Journal of Geoscience and Environment Protection, 2026, 14(8), 198-213
https://www.scirp.org/journal/gep
ISSN Online: 2327-4344
ISSN Print: 2327-4336

The Salt Wedge Influence Demonstration on Groundwater in a Coastal Sedimentary Environment with a Marl-Limestone Predominance in the Commune of Akanda, Libreville North, Gabon

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How to cite this paper: Boussougou Mouketou, I. S., M'Voubou, M. C. M., Pemba, L.-P. N., & Bourhane, A. (2026). The Salt Wedge Influence Demonstration on Groundwater in a Coastal Sedimentary Environment with a Marl-Limestone Predominance in the Commune of Akanda, Libreville North, Gabon. *Journal of Geoscience and Environment Protection, 14,* 198-213.
https://doi.org/10.4236/gep.2026.148011

Received: July 27, 2026
Accepted: August 28, 2026
Published: August 31, 2026

Abstract

This study focuses on demonstrating the saltwater intrusion impact on the groundwater the Akanda area, located in the coastal area north of Libreville, by Gabon. Three boreholes (Iwosso, Parlementaires, and Makouengué) in this municipality were studied by measuring the electrical conductivity of the water and the static groundwater levels using specific probes. Since July 2024, these measurements have been taken monthly for conductivity, while piezometric measurements have been taken continuously. The results of this integrated study revealed an increase in the water level in all three boreholes as soon as the rains arrived, reaching the surface in the Iwosso borehole, rising from −10 m/soil in August to −0.74 m/soil in November 2024. Electrical conductivity values were very high (1180 µS/cm) only in the Iwosso borehole during the dry season. This could be explained by the dynamic freshwater-saltwater interface, manifested by seawater intrusion into the Iwosso aquifer. These electrical conductivity values gradually decrease as rainfall becomes abundant (rainy season) and freshwater recharge progresses. This phenomenon of rising piezometric levels accompanied by a decrease in electrical conductivity during the rainy season was also observed in the other two boreholes. The proximity of the Iwosso borehole to the sea is likely not the only factor contributing to this salinity, given that the two other boreholes are also located near the sea. Further investigations will be conducted soon to fully understand the occurrence of the saline wedge at Iwosso.

Keywords

Central Africa, Groundwater, Piezometry, Salinity, Season

1. Introduction

Globally, groundwater is a resource that offers a better profile for human needs compared to surface water. In coastal areas, the saltier water influx into wells or boreholes often limits groundwater mobilization, as the groundwater becomes harmful or corrosive. A study conducted in India in 2007-2008 in 1165 villages by the Coastal Salinity Prevention Unit (CSPC) revealed that the consumption of brackish water by the people of the East Coast was the cause of diseases such as kidney stones, fluorosis, intestinal disorders, and many others (Siddha & Sahu, 2020).

The seawater intrusion phenomenon into porous coastal aquifers was first demonstrated by Ghyben and Herzberg at the end of the 19th century, who established an equation relating the freshwater-brackishwater interface (Verruijt, 1968). Under water stress, this interface advances into groundwater: this is known as marine intrusion. Comte et al. (2016), Bonnier (2012) and Bourhane et al. (2016, 2024) studied the phenomenon to locate the position of the freshwater-marine interface using analytical, geophysical, and modeling methods. In Gabon, on the outskirts of Libreville, and more specifically in Nkoltang, this phenomenon of saltwater wedge intrusion in a borehole drilled by Lafarge in 1970 was discussed in a study by Collignon & Ondo (2011).

The Akanda municipality, located in north of Libreville, despite its humid equatorial climate and high rainfall, faces challenges related to freshwater supply. This scarcity leads residents to rely on well or borehole water for their daily needs. However, some accounts mention a saline taste deemed unfit for human consumption. Currently, knowledge of the saltwater wedge influence on the groundwater in the Akanda area is very limited. It is based on this observation, and to address the concerns of the local population, that we undertook this study. Its overall objective is to demonstrate the existence of a saltwater wedge in the Akanda municipality groundwater, whose geology is predominantly marl-limestone and characterized by a network of fractures. Specifically, this will involve measuring the piezometry and groundwater electrical conductivity in Akanda through the Iwosso, Makouengué and Parlementaires boreholes.

2. Site Presentation

The Commune of Akanda covers an area of 475.2 km^2. It is bordered to the south by the commune of Libreville, to the north and west by the Atlantic Ocean, and to the east by Mondah Bay (**Figure 1**). This coastal area is relatively hilly inland, becoming flatter towards the coast. The northern part of this area is occupied by Akanda National Park, which includes the Mondah Classified Forest, a secondary forest with very dense vegetation. The central and southern parts of the commune are highly urbanized.

The hydrographic network is dense, with several small temporary and permanent streams meandering across the surface of this area. The rivers or tidal channels have noticeably low flows. These watercourses empty to the east into the Mondah estuary, to the north into Corisco Bay, and to the west into the Komo estuary or onto the Atlantic coast (Rogombe, 2022).

The Akanda commune is influenced by the hot and humid equatorial climate characteristic of Gabon. This climate is divided into two rainy seasons and two dry seasons. The main rainy season lasts from September to November, followed by a shorter rainy season from March to May. The main dry season lasts from June to August, and the shorter dry season from December to February.

