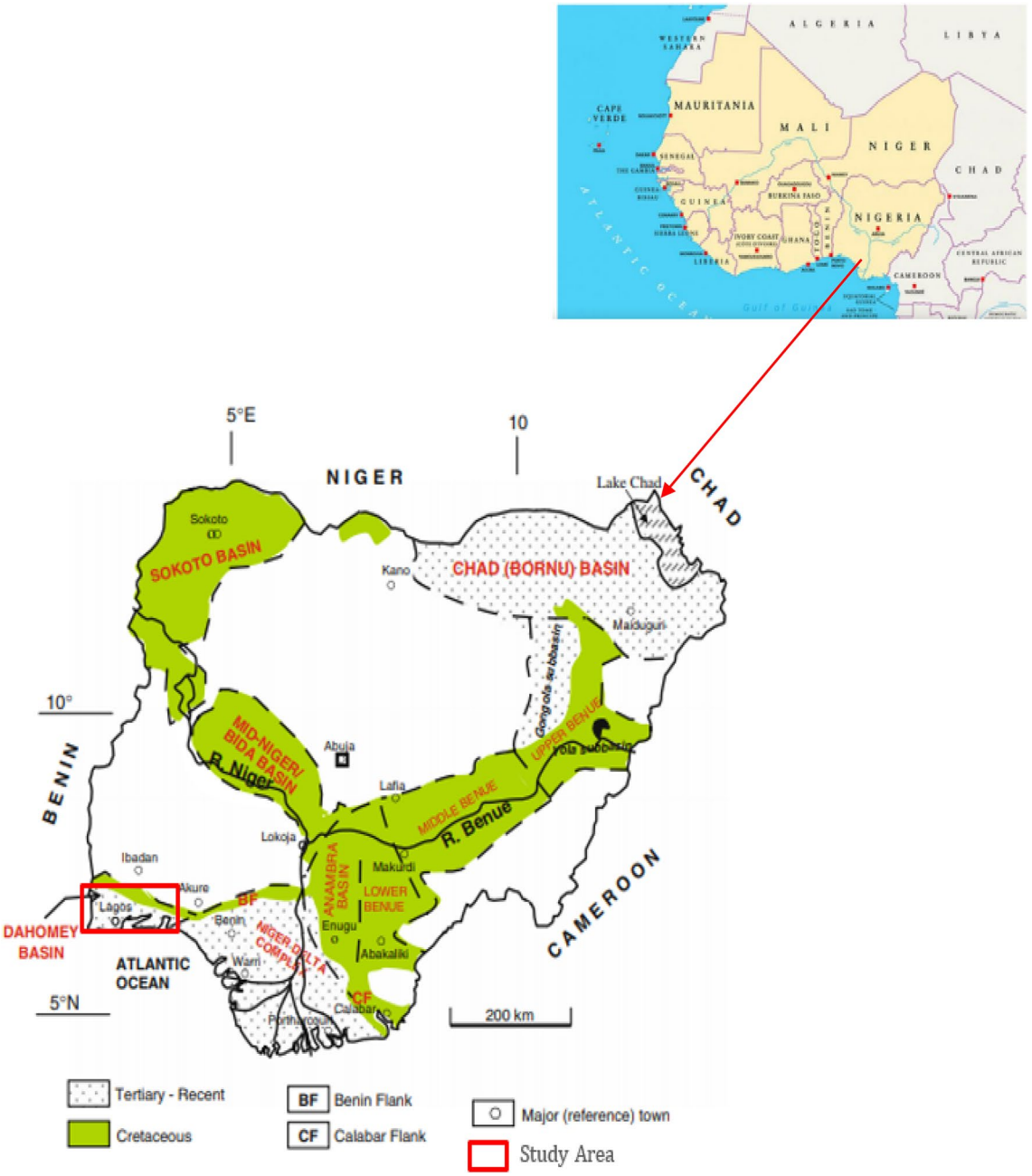


Fig. 1 Map of sedimentary basin of Nigeria showing Lagos within the Dahomey (Benin) Basin

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(Oyeyemi et al. 2015). This necessitates geophysical probe of the subsurface using geophysical borehole logs.

The extent of saltwater intrusion and percolation within the subsurface is enhanced by the nature of the geological formations, hydraulic gradient, rate of withdrawal of groundwater and its recharge (Oteri and Atolagbe 2003). Several researchers around the world have carried out studies on saltwater intrusion into fresh water in the coastal areas including the Lagos Coastal basin (Adeoti et al. 2010; Adepelumi et al. 2008; Jakovovic et al. 2016; Oteri and Atolagbe 2003; Oyedele 2001; Oyedele and Momoh 2009; Oyeyemi et al. 2015; Warner et al. 2010; Yusuf and Abiye 2019). Their studies involved geophysical investigation and geochemical analyses of water samples to delineate the interface between saline water and fresh water. In the eastern coast of Jordan, Batayneh (2006) adopted electrical resistivity method for deducing freshwater and saline water in the subsurface to establish their interfacial configuration. The use of geoelectrical techniques was also employed to assess interaction between saline water and coastal groundwater in the Lagos coastal basin and surmised that the aquifer in the coastal belt of Lagos is impacted not only by the Ocean water but also by the surrounding brackish waters (Ayolabi et al. 2013; Oyedele and Momoh 2009; Yusuf and Abiye 2018). However, in the present study, geophysical logs complemented with hydrophysical parameter analyses were used. Adoption of geophysical logs in evaluating physical properties of the rock matrix and contained fluids, has been recognised for many years in the petroleum industries where it was developed. However, application of geophysical logs in hydrogeological investigation has increasingly gained more attention in the recent years, particularly in shallow boreholes (Doveton and Prensky 1992; Kobr et al. 2005; Phongpiyah and Helmut 2012); coastal aquifers and salt/freshwater boundaries (Badaruddin et al. 2015; Buckley et al. 2001; Hwang et al. 2004); environmental investigations (Keys 1997; Krammer 1997; Taylor et al. 1990) and reviews of logging techniques applicable to hydrogeology of unconsolidated sedimentary aquifers (Buckley 1994). Several attempts have been made to equate the response of geophysical logs to geological and hydrogeological characteristics of the aquifers. In each case, in-depth knowledge of the local lithology and hydrogeology, and of the response of particular logging tools to that environment, has been the paramount factor in adjusting a theoretical equation to fit field conditions (Kobr et al. 2005). Geophysical methods applied in water resource researches include surface geophysical methods such as the electrical resistivity method, the electromagnetic method, as well as subsurface methods such as borehole logging which include natural gamma ray logs, resistivity logs, and spontaneous potential logs. The subsurface methods are considered more reliable, because the logging tools are in direct contact with the lithology, and the physical parameter related to the lithology can be determined directly. It is in this light that the present study is aimed at identifying and providing particular insight into the subsurface lithological units, saline water and freshwater horizons through determination of freshwater–saline water interface in the aquifer. The hydrogeological setting of the coastal areas of Lagos, as may be observed from this study, will give information on the lithostratigraphy and the current saline water extension so that the fresh groundwater aquifer can be effectively protected for future use.

Location and climate

The city of Lagos with a total land mass of 3474 km^2 (Wikipedia 2020) is located between longitude 002° 300′ E and 004° 30′ E, and latitude 6° 15′ N and 07°00′ N in southwestern Nigeria. The study area is an integral part of the southern flank of Lagos, situated between longitude 3° 14′ E and 3° 54′ E, and latitude 6° 20′ N and 6° 36′ N. Geographically, the study area is surrounded by water bodies, namely: the Atlantic Ocean, lagoons and creeks, and has large tract of land (Fig. 2). It is generally low-lying with a shallow water table (as shallow as 0.2 m), and some depressions were observed in places along the coastal belt which are prone to flooding as they are apparently below the surface of the lagoon. Coastal wetlands, sandy barrier islands, beaches, low-lying tidal flats and estuaries are typical landforms that characterise the area (Adepelumi 2008). The climate is tropical, with an annual average temperature and rainfall of about 27 °C and 1800 mm (70 inches), respectively (Oke et al. 2016). The area is characterised by torrential rainfall and governed essentially by two major seasons; the wet season spans between April and November, while the dry season covers the months of December to March.

Geological and hydrogeological settings

The metropolitan city of Lagos is situated on the stratified sedimentary rocks devoid of basement complex outcrops within the Dahomey Basin on the coastal belt. The Dahomey Basin extends from south-eastern Ghana in the west, through southern Togo and southern Benin Republic to south-west Nigeria as far as Okitipupa Ridge or Ilesha Spur. Detailed lithostratigraphic succession of the Dahomey Basin of which Lagos is an integral part is contained in Adekeye (2005); Obaje (2009) and Okosun (1990).

