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Vol. 8(1), pp. 16-30, January 2014
DOI: 10.5897/AJEST2013. 1554
ISSN 1996-0786 © 2014 Academic Journals
http://www.academicjournals.org/AJEST

African Journal of Environmental Science and Technology

Full Length Research Paper

Geophysical study of saline water intrusion in Lagos municipality

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Accepted 14 November, 2013

Saline water intrusion presently constitutes serious concerns in the Lagos municipality just like many other coastal cities, thus necessitating its intervallic study. The present study involving 52 borehole logs (consisting of natural gamma and electrical resistivity components) was aimed at delineating intruded and vulnerable zones. Saline water columns defined by low resistivity values in the range of 0.1 and 20 Ωm as compared to fresh water (≥ 100 Ωm) were delineated on 22 logs. Four of the geo-sections generated in this study indicate saline water intrusion at depths varying from surface in Satellite Town, Kirikiri, Ijora, Iganmu, Apapa, Lagos Island, Ikoyi, Victoria Island and Lekki to depths ranging from 40 m at Iganmu to 158 m at Lekki. Intrusions of 47 m (143 - 190 m) and 60 m (56 - 116 m) were delineated at Ajah; 50 m (265 - 315 and 258 - 308) at Lakowe; 57 and 112 m (51 - 108 m and 198 - 308) at Ibeju Lekki, Akodo and 122 m at (233 - 355m) at Awoyaya. The hydrogeologic importance of the Coastal Plain Sand aquifer unit in Lagos is under severe threat of continued sea water intrusion on its southern flank. This study illustrates the current extension of the sea water intrusion. It highlights the depreciation of the water resource due to over pumping at higher rate than the natural recharge and slow sea level rise.

Key words: Borehole logs, saline water intrusion/incursion, natural gamma, resistivity, freshwater sand.

INTRODUCTION

Seawater intrusion is an inevitable problem of coastal fresh water aquifer associated with urban area (Hwang et al., 2004). Coastal aquifers constitute a vital source of fresh water in these regions, and are increasingly used to meet the water supply needs (Pareek et al., 2006). There is vital need to monitor the feasible risk of saline water intrusion of the coastal aquifers because, once saline intrusion into coastal aquifer has occurred, it is extremely difficult to overcome and improve the management of the water resources based on long term strategy. Less than 2% of seawater intrusion in the fresh water can diminish the water's potability (Custodio, 1987). Frequently, bore-holes have to be abandoned and other water sources sought, often at high cost. The challenge of saline water contamination in coastal aquifers is driven by a violation of the delicate hydrogeological balance that exists between freshwater and seawater in coastal aquifers (Goldman and Kafri, 2004) due to large-scale ground-water abstraction occasioned by rapid urbanization (Pareek et al., 2006).

Due to the proximity of Lagos to the Atlantic Ocean (Figure 1), the general population is faced with problems of freshwater abstraction from the subsurface. It is becoming harder for groundwater developers to construct

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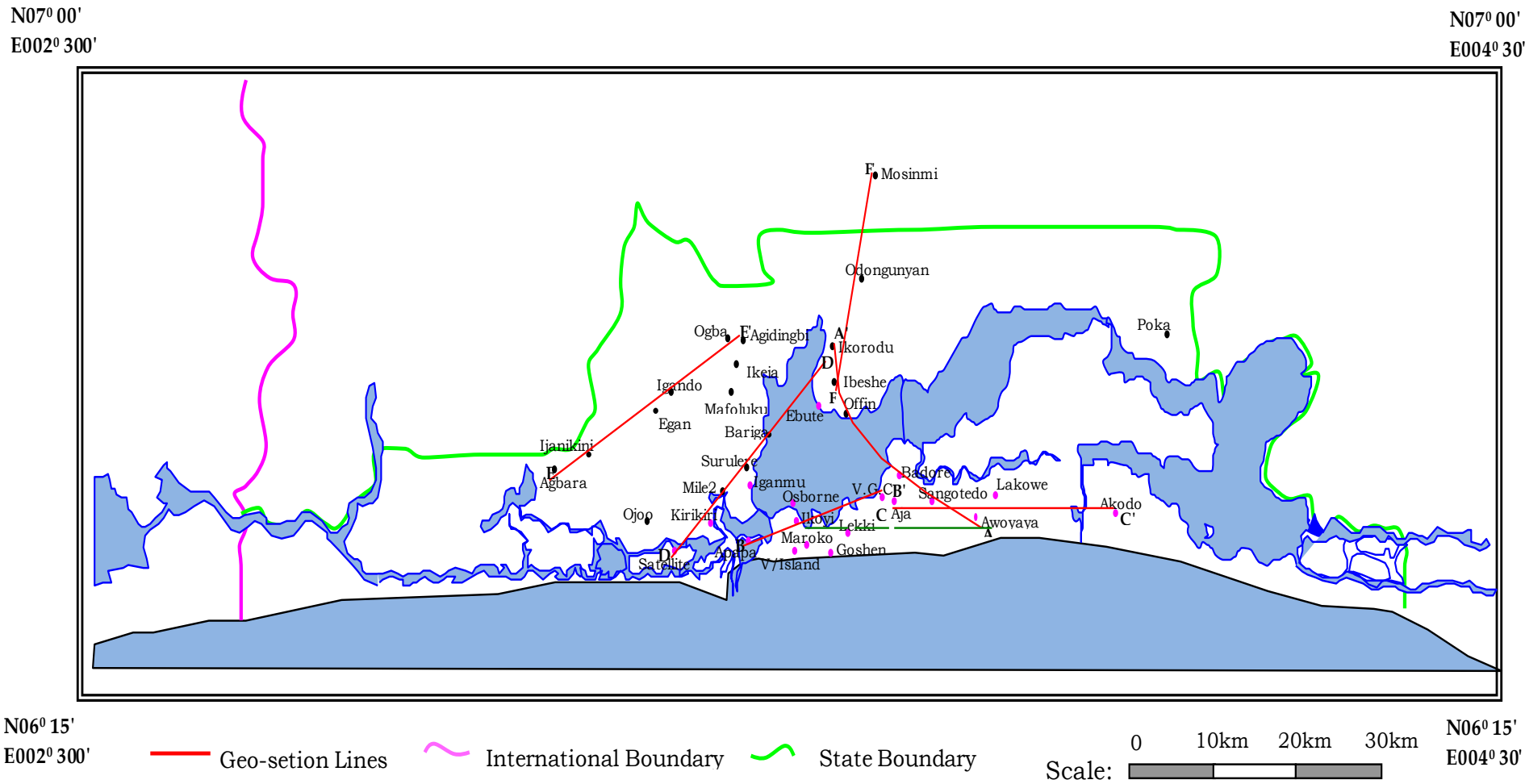

Figure 1. Map of Lagos State showing location of boreholes utilized for study and geo-section lines.

boreholes in areas adjoining the sea without encountering salt water. Some localities deemed to be very problematic within Lagos metropolis have been previously investigated using the electrical resistivity method (Ayolabi et al., 2003; Adepelumi et al., 2008).

Saline water intrusions vary in character and thickness. Accordingly, identification, distribution and nature of the intrusion can be used to identify areas where aquifer(s) may be more vulnerable to contamination to mitigate the degradation of the resources. The approximate thickness of the intrusion can be used to identify potentially sensitive areas.

The large resistivity contrast between salt water-

saturated formation and the fresh water-saturated formation has been used for studying the salt water intrusion in coastal areas (Bates and Robinson, 2000; Hwang et al,, 2004). Fitterman et al. (1999), Nowroozi et al. (1999) and Paillet et al. (1999) have reported the applicability of geophysical well logging and surface geophysical surveys for the evaluation of the seawater intrusion characteristics. Numerous measurements and studies have established correlation between resistivity values and groundwater salinities (Zarroca et al., 2011). In overall majority of cases, the portions of aquifers saturated with seawater present resistivity values that are generally below 3 Ωm (Goldman and Kafri, 2004). Portions saturated with brackish water exhibit resistivity values between 3 and 10 Ωm (Yechieli et al., 2001; Repsold, 1989).