The hottest month of the year is March, with an average temperature of 26.4˚C. The coldest month is July, with an average temperature of 24.3˚C.

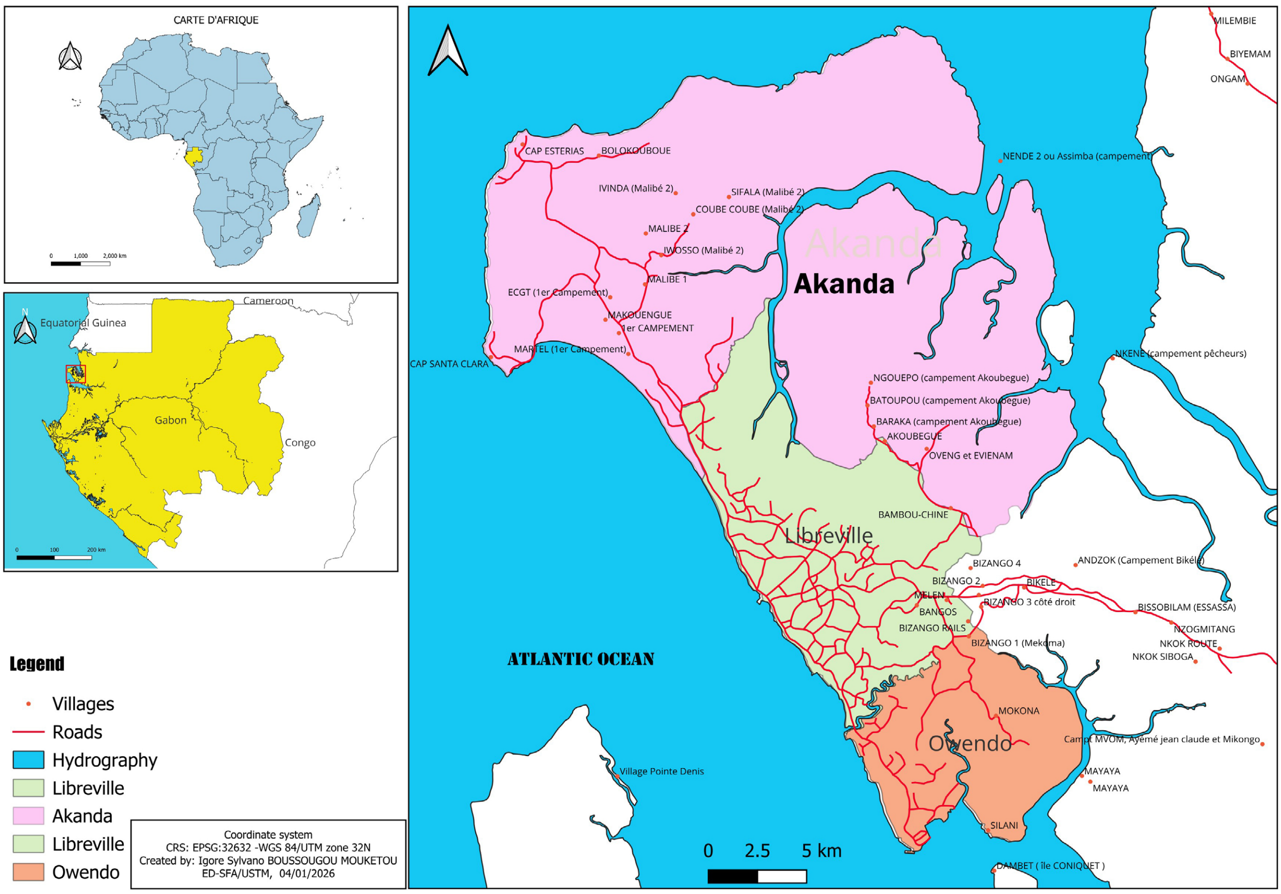

Figure 1. Akanda commune location (project area).

Geologically, the commune of Akanda extends over a plain of the coastal sedimentary basin whose structure is mainly made up of four distinct groups (Figure 2) which are: Alluvial formations (gravel, sand, claystone) of Quaternary age; the Anguille Group (sandstone, clayey sands, claystones) of Cenomanian to Maastrichtian age; the Sibang Group (limestones) of Turonian age and the Cape Lopez Group of Cenomanian age made up of limestones, claystones and silicified sands.

3. Materials and Methods

3.1. Analytical Equipment

This study focuses on the Akanda municipality groundwater, sourced from three boreholes belonging to the Ministry of Universal Access to Water and Energy. These boreholes are Iwosso, Makouengué, and Parlementaires. The boreholes selection was guided by the availability of unexploited aquifers, spatially distributed across the three main geological groups. The Iwosso borehole is unique in that it is located less than 10 meters from an exploited borehole that is 132 meters deep. The coordinates of the three boreholes were recorded using GPS and then projected onto a map of the study area (Figure 2) using QGIS.