The sedimentary formation of Lagos area ranges in age from Cretaceous through Tertiary to Quaternary sediments. The Cretaceous sediments are the Abeokuta Group, while the Ilaro, Oshosun, Akinbo and Ewekoro Formations are Tertiary (Obaje 2009). Quaternary sediments are recent littoral alluvial, lagoon and coastal plain sand deposits (Longe et al. 1987) (Fig. 3). The alluvium deposits could perhaps be

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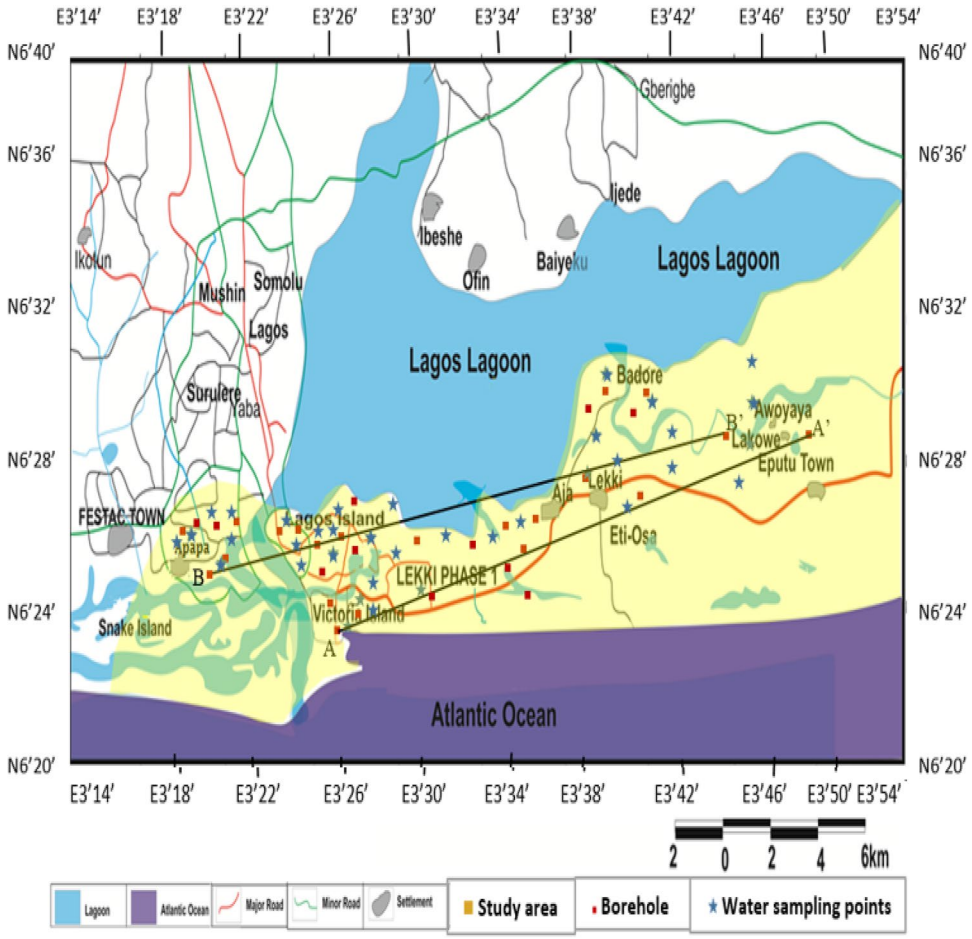


Fig. 2 Location map of study area

influenced by the fluctuation of the sea level during the Quaternary era. The sediments consist of admixture of coarse-to-medium grains and clean white loose sandy soil that graded into one another towards the lagoon and near the mouth of larger rivers (Oyeyemi et al. 2015; Yusuf et al. 2018). The subsurface is made up of semipermeable to impermeable geological formations (Akoteyon et al. 2011). The coastal plain sand in Lekki zone, estimated to be about 20 km wide, predominantly consist of clay, with only about 60 m of sand overlying about 240 m of clay, unlike the other areas of the basin where sand represents between 70 and 95% of about a 300 m thick horizon (Oteri and Atolagbe 2003; Yusuf and Abiye 2019).

The main aquifer in Lagos is the coastal plain sand, which is being tapped through hand-dug wells and boreholes. It is a multilayer aquifer consisting of three aquifer horizons separated by clayey and silty layers (Kampsax-Kruger and Sshwed 1977; Longe et al. 1987). The aquifer thickness increases from the northern area of the city towards the coast in the south. The sand percentage in the formation also varies from the north to the south (Longe et al. 1987). The first aquifer comprises loose, medium-to-coarse sand with an average thickness of about 10 m that underlies this sequence. This water table aquifer is exploited by shallow boreholes and hand-dug wells for domestic water use and it is highly prone to contamination (Longe et al. 1987). The first aquifer horizon is separated from the second sandy aquiferous zone by a semipermeable silty clay layer which attains a maximum thickness of 10 m. The second aquifer serves as an important groundwater resource for both domestic and industrial supplies and occurs between 20 and 70 m (Longe et al. 1987). The third aquifer zone ranging between 15 and 30 m in thickness, occurs at a greater depth in the Benin formation and can be accessed in the central Lagos metropolis at depths ranging between 118 and 166 m below sea level. This aquifer has a wide range of occurrence which underlies much of Lagos State and dips towards the coast (Longe et al. 1987). The Abeokuta Group aquifer is thick and extensive, and it contains water with recorded temperatures of up to 70 °C (Onwuka and Amadi 1989). It constitutes a deep aquifer only in the northern part of Lagos city (Ikeja area) where a few industrial boreholes intercept the aquifer at about 750 m below sea level. The general hydrogeological characteristics of aquifers of Lagos obtained through long-term pumping and step-drawdown tests was reported

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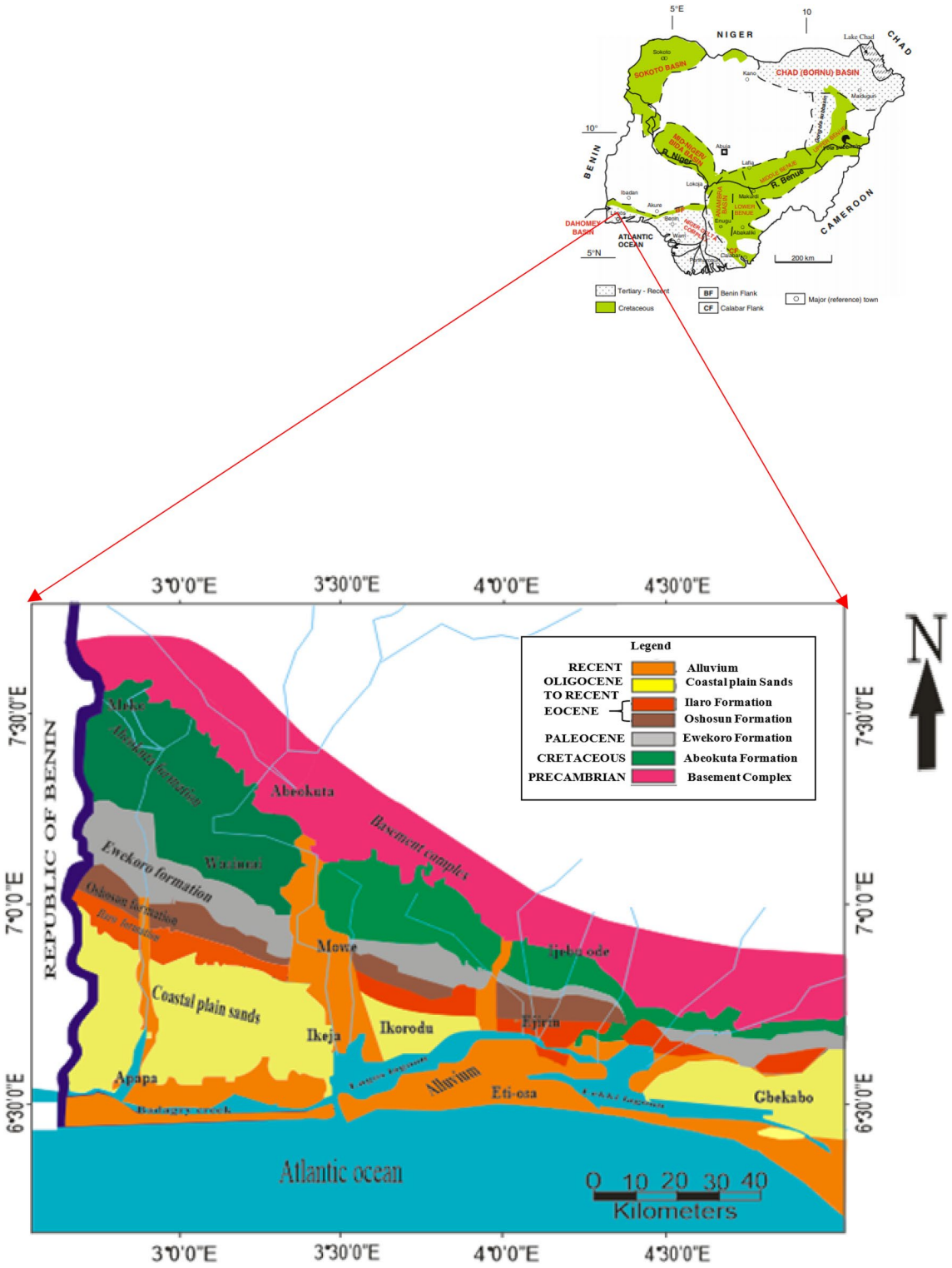


Fig. 3 Geological map of Lagos State (Source: modified after Billman 1976)

by Longe et al. (1987) as presented in Table 1. A considerable higher values of transmissivity, yield, specific capacity and permeability were recorded in the southern parts comprising Shomolu, Aguda and Apapa relative to

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Table 1 Average value of aquifer characteristics from long-term pumping and step-drawdown tests in parts of Lagos (Longe et al. 1987)

Long-term pumping tests						Step-drawdown tests		
Location	Aquifer horizon	Walton's (m^2s-1 × 10–3)	Theis' (m^2s-1 × 10–3)	Walton's (× 10–4)	Theis' (× 10–4)	Yield (m^2h^{-1})	Specific capacity(m^2h^{-1} m^{-1})	Permeability ($ms^{-1} \times 10^{-3}$)
Agege	3	–	1.38	–	–	54.4	2.96	7.5
Shasha	3	3.7	3.7	2.5	2.5	70.8	3.71	10
Shomolu	2	3.1	2.8	2.9	3	100.4	7.96	21.1
Shomolu	3	22.7	21.5	4.4	4.9	80.1	14.9	37
Aguda	3	25	23.8	3.1	3.8	97.2	28.6	245.8
Apapa	3	16.4	24	4	1.9	99.3	17	121.9

the northern region in Agege and Shasha-indicating higher aquifer productivity in the south.

