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An Assessment of Saltwater Intrusion in Coastal Regions of Lagos, Nigeria

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Abstract

This paper explains various factors that contribute to saltwater intrusion, including overexploitation of freshwater resources and climate change as well as the different techniques essential for effective saltwater intrusion management. The impact of saltwater intrusion along coastal regions and its impact on the environment, hydrogeology and groundwater contamination. It suggests potential solutions to mitigate the impact of saltwater intrusion, including effective water management and techniques for managing SWI. The application of A.I (assessment index) serves as a guideline to correctly identify wells with SWI ranging from no intrusion, slight intrusion and strong intrusion. The challenges of saltwater intrusion in Lagos and the salinization of wells were investigated using the hydro-chemical parameters. The study identifies four wells ("*AA*", "*CMS*", "*OBA*" and "*VIL*") as having high electric conductivities, indicating saline water intrusion, while other wells ("*EBM*", "*IKJ*, and "*IKO*") with lower electric conductivities, indicate little or no salt-water intrusion, and "*AJ*" well shows slight intrusion. The elevation of the wells also played a vital role in the SWI across coastal regions of Lagos. The study recommends continuous monitoring of coastal wells to help sustain and reduce saline intrusion. The findings of the study are important for policymakers, researchers, and practitioners who are interested in addressing the challenges of saltwater intrusion along coastal regions. We assessed the SWI across the eight (8) wells using the Assessment Index to identify wells with SWI. Wells in "**CMS**" and "**VIL**" has strong intrusions. A proposed classification system based on specific ion ratios categorizes water quality from good (+) to highly (−) contaminated (refer to **Table 4**). These findings underscore the need for attention and effective management strategies to address groundwater unsuitability for various purposes.

Keywords

Hydro-Chemical Data Analysis, Saline Incursion, Aquifer Sustainability and Management, Coastal Regions, Ground Water Intrusion

1. Introduction

Coastal aquifers play a vital role in providing fresh water to regions with increasing water supply demands (Pareek et al., 2006). As the usage of these aquifers grows, the potential risk of saltwater intrusion becomes a significant concern. Saltwater intrusion can disrupt the delicate balance between freshwater and seawater, making water management a complex challenge (Oloruntola et al., 2019). This issue becomes even more critical in urban areas, where groundwater extraction due to rapid urbanization can disrupt the hydrogeological equilibrium (Pareek et al., 2006). The intrusion of even a small percentage of seawater can render freshwater undrinkable, emphasizing the urgency of addressing this issue (Oloruntola et al., 2019). The challenges associated with saltwater intrusion are multifaceted. The delicate hydrogeological balance disrupted by urbanization-driven groundwater extraction exacerbates the issue (Pareek et al., 2006). Globally, saltwater intrusion has been recognized as a significant problem, leading to extensive research efforts at various scales (Akerele et al., 2023). Existing overarching reviews have explored saltwater intrusion from a global to a local perspective (Amadi et al., 1989). In the context of Nigeria, studies have documented instances of seawater intrusion in coastal aquifers, spanning from Lagos State to Cross River State (Amadi et al., 1989; Edet & Okereke, 2002). However, a comprehensive local study is essential to understand the specific challenges and motivations for managing saltwater intrusion. Lagos, Nigeria, situated along the Atlantic Ocean, faces unique challenges due to its coastal proximity. The local population's reliance on underground freshwater sources is hindered by the risk of encountering saltwater during borehole construction (Oloruntola et al., 2019; Yusuf et al., 2021). This makes hydrogeological engineering a complex task, with variations in intrusion characteristics and thickness. Identifying, understanding, and mapping these intrusions are crucial steps in mitigating the degradation of water resources (Himi et al., 2017). Groundwater's electrical conductivity (EC) serves as an indicator of intrusion, with higher EC values indicating seawater infiltration (Amadi et al., 1989; Robinson et al., 2007). The salinity in groundwater primarily results from the dissolution of chloride minerals (Connolly et al., 2020). In this context, the utilization of data from previous water sample analyses, alongside graphical representations, and ratios, contributes to understanding the potential outcomes of laboratory procedures (Prusty & Farooq, 2020). Various methods have been employed to detect saltwater intrusion, including assessing salinity changes, EC values, water level fluctuations, chemical composition shifts (such as increased chloride concentrations), temperature variations, isotopic analysis, geophysical surveys (e.g., resistivity imaging), hydrodynamic modeling, well monitoring, aquifer cross-section analysis, tidal influence observations, and ecological impact assessments (Macrotrends, 2023). This paper's objective is to determine whether saltwater intrusion in selected wells is solely from seawater intrusion or influenced by other sources. It also discusses techniques for managing and controlling saltwater intrusion, evaluating their pros and cons, and assessing their effectiveness. By analyzing hydro-chemical data and inferring from graphical representations of chemical parameters, this study sheds light on the extent of intrusion, with notable instances along the coast, like Victoria Island and CMS. Ultimately, this paper serves as a valuable resource for policymakers and researchers tackling the pressing issue of saltwater intrusion in coastal regions. In the face of growing threats posed by excessive groundwater extraction, this work contributes to a deeper understanding of the challenges faced by the coastal regions of Lagos and their reliance on groundwater aquifers for irrigation and other purposes.

2. Description of the Study Area Lagos, Nigeria

Lagos, Nigeria is one of the fastest-growing cities in the world, and its population has been increasing at an unprecedented rate in recent years. According to the United Nations, the population of Lagos was estimated to be around 14.8 million in 2020, making it the largest city in Nigeria and one of the largest cities in Africa (Akinwotu & Dixon, 2023; Yusuf et al., 2021). The population of Lagos has been growing at an average rate of 2.6% per year over the past decade, which is significantly higher than the national population growth rate of Nigeria (Akinwotu & Dixon, 2023). This growth is primarily due to the high birth rates, migration, and urbanization. Despite the significant growth of Lagos, the city's infrastructure and services have not kept pace with the population growth, leading to several challenges such as traffic congestion, inadequate housing, and inadequate access to basic services such as water, sanitation, and healthcare (Akinwotu & Dixon, 2023).

The primary aquifer in Lagos is the Coastal Plains Sands, which is accessed through hand-dug wells and boreholes. It consists of multiple aquifer layers separated by layers of silt or clay (Elueze & Nton, 2004). The thickness of the aquifer increases from its source in the northern part of the city towards the southern coast, and there are variations in the percentage of sand content in the formation from north to south (Elueze & Nton, 2004). The continuous increase in population growth and large industrial as well as agricultural practices has led to large demand for water within Lagos city and its environs. According to (Akinwotu & Dixon, 2023), the current metro area population of Lagos is estimated at 15,946,000, a 3.63% increase from 2022, while in 2022, it was 15,388,000, a 3.54% increase from 2021 as well as 14, 862, 000 in 2021, a 3.44% increase from

2020. Previously, the population of Lagos, estimated at 3.6 million in 1980 and 5 million in 1985. Lagos State is bounded between Ogun State to the north and east; and the Atlantic Ocean to the south (see **Figure 1**). Lagos geological formation is underlain by the Benin basin. This basin primarily consists of sand, shale, and some limestone deposits. These rock formations tend to thicken towards the west and the coast, as well as in the down-dip direction towards the coast (Elueze & Nton, 2004). Various authors have provided stratigraphic descriptions of the sediments found in the Benin basin (Rachid et al., 2017). Five lithostratigraphic formations spanning the Cretaceous to Tertiary ages have been identified. These formations, listed from oldest to youngest, include the Abeokuta Group (Cretaceous), Ewekoro Formation (Paleocene), Akinbo Formation (Late Paleocene - Early Eocene), Oshosun Formation (Eocene), and Ilaro Formation