This study is aimed at identifying the lithological units, saline water and fresh water horizons of the aquifer and thus enabling the determination of the interface between the saline water and freshwater aquifer sands. The hydrogeological setting of the coastal areas of Lagos as may be observed from this study will reveal information on the geological stratigraphy and the fresh water extension so that fresh groundwater aquifer can be effectively protected for future use.

Description of the geology, hydrogeology and geomorphology of Lagos

Lagos is underlain by the Benin Basin (Figure 2). The rocks of the Benin Basin are mainly sands and shales with some limestone which thicken towards the west and the coast as well as down dips to the coast (Oteri and Atolagbe, 2003). The stratigraphic description of sediments in the basin has been provided by various authors (Elueze and Nton, 2004; Nton, 2001; Okosun, 1990; Omatsola and Adegoke, 1981; Ako et al., 1980). Five lithostratigraphic formations covering the cretaceous to Tertiary ages have been described. The formations from the oldest to the youngest include: Abeokuta Group (Cretaceous), Ewekoro Formation (Paleocene), Akinbo Formation (Late Paleocene - Early Eocene), Oshosun Formation (Eocene) and Ilaro Formation (Eocene). The Abeokuta Group present an unconformity with the basement complex.

The Abeokuta Formation constitutes a deep aquifer only in the northern parts of Lagos city (Ikeja area) where boreholes to the aquifer are about 750 m deep. The Ilaro and Ewekoro Formations are not key aquifers in Lagos as they are predominantly composed of shale/clay. The only source of hydraulic information on the Ilaro formation was obtained at Lakowe where no fresh water horizon was intercepted. It has not been possible to differentiate the Ewekoro as a target aquifer in any boreholes or existing wells in the metropolis. The formation apparently represents a minor groundwater resource in Lagos.

The Coastal Plains Sands is the main aquifer in Lagos that is exploited through hand-dug wells and boreholes. It forms a multi-aquifer system consisting of three aquifer horizons separated by silty or clayey layers (Longe et al., 1987; Kampsax and Sshwed, 1977). The aquifer thickens from its outcrop area in the north of the city to the coast in the south and the sand percentage in the formation also changes from north to south (Longe et al., 1987).

MATERIALS AND METHODS

Fifty-two (52) borehole logs were used for the study. The logs consist of natural gamma ray, single point resistance, short and long normal resistivity (Figure 3). The log analysis involved the identification of lithology, fluid content, saline water zones, establishing of saline water horizon thickness and delineating of freshwater aquifer.

Resistivity is measured by means of the introduction of a known voltage through a probe consisting of R16, R32 and R64 units in a water filled hole. The natural gamma radiation of the logged rock encountered in the hole is also measured with the same sonde but with a different probe. The natural gamma content and the resistivity values are measured with ELGG^{TM} sonde. The logging tool utilized is the RG PC Logger II^{TM} (Plate 1) with PCL II^{TM} software. The natural gamma ray log component is interpreted qualitatively to describe the lithological sequence of the borehole formation while the resistivity component is interpreted to describe the water quality (Figure 4).

Coode et al. (1996) has correlated the natural gamma ray log obtained from different borehole locations in Lagos and their work forms the basis on which different sand aquifers were identified and classified. The resistivity data presented on the logs were interpreted qualitatively in terms of resistivity values of formation at various zones. Interpretations of the logs were based on the classifications of Zohdy and Martin (1993) and modified by Ibrahim (2008) (Table 1).

RESULTS AND DISCUSSION

The results of the study are presented as geo-sections and maps. The geo-sections enabled the identification of the various lithological units within the study area. The maps were utilized to illustrate the fresh/saline water lateral interface boundaries. Six sections were generated from the study for the following axes:

A-A' Ikorodu - Badore - Sangotedo - Awoyaya; B-B' Apapa - Ikoyi - Victoria Island - Lekki - Ajah; C-C' Victoria Garden City - Sangotedo - Awoyaya - Lakowe - Akodo; D-D' Satellite Town - Kirikiri - Iganmu - Bariga - Ikorodu; E-E' Agbara - Egan - Idimu - Agidingbi; F-F' Mosinmi - Odongunyan - Ikorodu - Ibeshe.

Twenty-two (22) of the 52 logs interpreted intercepted saline water at various depths. The shallowest saline water interface was obtained at Victoria Island area (southern flank of the metropolis) while the deepest interface was delineated at depth of 308 m in Lakowe area (southeast of the metropolis).

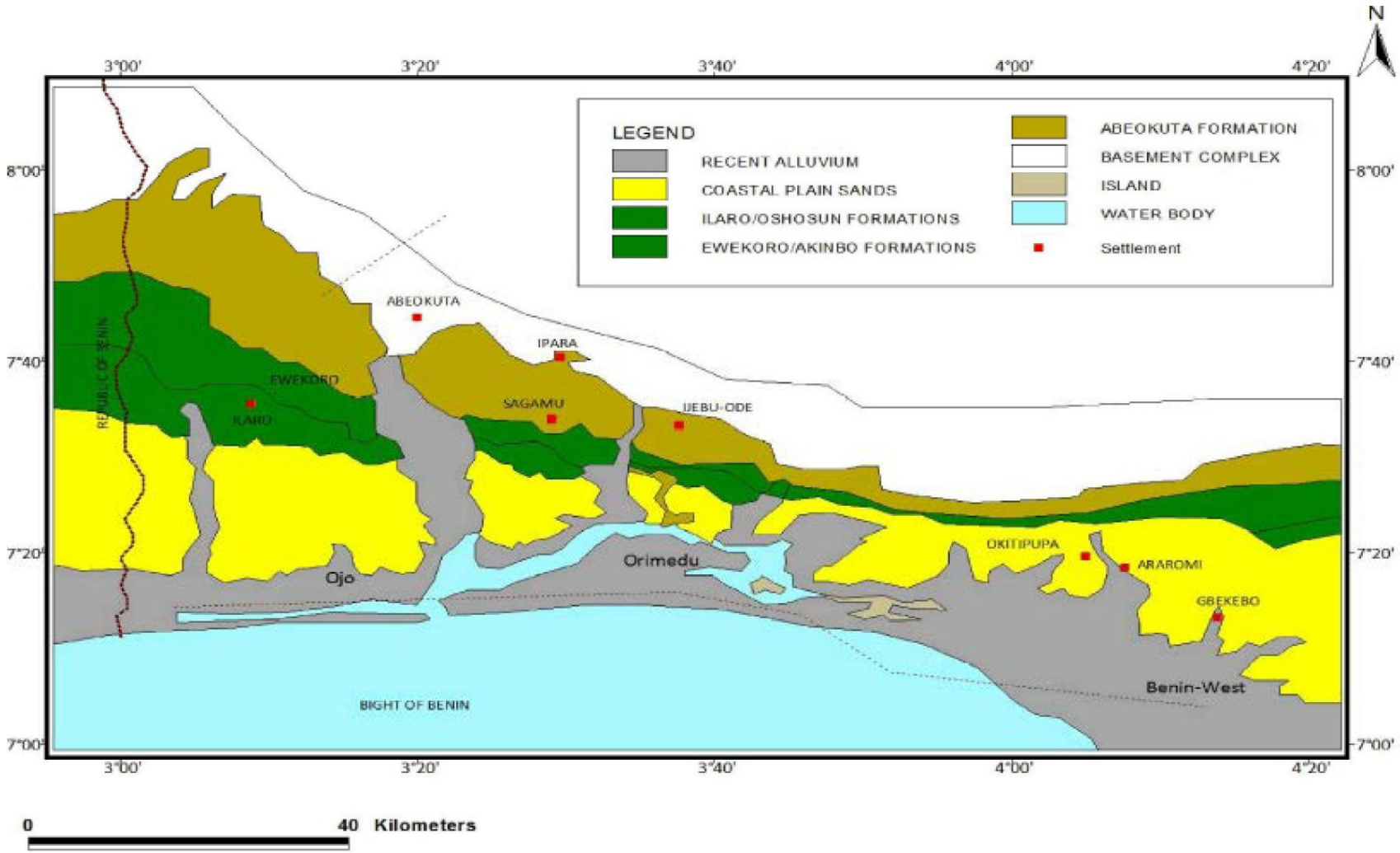

Figure 2. Geological map of Lagos.

