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Geophysical Exploration of Coastal Saline Water Intrusion: A Study of Ikoyi and Banana Island, Lagos State

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Abstract: *Groundwater is the primary source of potable water in Lagos State, Nigeria, particularly in coastal districts such as Ikoyi and Banana Island. In recent years, over-abstraction from coastal aquifers has accelerated seawater intrusion, threatening the availability of safe freshwater. This study investigates the extent of saline water encroachment and the distribution of freshwater in selected boreholes using integrated geophysical borehole logging. Nine wells were logged with gamma-ray and electrical resistivity tools, and the results were analyzed and correlated using Petrel® software to produce three lithostratigraphic panels along west–east and northeast–southwest transects. The gamma-ray logs distinguished alternating sand, sandy clay, clayey sand, and clay layers, revealing a multi-aquifer system separated by interbedded aquitards. Resistivity data classified aquifers into saline (<40 Ωm), brackish (40–100 Ωm), and fresh (>100 Ωm) water zones. Saline water was detected in seven of the nine wells, occurring at depths of 10–155 m. Brackish water interfaces extended between 10–210 m, while freshwater was found at shallow depths of 12–55 m and in deeper aquifers at 150–250 m. In the west–east profile, saline intrusion advanced from both flanks toward the central wells, though intrusion was minimal where population density and groundwater abstraction were lower. The deepest aquifers (beyond 150 m) consistently showed the highest freshwater potential. These findings demonstrate that borehole geophysical logging is an effective approach for mapping aquifer geometry and identifying safe groundwater zones in urban coastal environments. By highlighting the depth and distribution of saline intrusion, this study provides valuable insights for managing and protecting groundwater resources in Lagos vulnerable coastal districts..*

Keywords: *Groundwater, borehole logging, aquifer mapping, saline water intrusion, Lagos State*

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1.0 Introduction

The rapid growth of Lagos, both in terms of population and urban infrastructure, has placed enormous pressure on its freshwater resources. With limited surface water availability, the city relies heavily on groundwater for domestic, industrial, and agricultural needs. In coastal districts, however, this reliance comes with a serious challenge: the progressive intrusion of seawater into freshwater aquifers. Over-abstraction from these aquifers disrupts the natural balance between freshwater and seawater, drawing saline water upward or inland. Rising sea levels and climate variability are further amplifying this risk (Adepelumi et al., 2009). For many communities along the Lagos shoreline, drilling boreholes without encountering brackish or saline water has become increasingly difficult.

Seawater intrusion is not unique to Lagos; it is a global concern in densely populated coastal zones. It occurs when saline water replaces or mixes with freshwater in an aquifer, often as a direct consequence of excessive groundwater withdrawal (Al Barwani & Helmi, 2006; Sherif & Singh, 1999; Werner et al., 2013). In most coastal aquifers, the freshwater–saltwater interface is naturally stable. However, groundwater pumping lowers water levels, reverses hydraulic gradients, and allows saline water to encroach into production wells (Abdalla et al., 2010; Michael et al., 2017; Nanfa et al., 2022).

In Lagos State, where the Atlantic Ocean borders the southern coast and the Lagos Lagoon extends deep into the urban landscape, the threat to groundwater quality is particularly severe. Reports have documented a decline in freshwater availability in several parts of the city (Babatunde, 2012). In high-demand areas such as Ikoyi and Banana Island, locating potable water at accessible depths is becoming increasingly difficult. The proximity of these districts to saline water bodies, coupled with intense water demand from high-density residential and commercial developments, makes them critical zones for seawater intrusion studies.

Several investigations in Lagos have employed electrical resistivity surveys and borehole logging to assess aquifer conditions and map saline intrusion fronts (Ayolabi et al., 2003; Yusuf & Abiye, 2019; Oladapo et al., 2014). These methods exploit the distinct resistivity contrast between saline-saturated sediments and those holding freshwater. More recent studies have demonstrated that combining surface geophysical surveys with borehole logging provides high-resolution subsurface images and enables the tracking of intrusion patterns over time. Despite these advances, borehole logging techniques remain underutilized in some of Lagos's most vulnerable coastal districts, creating significant gaps in detailed subsurface characterization.

This study seeks to address that gap by applying integrated gamma-ray and resistivity borehole logging to selected wells in Ikoyi and Banana Island. Using Petrel software, lithostratigraphic correlation panels were developed along west–east and northeast–southwest transects to map aquifer geometry and evaluate groundwater quality at depth. The objective is to pinpoint zones affected by saline intrusion and to identify deeper, more secure freshwater aquifers that can support sustainable water supply in these coastal communities. By providing a clearer understanding of subsurface conditions, this work contributes to improved groundwater management and long-term water security for Lagos's coastal districts.

1.1 Study Area

The study area lies in the eastern part of the Dahomey Basin, covering sections of metropolitan Lagos in southwestern Nigeria. Geographically, it is located between latitudes 6°26′41.70″N and 6°27′34.10″N, and longitudes 3°24′33.30″E and 3°25′46.30″E (Fig. 1). The mapped zone includes parts of Lagos Island, notably Ikoyi and Banana Island, and extends inland toward portions of the Lagos mainland.

Lagos State shares its northern and eastern boundaries with Ogun State, borders the Republic of Benin to the west, and faces the Atlantic Ocean along its southern edge. Its coastline extends for about 180 km and is underlain by predominantly sedimentary formations. The landscape is mostly low-lying, with an average elevation of less than 15 m above sea level. The region experiences a humid equatorial climate, receiving over 1,800 mm of rainfall annually, with mean temperatures averaging about 27 °C. The weather pattern is marked by two distinct seasons: a rainy season from April to October and a dry season from November to March (Soladoye & Ajibade, 2014).