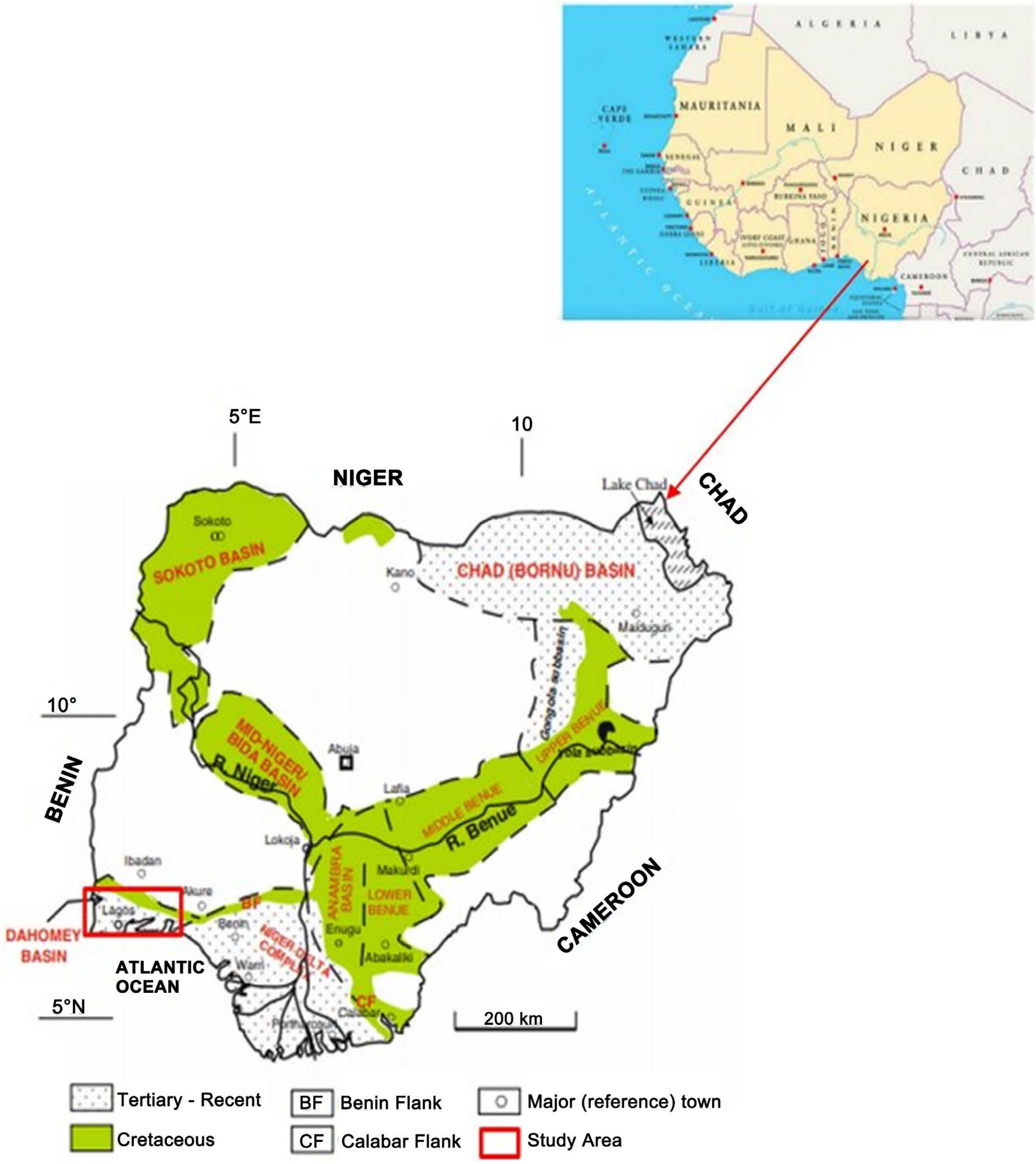

Figure 1. Location of the study area (Yusuf et al., 2021).

(Eocene) (Rachid et al., 2017). An unconformity exists between the Abeokuta Group and the underlying basement complex, the Abeokuta Formation serves as a deep aquifer only in the northern parts of Lagos city, specifically the Ikeja area, where boreholes reaching the aquifer can be as deep as 750 meters. On the other hand, the Ilaro and Ewekoro Formations are not significant aquifers in Lagos, as they predominantly consist of shale and clay (Elueze & Nton, 2004; Rachid et al., 2017). According to (Elueze & Nton, 2004), limited hydraulic information is available for the Ilaro Formation, with data obtained from Lakowe indicating the absence of a freshwater horizon intercept within it, the Ewekoro Formation has not been identified as a viable aquifer in any boreholes or existing wells within the Lagos metropolis, it appears to have limited significance as a groundwater resource in Lagos. The primary aquifer in Lagos is the Coastal Plains Sands, which is accessed through hand-dug wells and boreholes, this formation comprises a multi-aquifer system consisting of three distinct aquifer horizons separated by layers of silt or clay (Elueze & Nton, 2004; Rachid et al., 2017).

3. Literature Review

Saltwater intrusion (SWI) poses a global concern for coastal groundwater reservoirs, as it compromises the suitability of groundwater for its intended uses (Taniguchi et al., 2006). Consequently, comprehending the consequences of SWI holds vital importance for making well-informed choices regarding aquifer administration (Ozler, 2002; Szymkiewicz, 2022). Although techniques for evaluating SWI effects have progressed, the task of selecting suitable approaches remains difficult due to a multitude of variables, including aquifer traits, hydrogeochemical fluctuations, coastal landscape features, chemical transformations, and data accessibility, among other influencing factors (Al-Mashakbeh, 2017; Himi et al., 2017; Jones et al., 1999). Comprehending the intricacies and consequences of SWI is crucial due to the necessity of strategizing, overseeing, and adjusting efforts aimed at safeguarding the natural components (such as surface aquifers and the quality of groundwater) from pollution (Grundmann et al., 2016; Pareek et al., 2006). This also helps in lessening the socio-economic challenges that coastal communities may face, such as the disruption of a vital water supply, harm to water-related structures and systems, soil salt buildup, expenses related to treatment or seeking other water sources, and potential health concerns (Barlow, 2003). Coastal aquifers have two zones, one that contains freshwater and the other that contains saltwater. These zones are separated by a transition zone that facilitates mixing between the two zones and is sometimes referred to as the zone of dispersion. The transition zone in groundwater can be identified by measuring the concentration of total dissolved solids or chloride in observation wells. While there is no universally accepted definition for the transition zone, it is commonly characterized by total dissolved solids concentrations ranging from approximately 1000 to 35,000 mg/l and chloride concentrations ranging from about 250 to 19,000 mg/l (Atkinson, 1986). The overexploitation of coastal aquifers for freshwater supply can potentially be one of the primary reasons for saltwater intrusion. When too much fresh water is pumped out of the aquifer, it causes the pressure to decrease and allows saltwater from nearby seawater or relic saltwater from deeper layers of the aquifer to infiltrate the freshwater zone. In some cases, the pumping can also create a cone of depression that draws in saltwater from adjacent aquifers.

In the context of this paper, when we use the term "transition zone," we are referring to a shift in groundwater quality from freshwater to saltwater. This change is indicated by an increase in dissolved constituents such as total dissolved solids and chloride. In an idealized coastal aquifer, the dynamics of groundwater movement and the position of the freshwater-saltwater transition zone can be influenced by several factors. One crucial factor is the mixing of freshwater and saltwater within the transition zone (refer to **Figure 2**). This mixing process can result in the circulation of saltwater from the sea into the transition zone and subsequently back to the sea. This phenomenon occurs as saltwater infiltrates the aquifer from the sea, gradually mixing with the underlying freshwater. The movement of the transition zone is influenced by various factors, including groundwater flow patterns, tidal fluctuations, variations in aquifer permeability, and rates of freshwater recharge. Understanding and monitoring these processes are essential for managing and preserving the quality and availability of freshwater resources in coastal aquifers. This process is driven by the differences in density between freshwater and saltwater, as well as the hydraulic gradients within the aquifer. As freshwater flows towards the coast and into the transition zone, it mixes with saltwater and creates a zone of brackish water. The brackish water can then either move inland or seaward, depending on the hydraulic gradients and the direction of the regional groundwater flow. In

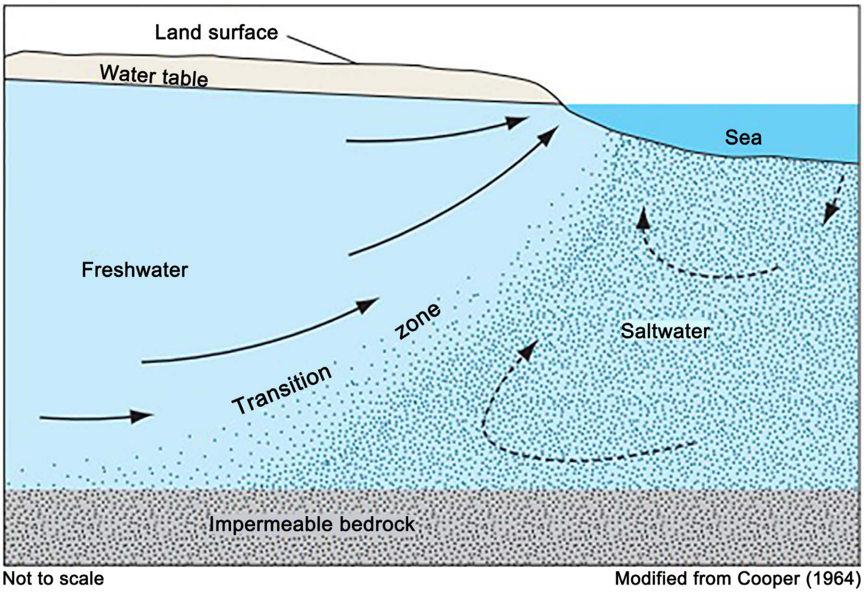

Figure 2. Ground-water flow patterns and the freshwater saltwater transition zone in an idealized coastal aquifer (Adapted from (Kim et al., 2006)).