Geo-section A-A': (Ikorodu - Badore - Sangotedo - Awoyaya)

The geo-section for profile A-A' is presented in Figure 5 while the interpretation summary is presented in Table 2. The section shows a general lithological dip in the south laterally in the NW-SE direction. Seven borehole logs covering four areas - Ikorodu, Badore, Sangotedo and Awoyaya were utilized for generating the section. The section shows a significantly thick clay/shale column from depth of 111 to 454 m (thickness of

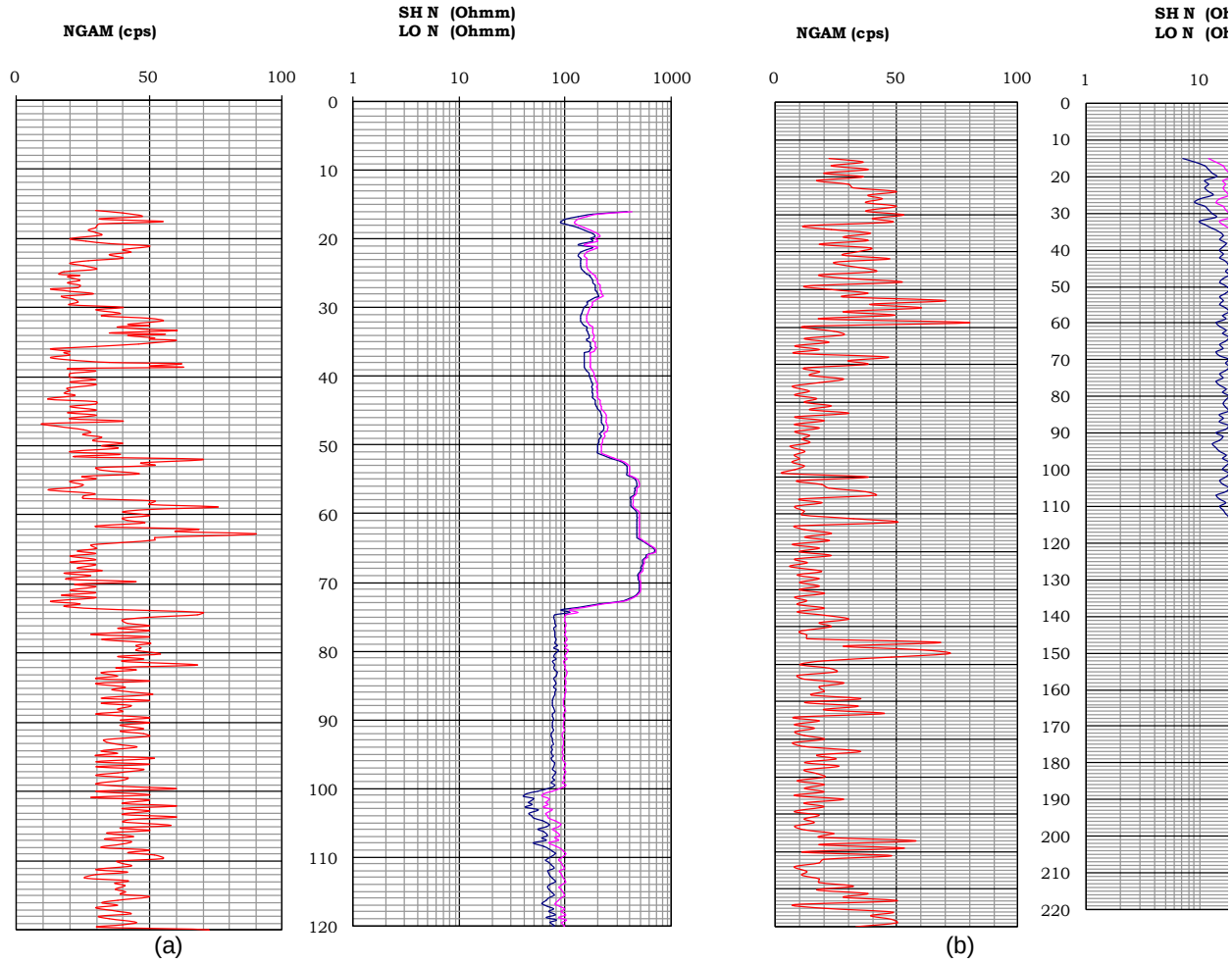

Figure 3. Typical borehole logs with (a) Odogunyan and (b) Osborne Estate Ikoyi logs (as examples) utilized for study.

Plate 1. The RG PC Logger II™ Unit mounted on sports utility vehicle used for borehole loggings utilized for the study.

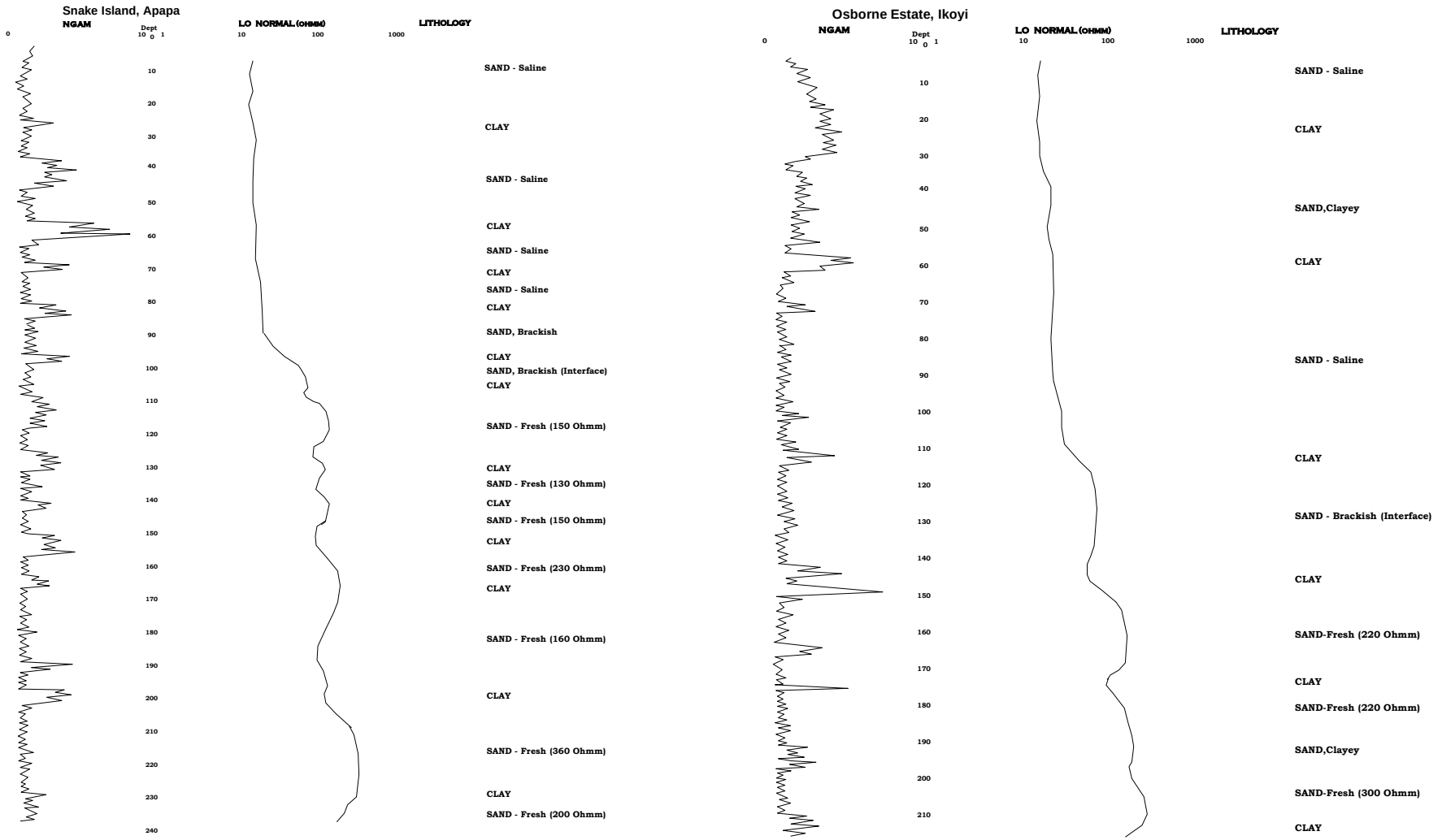

Figure 4. Typical logs and the lithology-water quality interpretation from the study area.

of 343 m) at Ikorodu. Thus, domestic boreholes may be terminated at limited depth of 110m within Ikorodu and environ while industrial boreholes should be drilled to depths in excess of 455 m.