Materials and methods

Lithological and geo-environmental assessments involving the analysis of 45 borehole logs and hydrophysical data from the study area were carried out. Geophysical logs acquired by government agencies and private drillers within a period of 10 years (2007–2017) were gathered and essentially used for the purpose of this research. The natural gamma content and the resistivity values were measured with ELGG™ sonde. The logging equipment used was composed of an RG PC Logger IITM (Plate 1) with PCL IITM software mounted on a vehicle. A known voltage was passed through a probe consisting of R16, R32 and R64 units in a water-filled hole and the resistivity was recorded. The natural gamma radiation of the lithology encountered in the hole was also measured simultaneously with a different probe. A natural gamma ray (scintillation) detector contains a sodium iodide crystal that gives a flash of light when struck by a gamma ray and the results of a gamma ray log are in counts per second. Nearly, all natural gamma rays in the earth come from a potassium isotope 40 and decay products of uranium and thorium. The logs obtained included natural gamma rays, short (SH N) and long normal (LO N) resistivity. The natural gamma rays were plotted against depth using Microsoft Office Excel. Natural gamma ray logs serve as a discriminatory tool in distinguishing and establishing the boundary between sand and clay. Natural gamma rays are usually highest in shales or clays (NGAM deflection to the right) and lowest in clean sand (NGAM deflection to the left), whereas on the ER log, high and low ER values connote presence of freshwater and salt/brackish water in the absence of clay/shale. Therefore, the types of lithology and lithological sequences were inferred from a qualitative interpretation of the natural gamma ray log component, while the combined NGAM and resistivity component interpretation gave an insight into the variations in litho-units and water qualities. The correlation of Coode et al. (1996), classifications of Zohdy and Martin (1993), modified by Ibrahim (2008) (Table 2), formed the basis of interpretations in the present study. In addition, representative logs for each area were chosen from the available geophysical logs and grouped into two axes: A and B for detailed analysis and discussion. The correlation of selected well logs into axes (A and B) from west to east was guided by the availability of borehole logs, its location, and the desire to develop a geological cross-section to enhance understanding of the subsurface hydrogeological processes. Representative borehole logs with the highest level of penetration were chosen for every locality across the stretch of study.

Furthermore, simplified conceptual models were proposed adopting combined knowledge gained from the NGAM and ER interpretations, and understanding of the

Table 2 Resistivity values for water and sediment rock (Zohdy and Martin (1993), modified by Ibrahim (2008)

Resistivity (Ω-m)	Sediment rock	Interpretation
0.5–2.0	Very porous sand, or saturated clay	Seawater, very saline water TDS = 20,000 mg/l
2.0–4.5	Porous sand, or saturated clay	saline water, TDS = 10,000 mg/l
4.5–10.0	Sandy saturated or Sandy clay	Salty brackish water, TDS = 10,000 − 5000 mg/l
10.0–15.0	Sandy clay, sandy gravel	Brackish water, TDS = 5000 − 1500
15.0–30.0	Sand, gravel, some clay	Poor quality fresh water, TDS = 1500 − 700 mg/l
30.0–70.0	Sand, gravel, minor clay	Intermediate quality fresh water, TDS ~ 100 mg/l
70.0–100.0	Sand, gravel, no clay	Good quality fresh water, TDS small
> 100.0	Coarse sand, gravel, no clay	Very good-quality fresh water, TDS very small

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hydrogeological settings of the area from literature. Based on the above, two models were developed in a parallel and vertical directions to the lagoon and Ocean, respectively. Specifically, the average value of upper and lower saltwater interfaces from geophysical boreholes for every discerned locality was used to conceive the parallel model, while the choice of boreholes adopted for vertical model prediction was based on the location of selected boreholes fitting to enable vertical borehole correlation between the lagoon and the Ocean from north to south.

To complement the geophysical borehole logs, water sampling consisted of 40 shallow hand-dug wells were combined. The samples were obtained in February 2017 essentially to determine the in situ physico-chemical parameters of the waters. In most cases, it was possible to sample groundwater directly from the dug wells, while being compelled to take samples via household taps at some places for the parametric measurements. The water level depth, temperature, and conductivity were taken on-site with the aid of a Solinst temperature, level and conductivity meter. The pH and total dissolved solids (TDS) were also measured in situ, using the Hanna HI 98,130 multiparameter water quality meter. The coordinates at every location were determined using a GARMIN GPS Map 60CSx Global Positioning System.

Results and discussion

Seventeen out of the 45 borehole logs interpreted were not affected by saline intrusions (Table 3). The A axis (A-A′) constituted logs at the southern part of the coastal belt next to the Ocean, while the B axis (B-B′) comprised the northern part of the coastline next to the lagoon. The A axis comprised Victoria Island–Lekki–Ajah–Sangotedo and Awoyaya, while the B axis was made up of Apapa–Ikoyi–Lakowe and Akodo from west to east. Generally, information from available borehole logs, combined with qualitative interpretation of the natural gamma rays, showed that the study area is underlain by alternation of sand and clay with admixture of varying proportions, indicated by changes in the values of gamma rays as related to different layers. The observed lithological sequences of sand, clayey sand, sandy clay and clay (Figs. 4 and 5) were consistent with the alternating sequence of clay and sand reported for the CPS in the Dahomey basin (Ayolabi et al. 2013; Jimoh et al. 2018; Yusuf and Abiye 2019). The surficial aquifer hosted by alluvium sand was essentially an unconfined in occurrence with perched characteristics in some places, while deep aquifer systems formed by the alternation sequence of clay/shale (aquiclude or aquitard), clayey sand and clean sand units delineated at depth constitute the confined aquifers in the study area. The logs revealed three aquiferous zones of varying thicknesses, the majority of which were mostly regional and traceable along distances, while others exhibited local occurrences (Figs. 4 and 5). The interpretation summary for various freshwater zones and freshwater/saline water interface(s) obtained from the integration of the natural gamma ray and resistivity logs for the entire study area, is presented in Tables 3 and 4 representing data summary used for the cross-sections development, while Tables 5 and 6 present data summary for both parallel and vertical models conceptualization. Generally, the depth to the surficial aquifers was generally shallow < 10 m (Figs. 4, 5). However, the depths to the top of the freshwater–saltwater interface for both upper and lower saline intrusion layers vary across the study area (Fig. 6). The shallowest depth of 14 m for the freshwater/saline water upper interface was recorded at the western and central parts of the study: at Apapa (BH 16) and Ikoyi (BH 42), while the deepest freshwater–saltwater interface depth of 88 m was intercepted at Lekki (BH 31) towards the east, thus connoting gradual increase in saline water intrusion depth from west to east (Table 3).

A-A′ axis (Victoria Island–Lekki–Ajah–Sangotedo–Awoyaya)

The A-A' axis traversed within the land tract next to the Ocean from the central part eastwards and the representative boreholes were drilled to 230 m (BH 26), 240 m (BH 25), 220 m (BH 20), 130 m (BH 2) and 360 m (BH 35) depths (Fig. 4). The resistivity values along A-A′axis (west to east) ranged between 44 Ωm and 51 Ωm; 48 Ωm and 54 Ωm; 64 Ωm and 68 Ωm with the corresponding freshwater–saltwater interface thicknesses ranging between 66 and 126 m; 49 m and 134 m; and 25 m and 157 m for Victoria Island, Lekki and Ajah. Sangotedo and Awoyaya were unaffected (Table 4A). The NGAM log shows values ranging between < 20 and 200 cps in the central (BH 26, BH 25, BH 20) and exhibits relative constant value of 50 cps except at the surficial level in the eastern part of the study (Fig. 4). This may be indicating lithological variation, particularly of sandy clay layer towards the east. This is further supported by the regional occurrence of the clay column along the traverse, which increases in thickness in an easterly direction, varying from 80 m at Sangotedo (BH 2) and extends to > 150 m at Awoyaya (BH 35) within the depth of investigation. The extensive occurrence of the clay unit which truncates the coastal plain sand aquifer in the south-eastern part of the study area probably accounted for the difficulty experienced in the availability and exploitation of fresh groundwater. Furthermore, combined interpretation of NGAM and ER identified three layers of fresh aquifers indicated by low NGAM values and high ER values (> 100 Ωm) hosted by sand and clayey sand. The aquifers are surficial aquifer with varying depths between 10 and

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Table 3 Ranges of freshwater–saltwater interface thicknesses and corresponding resistivities and freshwater zones