1.2 Geology and Hydrogeology

The Dahomey Basin extends across several West African countries, beginning in southeastern Ghana, passing through Togo and Benin, and terminating in southwestern Nigeria. The Nigerian segment is referred to as the Eastern Dahomey Basin and is characterized by diverse depositional environments, including inland, coastal, and offshore settings (Omatsola & Adegoke, 1981; Nton et al., 2009). The stratigraphic sequence within the Eastern Dahomey Basin is complex and ranges from the oldest Abeokuta Group, dated to the Maastrichtian–Neocomian, through a succession of younger formations. These include the Ewekoro Formation (Paleocene), the Oshosun and Ilaro Formations (Eocene), the Akinbo Formation (Pliocene), the Benin Formation (Oligocene to Pleistocene), and the most recent alluvial deposits (Fig. 2).

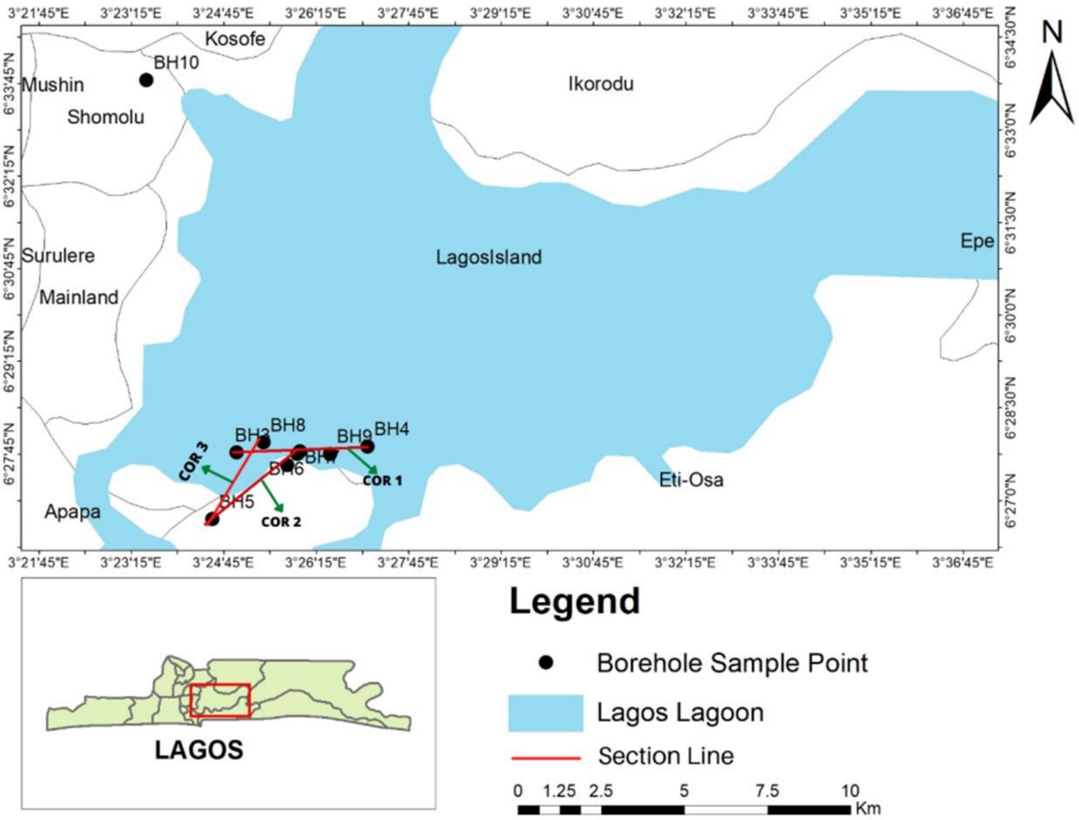

Fig. 1: Location and data acquisition map of the study area

In Lagos State, groundwater resources occur primarily within recent alluvial sediments, coastal plain sands, and the Abeokuta Formation. These aquifers are generally separated by intercalations of clay and sandy clay, which act as semi-confining units. Among them, the coastal plain sands constitute the most extensive and productive aquifer system. Their thickness increases progressively toward the southern coastal belt, creating zones of high transmissivity and enhanced groundwater yield. This thickening southward also coincides with areas of significant freshwater exploitation, thereby heightening their importance in water supply. Hydrologically, Lagos is strongly influenced by its coastal geomorphology. Wetlands and surface water bodies occupy more than 40% of the state's land area, while seasonal flooding affects an additional 10–15%. These conditions reflect a delicate balance between recharge, storage, and discharge processes. However, rapid urban expansion, coupled with high population density, has intensified the demand for groundwater and disrupted this natural equilibrium. The heavy reliance on coastal aquifers, combined with their proximity to the Atlantic Ocean and the Lagos Lagoon, makes them highly susceptible to saline water intrusion (Longe et al., 1987).

2.0 Materials and Method

To evaluate aquifer lithology and water quality, nine boreholes were selected across the coastal belt between Ikoyi and Banana Island (Fig. 1). Each borehole was logged with a combination of gamma-ray (GR) and electrical resistivity (ER) tools. The resulting composite logs were processed and correlated using Petrel software. Three correlation panels (Table 1–3) were generated along west–east and northeast–southwest transects. These panels allowed stratigraphic units to be traced laterally and vertically by linking equivalent lithological horizons across wells.