some cases, the circulation of saltwater can be enhanced by the pumping of freshwater from wells located near the coast, which can create a cone of depression and draw saltwater from the sea into the aquifer (Terzić et al., 2010). It is important to note that the location and thickness of the transition zone can vary depending on the specific geology and hydrology of the aquifer. In some cases, the transition zone can be relatively narrow and well-defined, while in other cases it can be wider and more diffuse. The characteristics of the transition zone can also change over time in response to changes in the groundwater recharge rates, sea level fluctuations, and pumping rates (Werner et al., 2013). Therefore, a comprehensive understanding of the groundwater flow patterns, and the location of the transition zone is essential for the management and protection of groundwater. The issue of saltwater intrusion in coastal aquifers has been recognized since the 19th century when the affected aquifers started experiencing a decline in water quality, rendering it unsuitable for drinking (Jerrett et al., 2009). Despite extensive efforts to comprehend and mitigate this problem, the salinization of groundwater is increasingly observed along many coastlines. The primary cause of saltwater intrusion is the excessive extraction of freshwater from coastal aquifers, resulting in a decrease in hydrostatic pressure and the subsequent intrusion of saltwater into the aquifer. The intrusion of saltwater can originate from the ocean itself or from fossil saltwater present in deeper layers of the aquifer or in nearby aquifers. Even a small proportion of seawater, as low as 1%, can render the groundwater unsuitable for drinking due to its high salt content and associated salty taste. Efforts are required to address this issue and ensure the sustainability and availability of freshwater resources in coastal areas. Based on (Atkinson, 1986), salts are dissolved chemical substances that are present in all water sources, when their concentration exceeds a certain threshold, the water is referred to as "**saltwater**," "**salty**," "**brackish**," or "**saline**." The usage of these terms can sometimes be confusing as they are often used interchangeably. To address this, several methods have been developed to distinguish between freshwater and saltwater and to measure the level of salinity, which is determined by the concentration of total dissolved solids in the water. Saltwater intrusion can have severe consequences on coastal agriculture. It occurs when saltwater infiltrates freshwater aquifers and replaces fresh groundwater, leading to a reduction in soil quality, harm to crops, and an overall change in ecosystems. The effects of saltwater intrusion can be long-lasting, leading to the loss of productive farmland and devastating impacts on the economy and the environment (Barlow, 2003). To mitigate the threat of saltwater intrusion, a range of solutions, such as the implementation of sustainable water management practices, is needed. This paper utilizes a classification method that defines freshwater as having a total dissolved solids (TDS) < 1000 mg/l (Akerele et al., 2023; Oloruntola et al., 2019). In certain regions of the United States where water with low dissolved solids concentration is scarce, water sources with total dissolved solids (TDS) concentrations exceeding 1000 mg/l have been utilized for domestic water supply (Freeze & Cherry, 1979). However, water with total dissolved solids exceeding 2000 to 3000 mg/l is generally considered unsuitable for drinking due to its high salt content (Hem, 1989). Brackish water, on the other hand, typically has a total dissolved solids concentration ranging from 1000 to 35,000 mg/l. The upper limit for brackish water is equivalent to the concentration of seawater, which is around 35,000 mg/l. The revised **Table 1** below provides average concentrations of major dissolved constituents found in seawater, including chloride, sodium, sulfate, and magnesium, which are present in significant amounts. Water with dissolved solids concentration higher than that of seawater is referred to as brine.

When fresh groundwater mixes with seawater, it poses a challenge due to the high chloride concentrations found in seawater, typically around 19,000 mg/l (see revised **Table 1**). Even a small proportion of seawater, such as less than 2%, mixed with fresh groundwater would result in the water becoming unsuitable for public water supply. The atmosphere contains a significant quantity of salts, primarily sourced from the oceans, Na^+ and Cl^- are the dominant ions found in air masses over the sea and as a result, coastal air masses tend to have high concentrations of these ions (USGS, 2019). However, as one moves further inland, these concentrations decrease rapidly (Hudec & Jackson, 2012). These salts are introduced into coastal watersheds through precipitation. It's worth noting that the Cl^- concentrations in precipitation are relatively low compared to seawater. Through processes such as evaporation and evapotranspiration, Na^+ and Cl^- concentrations can increase in soils, shallow surface waters, and groundwater (Atkinson, 1986). The intrusion of saltwater into coastal aquifers can have significant consequences for both human populations and natural ecosystems. Furthermore, saltwater intrusion can cause soil and vegetation to become more saline, which can have negative impacts on agriculture and natural habitats.

Table 1. Average concentrations of major dissolved constituents of seawater (USGS, 2019).

Dissolved Constituent of Seawater	Concentration (mg/l)
Chloride	19,000
Sodium	10,500
Sulfate	2700
Magnesium	1350
Calcium	410
Potassium	390
Bicarbonate	142
Bromide	67
Strontium	8
Silica	6.4
Boron	4.5
Fluoride	1.3

In addition to the previously mentioned sources, deposits of evaporites (i.e., halite, anhydrite, and gypsum) serve as another significant source of salinity in groundwater. These deposits dissolve in water and contribute to the overall salinity of the water (Michael et al., 2005). Moreover, human activities can also contribute to increased groundwater salinity. Pollution from sewage, certain industrial effluents, brines from oil and gas fields, road deicing salts, and the return flows of irrigation water are examples of anthropogenic sources that can elevate the salinity of groundwater. In summary, groundwater salinity can be influenced by various factors, including atmospheric salt, accumulation of sea-spray, remnants of ancient seawater, evaporitic deposits, and human-induced activities.

Saltwater intrusion in coastal aquifers can be worsened by various factors in addition to over-pumping. The rise in sea level is a significant factor that can disrupt the hydrostatic balance between coastal aquifers and the ocean. Historical evidence shows that during the last glacial period, a substantial increase in sea level occurred, resulting in the flooding of continental shelves worldwide. This led to the infiltration of seawater into coastal aquifers (Hansen et al., 2016). Even a relatively small rise in sea level, such as 10 cm, can have significant implications for coastal aquifers. For instance, on a coastal plain with a slope of 1:1000, a 10 cm rise in sea level can cause seawater to intrude approximately 100 meters inland into the aquifer (Jerrett et al., 2009). These findings highlight the vulnerability of coastal aquifers to sea-level rise and emphasize the need to consider this factor in managing and protecting freshwater resources in coastal regions (Akerele et al., 2023). This intrusion of seawater may have long-lasting effects on the coastal aquifers, and mitigation strategies need to be developed to combat this phenomenon. The intrusion of saltwater into freshwater resources could impact the availability of safe and clean drinking water for humans, agriculture, and various industries. Therefore, it is important to monitor and understand the changes in sea level and their effects on coastal aquifers, to ensure sustainable use of these resources for future generations.

According to (Tolman & Poland, 1940), the predicted rise in sea level of at least one meter during this century will worsen the problem of saltwater intrusion. Other human activities that lead to surface runoff instead of groundwater recharge also contribute to this problem. Furthermore, various human activities such as the construction of piers and bridges, installation of building pilings, and dredging of harbors can have detrimental effects on the confining layers that protect coastal aquifers. These activities can cause damage to the confining layers, creating pathways for seawater intrusion into the aquifer. Consequently, human actions are causing significant modifications to coastal aquifers on a global scale, leading to an acceleration of saltwater intrusion at rates that are often overlooked or underestimated (Jerrett et al., 2009). It is crucial to recognize and address the impact of these human activities to better manage and mitigate the risks associated with saltwater intrusion in coastal aquifers. The problem of saltwater intrusion is usually centered on the essential requirement of communities for clean water, as well as the requirements of various industries and agriculture for freshwater. This is why most discussions about the issue center around sodium and chloride concentrations. However, in this paper, we will explore other factors that could lead to saltwater intrusion.