	Address	Coordinates		Freshwater–saltwater interface (m)		Resistivity at freshwater–saltwater interface (Ωm)		NGAM at freshwater–saltwater interface (cps)		Freshwater zones (m)	Remarks
				Top	Bottom	Top	Bottom	Top	Bottom		
BH1	1st Avenue Ikoyi	N 06 26.781′	E003 27.106′	75	108	18	21	18	13	0–27, 37–45, 47–55, > 130	Affected
BH2	Ajayi Apa /Sangotedo	N 06 26.010′	E003 44.216′	–	–	–	–	–	–	14–53	Unaffected
BH3	Ajegunle water works	N 06 25′44.34″	E003 19′10.61″	30	70	4	18	23	18	0–21, 76–130	Affected
BH4	Osborne Estate Ikoy	N 06 24.781′	E003 28.205′	51	112	9	15	10		10–13, > 113	Affected
BH5	Badore	N 06 29.781	E003 42.205′	–	–	–	–	–	–	5–10, 53–76, 80–130	Unaffected
BH6	MRS Apapa	N 06 25.499′	E003 20.138′	–	–	–	–	–	–	10–18, 30–36, 37–50, 52–70	Unaffected
BH7	Etim nyang CRT. VI	N 06 24′00.20″	E003 26′02.60″	–	–	–	–	–	–	16–34, 66–93,106–127, 148–277	Unaffected
BH8	APMTYARD, APAPA	N 06 26′31.53″	E003 22′47.98″	–	–	–	–	–	–	13–25, 30–37,51–116, 124–190	Unaffected
BH9	Azare cr.Apapa	N 06 26 .109′	E003 21.964′	–	–	–	–	–	–	5–35,47–54, 58–120,135–228	Unaffected
BH10	Oniru Estate	N 06 25′48.90″	E003 29′55.00″	71	128	20	28	17	13	16–27, 167–202	Affected
BH11	Cappa VI	N 06 26′27.50″	E003 26′01.20″	77	117	28	31	21	14	15–30, 137–180, 183–198, 206–220	Affected
BH12	Ijora Olopa	N 06 27′58.20″	E003 22′43.00″	17	66	46	50	20	14	12–15, 106–145, 157–158,169–217, 225–229	Affected
BH13	Ijora CFAO	N 06 27′13.50″	E003 22′08.30″	–	–	–	–	–	–	28–35, 38–42, 46–91, 104–123, 128–132	Unaffected
BH14	Clover,Lekki	N 06 25′30.34″	E003 30′47.44″	39	114	42	49	21	16	14–18, 170–189,199–207	Affected
BH15	Apapa Wharf	N 06 25′32.80″	E003 22′34.29″	39	115	21	31	23	11	33–38, 124–170	Affected
BH16	Apapa DSTV	N 06 26.386′	E003 19.614′	14	58	57	56	14	15	11–13, 78–116, 131–160, 168–174, 177–179	Affected
BH17	Ajah/Eastline project	N 06 26.572′	E003 35.156′	–	–	–	–	–	–	24–43, 52–58, 64–70, 74–147	Unaffected
BH18	Victoria Island	N 06 25′38.90″	E003 25′59.40″	63	129	39	35	24	14	155–208, 217–222, 234–272	Affected
BH19	Lagos Island/FIRS	N 06 26.922′	E003 23.775′	–	–	–	–	–	–	14–19, 33–56, 70–112, 132–178	Unaffected
BH20	Ajah/ITB Construction	N 06 26.819′	E003 32.985′	25	157	64	68	12	12	18–24, 158–165, > 200	Affected
BH21	Lekki/JP EST. PHS III	N 06 27′48.10″	E003 34′40.10″	78	130	68	68	25	20	28–36, 47–74, 131–143,158–165, 174–183,190–230	Affected
BH22	V/I Joseph N. Close	N 06 25′33.00″	E003 25′32.40″	66	135	35	37	14	13	155–190, 196–212, 217–236	Affected
BH23	MTN Call Centre Lekki	N 06 27.966′	E 003 34.120′	–	–	–	–	–	–	5–13, 25–31, 38–43, 60–116	Unaffected
BH24	NNS Beecroft Naval Base, Apapa	N 06 27′32.8″	E 003 22′16.7″	–	–	–	–	–	–	12–21, 26–35, 42–48, 53–162, 192–214	Unaffected
BH25	OMORIRE JOHNSON, Lekki	N 06 26′ 11.90″	E 003 31′ 32.40″	49	128	48	54	27	21	6–26, 173–187, > 209	Affected
BH26	OZUMBA NBADIWE, VI	N 06 24′ 22.10″	E 003 25′ 04.06″	66	126	44	51	30	12	12–30, 139–194, > 202	Affected
BH27	Tin-Can, APAPA	N 06 26′ 07.72″	E 003 20′ 09.88″	–	–	–	–	–	–	6–23, 31–36, 87–199, > 208	Unaffected
BH28	PRODECO Guest House,VI	N 06 24′ 20.796″	E 003 24′ 49.62″	45	134	26	40	42	14	15–21, 148–153, 160–170, 173–215	Affected
BH29	IKATE ELEGUSHI, Lekki	N 06 26′ 36.60″	E 003 29′ 35.20″	–	–	–	–	–	–	20–30, 98–118, 128–194, > 208	Unaffected
BH30	Femi Okunnu, Lekki	N 06 26′ 33.30″	E 003 30′ 26.90″	82	115	46	49	20	16	12–14, 182–220	Affected
BH31	WILLOW GREENS Estate, Lekki	N 06 26′ 55.70″	E 003 30′ 38.60″	88	115	47	49	20	20	12–13, 166–189,200–236,243–247	Affected
BH32	Zenith Bank Head Office, VI	N 06 25′ 48.20″	E 003 26′ 04.60″	66	129	40	38	21	20	153–205, 217–240	Affected
BH33	Civil Centre Nigeria	N 06 25.781′	E003 27.106′	–	–	–	–	–	–	20–106	Unaffected

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Table 3 (continued)

	Address	Coordinates		Freshwater–saltwater interface (m)		Resistivity at freshwater–saltwater interface (Ωm)		NGAM at freshwater–saltwater interface (cps)		Freshwater zones (m)	Remarks
				Top	Bottom	Top	Bottom	Top	Bottom		
BH34	Oniru Royal Estate	N 06 25.781′	E003 27.106′	22	90	10	24	30	10	–	Affected
BH35	Eko Akete, Awoyaya	N 06 28.213′	E 003 46.970′	–	–	–	–	–	–	26–47, 230–270	Unaffected
BH36	Federal Palace Hotel	N 06 25.796′	E 003 24.431′	21	130	17	30	20	54	–	Affected
BH37	Victoria Island	N 06 25.451	E 003 25.705	38	97	20	20	14	9	18–31,107–238	Affected
BH38	HFP Cemetery, Lakowe	N 060 28.241	E 0030 47.900	–	–	–	–	–	–	13–36, 70–95	Unaffected
BH39	NIGERDOCK,SNAKE ISLD	N06 25.528	E003 19.422	28	58	12	17	21	20	109–129	Affected
BH40	LSWC, Ikoyi	N 06 25.781′	E003 25.754′	18	66	3	5	51	24	110–130	Affected
BH41	Niger Biscuit, Apapa	N 06 25. 781′	E003 19 106′	53	117	22	28	9	32	123–130	Affected
BH42	Osborne Est, Ikoyi	N 06 25.781′	E003 26 106′	14	136	12	52	22	9	137–142, 150–220	Affected
BH43	Police Headquarters, Obalende	N 06 26.913	E 03 24.448	26	47	36	18	22	26	51–112	Affected
BH44	Takwa Bay Island, Apapa	N 06 25.789	E 0030 23.304	38	105	18	20	23	25	10–21, 26–35, 106–143, > 188	Affected
BH45	L/I, Apongbon wwks	N 06 27.634	E 003 22.899	–	–	–	–	–	–	50–57,74–104,110–217,221–246	Unaffected

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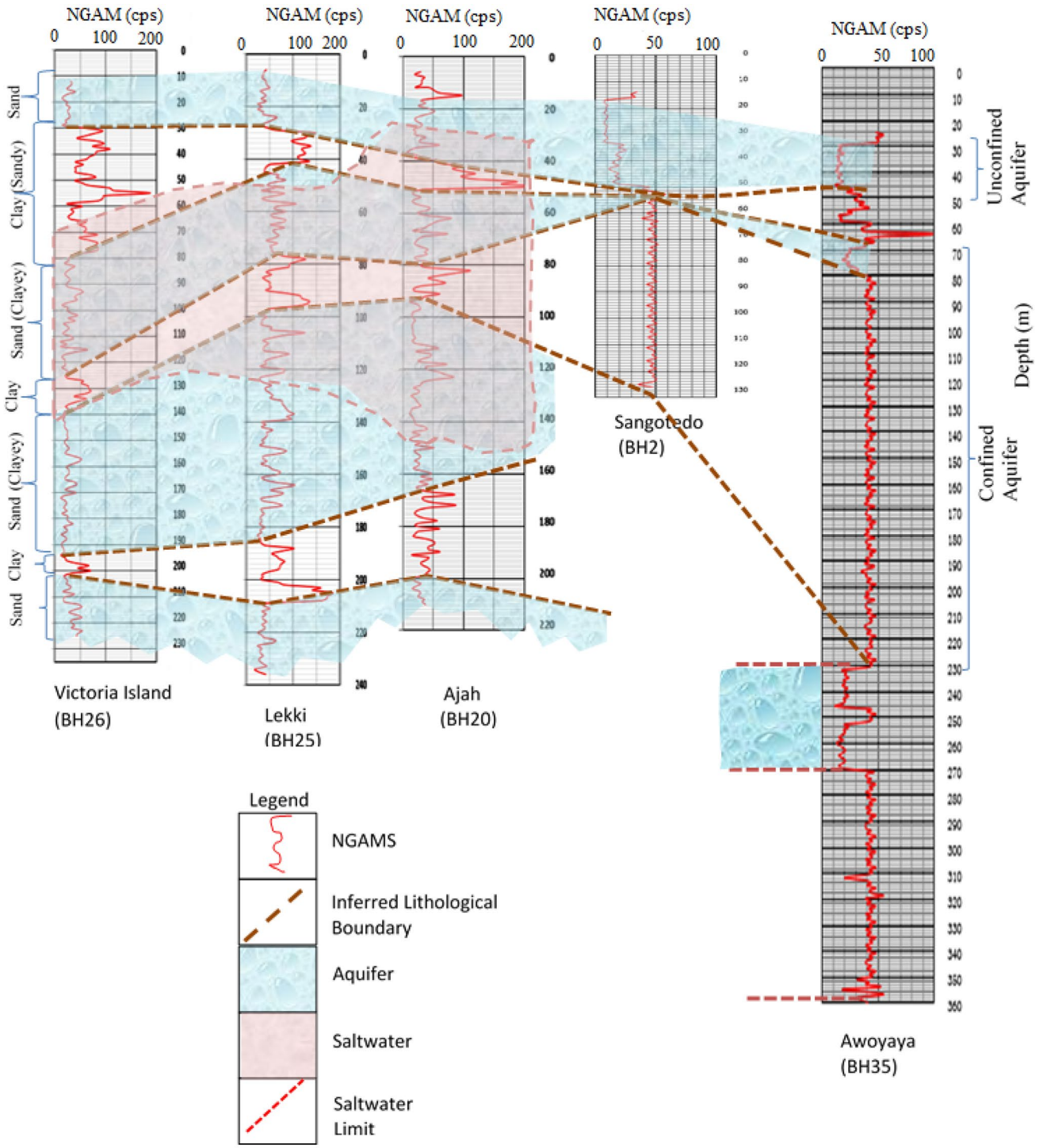