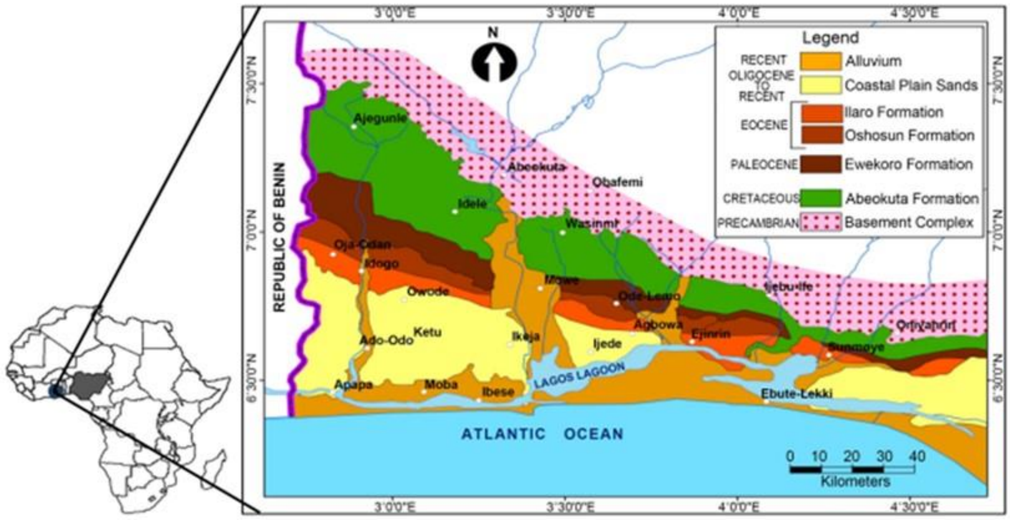

Fig. 2: Geological map of the Eastern Dahomey Basin (modified after Gebhardt et al., 2010)

Table 1: Correlation Panel 1 (COR 1)

Borehole Reference	Location
BH3	Bridge House College, Osborne Estate, Ikoyi
BH8	Plot 4, Block Ix, 12th Street, Ikoyi
BH7	Modupe Alakija Crescent, Ikoyi
BH6	Lagos Nestle Oil Residence, Ikoyi
BH9	Parkview Estate, Ikoyi
BH4	Desiderata, Banana Island

Table 2: Correlation Panel 2 (COR 2)

Borehole Reference	Location
BH5	Gtb Data Center, Ikoyi
BH1	Temple Road, Ikoyi
BH7	Modupe Alakija Crescent, Ikoyi

The gamma-ray log measures natural radioactivity and is used to delineate lithologies and carry out lithologic correlation across formations due to differences in the concentration of radioactive materials across formations. Its primary application is to distinguish shales from sand. The gamma-ray log on the first track is scaled from 0–150 American Petroleum Institute (API) in ascending order. The midway (75) served as a baseline between the two lithologies.

Table 3: Correlation Panel 3 (COR 3)

Borehole Reference	Location
BH5	Gtb Data Center, Ikoyi
BH3	Bridge House College, Osborne Estate, Ikoyi
BH8	Plot 4, Block Ix, 12th Street, Ikoyi

Deflections to the left of the baseline indicate clean sands (low radioactivity), while deflections to the right mark clay-rich zones (high radioactivity). Lithological classification was supported by calculating the Gamma Ray Index (IGR) (Schlumberger, 1974).

$$I_{GR} = \frac{GR_{log} - GR_{min}}{GR_{\max} - GR_{min}} \qquad (1)$$

where GRlog = gamma-ray value at the depth of interest or of the formation, GRmin = minimum GR value (sand), and GRmax = maximum GR value (shale). Interpretation thresholds were applied such that 0–60 API was interpreted as sand; 60–90 API as sandy shale or sandy clay; 90–120 API as clayey sand or shaley sand; and 120–150 API as shale or clay.

The resistivity log provided additional insight into formation fluid types. High resistivity values greater than 100 Ω·m were typically indicative of freshwater, while moderate resistivity values between 40–100 Ω·m suggested brackish water conditions, and low resistivity values below 40 Ω·m were characteristic of saline water (modified from Ibrahim, 2008).

The depth of investigation for the boreholes ranged from 190 m to 251 m. Electrical resistivity and gamma-ray data were interpreted in combination to map aquifer zones, identify saline intrusion depths, and distinguish freshwater-bearing intervals across the study area.

3.0 Results and Discussion

The integration of gamma-ray and resistivity logs from nine boreholes yielded a detailed characterization of subsurface lithology, aquifer architecture, and groundwater quality in the Ikoyi and Banana Island coastal districts. Petrel®-based correlation panels revealed consistent stratigraphic patterns across the west–east (COR-1) and northeast–southwest (COR-2 and COR-3) transects. The results provide important insights into saline intrusion dynamics, aquifer geometry, and water-bearing properties.

3.1 Subsurface Geological Sequence

The gamma-ray logs established lithostratigraphic sections along both west–east and northeast–southwest transects (Figs. 3–5). The stratigraphy is composed of alternating sand, sandy clay, clayey sand, and shale layers. Natural gamma values (0–150 API) were grouped into four distinct lithological classes, namely, (i) 0–60 API: clean sands (principal aquifers), (ii) 60–90 API: sandy shale or sandy clay, (iii) 90–120 API: clayey sand or shaley sand and (iv) 120–150 API: clay-rich beds/shale.

The west–east transect (BH3, BH8, BH6, BH7, BH9, and BH4) displayed alternating sand–clay sequences, with shallow clean sands (10–50 m) interspersed by thin clayey sands, and thicker aquiferous sand bodies developing at depths greater than 150 m. Lateral continuity of sand horizons was observed, although pinch-outs of clay layers suggested localized depositional variability. The northeast–southwest profiles (BH6, BH7, BH1, BH5; BH3, BH8, BH5) exhibited similar patterns but with thicker clay-rich intervals in southwestern boreholes, likely reflecting proximity to lagoonal depositional settings.