4. Methodology

Assessment and monitoring of saltwater intrusion in the coastal regions of Lagos using hydro-chemical parameters obtained from (Olufemi, 2010). Water samples from eight selected boreholes within the study area and physicochemical analyses were conducted. Parameters such as pH, temperature, electrical conductivity, and Eh (redox) using appropriate measuring instruments were done in-situ. The electrical conductivity was measured with a Horiba U90 meter with an accuracy of 0.001 µs/cm, while the alkali metals were determined by flame absorption spectrophotometry. The Salt-water Index (SWI) was also used to show the rate of saltwater intrusion in different locations within the study area (see revised **Table 5**). The use of these tools and techniques highlights the rigor and scientific approach of the research and strengthens the reliability of the findings. We compared the obtained hydro-chemical data with stipulated permissible limits provided by WHO standards to determine which the hydro-chemical concentrations are within or above the stipulated standards (see revised **Table 3**). We developed a guideline known as assessment index (A.I) to determine which of the sampled wells has Strong Intrusion, Slight Intrusion or No Intrusion (see **Table 6**). Based on the WHO permissible limits, the hydro-chemical parameters were compared across the eight (8) sampled locations to see which of the hydro-chemical parameters meets the stipulated permissible limits. According the compared hydro-chemical parameters: pH, SO_4^{2-}, PO_4^{3-}, Ec and $CaCO_3$ meets the stipulated standards with the exception of Cl^- (refer to **Table 4**). The study's methodology can be replicated in other studies investigating saltwater intrusion in coastal aquifers, providing a basis for further research, and informing water resource management and policy decisions.

The sampling points of the eight (8) wells were plotted using computing software called ***Surfer11.0***, a widely used software package for mapping and visualization of geological data (refer to **Figure 3**).

Elevation across coastal regions can play a significant role in influencing saltwater intrusion into groundwater. The relationship between elevation and saltwater intrusion is often tied to factors such as land subsidence, sea-level rise, and geological characteristics. From **Table 2**, it can be observed that samples from "**VIL**" are likely to be more contaminated with saline water compared to samples from "**EBM**". According to **Table 6**, the concentrations of TDS, Na^+, and Ca^{2+} indicate that there is no intrusion at EBM, while there is strong intrusion at VIL. This highlights the crucial role of elevation in saltwater intrusion (refer to **Table 6**).

5. Results

Hydro-chemical parameters play a crucial role in groundwater monitoring due

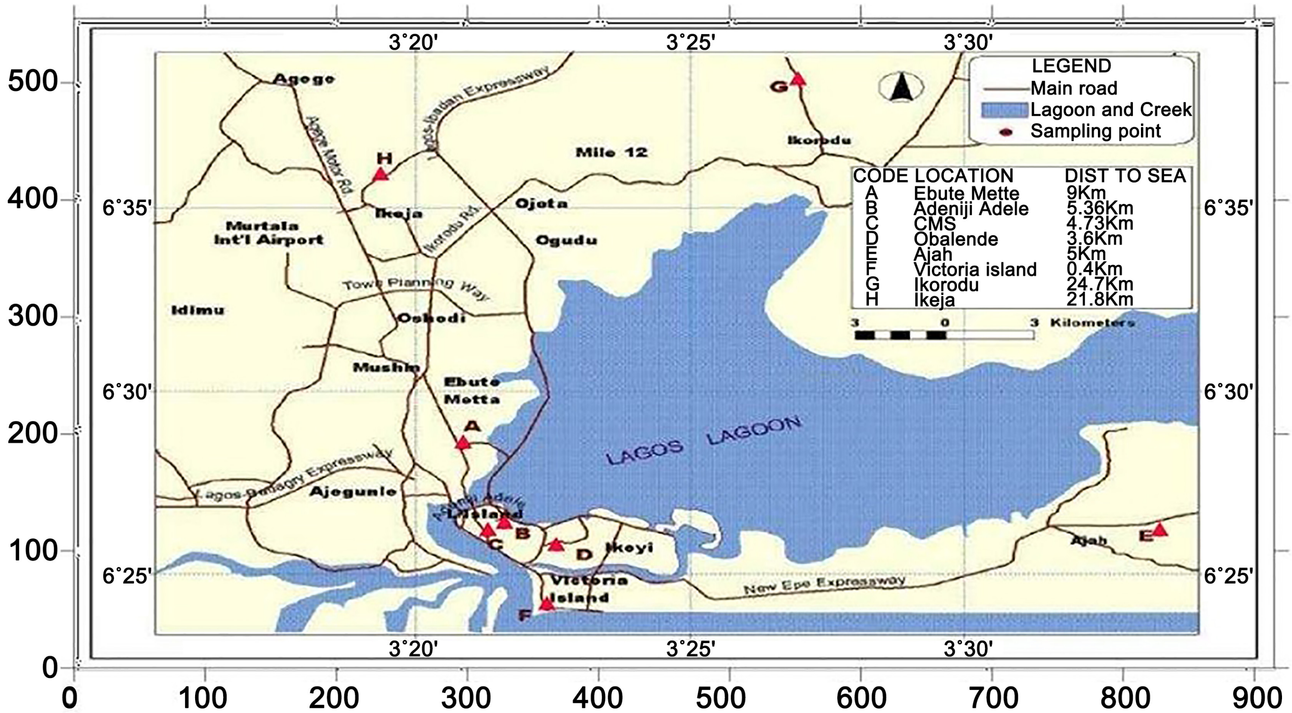

Figure 3. Map Showing sampling points, modified from (Olufemi, 2010).

Table 2. Showing sampling points, GPS coordinates and relative positions from the ocean (Olufemi, 2010).

S/N	Locations	Elevation (ft.)	Distance from Ocean (m)	Latitude	Longitude
A	Adeniji Adele	52	3600	6.4572	*3.3961*
B	Ajah	57	2470	6.4686	*3.5924*
C	CMS	68	2180	6.4541	*3.3902*
D	Ebutte Metta	77	9000	6.4903	*3.3813*
E	Ikeja	91	4730	6.6065	*3.3482*
F	Ikorodu	102	5000	6.6411	*3.4806*
G	Obalende	116	5360	6.4489	*3.1482*
H	*Victoria Island*	*23*	*400*	*6.4211*	3.4806

to their significance in assessing the quality and health of groundwater resources. Hydro-chemical parameters provide valuable information about the composition and characteristics of groundwater. They help in evaluating the presence and concentration of various substances such as major ions (e.g., calcium, magnesium, sodium, chloride), trace elements, heavy metals, nutrients, and pollutants. By monitoring parameters such as pH, electrical conductivity, total dissolved solids (TDS), and specific ions, changes in groundwater chemistry can be detected. Hydro-chemical parameters are essential tools in groundwater monitoring, providing valuable insights into water quality, pollution sources, groundwater-surface water interactions, long-term trends, and early warning systems.

The revised **Table 3** is a summary of the results obtained from the measured hydro-chemical parameters in the study area. The hydro-chemical parameters were compared with the WHO permissible limits and based on that **Table 4** was generated.

Table 4 shows the hydro-chemical parameters that meet the stipulated permissible limits and those that didn't meet the permissible limits when compared with the WHO standards.

Figure 4 and **Figure 5** show the different distribution of electrical conductivity and total hardness concentrations along the Coastal parts of Lagos at the 8 sampling points. The highest values of total hardness were observed at the CMS area of Lagos while Ebutte-Metta and Ikeja areas have the lowest values (see **Figure 5**). The high values of electrical conductivity along the coastal parts of the study area signifies that there is intrusion between the Atlantic Ocean and the

Table 3. Hydro-chemical parameters of the study areas (Olufemi, 2010).

LOCATIONS	AA	AJ	CMS	EBM	IKJ	IKO	OBA	VIL	WHO (permissible limit)
pH	6.01	6.38	6.68	6.76	6.59	6.45	5.93	6.63	6.5 - 8.5
SO_4^{2-} (mg/l)	34.91	29.68	63.4	24.3	32.6	32.71	44.07	42.13	400
PO_4^{3-} (mg/l)	0.01	ND	ND	0.03	ND	ND	ND	ND	---
Ca^{2+} (mg/l)	120.9	89.24	121.2	28	41.7	47.32	148.8	119.2	200
Hardness/$CaCO_3$ (mg/l)	1090	998.6	1233	522	526	890.5	1132	926.3	500
Cl^- (mg/l)	94.3	61.28	58.2	22.3	19	28.98	92.16	109.5	600
Na^+ (mg/l)	232.8	157	483.4	46.8	56.2	91.99	311.2	430.07	200
K^+ (mg/l)	86.67	36.01	193.2	8.67	10.9	20.46	92.88	341.7	---
Ec (μS/cm)	1251	407	1520	130	126	288	940	1565	900 - 1200
TDS (mg/l)	625.5	203.5	760	65.1	63.3	144.1	470	782.51	1500

Table 4. Assessment of water samples based on the stipulated limits (Olufemi, 2010).