Fig. 4 Typical fresh/saline water interface along the A–A′ axis using natural gamma ray logs

40 m and the deep aquifer ranging between 135 and 190 m and 200 m to 270 m from west to east, respectively. The delineated aquifer is consistent with water table aquifer, upper CPS and lower CPS reported by Longe et al. (1987). The saltwater zone, however, is indicated by a low ER Values usually < 70 Ωm and low NGAM values generally ≤ 30 cps and the freshwater/saline water interface was found to occur from 25 to 157 m in the subsurface between upper and lower freshwater layers. The occurrence of phreatic aquifer at such a shallow depth subject it to high vulnerability due to infiltration of contaminants from surface as well as saltwater intrusion. Therefore, groundwater exploration of this

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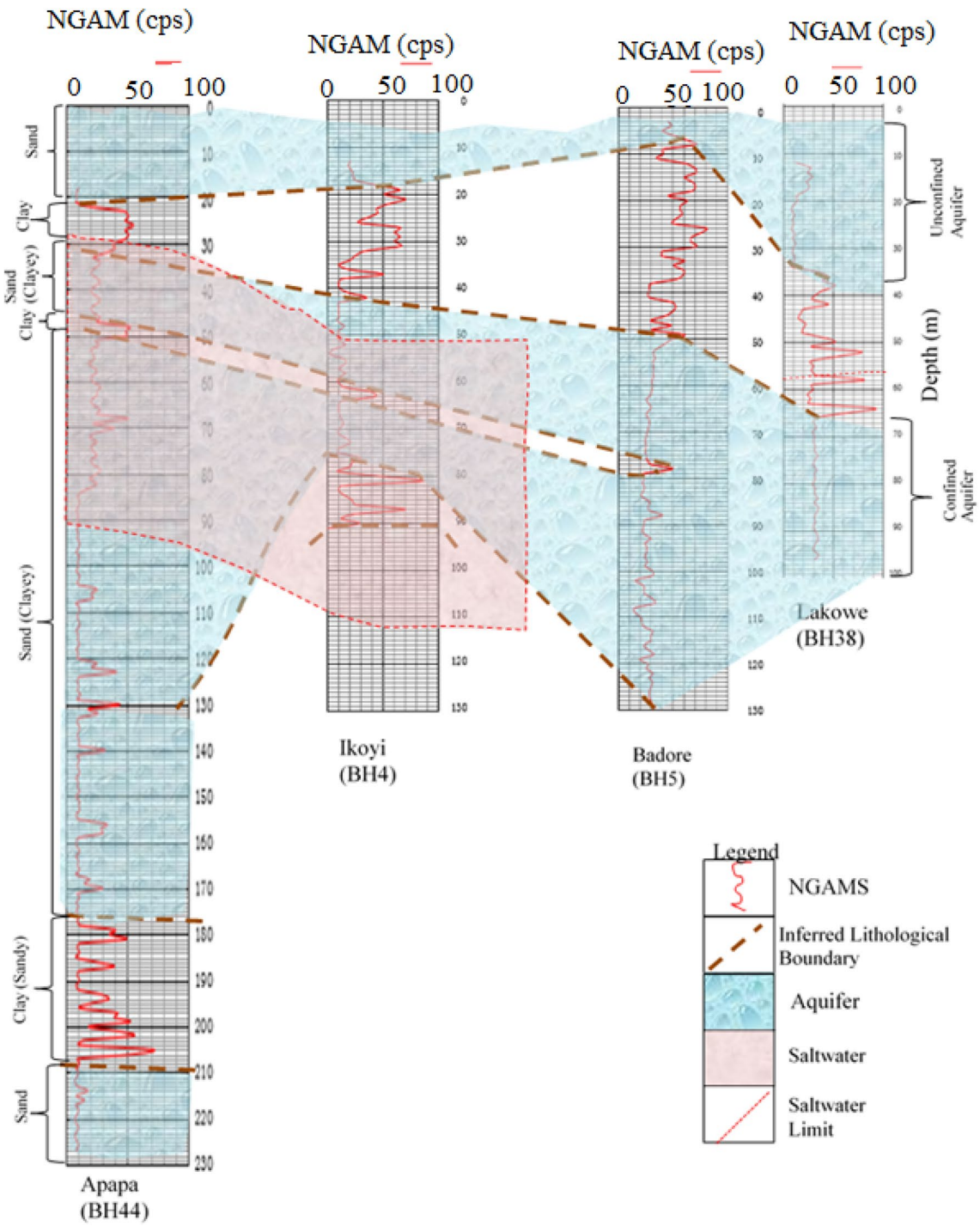


Fig. 5 Typical fresh/saline water interface along the B–B′ axis using natural gamma ray logs

aquifer for drinking and other domestic purposes portends great danger for the inhabitants (Ayolabi et al. 2013; Jimoh et al. 2018; Yusuf and Abiye 2019). However, due to the depth of occurrence of deep aquifer layers, it is considered the most reliable and promising zone for fresh groundwater exploration.

B-B′ axis (Apapa–Ikoyi–Badore–Lakowe)

The geo-section in the B-B' axis next to the lagoon in the north comprises the following boreholes and corresponding depths; BH 44 (220 m), BH 4 (130 m), BH 5 (130 m) and BH 38 (100 m), from Apapa in the west to Lakowe in the

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Table 4 Data summary of geo-section parameters for A and B axes

S/N	Location	Drilled depth (m)	Resistivity at the interface (Ωm)		NGAM at the interface (cps)		Interface depths (m)	
			Upper	Lower	Upper	Lower	Upper	Lower
A: A-axis								
BH26	Victoria Island	230	44	51	30	12	66	126
BH25	Lekki	240	48	54	27	21	49	128
BH20	Ajah	220	64	68	12	12	25	157
BH2	Sangotedo	130	–	–	–	–	–	–
BH35	Awoyaya	360	–	–	–	–	–	–
B: B-axis								
BH44	Apapa	220	18	20	23	25	38	105
BH4	Ikoyi	130	9	15	10	–	51	112
BH5	Badore	130	–	–	–	–	–	–
BH38	Lakowe	100	–	–	–	–	–	–

Table 5 Model parameters for the parallel conceptual model

Location	Upper intrusion zone		Lower intrusion zone			
	Average upper interface depth (m)	Average lower interface depth (m)	Intrusion thickness (m)	Average upper interface depth (m)	Average lower interface Intrusion depth (m)	Intrusion thickness (m)
Apapa	28	108	80	–	–	–
Victoria Island A	30	110	80	133	168	35
Victoria Island B	68	120	52	128	157	29
Lekki	40	70	30	92	170	78
Ajah	15	65	40	82	120	38
Sangotedo	Unaffected	Unaffected	Unaffected	Unaffected	Unaffected	Unaffected
Awoyaya	Unaffected	Unaffected	Unaffected	Unaffected	Unaffected	Unaffected

Table 6 Model parameters for the perpendicular conceptual model

Location	Upper interface depth (m)	Lower interface depth (m)	Intrusion thickness (m)
Ikoyi A	18	66	48
Ikoyi B	56	124	68
Victoria Island A	45	134	89
Victoria Island B	66	135	69

east (Fig. 5). The resistivity values range between 18 Ωm and 20 Ωm, and 9 Ωm and 15 Ωm, with freshwater–saline water interface occurrence at depth ranging between 38 and 105 m; and 51 and 112 m for Apapa and Ikoyi, respectively. However, the exceptions are Badore and Lakowe devoid of saline intrusion within the depth of investigation towards the east (Table 4b). Therefore, the occurrence of intrusion tends to be enhanced by the location and lithology of the aquifer. The NGAM values range between a minimum of 25 cps and a maximum of 100 cps connoting variation in lithology and three aquifer layers were identified from the combined interpretation of NGAM and ER logs (Fig. 5). The observed increase in resistivity values as shown in the resistivity logs can be explained with an increase in sand content and the occurrence of more freshwater or water with a lower TDS value than the layers above and below (Zohdy et al. 1993). It is, however, expected that resistivity gradually grades through intermediate water to good-quality water as it increases with depth.