These findings confirm earlier reports that the Lagos coastal aquifer system consists of unconsolidated sands interbedded with aquitards (Longe et al., 1987).

3.2 Aquifer Delineation

Correlation panels revealed four to five major aquifer horizons, predominantly hosted in clean sand units (Figs. 6–8). Horizon thickness varied spatially. Horizon 1 occurs at shallow depths (10–50 m) and is relatively thin (10–20 m). Horizon 2 (50–100 m) is thicker, ranging from 20–30 m. Horizon 3 (100–150 m) is variable, ranging between 15–40 m, with aquitards providing partial confinement. Horizon 4 (150–200 m) is thicker (40–55 m) and shows strong lateral continuity. Horizon 5 (>200 m) is the most extensive, with thicknesses of up to 70 m in some boreholes.

These results highlight that the Lagos aquifer system is not a single homogeneous body but rather a multi-aquifer system, with distinct horizons that have different water-bearing and quality characteristics. The recognition of these discrete aquifer horizons has major implications for sustainable groundwater development, particularly in identifying deeper freshwater units less vulnerable to saline intrusion.

4.3 Saline Water Intrusion Assessment

Resistivity logs classified groundwater into saline (<40 Ω·m), brackish (40–100 Ω·m), and freshwater (>100 Ω·m) zones, clearly revealing widespread saline intrusion in the study area (modified from Ibrahim, 2008). Saline water was detected in seven of the nine wells (BH3, BH4, BH5, BH6, BH7, BH8, and BH9), absent only in BH1 and BH10, with the latter lying outside the primary coastal zone. From Table 4, saline zones occur at depths ranging between 10 and 155 m, with an average thickness of about 85 m (5–140 m). Brackish interfaces extend down to ~210 m, with an average thickness of 30 m per zone, while freshwater occurrences dominate shallow intervals (12–55 m) and deeper zones below 150 m.

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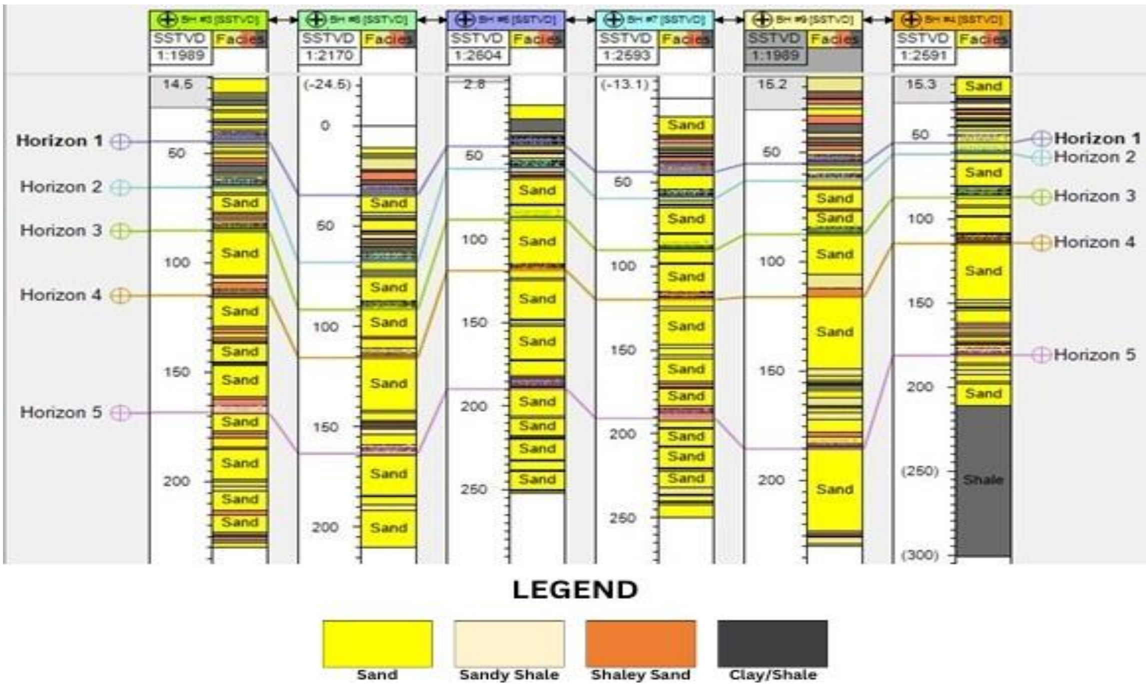

Fig. 3: Lithologic units of wells BH3, BH8, BH6, BH7, BH9, and BH4 as delineated using gamma-ray logging along Correlation Panel 1 (COR 1).