Location	**pH**	**SO_4^{2-}**	**PO_4^{3-}**	**Cl^-**	**Total Hardness**	**Elect. Conductivity**
AA	+	+	+	+	−	+
AJ	+	+	+	+	−	+
CMS	+	+	+	+	−	−
EBM	+	+	+	+	−	+
IKJ	+	+	+	+	−	+
IKO	+	+	+	+	−	+
OBA	+	+	+	+	−	+
VIL	+	+	+	+	−	−

+ meets the stipulated permissible limits; − fails to meet the stipulated permissible limits.

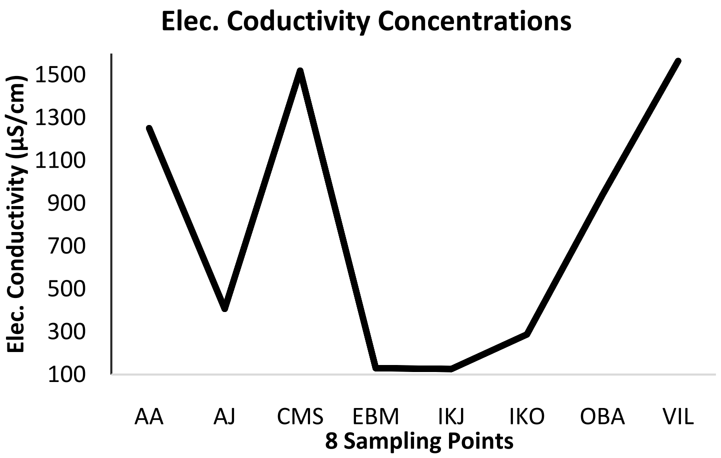

Figure 4. Concentration of electrical conductivity.

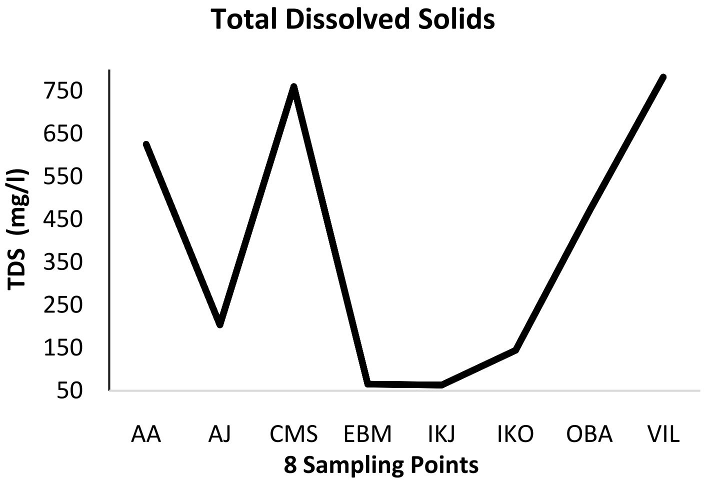

Figure 5. Total hardness distribution.

aquifer in that region. Based on Figure 5, the highest value of electrical conductivity occurred in the lower (southern parts) elevation of the study areas (CMS, VIL). Thus, it signifies a high possibility of saltwater intrusion into most of the aquifers within that region due to its distance to the Atlantic Ocean (refer to Table 2). The revised Table 3 shows that the phosphate concentration across the study area is not detectible (nd). The sulfate and chloride concentration show a lower value compared to WHO permissible limit (refer to Table 3). There is slight variation in the distribution of sulfate and chlorine concentrations, with the lowest value observed at EBM and IKJ, respectively (see Figure 6, Figure 7).

Figure 8, Figure 9 shows that the Na^+ and Ca^{2+} are lowest in "EBM", "IKJ", "IKO" whereas the highest concentration occurred at "CMS" and "VIL" respectively. The concentration of Na^+ in some locations is greater than the WHO permissible limit while that of Ca^{2+} did not exceed the WHO permissible limit throughout the study area (see revised Table 3). It is very vital to know that if soil pore water contains too much dissolved Na^+ relative to Ca^{2+} and Mg, the Na^+ ion can replace Ca^{2+} and Mg ions that are absorbed to the clay particles in the

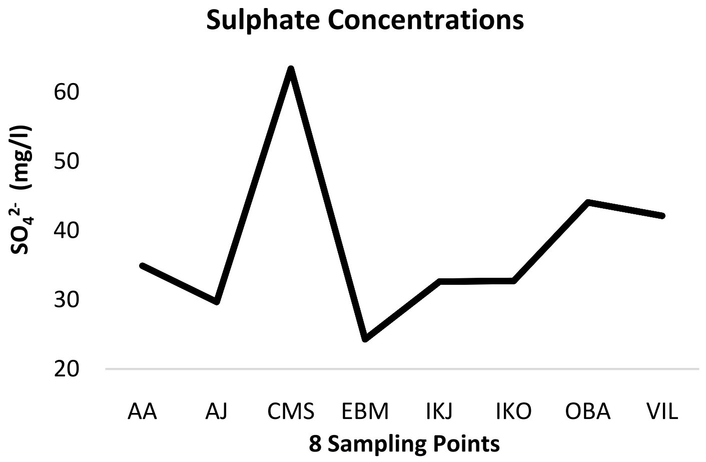

Figure 6. Concentration of sulphate.

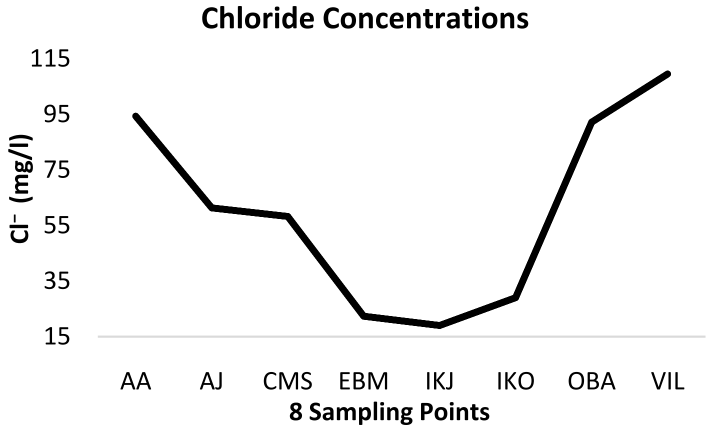

Figure 7. Concentration of chloride.

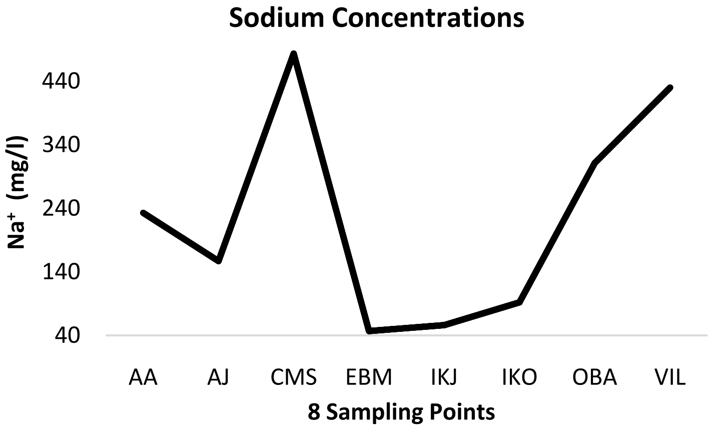

Figure 8. Concentration of sodium.

soil. This can destroy the soil structure making the soil difficult to cultivate, thereby reducing water availability in the soil profile [37]. It was observed that the concentration of Ca^{2+} was lower than the specified WHO permissible limit. The concentration of Ca^{2+} was highest at "OBA" and lowest at "EBM" (see **Figure 9**).