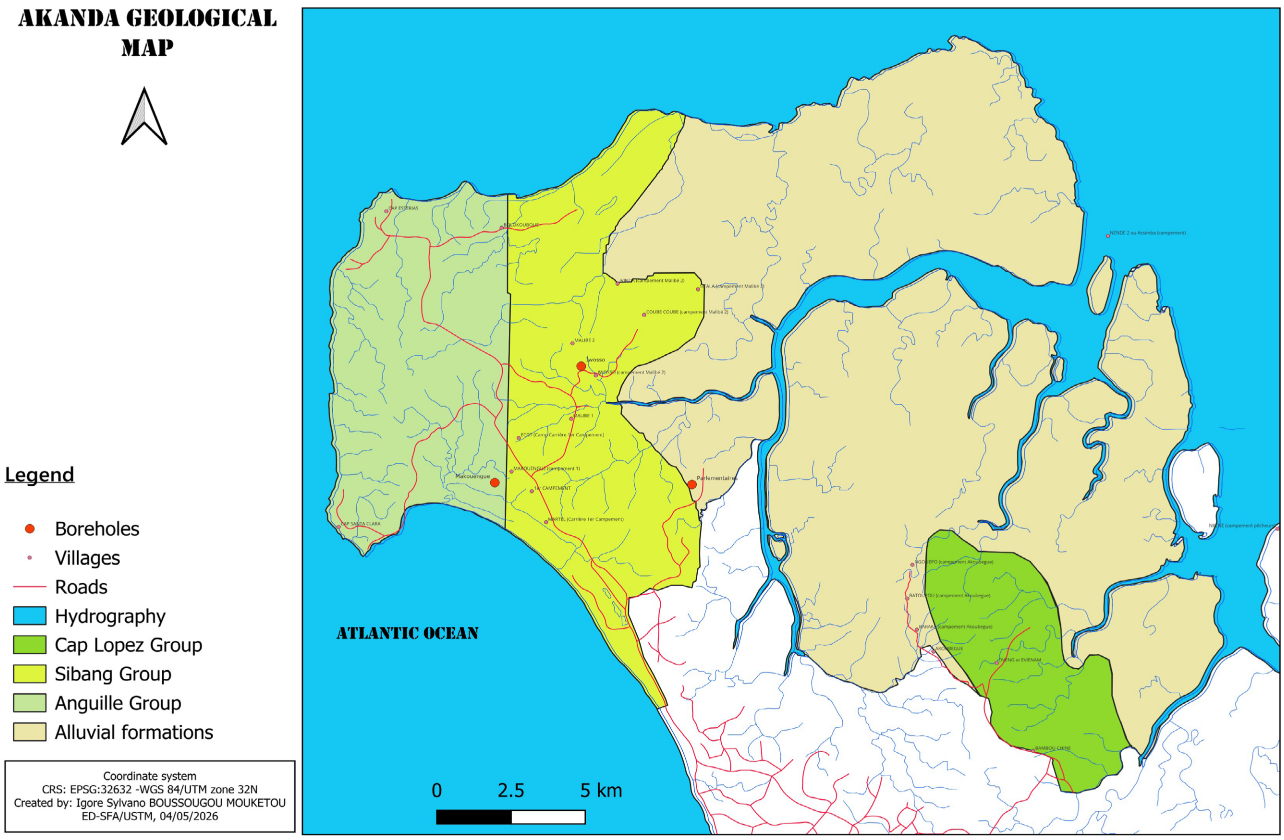

Figure 2. Boreholes location and geology of the Akanda area.

3.2. Analytical Methods

The marine intrusion investigation into the Akanda commune groundwater involved monitoring electrical conductivity and static groundwater levels in each borehole during the dry and rainy seasons (NASA POWER DATA, NASA, 2024), from June 2024 to November 2024. Three Diver-type pressure probes were installed in each of the Iwosso, Makouengué, and Parlementaires boreholes to obtain continuous records of their piezometric levels. To compensate for the lack of a barometric probe, we calibrated the water level of the aquifer above the pressure probe using the water level recorded with the sonic piezometer. Monthly measurements were taken using a sonic piezometer before each electrical conductivity measurement using a CTD (Conductivity Temperature Depth) probe. Each month, an electrical conductivity log was recorded per borehole with a recording time interval of one second and a space sampling interval of 40 cm, starting from the surface to the bottom. The tidal data (MAREE SHOM, SHOM, 2024) and the recorded data were collected using a Diver probe reader and processed in Excel to generate conductivity logs (vertical profiles) and piezometric variation time curves. (Kloppmann et al., 2011; Bailly-Comte et al., 2018) and is also used on Réunion Island (Bourhane et al., 2024; Frissant et al., 2005).

4. Results

4.1. Lithological Description of Boreholes and Piezometric Levels

The Parlementaires borehole, 60 m deep, was drilled into Quaternary alluvium. It alternates between layers of fine sand and claystone, 10 m thick, then a 37 m thick layer of ochre claystone, followed by a layer of fractured limestone, the first 13 m of which form the base of the well (**Table 1**). Water is drawn from this fractured limestone formation located beneath the 37 m thick layer of claystone, and the static water level in August was 3.9 m NGG.