Furthermore, comparison of A-axis (next to the Ocean) with B-axis (next to the lagoon) revealed higher thickness of the saline water zone in A-axis relative to B-axis and vice versa (Figs. 4, 5) and probably indicated more availability of freshwater in proximity to the lagoon than the Ocean. According to Barlow (2003) and Jimoh et al. (2018), in a coastal region, groundwater generally flows from inland recharge areas, where the hydraulic head/pressure is higher to a lower hydraulic gradient or less pressure areas in the coast. In the present study, the general groundwater flow is in a north–south direction from the inland towards the Ocean (Yusuf and Abiye 2019). However, variations in

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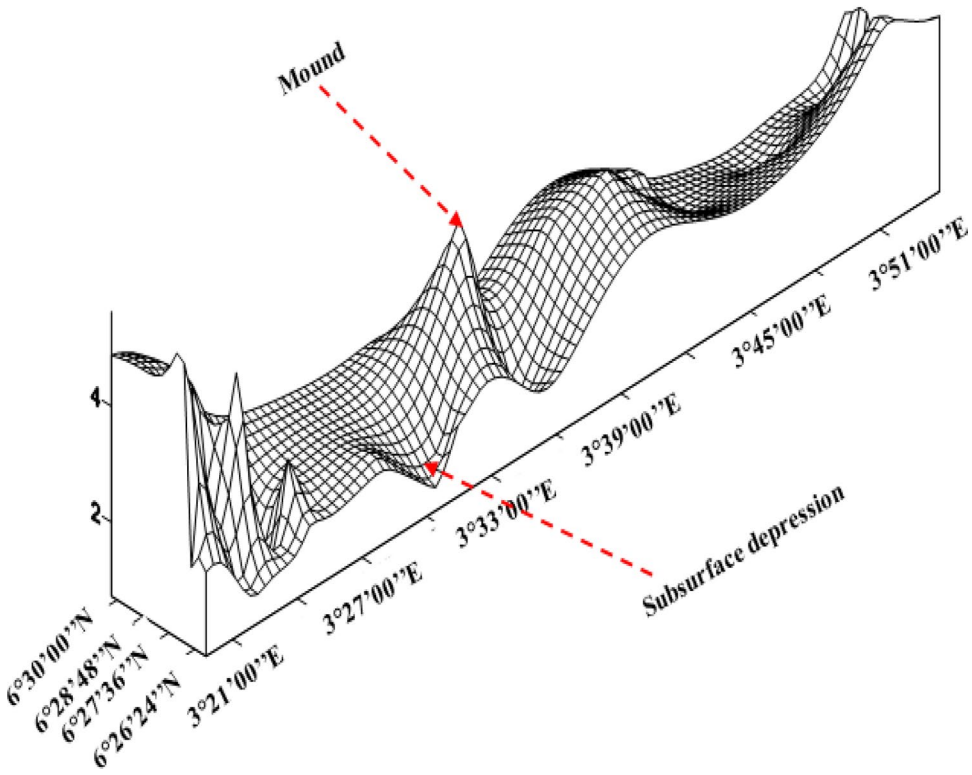


Fig. 6 Three-dimensional view of the subsurface topographical features controlling groundwater flow direction in the study area

groundwater flow may be dictated by topographical features such as mounds, subsurface depressions and the occurrence of alternating clay layers (Figs. 6, 7). The observed depression zone is well in agreement with Kingston et al. (1983) who suggested that the subsurface features in the study area were part of miogeoclinal depressions formed at the edge of the rifting Atlantic Ocean in the Quaternary. In addition, due to density difference between freshwater and saline water at the interface, the freshwater (lighter density) remains afloat the saline intrusion (heavier density) and this could possibly explain the presence of surficial freshwater aquifer above saltwater intrusion.

In addition, conceptual models for the saline intrusions were predicted based on the average values of upper and lower freshwater/saltwater interface obtained for a particular locality across the length of the study area. Two distinct models were proposed for the basin, namely the specific model taken parallel and perpendicular to the

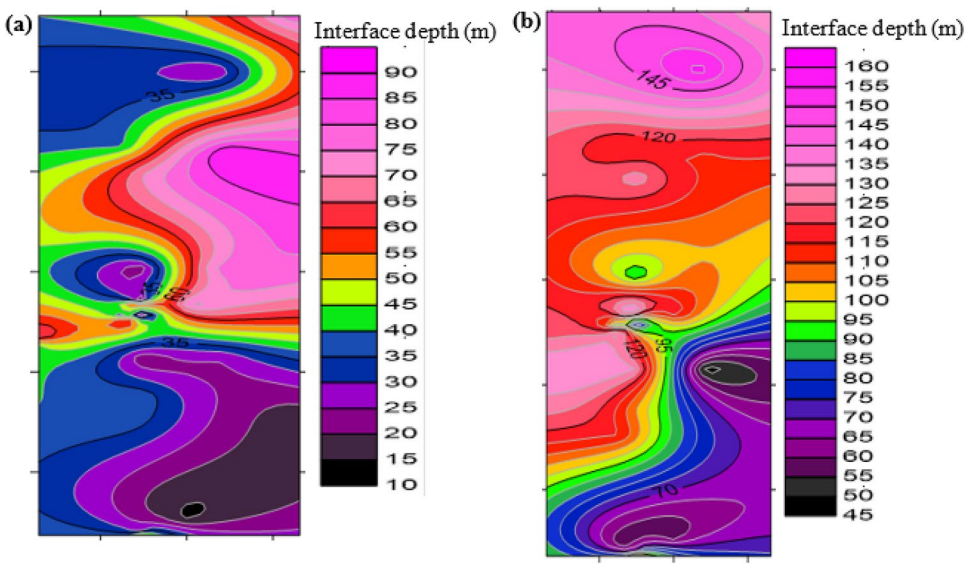


Fig. 7 Map showing depth to the top of the saltwater–freshwater interface **a** upper intrusion layer **b** lower intrusion layer across the study area

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ocean in a west–east and north–south directions, respectively (Figs. 8, 9) as well as the modification of general model proposed by Yusuf et al. (2018) (Fig. 10).

The first predictive model (Fig. 8) was conceived parallel to the Ocean and along the coast and highlighted the lateral and vertical extent of seawater intrusion. From the model, it is apparent that two distinct major saltwater zones with varying thicknesses, separated by clay layer, existed beneath the study area around the depth between 15 and 120 m; and 82 and 170 m. Generally, the depth to the top of the first saline intrusion layer varied between 15 and 68 m, while the upper interface of the second layer ranged between 82 and 133 m. The thickness of the first and second intrusion layers from west to east varied between 80 and 30 m; and 78 and 29 m, respectively (Table 5). This is in agreement with the two zones of saltwater intrusion delineated by Adepelumi et al. (2008) at depth ranging between 10 and 30 m; and 60 and 100 m in parts of the study area. However, the present study revealed wider spread of saline incursion into the groundwater of Lagos coastal basin connoting possible advancement of saline invasion and further deterioration of the fresh coastal aquifer. Besides aquifer geometry and configuration, the greater impact of the intrusion observed at the western and central parts of the study area may be due to location (proximity to saline/brackish water source) and human-induced activities. This may be supported by reduction in magnitude of the intrusion and it eventual pinch out at some points near the surface at a distance away from saline sources in the eastern limit of the study area.

The observed local saltwater intrusion of the phreatic aquifer above the main zone of intrusion wedge at Ajah (Fig. 8) was probably due to over-exploitation through excessive pumping of the limited fresh groundwater resources and thus perturbed the hydrodynamic equilibrium in the aquifer and/or reduction in groundwater gradients, thus leading to the displacement of freshwater by saltwater (Adepelumi et al. 2008; Lee and Song 2007; Oyedele and Momoh 2009). In general, the depth to saline water is shallower in proximity to the saline source except where it is constrained by geological features. Therefore, groundwater users around the study area, targeting high quality and reliable fresh groundwater accessibility, may have to drill conservatively to various depths ranging between 150 and 200 m.

The vertical model (Fig. 9) was conceived perpendicular to the Ocean in the south and the lagoon in the north to show the variations in the extent of saline intrusion. The interface depths from the north (lagoon) to the south (Ocean) ranged between 18 and 66 m for the upper interface while the lower interface varies between 66 and 135 m (Table 6). It is obvious that the saline incursion into the coastal aquifer in the central parts of the study is bi-polar in nature, i.e. saline incursion from the brackish lagoon water in the north as well as the Atlantic Ocean in the south. The depth to the saline water zone was found to be relatively shallow, except where