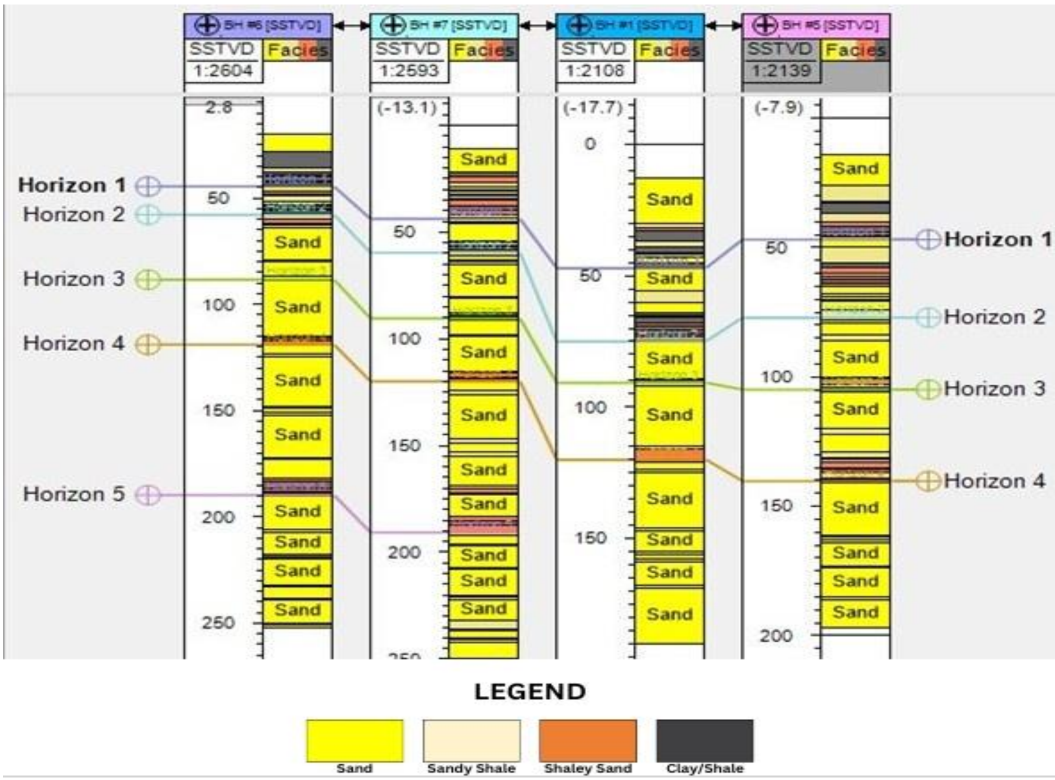

Fig. 4: Lithologic units of wells BH6, BH7, BH1, and BH5 as delineated using gamma-ray logging along Correlation Panel 2 (COR 2)

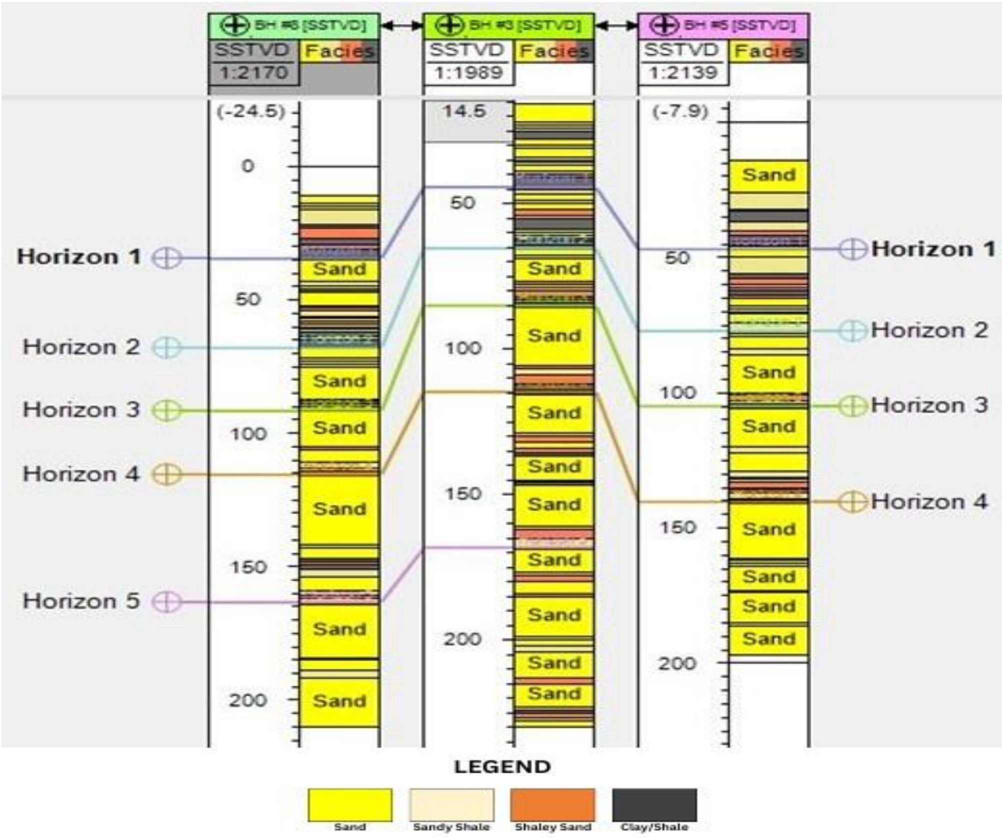

Fig. 5: Lithologic units of wells BH3, BH8, and BH5 delineated with the gamma-ray tool (COR 3

Saline intrusion advances inland from coastal flanks. In COR-1 (Fig. 6), saline zones encroach from the west (BH3: 25–115 m) and east (BH4: 20–130 m), converging near central wells such as BH6 (65–125 m) and BH7 (10–140 m intermittent). Intrusion in BH6 and BH7 is comparatively limited, which correlates with lower abstraction rates and reduced population density in those areas, further highlighting the influence of hydraulic gradients on saline encroachment (Werner et al., 2013). Northeast–southwest transects (Figs. 7–8) show salinity increasing southwestward, with BH1 recording only brackish (55–156 m) and freshwater, likely due to its relative distance from the lagoon and the presence of hydrogeologic barriers.