Located in the Centre-West region at a depth of 100 m, the Makouengué borehole penetrated the Cenomanian to Maastrichtian-aged Anguille Group, composed of claystones, clayey sandstones, sandstones, marls, and limestones (**Table 1**). It draws water from the limestone layer located beneath the 27 m thick marl layer, with a static level averaging 17 m above sea level (NGG).

The Iwosso drilling, with a depth of 70 m, was carried out in the Sibang Group of Turonian age made up of claystones and limestones. This borehole is fed by water coming from the layer of fractured limestone 65 m thick located under a layer of sandy clay 4 m thick and the static level is 12 m NGG in August.

Table 1. Lithology and description of boreholes.

Borehole name	Altitude Z(m)	Depth (m)	Geology	Intake depth (m)	Layers captured	Piezometric level (m NGG)	Distance sea/firth (m)
Parlementaires	23	60	Soil, claystone, fine sand, limestone	50,45/59	Limestone (fractured)	3,9	5414/2089
Makouengué	25	100	Soil, marl, limestone	33,45/36,30 47,70/50,55 67,65/73,35 93,30/96,15	Limestone	17	1270
Iwosso	22	70	Soil, claystones, limestones	55/67	Limestone (fractured)	12	6432,5/1537

4.2. Electrical Conductivity

Across all three boreholes, the maximum electrical conductivity values of the borehole water ranged from 40 µS/cm to 1180 µS/cm (Figure 3). The highest value (1180 µS/cm) was recorded in Iwosso, and the lowest (40 µS/cm) in Parlementaires borehole. Seasonally, values in Makouengué and Iwosso were slightly higher during the dry season than during the rainy season. Conversely, in Parlementaires, they remained constant throughout the year.

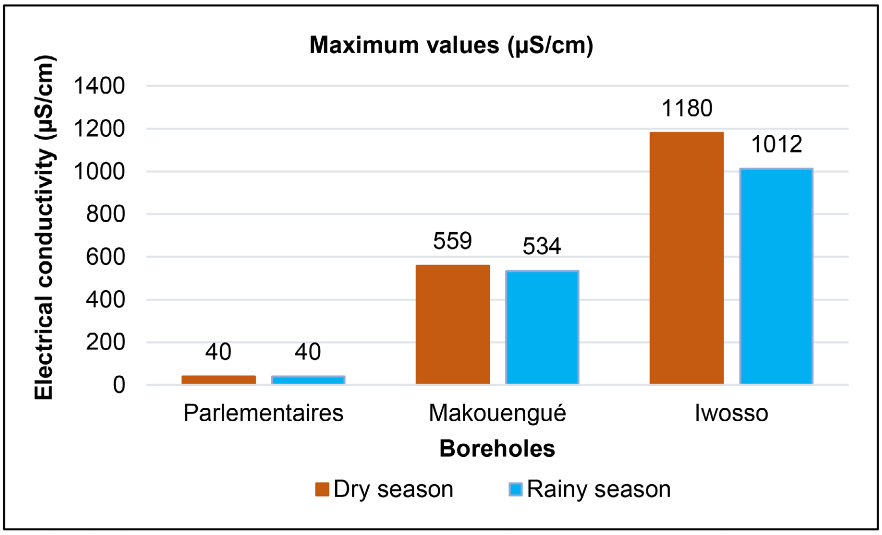

Figure 3. Electrical conductivity variations according to the seasons.

4.3. Parlementaires Borehole

In the Parliamentary aquifer (Figure 4), approximately 15 m of the wellbore were drilled (between 15 and 30 m). Electrical conductivity varies from 30 µS/cm to 40 µS/cm during the dry season (June 2024) and from 20 µS/cm to 40 µS/cm during the rainy season (October 2024).

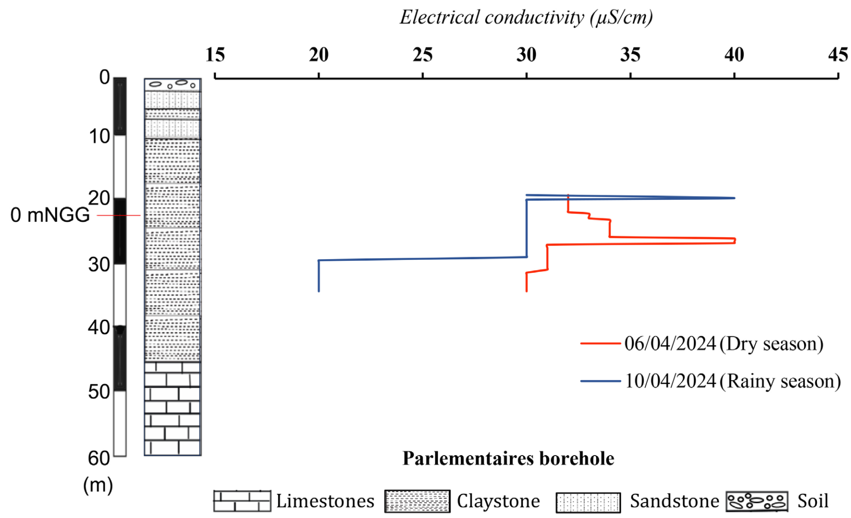

Figure 4. Electrical conductivity log in the borehole Parlementaires.