Geo-section B-B': (Apapa - Ikoyi - Victoria Island - Lekki - Ajah)

This axis constitutes the western half of west-east flank of the State and it is proximal to the Atlantic Ocean shore line. The axis connects the south-west edge of the metropolis to the south edge. Fourteen (14) borehole logs studied within the axis

Table 1. Resistivity values for water and sediment rock.

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 = 10.000-1500 mg/l
10.0 -15.0	Sandy clay, sandy gravel	Brackish water, TDS = 5000-1500 mg/l
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
More than 100.0	Coarse sand, gravel, no clay	Very good quality fresh water, TDS very small

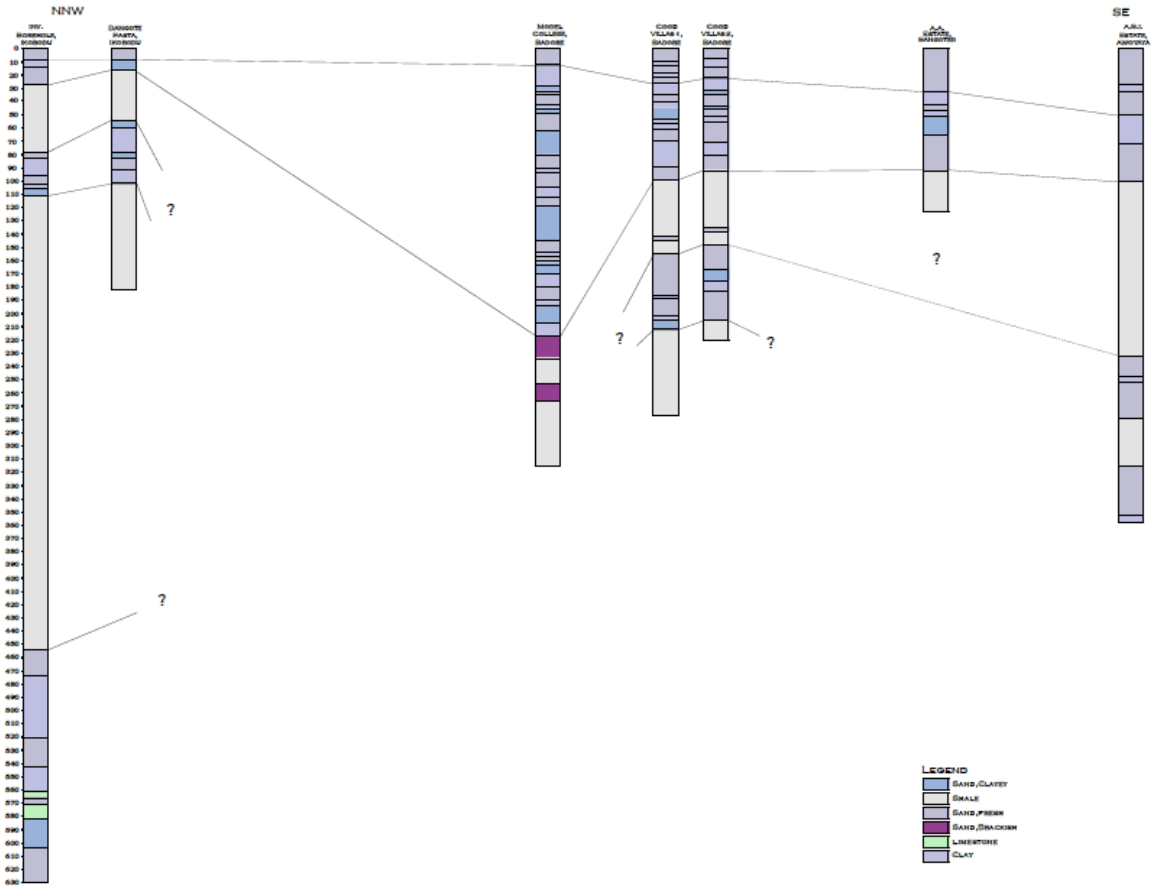

Figure 5. Geo-section A-A' showing lithology correlation across Ikorodu - Badore - Sangotedo - Awoyaya axis.

Table 2. Interpretation summary of borehole logs within profile A-A'.

Location	Elevation (m)	Fresh water zone depth (m)	Saline water zone depth (m)
Lagos Road waterworks, Ikorodu	114	15-27, 78-83, 96-102,105- 111,455-474, 520-544, 566-571, 605-627	None
Dangote Spata, Ebute	18	80-90	None
Model College, Badore	31	40-48,54-64,76-112,118-124,144-154, 180-196	None
Coop Villa Bh1, Badore	28	12-17, 20-24.8, 155-166, 173-186, 188-202,	None
Coop Villa Bh2, Badore	27	13-20, 62-70, 150-164, 176-188, 196-202,	None
Ajayi Apata, Sangotedo	22	16-33, 43-46	None
Eko-Akete, Awoyaya	20	18-24, 30-44	233 - 355