Brackish water zones typically serve as transition layers between fresh and saline water. These zones occur at an average of two to three per well, indicating gradual mixing processes rather than sharp salinity interfaces.

Compared to earlier studies, this work reveals more extensive shallow intrusion than reported by Adepelumi et al. (2009), who found intrusion depths of 50–100 m in the Lekki Peninsula. The discrepancy suggests an accelerated rate of intrusion in Ikoyi and Banana Island, possibly driven by increasing urbanization and abstraction pressures.

4.4 Aquifer Vulnerability and Freshwater Potential

Shallow aquifers (<150 m) are highly vulnerable, with most wells showing varying degrees of saline contamination. The contamination is primarily linked to over-abstraction and the proximity of the aquifers to saline water bodies. Although clay aquitards provide localized protection, their discontinuity reduces effectiveness, making vertical upconing likely in heavily pumped zones.

In contrast, deeper aquifer horizons (>150 m) consistently yield freshwater. On average, deep freshwater thickness reaches ~40 m across wells affected by saline intrusion, offering significant untapped potential for long-term water supply if managed sustainably. Geographically, wells closer to the Lagos Lagoon show thicker saline zones (~110 m) compared to more inland wells, underscoring the influence of lagoonal hydraulics on aquifer vulnerability. In addition, climate variability and sea-level rise are likely to further amplify this vulnerability, consistent with trends reported in global coastal aquifers (Werner et al., 2013).

4.5 Implications for Groundwater Management

The findings emphasize the need for targeted groundwater extraction strategies in Lagos's coastal districts. Sustainable management should prioritize tapping deeper aquifer horizons (Horizons 4 and 5), where freshwater remains largely unthreatened, while regulating abstraction from shallow horizons to prevent further saline intrusion. Groundwater policy should also integrate monitoring programs using borehole logging to track saline interfaces and inform adaptive pumping regimes.

This study not only validates intrusion patterns reported in earlier investigations of Lagos but also provides higher-resolution lithological and hydrogeophysical evidence. By identifying intrusion depths, aquifer horizons, and transition zones, the findings offer a strong framework for sustainable groundwater development and water security in Ikoyi, Banana Island, and comparable coastal environments.

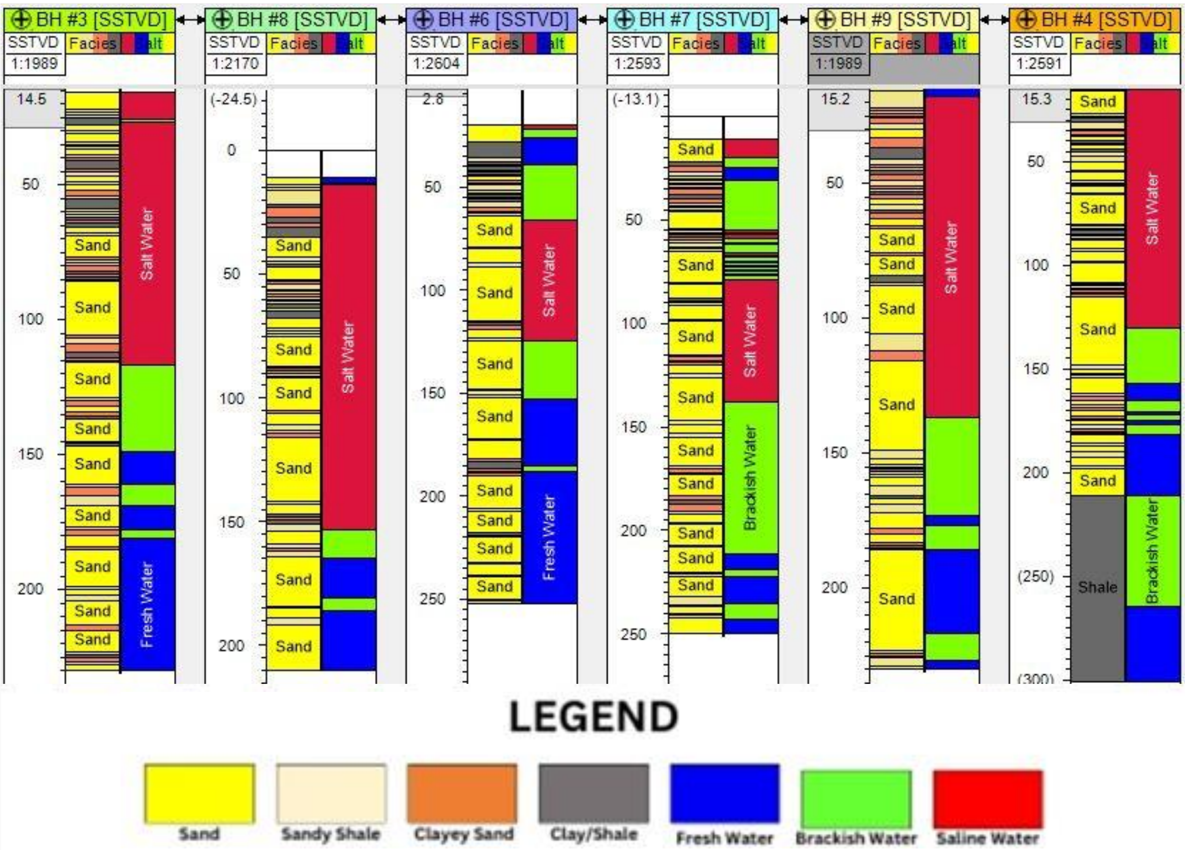

Fig. 6: Composite gamma-ray and resistivity logs delineating lithologic units and fluid types, correlated along the west–east transect in the study area (Correlation Panel 1, COR 1)