The conductivity values are not uniform. There is a signal disturbance accompanied by a drop in values starting at a depth of 25 m (**Figure 4**). This depth corresponds to sea level. From June to October 2024, we observe a decrease in electrical conductivity values at the same depths. Thus, at 25 m there is a transition from 34 µS/cm to 30 µS/cm and at 30 m a transition from 31 µS/cm to 20 µS/cm.

4.4. Makouengué Borehole

The Makouengué aquifer, covering the western part of the area, was drilled to a depth of 100 m, including 75 m below sea level. During the dry season (June 2024), electrical conductivity values ranged from 420 µS/cm to 559 µS/cm from the surface to depth, and from 453 µS/cm to 534 µS/cm during the rainy season (November 2024). The contrast between the two seasons is marked by a difference in seasonal averages, which are 524.87 µS/cm and 494.58 µS/cm, respectively (**Figure 5**).

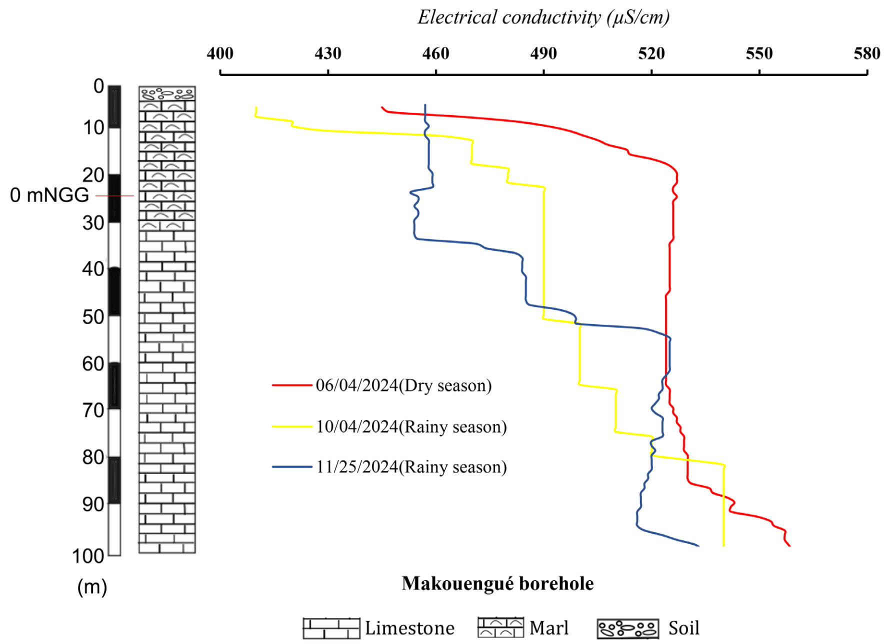

Figure 5. Electrical conductivity log in the borehole Makouengué.

The borehole logs show a progressive increase in electrical conductivity values as the aquifer is drilled down to a depth of 25 m, reaching 527 µS/cm (in June), 490 µS/cm (in October), and 455 µS/cm (in November). At this depth, a signal disturbance is observed in all seasons, and this depth corresponds to sea level. Furthermore, this disturbance is followed by a near-stabilization of the values, extending down to a depth of 50 m for the recorded signals of 524 µS/cm (in June) and 490 µS/cm (in October 2024), marking the beginning of the dry season and the start of the rainy season. The rainy season signal, for its part, indicates a near-stabilization at 471 µS/cm (in November) between 25 m and 35 m. This near-stabilization of conductivity values during the dry season is observed down to 85 m, with values of 530 µS/cm, before gradually increasing again down to 100 m, reaching 559 µS/cm. This inflection point of 518 µS/cm conductivity is found at a depth of 96 m during the rainy season.

4.5. Iwosso Borehole

A considerable difference in groundwater electrical conductivity values is observed compared to the other aquifers studied. The signal recorded during the electrical conductivity logging of water in the Iwosso borehole at the beginning of September (the peak of the dry season) shows a gradual increase in values down to a depth of 20 m, from 376 µS/cm to 414 µS/cm (**Figure 6**). There is then a rapid increase in values down to 24 m, where they stabilize at 608 µS/cm. Between 24 m and 38 m, the values follow a stable trend before resuming a gradual increase down to 49 m, where the electrical conductivity is 756 µS/cm. From 49 m to 68 m, there is a rapid increase in values starting at 64 m, rising from 764 µS/cm to 1180 µS/cm at the bottom of the borehole (68 m). It appears that during the dry season, as the depth increases, the electrical conductivity values of the Iwosso aquifer also increase, reaching values of 1180 µS/cm.