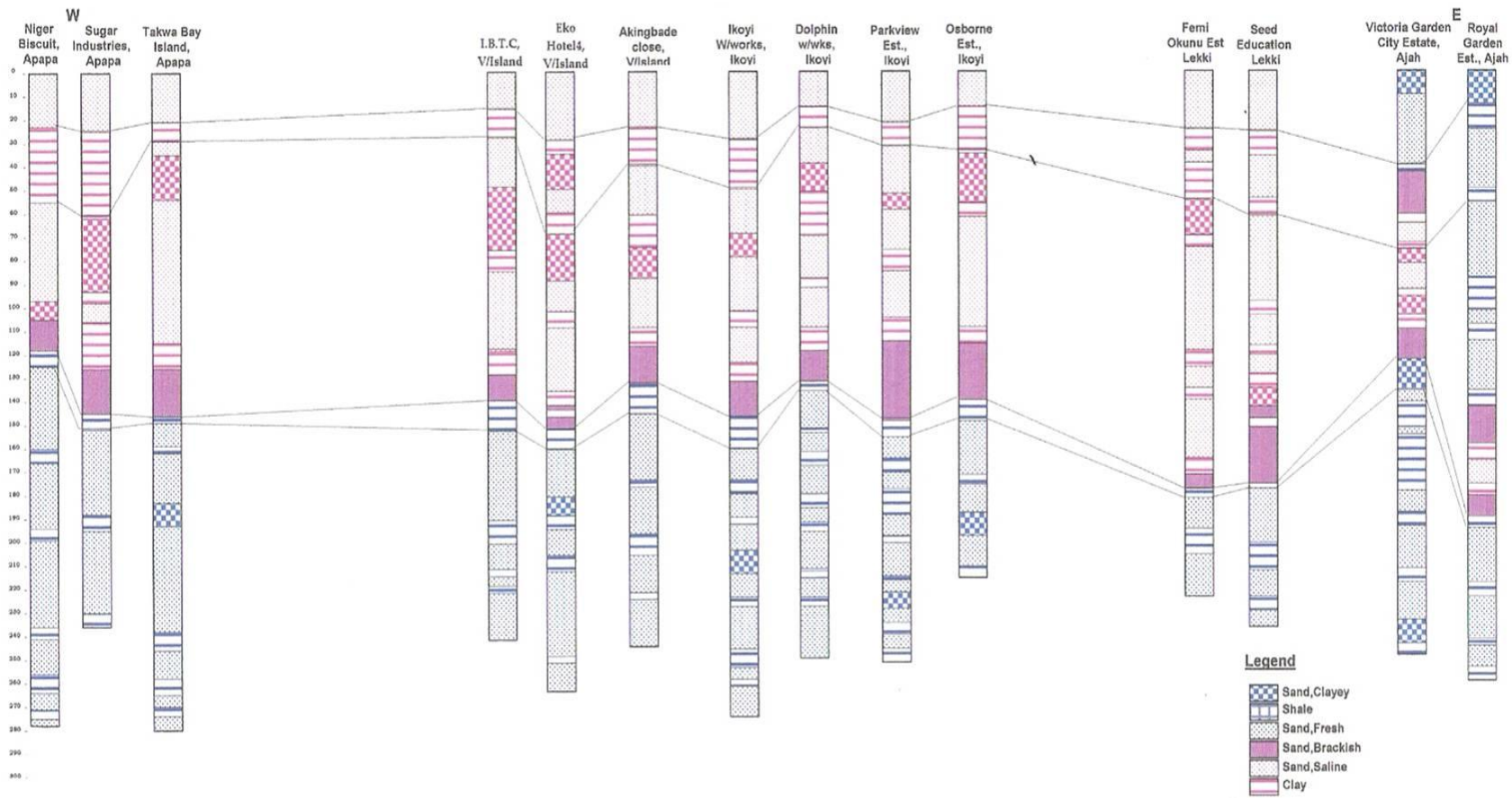

Figure 6. Geo-section B-B' showing lithology correlation across Apapa - Ikoyi - Victoria Island - Lekki - Ajah axis.

were obtained at Ikoyi, Dolphin, Victoria Island and Lekki. The geo-section generated for the axis is presented in Figure 6 while the interpretation summary is presented in Table 3. Within the axis, the delineated sand units are saline water saturated to depths varying between 118 and 196 m in Apapa and Ajah, respectively. At Ajah however, lenses of fresh water were delineated within the thick saline water sand. Net thickness of saline water sand units varies between 21 and 48 m in Ajah.

Geo-section C-C': VGC (Ajah) - Sangotedo - Awoyaya - Lakowe - Akodo Axis

This is the eastern half of the west-east axis of the study area which connects the southern limit to the south-eastern edge. Eight borehole logs were obtained for this study in the axis. The section generated from the logs is presented in Figure 7 while the interpretation summary is presented in Table 4. The net thickness of saline water sand increases eastwards (from Sangotedo) within the axis thus making freshwater abstraction more difficult on the eastern flank. However, at Akodo two lenses of freshwater were delineated.

Table 3. Interpretation summary of borehole logs within profile B-B'.

Location	Elevation (m)	Fresh water zone depth (m)	Saline water zone depth (m)
Niger Biscuit, Apapa	4	148-159, 162-183, 192-238, 246-258, 264-270, 274-280	0 - 125
Sugar Industries 1, Apapa	6	149-159, 162-184, 208-226, 232-236, 239-248	0 - 136
Tarkwa Bay Island, Apapa	10	148-155, 158-168, 171-179, 182-186, 188-193, 206-226	0 - 130
Ikoyi Bh1 W/works, Ikoyi	15	161-174, 179-190, 193-204, 215-224, 228-246, 253-259, 261-276	0 - 138
Dolphin W/wks, Ikoyi	5	137-152,154-162,169-180,187-192,195-214, 218-224, 229-250	0 - 131
Parkview Estate, Ikoyi	8	156-165, 171-178, 189-198, 201-215, 217-222, 230-235, 240-245	0 - 138
Osborne Estate, Ikoyi	5	164-172,176-193,202-208	0 - 148
IBTC, V/Island	20	154-191, 203-213, 215-219, 222-242	0 - 144
Eko Hotel Bh4, V/Island	19	153-193,194-208, 214-237	0 - 144
Akingbade Close, V/Island	18	148-174, 176-198, 208-220, 224-242	0 - 140
Femi Okunnu Estate, Lekki	27	182-196, 206-224	0 - 140
Seed Education, Lekki	15	166-188,192-196,198-232	0 - 158
Victoria Garden City Estate., Ajah	17	30-40, 136-141,152-155, 179-188, 193-212, 217-234	56 - 116
Royal Garden Estate, Ajah	17	46-50, 57-88, 102-108, 114-136, 190-218, 223-242, 245-252	None

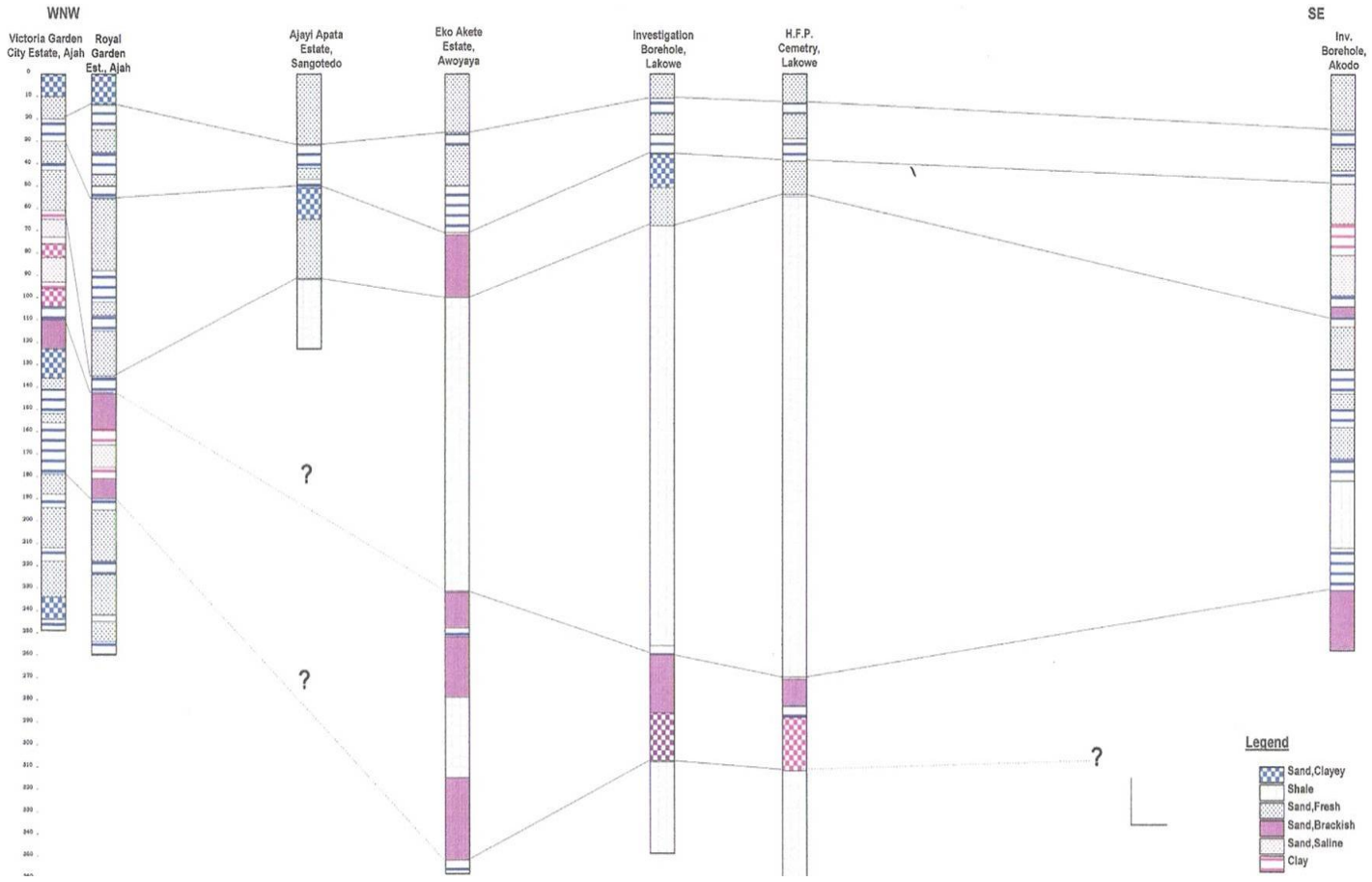

Figure 7. Geo-section C-C' showing lithology correlation across Victoria Garden City (Ajah) - Sangotedo - Awoyaya - Lakowe - Akodo axis.