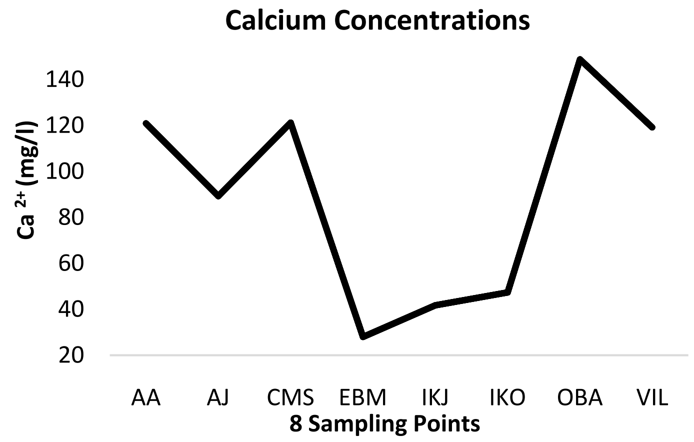

Figure 9. Concentration of calcium.

The concentration of K^+ was highest at "VIL" and extremely low at "EBM" and "IKJ" (see **Figure 10**). There was variations in the water quality especially in terms of total hardness, it was observed that the highest values of total hardness occurred at "CMS" axis of the Ocean (refer to **Figure 11**).

Monitoring Seawater Intrusion

For proper monitoring of the influence of seawater on coastal aquifers, one must ensure installations of monitoring wells and periodic monitoring of the differences in concentration of hydro-geochemical parameters. These parameters serve as major indicators of saltwater intrusion e.g., total dissolved solids (TDS), sodium (Na), Chloride (Cl) and Br/Cl ratio. To assess the level of intrusion at least semi-quantitatively, an assessment index (AI) is proposed and computed based on Equation (1) below:

$$\text{A.I} = \frac{\text{TDS}_C, \text{Na}_C, \text{Cl}_C, \text{Br}/\text{Cl}_C}{\text{TDS}_m, \text{Na}_m, \text{Cl}_m, \text{Br}/\text{Cl}_m} \tag{1}$$

where TDS_C, Na_C, Cl_C, Br/Cl_C are determined concentrations of TDS, Na, Cl, Br/Cl and TDS_m, Na_m, Cl_m, Br/Cl_m are the guide or /and maximum permissible concentration [5].

According to **Table 5**, the Assessment Index helps to classify hydro-chemical parameters into No Intrusion, Slight Intrusion and Strong Intrusion. According to **Table 6**, there was no intrusion in "EBM", "IKJ" and "IKO" while the other wells showed slight to strong intrusion.

According to **Table 7**, the percentage of hardness of water samples across the eight (8) sample wells shows that all the wells within the coastal regions of Lagos are very hard. The percentage hardness (Ca^{2+}) of the water samples by [30] indicated that all the selected wells are made up of 100% very hard water. The levels of total hardness across our study areas show a high level of hardness with ≥300 mg/l (see **Figure 11**). In addition, the Assessment Index were calculated using the formula as shown in Equation (1). The measured permissible levels of sodium (Na^+) and potassium (K^+) concentrations were found to be

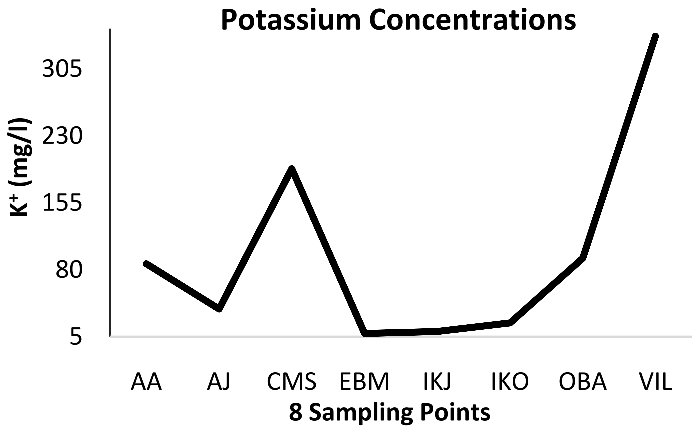

Figure 10. Concentration of potassium.

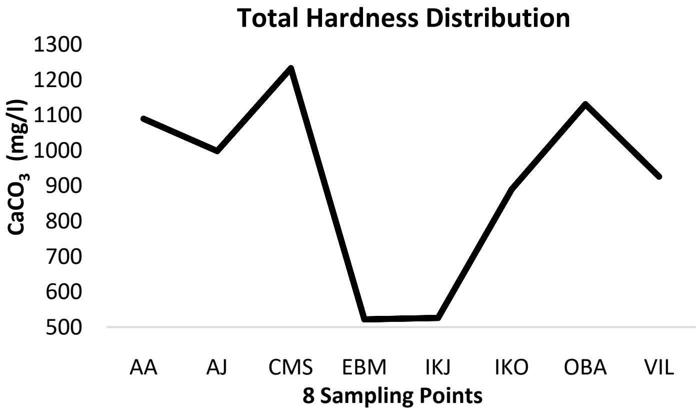

Figure 11. Concentration of total hardness.

Table 5. Monitoring scheme (adapted from [5]).

Class	Assessment Index (AI)	Remarks
1	<25	No Intrusion
2	25 - 50	Slight Intrusion
3	>50	Strong Intrusion

Table 6. The assessment index of SWI level (Salt-Water Intrusion Level).

Locations	TDS	Na^+	Ca^{2+}	SWI LEVEL (Remarks)
Adeniji Adele (AA)	41.7	47.51	60.45	Slight-Strong Intrusion
Ajah (AJ)	13.57	32.04	44.62	No-Slight Intrusion
CMS	50.67	98.66	60.6	Strong Intrusion
Ebutte Metta (EBM)	4.34	9.55	13.99	No Intrusion
Ikeja (IKJ)	4.22	11.46	20.87	No Intrusion
Ikorodu (IKO)	9.61	18.77	23.66	No Intrusion
Obalende (OBA)	31.33	63.52	74.38	Slight-Strong Intrusion
Victoria Island (VIL)	52.17	87.77	59.6	Strong Intrusion

Table 7. Percentage hardness of the water samples (modified from (Olufemi, 2010)).

Total Hardness (mg/l)	Water Classification	% Result of this Study
0 - 75	Soft	-
75 - 150	Moderately hard	-
150 - 300	Hard	-
>300	Very Hard	100%

remarkably high across "VIL", "OBA", and "CMS" making the water from those wells unsuitable for both domestic and agricultural purposes. In terms of cation concentration sequence, the order is $Na^+ > K^+ > Ca^{2+}$, indicating higher levels of Na^+ followed by K^+ and Ca^{2+}. Regarding anions, the sequence is $Cl^- > SO_4^{2-} > PO_4^{3-}$, with Cl^- being the dominant ion, followed by SO_4^{2-} and then PO_4^{3-} (refer to **Table 3**). These concentration patterns provide important insights into the composition and suitability of the water for various purposes, highlighting the potential challenges and limitations associated with its use. The pH values of groundwater samples from the selected boreholes range from 6.01 to 6.63, while electric conductivity values vary from 126 µS/cm in Ikeja (IKJ) to 1565 µS/cm in Victoria Island (VIL), as shown in revised **Table 3**. The high electrical conductivity values were found in the coastal areas such as "CMS", and "VIL", while lower values were observed in other parts of the study areas when compared with the WHO permissible limits. These higher conductivity values indicate saturation of the water with respect to saltwater intrusion, suggesting that these waters have been in prolonged contact with the ocean. The revised **Table 4** classified the physiochemical parameters into positive (+) and negative (−) stipulated permissible limits. The revised **Table 6** shows the calculated SWI levels, which reveal low conductivities and TDS for samples taken from "IKJ", "IKO", and "EBM" thus indicating no saltwater intrusion at those locations. This indicates that there is no intrusion in these areas, and it is important to continue monitoring the wells within the coastal areas to sustain and reduce saltwater intrusion.