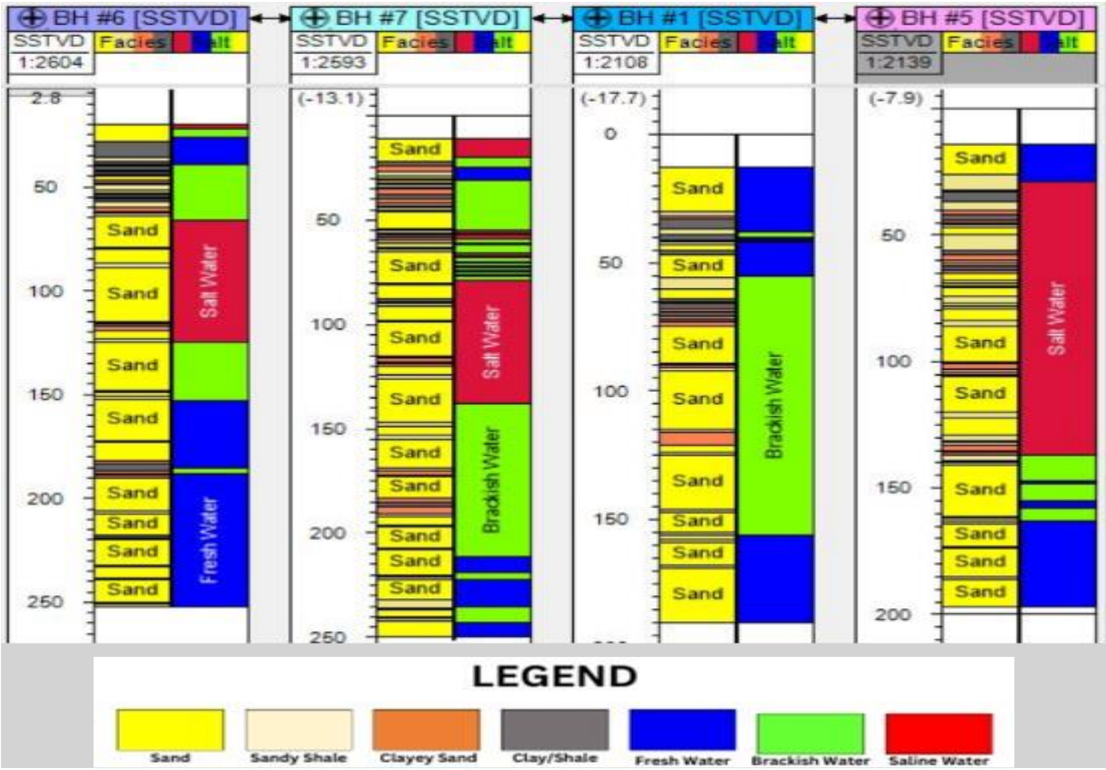

Fig. 7: Composite gamma-ray and resistivity logs delineating lithologic units and fluid types, correlated along the northeast–southwest transect in the study area (Correlation Panel 2, COR 2)

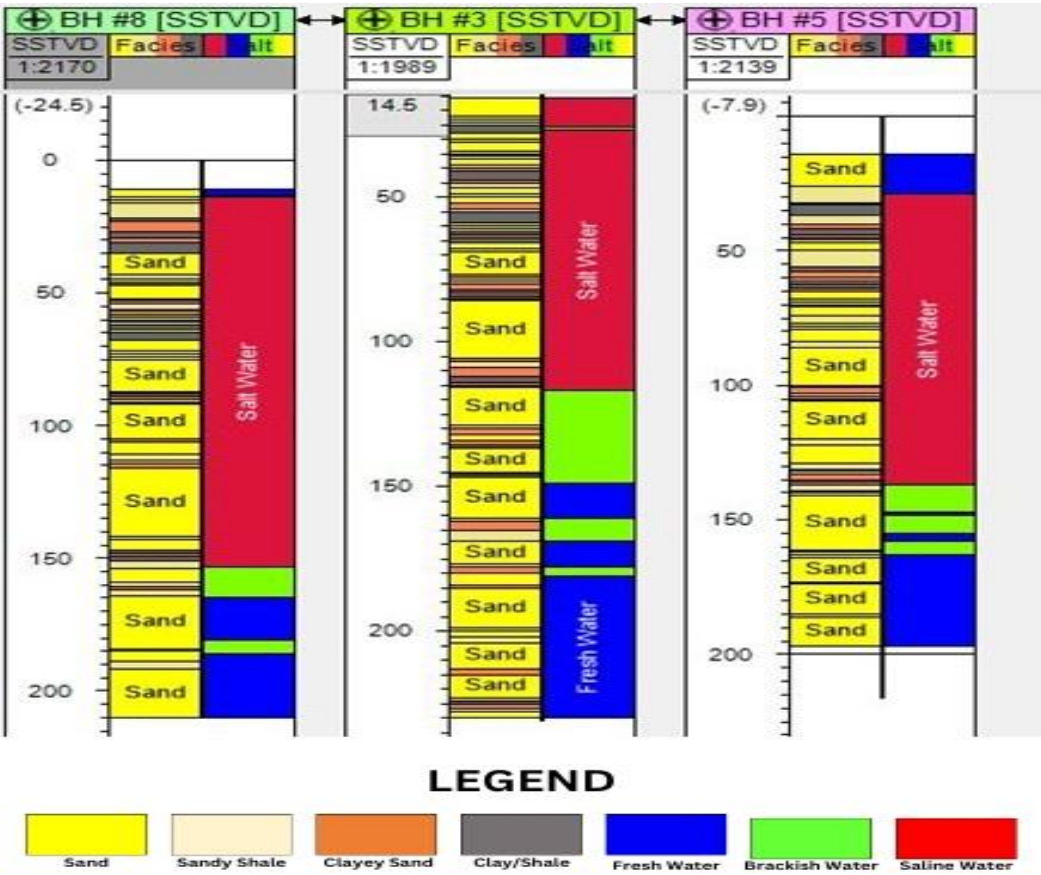

Fig. 8: Composite gamma-ray and resistivity log showing lithology and fluid type,