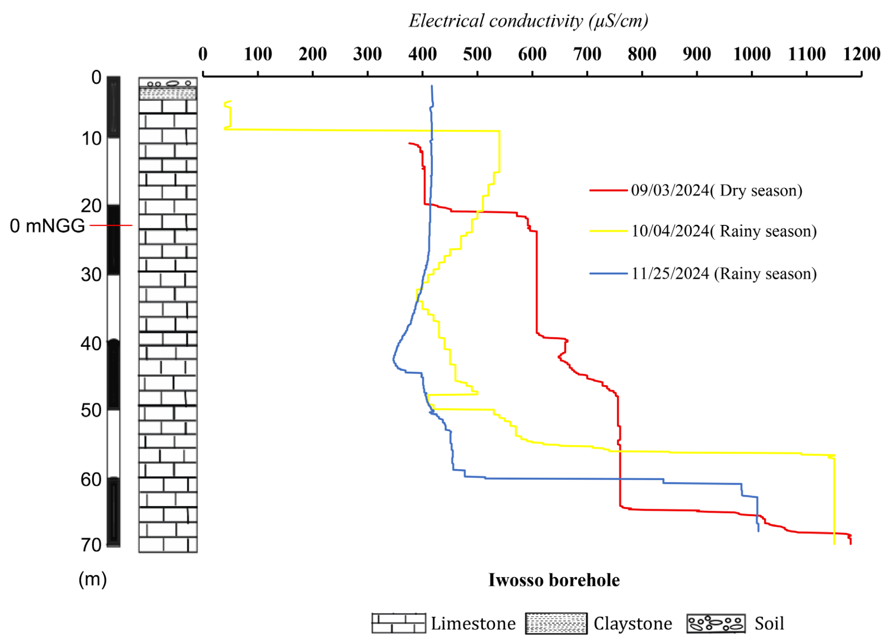

Figure 6. Electrical conductivity log in the borehole Iwosso.

During the rainy season (November), electrical conductivity log readings show a downward trend in the values recorded in October and November 2024. This downward trend is also visible with increasing depth, decreasing from 540 µS/cm and 418 µS/cm at 9 m and 397 µS/cm at 32 m and 351 µS/cm at 43 m. Beyond these two depths, the downward trend continues over time and with increasing depth. At the bottom of the borehole, a reversal of this trend is observed, marked by an increase in electrical conductivity values, reaching 1150 µS/cm and 1012 µS/cm in October and November, respectively (**Figure 6**).

4.6. Piezometrics

The piezometric measurement campaign continuously covers the period from August to November 2024 for the Parliamentary and Makouengué boreholes (Figure 7(a) and Figure 7(b)) and from October to November 2024 (Figure 7(c)) for the Iwosso borehole.