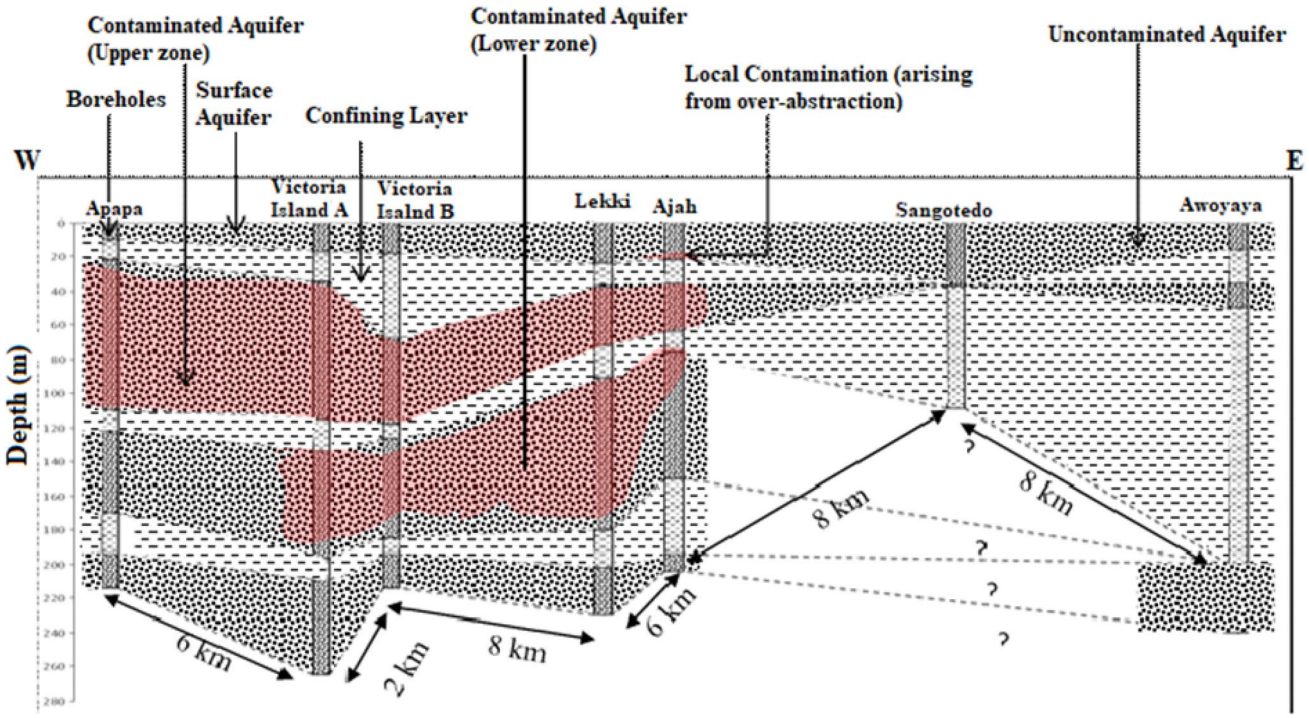


Fig. 8 Conceptual cross-section model parallel to the Ocean and lagoon

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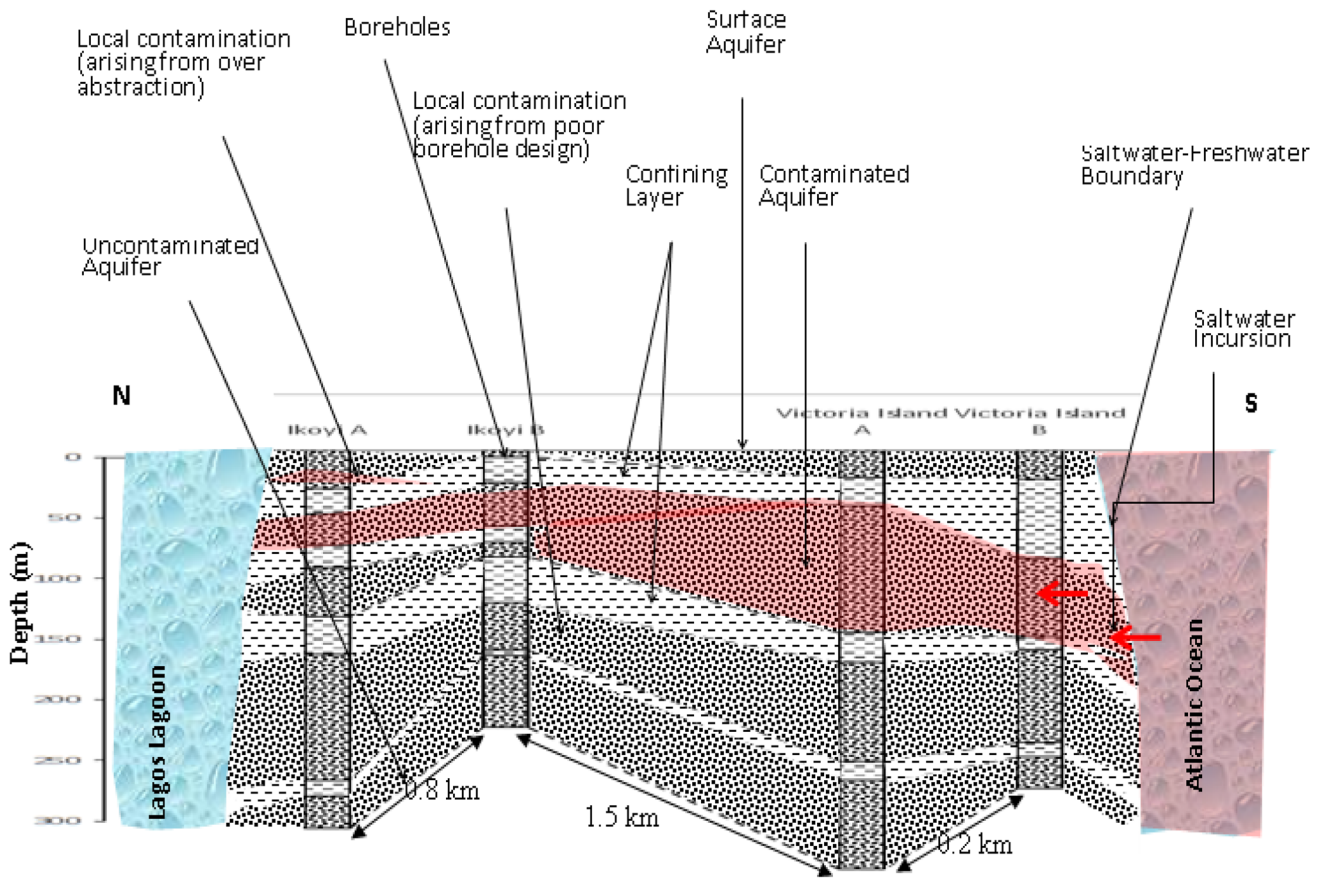


Fig. 9 Conceptual cross-section model perpendicular to the Ocean and lagoon

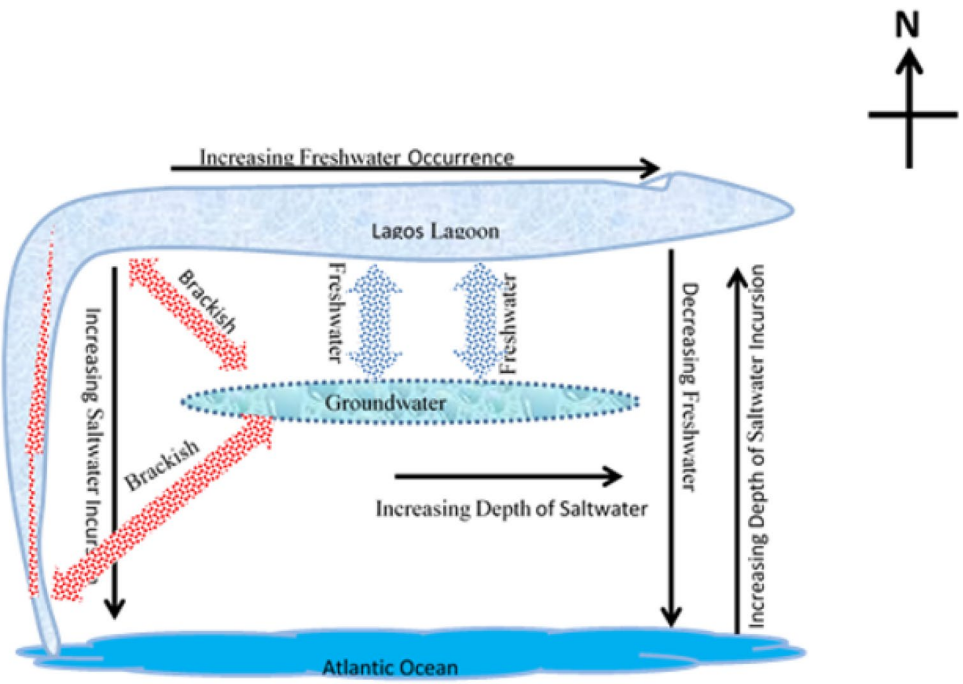


Fig. 10 General conceptual model for the study area

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it was constrained by a confining bed. Greater thickness of the saline water zones between 69 and 89 m was observed towards the ocean in Victoria Island, while less thick beds ranging between 48 and 68 m separated by local clay units were found towards the lagoon coastline at Island and Ikoyi.

Local saltwater contaminations were observed at the phreatic aquifer suspected to be arising from over-abstraction of the groundwater (Fig. 9). The saline invasion of fresh coastal aquifer as deduced from the geophysical logs is consistent with the hydrogeochemical study of the shallow groundwater in parts of the area under investigation by Oyeyemi et al. (2015) who attributed high TDS and Cl concentration ranges between 10,405 and 12,005 mg/l and 432 and 724 mg/l, respectively, to interaction between saline/brackish water and freshwater. Moreover, Over-pumping of groundwater can lead to land subsidence as reported in many groundwater aquifers by various authors around the world (Galloway et al. 1999; Galloway and Burbey 2011). Therefore, unless proactive measures are taken, over-exploitation of groundwater in the study area may enhance possible occurrence of regional/local land subsidence.