Table 4. Interpretation summary of borehole logs within profile C-C'.

Location	Elevation (m)	Fresh water zone depth (m)	Saline water zone depth (m)
Victoria Garden City Est., Ajah	17	30-40,136-141,152-155, 179-188, 193-212,217-234	56 - 116
Royal Garden Est., Ajah	17	26-35, 46-50, 57-88, 102-108, 114-136, 190-218, 223-242, 245-252	143 - 190
Golden Park Est., Sangotedo	22	20-36, 44-57, 60-68, 82-100, 112-124	None
Ajayi Apata, Sangotedo	22	16-33, 43-56	None
Eko-Akete, Awoyaya	20	18-24, 30-50	233 - 355
HFP Cemetry, Lakowe	29	15-54	265 - 315
Lakowe Gram.Sch. Lakowe	26	21-27	258 - 308
Ibeju-Lekki Secretariat, Akodo	10	12-18, 36-46,108-132, 144-150, 159-168	51 - 108, 196 - 308

The hydrogeological setting on the axis is fairly complex. Saline water intrusion within the coastal plain sand within the axis is interspersed with lenses of freshwater sand units on the western flank around Ajah. At Victoria Garden City, the saline water sand is dominant from 62 to 124 m. At Sangotedo, Awoyaya and Lakowe, a significantly thick clay/shale column predominates with thickness varying from 133 m to 214 m at Awoyaya and HFP Cemetry in Lakowe, respectively, thus truncating the coastal plain sands (Figure 7). At Akodo, the coastal plain sand is again intercepted with a sequence of consisting of alternation of fresh and saline sand units.

Geo-section D-D': Satellite Town - Kirikiri - Iganmu - Bariga - Ikorodu Axis

The geo-section (Figure 8) which transverses southwest to northeast of the metropolis, was generated using seven logs obtained from Satellite town, Amuwo-Odofin, Iganmu, Bariga and Ikorodu. Summary of the interpretation is presented in Table 5. Saline water intrusion is prevalent at shallow levels on the South-western and central areas of the section around Satellite Town, Kirikiri, Ijora Badia and Iganmu.

Geo-section E-E': E-E' Agbara - Egan - Idimu - Agidingbi axis:

The geo-section (Figure 9) transverses the north-western flank of the metropolis utilizing seven geophysical borehole logs. The geo-section covers Agbara, Igando and Ogba and spans about 39 km. According to the summary (Table 6), there is no saline water sand unit incursion within the flank. Thus, the area is generally underlain by the vital fresh water sand units. A significantly thick shale unit was penetrated at Agbara.

Geo-section F-F': Mosinmi - Odongunyan - Ikorodu - Ibeshe axis

Geo-section of profile F-F' is presented in Figure 10. The profile transverses the northern flank of the metropolis in SSW-NNE direction and crosses into nearby Ogun State in the north. Just like the Geo-section of profile E-E', there is no observable incursion of saline water in the northern flank of the metropolis from Ibeshe in the south to Mosinmi in the north at the time of study (see Table 7).

Saline water intrusion map of Figure 11 was generated from the twenty two geophysical borehole logs showing penetration into saline water incursion zones (Figure 11). The map highlights the lateral extent of saline water incursion within the city. We can observe that the saline water intrusion is severe on the southern coastal areas of the city. The areas mostly affected are Apapa, Kirikiri, Ijora, Satellite Town, Iganmu, Bariga, Lagos Island, Victoria Island, Lekki, Ajah, Badore, Sangotedo, Awoyaya, Lakowe and Akodo areas.

Conclusions

Four of the geo-sections generated in this study (profiles A-A', B-B', C-C' and D-D') indicate saline water incursion at depths varying between 0 m (surface) in Satellite Town, Kirikiri, Ijora, Iganmu, Apapa, Lagos Island, Ikoyi, Victoria Island and Lekki to depths ranging from 40 m at Iganmu to 158 m at Lekki. Intrusions of 47 (143 - 190 m) and 60 m (56 - 116 m) were delineated at Ajah; 50 m (265 - 315 and 258 - 308) at Lakowe; 57 and 112 m (51 - 108 and 198 - 308 m) at Ibeju Lekki, Akodo and 122 m (233 - 355 m) at Awoyaya. The hydrogeologic importance of the Coastal Plain Sand aquifer unit in Lagos is under severe threat of continued sea water incursion and intrusion on its southern coastal flank. Results presented in this paper show that the process of salt water intrusion is active on southern flank of Lagos metropolis and geophysical wireline logs have proved to be precious