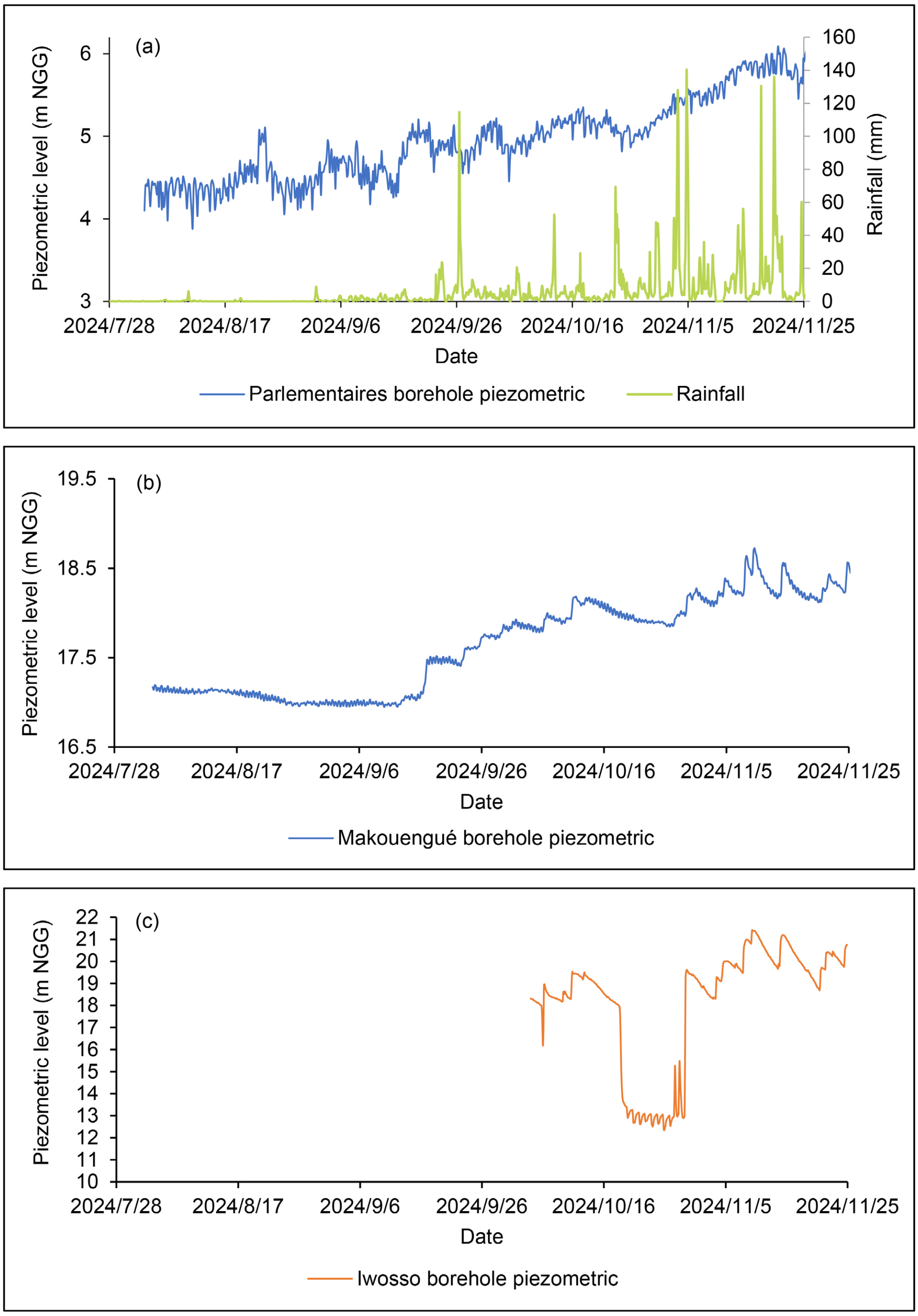

Figure 7. Rainfall (a) and continuous monitoring of piezometric levels using a Diver probe of the Parliamentary (a), Makouengué (b) and Iwosso (c) boreholes.

4.7. Parlementaires Borehole

In the Parliamentaires borehole (**Figure 7(a)**), the piezometric level fluctuates between 3.88 m NGG and 6.09 m NGG, values recorded respectively on August 12, 2024 (main dry season) and November 21, 2024 (main rainy season). Thus, from August to November 2024, although highly variable, the piezometric level shows an upward trend of approximately 2.21 m. The lowest values are recorded during the main dry season, while the highest are recorded during the main rainy season. However, a sharp increase in the piezometric level, reaching 5 m NGG, is observed during the main dry season. This sharp increase in the water level, approximately 0.68 m, was observed between August 23 and August 24, 2024 (**Figure 7(a)**). Apart from this peak, the piezometric level is generally stable during the dry season, whereas it varies much more during the rainy season. A dip in the piezometric level of approximately 0.48 m is observed during the rainy season between October 18, 2024, and October 26, 2024. In general, the piezometric fluctuations show a slow rise in water levels followed by a rapid fall from one event to the next.

4.8. Makouengué Borehole

In the central-western part of the Akanda region, at the Makouengué borehole (**Figure 7(b)**), the piezometric level varies between 16.94 m NGG during the dry season (August) and 18.72 m NGG during the rainy season (November). These values, recorded on August 27, 2024, and November 10, 2024, respectively, mark the peak of the low water level and the peak of the highest water levels. Between August 4, 2024, and September 12, 2024, a nearly stable trend in piezometric levels was observed, with a decrease of 0.19 m (**Figure 7(b)**). Between September 12, 2024, and November 10, 2024, there was an increase in piezometric levels of approximately 1.84 m, rising from 16.94 m NGG to 18.72 m NGG. Conversely, a decrease in piezometric levels was observed between October 14, 2024, and October 28, 2024, falling from 18.14 m NGG to 17.87 m NGG, a drop of 0.27 m in 14 days. Overall, the fluctuations in piezometric levels show a rapid rise in water levels followed by a slow decline after each event (**Figure 7(b)**).

4.9. Iwosso Borehole

In the Central-East region, the piezometric fluctuations of the Iwosso borehole (**Figure 7(c)**) show an increase in the water level between October and November of approximately 9.04 m, within the range of 12.34 m NGG recorded on October 26, 2024, to 21.38 m NGG recorded on November 10, 2024 (**Figure 7(c)**). A piezometric depression was observed between October 13, 2024, and October 26, 2024, resulting in a drop of 7.16 m in the water level in the borehole, from 19.50 m NGG to 12.34 m NGG (**Figure 7(c)**). During this period, the highest water level in the borehole was reached on November 10, 2024, with a piezometric head of 21.38 m NGG, or 0.62 m below ground level. Furthermore, the piezometric fluctuation signal shows a rapid rise and a slow fall in the water level in the borehole with more stable, i.e., low-noise, oscillations.

5. Discussion

5.1. Fluctuations in the Piezometric Levels of Boreholes

Variations in the piezometric level of an aquifer generally depend on several factors, such as geology, sensitivity to precipitation, surface water-groundwater exchange, and boundary conditions. These factors allow for a better understanding of the spatiotemporal behavior of the piezometric level (recharge conditions) of each aquifer included in this study (Latifi, 2018).

In the Parlementaires borehole, the arrival of the rainy season is marked by an increase in the piezometric level from the beginning of September (Obami, 2020), and this increase becomes more pronounced with the extended period of rainfall. The hypothesis of the influence of rainfall on the groundwater level is reinforced by the sudden and localized rise in the water level in the Parlementaires borehole in the middle of the dry season (August), and by the depression observed at the height of the rainy season in October (Collignon & ondo, 2011). The highly noisy static level signal in the borehole indicates a pronounced instability in the water level of the Parlementaires aquifer, which is thought to be linked to the influence of tidal movements and the nature of the layers (Frissant et al., 2005). The nature of the aquifer roof, consisting of a thick layer of claystones, would play a retarding role in the recharge of the water table, which would explain this slow rise in the water level (Obami, 2020), and the rapid descent could be explained by the phenomenon of downward drainage and evaporation.