Table 4. Summary of Interpreted Borehole Data

Borehole (BH)	Location	Drilled Depth (m)	Depth Logged (m)	Saline Water Zone Depth & Thickness (m)	Brackish Water Zone Depth & Thickness (m)	Freshwater Zone Depth & Thickness (m)
BH1	Temple Road, Ikoyi	204	190	–	55–156 = 101	12–55 = 43; 156–190 = 34
BH3	Bridge House College, Osborne Estate, Ikoyi	231	231	25–115 = 90	115–150 = 35; 160–170 = 10; 180–185 = 5	150–160 = 10; 170–180 = 10; 185–230 = 45
BH4	Desiderata, Banana Island	211	211	20–130 = 110	130–154 = 24; 165–170 = 5; 175–180 = 5; 210–265 = 55	154–165 = 11; 180–210 = 30; 265–300 = 35
BH5	GTB Data Center, Ikoyi	216	198	30–140 = 110	140–155 = 15; 158–164 = 6	14–30 = 16; 155–158 = 3; 164–198 = 34
BH6	Lagos Nestle Oil Residence, Ikoyi	252	252	65–125 = 60	22–26 = 4; 40–65 = 25; 125–154 = 29	26–40 = 14; 155–250 = 95
BH7	Modupe Alakija Crescent, Ikoyi	251	251	10–20 = 10; 55–60 = 5; 80–140 = 60	20–25 = 5; 30–55 = 20; 140–212 = 72; 235–245 = 10	25–32 = 7; 212–235 = 23
BH8	Plot 4, Block IX, 12th Street, Ikoyi	210	210	15–155 = 140	155–166 = 11; 180–186 = 4	10–15 = 5; 166–180 = 16; 186–210 = 24
BH9	Parkview Estate, Ikoyi	231	231	20–137 = 117	140–171 = 31; 177–185 = 8	185–217 = 32; 217–230 = 103
BH10	Yetunde Brown Street, Ifako-Gbagada	70	33	–	29–33 = 4	5–29 = 24

The interpretation of borehole geophysical data across ten wells (BH1–BH10) in Ikoyi, Banana Island, and its environs reveals significant variability in aquifer depth, thickness, and water quality. Saline water zones were predominantly observed at depths between 10 m and 155 m, with thicknesses ranging from 60 m in BH6 to as much as 140 m in BH8. Brackish water layers were also identified, often acting as transitional zones between saline and fresh aquifers. For instance, BH4 exhibited multiple brackish intervals between 130 m and 210 m, highlighting gradual mixing processes rather than abrupt salinity boundaries. Freshwater aquifers were consistently identified below 150 m, with notable thick intervals exceeding 90 m in BH6 and over 100 m in BH9. In contrast, BH10, located inland at Ifako-Gbagada, presented predominantly fresh and brackish water horizons, with no significant saline intrusion, underscoring the influence of coastal proximity on aquifer salinity.

These findings confirm that the Lagos aquifer system is highly heterogeneous, with the degree of saline intrusion varying according to location, depth, and abstraction intensity. Wells situated closer to the lagoon and coastal flanks showed the thickest saline intrusions (BH3, BH4, BH8, BH9), while inland wells such as BH1 and BH10 recorded predominantly brackish and fresh horizons, suggesting the protective role of distance and local hydrogeologic barriers.

4.0 Conclusion

This study employed borehole geophysical logging to characterize the lithology and assess groundwater quality in coastal aquifers of Ikoyi and Banana Island, Lagos State. The integration of gamma-ray and resistivity logs revealed a multi-aquifer system dominated by coastal plain sands, with interbedded sandy clay and clay units acting as partial confining layers. Five major aquifer horizons were delineated, with the deeper aquifers emerging as the most viable for long-term freshwater supply.

Resistivity interpretations confirmed that shallow aquifers (10–155 m) are highly vulnerable to saline water intrusion, while deeper horizons (>150 m) consistently yield significant freshwater reserves. The extent of saline encroachment is largely controlled by hydrogeological setting, abstraction intensity, and proximity to the lagoon and Atlantic Ocean. Notably, Ikoyi and Banana Island show more extensive shallow intrusion compared to inland sites, reflecting the pressures of rapid urbanization and increasing groundwater demand.

To ensure sustainable groundwater use, this study recommends prioritizing the exploitation of deeper aquifers (Horizons 4 and 5) while limiting withdrawals from vulnerable shallow systems. Groundwater management strategies should include: (i) continuous monitoring of the freshwater–saltwater interface through integrated geophysical logging; (ii) regulation of abstraction rates, particularly in high-demand coastal districts; (iii) promotion of artificial recharge projects to maintain hydraulic balance; and (iv) incorporation of aquifer protection measures into urban planning. Implementing these measures will be critical for safeguarding potable water supplies and mitigating the risks of saline intrusion in Lagos's rapidly urbanizing coastal zone.

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Declaration

Consent for publication

Not applicable

Availability of data

Data shall be made available on demand.

Competing interests

The authors declared no conflict of interest

Ethical Consideration

Not applicable

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Authors' Contribution

Both authors participated in design, development, writing and corrections concerning the work.