The generalised conceptual model (Fig. 10) for the study area explains the possible interaction between groundwater and surface water bodies. The model was developed based on the understanding of the hydrogeology of the subsurface from previous works, including isotope studies, geophysical and chemical data from the present study. The basin is subject to intrusion from the lagoon in the north-west, creeks and canals connected to the lagoon in the south-west and Ocean in the south (Fig. 10). This shows that saltwater can contaminate the freshwater aquifer through several pathways, including lateral invasion, upward saline movement (up-coning) and downward movement (infiltration or percolation) from coastal waters. The model revealed that an aquifer in close proximity to the saline lagoon and creek waters suffers from acute saltwater intrusion as a result of interaction between the surface water bodies and the coastal fresh groundwater. The severity of the intrusion is thus prominent at the western limit and central part of the study where all the tributaries are connected to the saline parts of the lagoon, linking the Atlantic Ocean via the commodore channel (Oyedele and Momoh 2009). However, the salinity of the surface water bodies depends on the amplitude and direction of the Ocean tides (Oyedele and Momoh 2009). The very high permeable nature of the aquifer at the southern parts coupled with the gradual decrease in electrical conductivity (EC) values of both surface water and groundwater away from the Ocean is a further attestation to interaction between the water bodies. Also, another factor contributing to salinity that is worthy of note is the occasional coastal flooding resulting from climatic change which led to a rise in the sea level and its consequent transgression in a landward direction. Repeated changes in sea level influence and change the direction of groundwater flow in coastal aquifers as reported by Buckley et al. (2001) and Jimoh et al. (2018). When the sea level rises, the freshwater–saltwater interface is pushed landward (reversed groundwater flow), and freshwater zones of the aquifer are displaced by saltwater. This may be responsible for the reversed transition observed at the deep confined aquifer, where saltwater overlies the freshwater aquifer. This, and excessive-drafting of groundwater (combined), are making the problem worse.

Finally, Table 7 presents the physical parameters measured in situ. It was revealed that the groundwater samples are odourless and colourless in most places, while a few samples have shown a yellowish colour with offensive odour. The yellowish colour may be related to the presence of suspended solids. The obtained pH value ranging from 5.1 to 8.6 indicated a slightly acidic to slightly saline water around the study area. It was observed that less than 1% fell below the permissible limit of 6.5. All other samples, except three, were within the desirable limit of 8.5 as suggested by the World Health Organization (WHO 2006). The variations in pH might have been influenced by atmospheric contributions, organic matter decomposition and anthropogenic inputs. The EC and TDS recorded varied between 48 and 3832 µS/cm; and 35 and 1916 mg/L, respectively. The observed EC and TDS exceeded the permissible limit of 750 µS/cm and 500 mg/L (WHO 2006) in about 90% of the samples from Apapa in the west to the central parts of the study (GW1–GW19), while about 90% of the samples (GW20–GW45) towards the east were within the allowable limit of the WHO (2006). Generally, water containing more than 500 mg/L of TDS is not considered potable. According to Freeze and Cherry's (1979) classification, over 90% of the entire groundwater studied were categorised as freshwater (TDS < 1000 mg/L), while about 10% occurring within the west and central parts, were in the brackish water category (TDS > 1000 mg/L). This corroborates the severity of saline intrusion in the western and central parts of the study relative to the eastern region as deduced by the analysis of geophysical logs. There is thus an urgent need for government intervention, not only to formulate a policy to regulate abstraction rates of groundwater within the coastal areas, but also to erect and mount wave breakers of an appropriate height along the Ocean shore to prevent a future calamity. Other forms of remediation strategy include, but are not limited to, freshwater injection through remediation wells, erection of artificial barriers and saltwater extraction techniques to prevent or impede the salinisation process within coastal aquifer systems (Labregére et al. 2006; Raicy et al. 2012).

Conclusion

The combined analyses of geophysical well logs and hydrophysical parameters gave a reasonable and reliable information adoptable towards understanding the interaction

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Table 7 Physical parameters of surficial water samples in the study area

Sample ID	Site	X	Y	PH	Temp (°C)	Depth (m)	EC (μS/cm)	TDS (mg/l)
GW1	APAPA	06°26.520′	003°19.876′	7.5	29.2	3	1542	785
GW2	APAPA	06°26.631′	003°19.775′	7.4	28.7	1.69	949	536
GW3	APAPA	06°27.854′	003°20.315′	AD	AD	AD	AD	AD
GW4	APAPA	06°28.163′	003°21.560′	5.1	28.7	4.44	1912	1020
GW6	APAPA	06°26.555′	003°22.017′	7.6	29.8	1.15	3089	1637
GW7	APAPA	06°26.899′	003°19.837′	7	29.6	6.16	1360	728
GW8	ISLAND	06°27.196′	003°23.052′	8.5	30.6	3.06	3832	1916
GW9	ISLAND	06°26.908′	003°24.627′	7.2	29.2	2.88	1023	558
GW10	ISLAND	06°27.483′	003°23.925′	7.6	29	0.65	1681	862
GW11	ISLAND	06°27.322′	003°23.600′	7.6	29.4	0.49	1119	621
GW12	ISLAND	06°27.815′	003°23.259′	7.6	28.6	1.71	1150	641
GW13	ISLAND	06°27.464′	003°22.938′	7.6	30	5	1250	685
GW14	V/ISLD	06°25.891′	003°24.590′	7.6	29	1.84	982	537
GW15	IKOYI	06°26.629′	003°25.243′	7.6	28.2	1.79	643	387
GW16	IK0YI	06°26.648′	003°24.640′	AD	AD	AD	AD	AD
GW17	V/ISLD	06°26.213′	003°24.317′	7.6	30.1	1.54	418	263
GW18	LEKKI	06°26.341′	003°28.077′	7.7	30.2	2.16	809	505
GW19	LEKKI	06°26.218′	003°29.444′	8.5	31.5	–	2648	1324
GW20	IGBEF	06°26.268′	003°31.209′	8.3	28	1.41	620	375
GW21	LAFJ	06°25.884′	003°32.618′	8.7	29.2	2.36	275	114
GW22	AJIWE	06°28.161′	003°34.789′	7.5	28.8	2.69	179	121
GW23	ETIOSA	06°29.328′	003°34.864′	8.6	29.6	–	693	412
GW24	ETIOSA	06°29.861′	003°35.154′	7	28	2.22	908	528
GW25	ETIOSA	06°30.124′	003°36.007′	6.3	28.9	2.06	588	368
GW26	ETIOSA	06°27.307′	003°35.201′	7.4	29.2	0.89	266	171
GW27	IBEJU/L	06°27.820′	003°40.300′	7.6	29.2	3.82	142	123
GW28	IBEJU/L	06°28.139′	003°42.195′	7.2	29.9	2.85	48	35
GW29	IBEJU/L	06°28.427′	003°48.325′	7.3	28.3	1.64	155	107
GW30	IBEJU/L	06°29.103′	003°53.303′	AD	AD	AD	AD	AD
GW31	IBEJU/L	06°28.014′	003°47.801′	5.9	28.4	2.16	201	201
GW32	ETIOSA	06°28.415′	003°38.133′	5.6	29.3	3.27	553	553
GW33	ETIOSA	06°28.466′	003°34.616′	6.7	29.6	3.13	340	340
GW34	ETIOSA	06°30.265′	003°34.796′	7.4	28	0.68	1170	663
GW35	ETIOSA	06°29.888′	003°34.940′	7.5	27.6	2.32	1629	878
GW36	AJAH	06°28.121′	003°33.873′	8.4	28.3	4.54	555	345
GW37	ETIOSA	06°26.380′	003°31.305′	7.4	29.9	1.37	530	323
GW38	ETIOSA	06°26.016′	003°31.395′	7.6	30.7	1.95	1051	591
GW39	ETIOSA	06°25.958′	003°30.443′	7.1	28.2	1.08	951	549
GW40	ETIOSA	06°26.959′	003°32.928′	–	29.5	2.95	102	75
GW 41	Ogombo	06°26′58.6″	006°36′45.2″	7.5	28.3	1.92	447	278
GW 42	IBEJU/L	06°29′21.1″	003°53′46.2″	8.6	28.4	3.23	357	270
GW 43	Eleko town	06°26′26.0″	003°51′21.6″	7.1	29.9	4.25	388	247
GW 44	Lakowe	06°28′27.3″	003°43′49.2″	6.8	28.9	1.97	845	507
GW 45	Awoyaya	06°28′40.7″	003°42′40.9″	6.9	30.1	3.1	477	348

AD access denied

between freshwater and saltwater intrusion in the study area. The study revealed that the subsurface lithology comprised an alternating sequence of sand, clayey sand, sandy clay and clay. The aquifer consists of shallow and deep freshwater aquifers hosted essentially within sand and clayey sand units. The shallow aquifer are unconfined in occurrence, while the

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deep aquifers in contrast are essentially confined by clay or sandy clay layers. The coastal aquifers have been variably intruded at an astonishing rate by saltwater from the adjacent saline waterbodies. The conceived parallel model revealed occurrence of two layers of saline intrusion at different depths dictated by the interbedded clay intervals, while the vertical model, however, showed higher thickness of intrusion in proximity of the Ocean in the south than the lagoon in the north. The freshwater–saltwater interface ranges between 25 and 157 m depending on the area. The extent of the intrusion revealed by the geological cross-section was in tandem with hydrophysical study confirming the ceaseless impact of saltwater intrusion in the western and central parts of the study. Therefore, to ensure sustainability of coastal fresh aquifers in the study area, adequate policies and regulations coupled with necessary enforcement are urgently required. The conceptual models herein presented represent the present status of the aquifer and thus can be improved with availability of more recent data, nonetheless, this study has demonstrated the importance of geophysical borehole logging in the choice of location and design of boreholes.

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Declarations

Conflict of interest The authors declare no conflicting/competing interests.

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