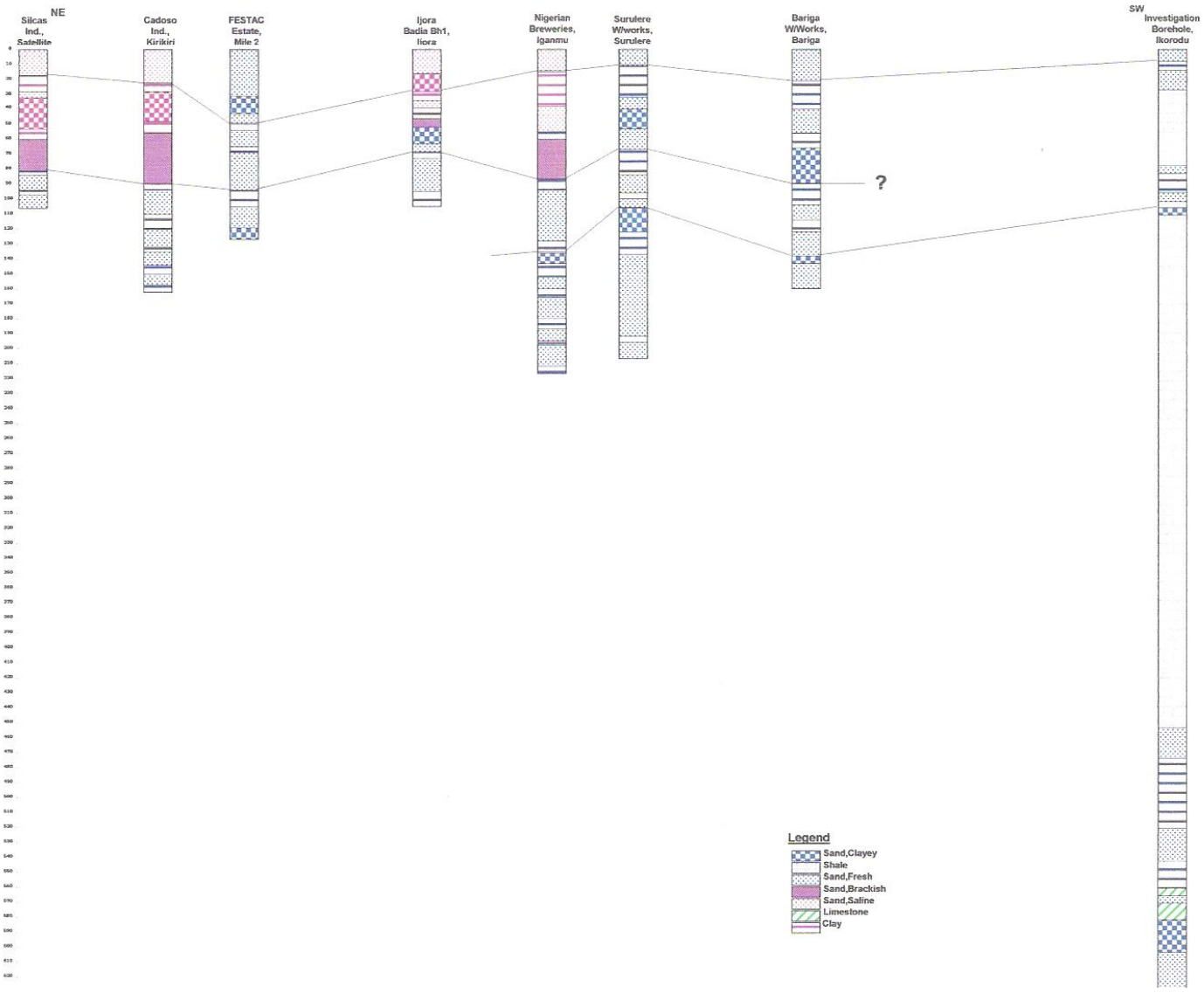

Figure 8. Geo-section D-D' showing lithology correlation across Satellite Town - Kirikiri - Iganmu - Bariga - Ikorodu axis.

Table 5. Interpretation summary of borehole logs within profile D-D'.

Location	Elevation (m)	Fresh water zone depth (m)	Saline water zone depth (m)
Silcas Ind., Satellite Town	23	82-94, 96-104	0 - 80
FESTAC Estate, Mile 2	31	18-32, 40-50, 56-64, 66-94, 106-118	None
Cadoso Ind., Kirikiri	27	100-110, 120-132, 134-144, 149-156	0 - 92
Ijora Badia Bh1, Ijora	17	62-68, 72-92	0 - 54
Nigerian Breweries, Iganmu	23	58-88, 96-128, 152-160, 166-180, 188-194, 198-212	0 - 40
Surulere W/works, Surulere	49	32-40, 54-66, 84-95, 100-106, 138-198, 194-206	None
Bariga W/works, Bariga	37	14-20, 40-56,106-114,122-138, 144-160	None
Lagos Road waterworks, Ikorodu	115	15-27, 78-83, 96-102,105- 111, 455-474, 520-544, 566-571, 605-627	None

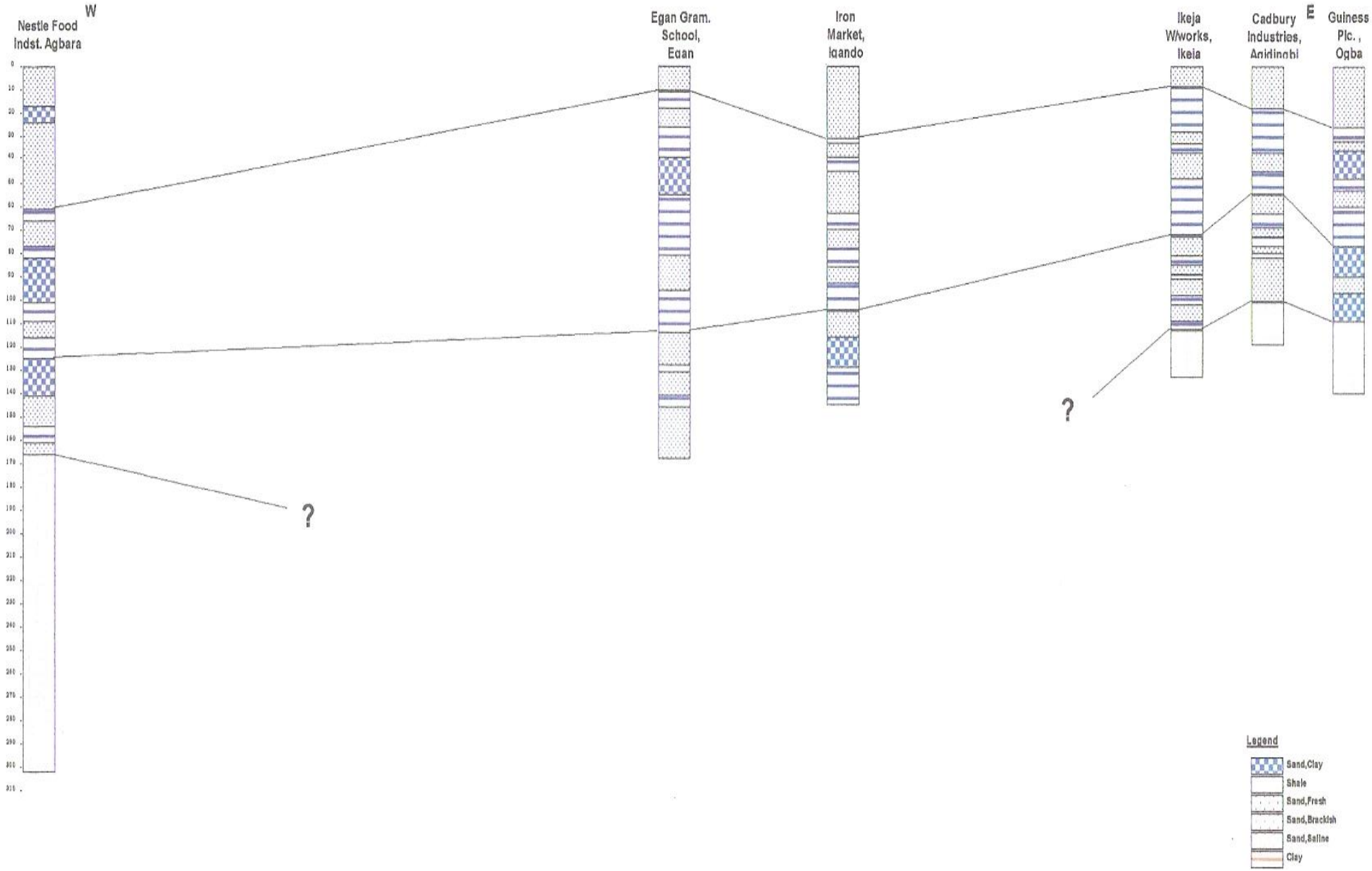

Figure 9. Geo-section E-E' showing lithology correlation across Agbara - Egan - Idimu - Ikeja - Ikorodu axis.

Table 6. Interpretation summary of borehole logs within profile E-E'.

Location	Elevation (m)	Fresh water zone depth (m)	Saline water zone depth (m)
Nestle, Agbara	29	24-54, 56-61, 82-101, 110-114, 142-155,	None
Egan Gram. Sch. Egan	19	81-96,114-129,132-141, 146-164	None
Iron Market, Igando	66	14-32, 34-39, 46-62, 70-76, 88-93, 106-116	None
Ikeja W/works, Ikeja	64	29-32, 40-48, 74-80, 86-88, 90-96, 104-108	None
Cadbury, Ogba	44	57-62, 65-72, 77-80, 82-100	None
Guiness, Agidingbi	65	14-25, 30-36, 52-60, 82-108	None