6. Discussion

In certain areas of the study region, groundwater with exceptionally high concentrations of total hardness (as shown in **Figure 11**), total dissolved solids (TDS), and salinity has been documented. The maximum concentration levels for TDS, sodium (Na^+), potassium (K^+), calcium (Ca^{2+}), chloride (Cl^-), and sulfate (SO_4^{2-}) are as follows: 782.51 mg/l, 483.42 mg/l, 341.7 mg/l, 148.76 mg/l, 109.5 mg/l, and 44.07 mg/l, respectively (as indicated in the revised **Table 3**). These elevated values exceed the acceptable limits for domestic and agricultural purposes. When considering the ion concentration sequences, the cations follow the order of $Na^+ > K^+ > Ca^{2+}$, indicating higher levels of sodium, followed by potassium and calcium. In terms of anions, the sequence is $Cl^- > SO_4^{2-} > PO_4^{3-}$, with chloride being the dominant ion, followed by sulfate and phosphate. These findings emphasize the unsuitability of the groundwater for various practical applications, warranting attention and appropriate management strategies. From the revised Table 3, it is observed that the pH values of groundwater from the selected boreholes vary from 6.01 to 6.63. Electric conductivity values vary from lowest value in Ikeja (IKJ) 126 μS/cm in to 1565 μS/cm in VIL. Higher conductivity (salinity) values were found along the coast areas like AA, CMS, and VIL whiles lower values were observed in other parts of the study areas. The high conductivity values are an indicator of saturation of these water with respect to the saltwater intrusion, which implies that there might have been a long-time contact of these waters with the ocean. Further clarification can be seen from the calculated Saltwater Index level (see revised Table 6). Equation (1) was used to calculate the SWI (Saltwater Intrusion Index), where a measured concentration < 25 mg/l indicates no intrusion, a concentration between 25 and 50 mg/l indicates slight intrusion, and a concentration > 50 mg/l indicates strong intrusion (see revised Table 5). Out of the 8 samples, only EBM, IKJ, and IKO show no intrusion, whereas CMS and VIL show strong intrusion (see revised Table 6). This could also be attributed to the elevation and distance to the ocean (see revised Table 2). Low conductivities and TDS were observed for samples taken from IKJ, IKO, and EBM, which corresponds to the SWI (see revised Table 5, Table 6), indicating that there is no intrusion in these areas.

Most of the water in the wells is slightly—injuriously contaminated based on the differences in the ionic ratios as illustrated in the revised Table 8. According to a study conducted by (Todd & Mays, 2005), saline water resulting from seawater intrusion exhibits distinct characteristics compared to seawater. These include low Na/Cl ratios and high $Ca^{2+}/\left(HCO_3^- + SO_4^{2-}\right)$ and Ca^{2+}/SO_4^{2-} ratios.

Based on these ratios, a classification system has been proposed, consisting of five classes ranging from good quality water (ratio of 0.5) to highly contaminated water (ratio of 15.5) (Ma et al., 2019). Seawater solutes are characterized by an excess of chloride (Cl^-) in relation to alkali ions such as sodium (Na^+) and potassium (K^+). This classification system helps differentiate between different levels of water contamination caused by seawater intrusion based on the specific ion ratios (see revised Table 9).

Table 8. Ionic ratios of the wells in the study area (Vengosh et al., 2002).

Locations	Na^+/Cl^-	Ca^{2+}/Cl^-	K^+/Cl^-	SO_4^{2-}/Cl^-	Ca^{2+}/SO_4^{2-}	Na^+/Ca^{2+}
AA	2.47	1.28	0.92	0.37	3.46	1.92
AJ	2.56	1.46	0.59	0.48	3.01	1.76
CMS	8.31	2.08	3.31	1.09	1.91	3.99
EBM	2.09	1.25	0.39	1.09	1.15	1.67
IKJ	2.95	2.20	0.57	1.72	1.28	1.35
IKO	3.17	1.63	0.71	1.13	1.45	1.94
OBA	3.38	1.61	1.01	0.49	3.38	2.09
VIL	3.93	1.09	3.12	0.38	2.83	3.61

6.1. Aquifer Sustainability and Management Procedures

In the hydrological system on land, if the extraction of fresh groundwater through pumping wells exceeds the rate at which it is replenished, it leads to a lowering of the water table known as drawdown (Hudec & Jackson, 2012). In coastal areas, this drawdown along with the decreased hydrostatic pressure allows saltwater from the ocean to intrude into the freshwater aquifer (Hudec & Jackson, 2012). This phenomenon is observed not only in the coastal regions of Lagos, Nigeria but also in other coastal areas worldwide. The consequence of this intrusion is the contamination of freshwater supplies with saltwater (see **Figure 12**).

Based on (Motallebian et al., 2019), there is inadequate proper monitoring of salt-water intrusion and some of the practices that contribute to the problem of saltwater intrusion in coastal regions of Lagos, Nigeria includes:

1) Unregulated development of confined and unconfined aquifers.

2) Lack of proper sealing of abandoned wells due to saltwater intrusion.

3) Inadequate borehole completion and insufficient protection against corrosion are significant issues, particularly when the freshwater aquifer is situated beneath sands containing saline water.

The following is a list of measures, for both hydraulic and engineering approaches, that can be adopted to control saltwater intrusion (Armanuos et al., 2020; Motallebian et al., 2019; Yuan et al., 2022).

Table 9. Ionic ratios of the wells in the study area (modified after (Ma et al., 2019)).

Classification System	Ionic Ratio
Good Quality Water	< 0.5
Slightly Contaminated	0.5 - 1.3
Moderately Contaminated	1.3 - 2.8
Injuriously Contaminated	2.8 - 6.6
Highly Contaminated	>15.5

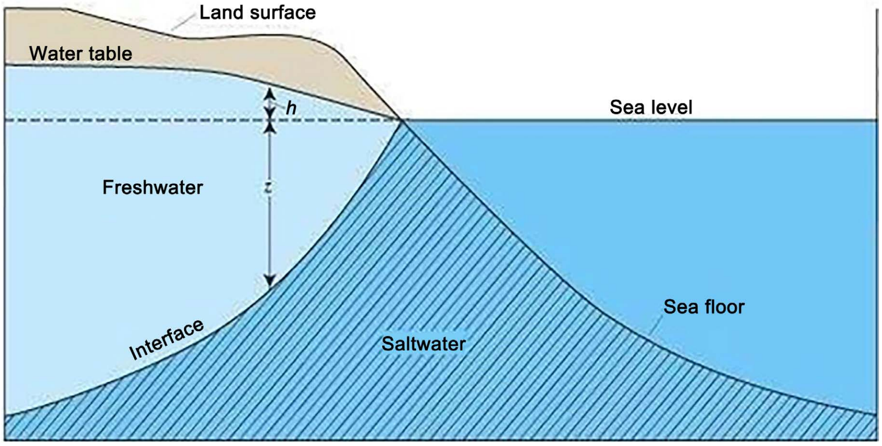

Figure 12. Concept of saline water intrusion (adapted from (Kim et al., 2006)).

1) Direct increase of recharge rate of the aquifer (artificial recharge/primarily surficial aquifers); various means to control runoff of freshwater lost through fractures, karst, and rivers.

2) Extracting/injecting combination or Extracting seawater before it reaches the wells.

3) Relocating wells or redesigning well fields.

4) Freshwater recharging into wells paralleling the coast, creating a hydrodynamic barrier.

5) Reducing pumping rate, to avoid the discharge rate exceeding the recharge rate.

The four basic components that are very necessary for proper management of groundwater resources against saltwater intrusion are listed below.

Delineation:	***Monitoring***:	***Modeling***:	***Modification***:
This involves the characterization of the existing conditions so that people can have an adequate understanding of the hydrogeological conditions and a detailed spatial characterization of the saltwater interface (Hussain et al., 2019). In this report, all data obtained were gotten through direct (hydrogeochemical parameters).	It involves a monitor program that can monitor conditions and provide a reasonable accurate assessment of the changes in the saltwater interface (Barlow, 2003; EPA, 2023). This can be achieved by accurately selecting the location of monitoring wells and providing sufficient screens length to monitor the changes in the saltwater interface (Ashcroft & Mubashar, 2011).	It is the use of Numerical modeling to predict long-term behavior of saltwater interface in response to changes in rainfall, water use and other activities or actions, which affect groundwater (Ashcroft & Mubashar, 2011). The numerical modeling that is often used is Finite Element Model and Finite definite Model. They are both good at solving complicated boundary value problems through discretization (Ashcroft & Mubashar, 2011).	Based on the results provided in the other three steps. There must be a modification of the pumping and control runoff or re-injection of wastewater to maintain the freshwater head to prevent further encroachment of saltwater (Hussain et al., 2019).

These four components delineation, monitoring, modelling, and modification must be accomplished for an effective management of groundwater resources against saltwater intrusion.

6.2. Techniques for Managing and Controlling Saltwater Intrusion

Saltwater intrusion is the process in which saltwater infiltrates freshwater aquifers or surface water bodies. The primary cause of saltwater intrusion is human activity, including the overexploitation of freshwater resources, climate change, and sea-level rise (WRMA, 2019). Saltwater intrusion can cause significant environmental and economic problems, including a reduction in water quality, damage to ecosystems, and economic losses in agriculture and industry. Therefore, it is essential to control saltwater intrusion to ensure the availability of freshwater resources and protect the environment (WRMA, 2019). There are several techniques for managing and controlling saltwater intrusion, including physical, chemical, and biological methods (Hussain et al., 2019; WRMA, 2019).

6.3. Physical Techniques

6.3.1. Barrier Techniques

Barrier techniques are physical methods of controlling saltwater intrusion that involve the construction of barriers to prevent saltwater from entering freshwater aquifers or surface water bodies (Motallebian et al., 2019). The most common barrier techniques are listed below:

***Coastal Dams*:**	***Injection Wells*:**	***Underground Dams*:**
Coastal dams are constructed along the coast to prevent the intrusion of saltwater into estuaries or rivers. Coastal dams are effective in controlling saltwater intrusion in low-lying areas and can also be used to regulate water flow (EPA, 2023).	Injection wells are used to inject freshwater into the aquifer to create a hydraulic barrier that prevents the intrusion of saltwater. Injection wells are most effective in areas where the freshwater aquifer is shallow (Peters et al., 2022).	Underground dams are constructed to prevent saltwater from entering freshwater aquifers. Underground dams are most effective in areas with a deep freshwater aquifer and a thin layer of permeable soil (Armanuos et al., 2020).

6.3.2. Pumping Techniques

Pumping techniques involve the pumping of freshwater into the aquifer to create a pressure gradient that prevents saltwater from entering the freshwater aquifer. The most common pumping techniques are listed below:

***Constant Rate Pumping*:**	***Variable Rate Pumping*:**	***Reverse Osmosis*:**
Constant rate pumping involves the pumping of freshwater into the aquifer at a constant rate to maintain the pressure gradient that prevents saltwater from entering the aquifer (Naderi & Gupta, 2020).	Variable rate pumping involves the pumping of freshwater into the aquifer at varying rates to maintain the pressure gradient that prevents saltwater from entering the aquifer (EPA, 2023; Naderi & Gupta, 2020). ***Variable rate pumping*** is more effective than ***constant rate pumping*** in areas with changing hydrological conditions (Yuan et al., 2022).	Reverse osmosis is a water treatment process that involves the removal of salt and other impurities from water (EPA, 2023; Naderi & Gupta, 2020; Peters et al., 2022). It is an effective technique for producing freshwater from saltwater.

6.4. Chemical Techniques

Chemical techniques involve the injection of chemicals into the aquifer to reduce the salinity of the water (Tonner & Tonner, 2004; Yuan et al., 2022). The most common chemical techniques are listed below:

***Electro-Dialysis*:**	***Ion-Exchange*:**	***Reverse Osmosis*:**
Electro-dialysis involves the application of an electrical current to the saline water to separate the salt ions from the water molecules (Naderi & Gupta, 2020; Tonner & Tonner, 2004; Yuan et al., 2022). It is an effective technique for producing freshwater from saline water.	It involves the exchange of ions between the saline water and resin bed (Subban & Gadgil, 2019). It is an effective technique for reducing the salinity of water.	Reverse osmosis is a water treatment process that involves the removal of salt and other impurities from water (Motallebian et al., 2019). It is an effective technique for producing freshwater from saltwater.

6.5. Biological Techniques

Biological techniques involve the use of plants and other organisms to control saltwater intrusion (Armanuos et al., 2020; Reef & Lovelock, 2015; WRMA, 2019). The most common biological techniques are listed below:

***Mangroves*:**	***Wetlands*:**
Mangroves are salt-tolerant trees that can grow in saline water. They can absorb excess salt from the water and prevent saltwater from entering freshwater aquifers (Reef & Lovelock, 2015).	Wetlands are areas of land where water is near the surface (EPA, 2023; Peters et al., 2022). They can absorb excess salt as well.

7. Conclusion

The main aim of this paper was to investigate saltwater intrusion in the Coastal parts of Lagos, Nigeria it is however quintessential to know that salinization of wells in this region is mainly because of a lack of proper management and elevation of the wells. The higher electrical conductivities of samples taken along the coastal part coupled with other analyses indicate that salinization of these wells is a result of saltwater intrusion. The dominant factor for salinization of wells in the other parts is due to dissolution of rock salt in the soil zone. Four of the wells generated in this study (wells: AA’, CMS’, OBA’ and VIL’) indicate saline water intrusion with very high values of electric conductivities ranging from (1251’, 1520’, 940’, 1565) respectively. It was also confirmed from the Assessment Index (A.I) that wells from “EBM”, “IKJ”, “IKO” have lower values of electric conductivities which indicates no salt-water intrusion. The Coastal Plain Sand aquifer unit in Lagos is of significant hydrogeological importance, but it faces a severe threat from ongoing seawater incursion and intrusion along its southern coastal boundary. The findings presented in this paper indicate that saltwater intrusion is actively occurring on the southern side of the Lagos metropolis. The coastal aquifers in Lagos experience a range of groundwater challenges, including declining groundwater levels, lowered piezometric surfaces, reduced yields, and the intrusion of saline water from multiple sources. These issues pose significant concerns for the sustainable management and utilization of groundwater resources in the region. However, monitoring of the wells within the coastal parts will help to sustain and reduce saltwater intrusion. The hydrological system on land is susceptible to saltwater intrusion when the extraction of fresh groundwater exceeds its replenishment rate, leading to drawdown. This phenomenon, observed in coastal areas globally, including Lagos, Nigeria, allows saltwater from the ocean to intrude into freshwater aquifers, resulting in the contamination of freshwater supplies with saltwater. The study also highlights the challenges and contributing factors to saltwater intrusion in coastal regions of Lagos. Inadequate monitoring practices, unregulated aquifer development, and improper well sealing contribute to the problem. Effective management strategies are crucial for addressing these issues. The proposed measures for controlling saltwater intrusion include hydraulic and engineering approaches. Techniques such as increasing aquifer recharge, relocating wells, and reducing pumping rates can be instrumental in managing saltwater intrusion. The delineation, monitoring, modeling, and modification components are essential for proper groundwater resource management against saltwater intrusion. This paper emphasizes the need for meticulous delineation and monitoring to comprehend hydrogeological conditions accurately. Numerical modeling, such as Finite Element Model and Finite Definite Model, aids in predicting long-term behavior and guiding modification strategies.

Furthermore, the paper discusses various physical, chemical, and biological techniques for managing and controlling saltwater intrusion. Coastal dams, injection wells, and underground dams serve as effective barrier techniques. Pumping techniques, including constant and variable rate pumping, along with reverse osmosis, offer viable options. Chemical techniques such as electro-dialysis and ion-exchange contribute to reducing salinity. Biological techniques involving mangroves and wetlands are also considered.

In summary, a combination of these techniques, tailored to the specific conditions of the coastal area, is essential for effective saltwater intrusion management. Proper implementation of delineation, monitoring, modeling, and modification components, along with the application of suitable techniques, will contribute to safeguarding freshwater resources against the adverse impacts of saltwater intrusion.

Declaration of Competing Interest

The authors declare that there are no competing financial interests that might have influenced the works presented in this paper. The authors declare that there are no competing personal relationships or financial interests that could have influenced the works or data presented in this paper.

Author Contribution Statement

The authors have read and approved the final version of this manuscript for publication. We also confirm that we have carried out the conception or design of the work, or the acquisition, analysis, or interpretation of data for the study. We are responsible for all the important intellectual content and agree to be accountable for all aspects of the work in ensuring that questions related to the accuracy or integrity of any part of the work are appropriately investigated and resolved.

Ethical Considerations

The authors declare that all research ethical considerations have been duly followed and that there are no human data or animal data used in this study. This study does not affect any group, and personal details are not applicable in this work.

Data Availability

The datasets analyzed during the current study are available at Olufemi, A.G “Assessment of Groundwater Quality and Saline Intrusions in Coastal Aquifers of Lagos Metropolis, Nigeria. J. Water Resour. Prot. 02, 849-853 (2010). https://doi.org/10.4236/jwarp.2010.210100”. Other raw data are available from the corresponding author on reasonable request.

Declaration of Competing Interest and Funding

The authors declare that there are no competing financial interests or personal relationships that could have influenced the works or data presented in this paper. We did not receive any funding for this research.

Conflicts of Interest

The authors declare no conflicts of interest regarding the publication of this paper.

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