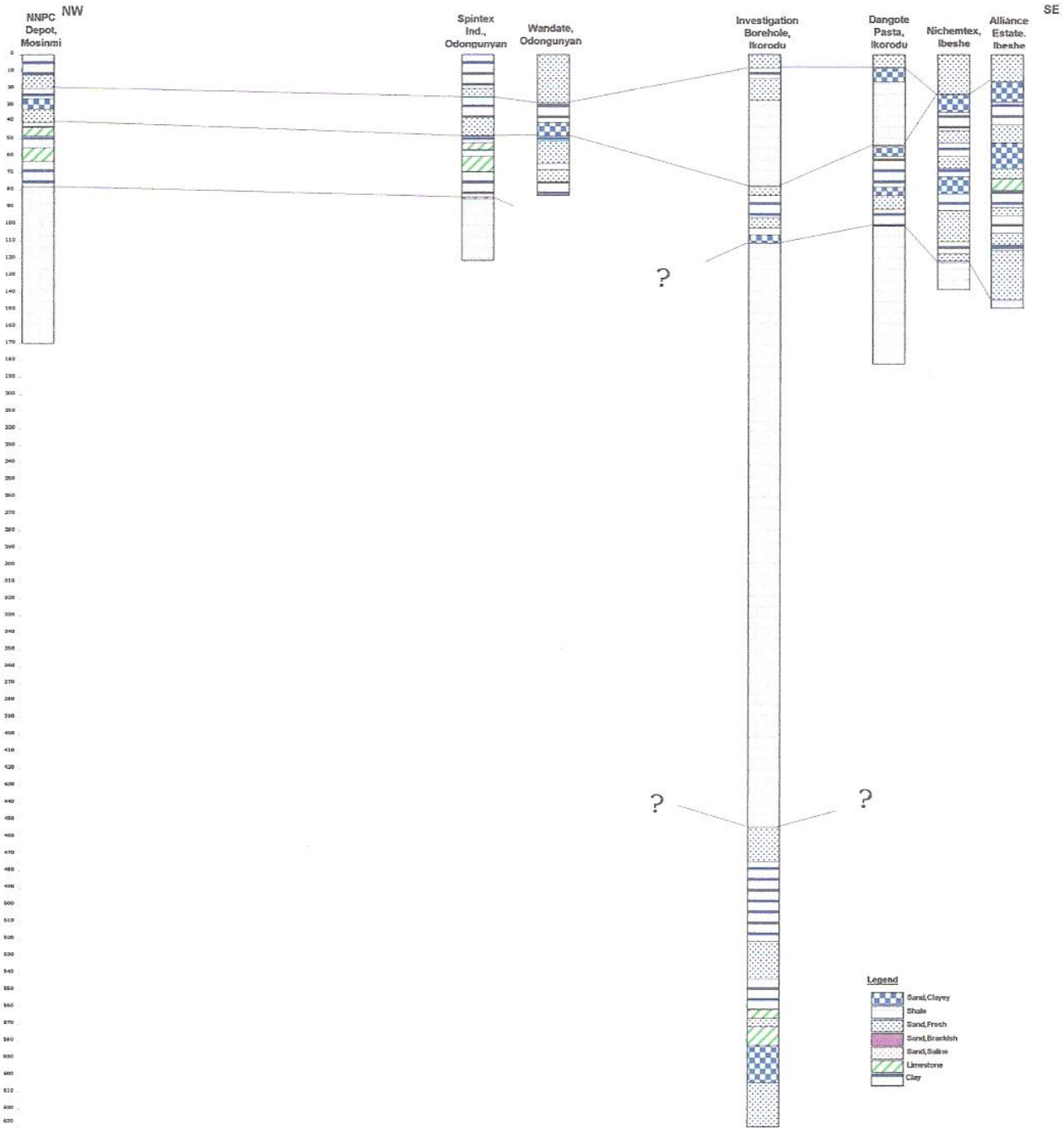

Figure 10. Geo-section F-F' showing lithology correlation across Mosinmi - Odongunyan - Ikorodu - Ibeshe axis.

Table 7. Interpretation summary of borehole logs within profile F-F'.

Location	Elevation (m)	Fresh water zone depth (m)	Saline water zone depth (m)
NNPC Depot, Mosinmi	94	13-20, 34-40, 44-47, 56-63	None
Spintex, Odongunyan	46	22-24, 42-48, 58-69	None
Wandate, Odongunyan	91	12-30, 50-64, 67-78	None
Lagos Road waterworks, Ikorodu	115	15-27, 78-83, 96-102,105- 111, 455-474, 520-544, 566-571, 605-627	None
Dangote Spata, Ebute	18	80-90	None
Nichemtex, Ibeshe	15	46-52, 60-68, 91-110, 115-122	None
Alliance Est. Ibeshe	18	42-52, 104-111, 114-144	None

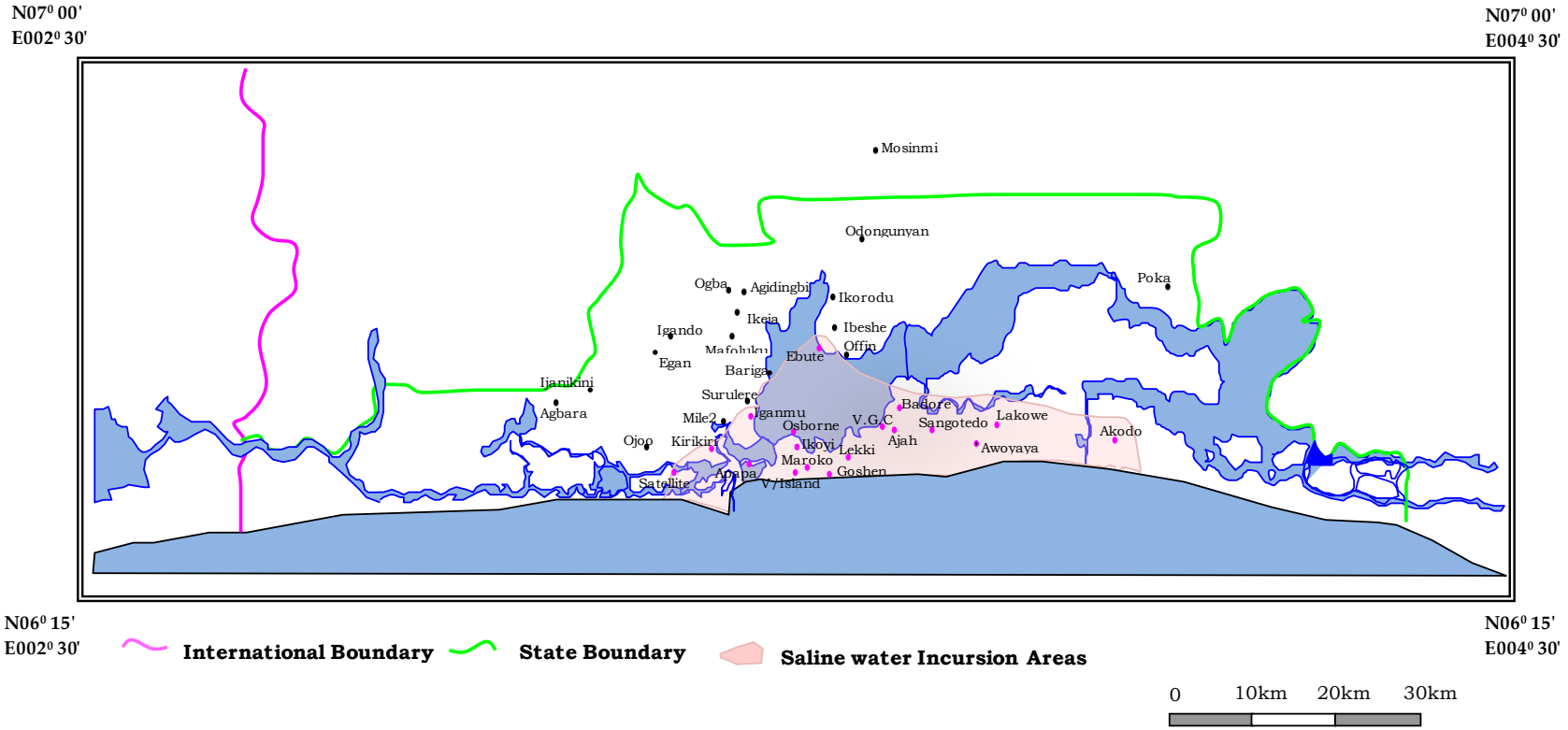

Figure 11. Map of Lagos showing the lateral extent of saline water intrusion within the metropolis.

tools for periodically monitoring the intrusion.

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