In the Makouengué borehole, the scarcity of rainfall due to seasonal variations impacts the piezometric level. The decrease in rainfall during the second half of October leads to a piezometric depression of the water table, reflected in a drop in the static water level in the borehole (Frissant et al., 2005). The pattern of static water level fluctuations in this borehole indicates a weak influence of tidal movements, which would be attenuated by the nature of the more compact layers, such as undisturbed limestone and marl. The rapid rise and slow fall of the water table (Collignon & Ondo, 2011) could be explained by the nature of the marl cap, which would facilitate aquifer recharge.

In the Iwosso area, the piezometric level of the water table rises as rainfall increases, which would explain the rise in the static water level in the borehole, almost reaching the ground surface. The layer of claystone forming the aquifer's top layer is not thick enough to delay groundwater recharge, hence the tendency for a rapid rise in the water level and a slow fall, which is certainly linked to low downward drainage. The piezometric depression visible during the second half of October is linked to the scarcity of rainfall during this period and exacerbated by its location in the catchment area of the borehole operated by a public pump (El Mokhtar et al., 2018).

5.2. Comparison of Piezometric Levels in Boreholes

The three Parliamentary, Makouengué, and Iwosso boreholes, located in three different geological formations, exhibit similar piezometric level behavior influenced by seasonal variations (El Mokhtar et al., 2018). The rainfall event that caused the piezometric level to rise at Parliamentary during the dry season is not observed at Makuengué, where the water table level continues to decline, which would be consistent with the spatio-temporal variability of rainfall characteristic of Gabon (Maloba, 2015). The piezometric depression that appeared in the second half of October is visible in all three boreholes. This could be explained by a general decrease in rainfall across the entire study area.

The Parlementaires borehole has the lowest piezometric levels, close to sea level (less than 5 m NGG), compared to the other two boreholes, which have levels above 15 m NGG. The oscillations of the piezometric surface fluctuations are noisier in the Parlementaires borehole than in the other two. This noise is observed continuously in the Iwosso borehole only during periods of low pressure, when the piezometric level approaches sea level (around 10 m NGG), thus making the aquifer more sensitive to tidal variations (Frissant et al., 2005). Therefore, it can be hypothesized that, in a coastal sedimentary environment with less compact layers, the closer a borehole's piezometric level is to sea level, the more piezometric surface fluctuations are influenced by tidal movements.

5.3. Evidence of the Salt Wedge in Groundwater

The Parlementaires borehole exhibits electrical conductivities below 50 µS/cm in both the dry and rainy seasons for the sampled depths. These values indicate soft, slightly mineralized water (Métivier et al., 2024). Therefore, such values cannot suggest the presence of seawater in this borehole, or at least not detectable seawater in the upper part of the borehole.

The waters from the Makouengué and Iwosso boreholes have electrical conductivity values exceeding 500 µS/cm, reaching almost 1200 µS/cm in the Iwosso borehole. These values indicate water salinity where the borehole reaches or intersects the interface of the saline wedge (Frissant et al., 2005). The often complex distribution of high- and low-salinity zones sometimes reflects the history of past transgressions and regressions that may have left lenses of saline or fresh water in certain parts of the aquifer (De Montety, 2008). The reference value between fresh water and salt water is 500 µS/cm and the transition zone is between 500 µS/cm and 1000 µS/cm, because there is a possible salt intrusion and for electrical conductivity greater than 1000 µS/cm there is a strong suspicion of salt intrusion (Frissant et al., 2005).

In both boreholes, salinity (electrical conductivity) is higher during the dry season than during the rainy season (Comte et al., 2016). These seasonal and spatio-temporal variations in water salinity, which increase with depth, are controlled by an external factor that could be marine intrusion, and therefore the presence of the interface interface (Arfib, 2022; Vallet-Coulomb et al., 2009). At Iwosso, the interface is located at −30 m NGG, resulting in a sharp increase in electrical conductivity during both the dry and rainy seasons. This observation was made on the west and south coasts of Réunion Island, highlighting two types of interfaces (intense and diffuse) between freshwater and saltwater, controlled by recharge from surface waters (Bonnier, 2012).

5.4. Relationship between Salt Wedge and Piezometry

Groundwater recharge by precipitation under some conditions regulates the saltwater wedge influence in coastal environments. The small variations in piezometric levels are explained by the fact that, in the presence of a saltwater wedge, freshwater rests on saltwater, and the aquifer has two free surfaces: one at the freshwater-air interface and the other at the freshwater-saltwater interface. This Ghyben-Herzberg law implies that only 2.5% of the variation is visible at the upper surface, and the majority merges with the interface in the lower part (Métivier et al., 2024).

In the Moukengué borehole, during the dry season (June), the saline interface (the boundary between fresh and salt water) is located at a depth of 25 m. During the rainy season (November), this interface deepens to a depth of −50 m (**Figure 6**). The recharge provided by rainfall induces a thickening of the freshwater layer to a depth of nearly 25 m at the Makouengué borehole and pushes back the interface (Frissant et al., 2005).

Due to its greater depth (100 m), the Makouengué borehole is likely influenced by freshwater infiltration on the one hand and the impact of the saline wedge on the other.

- During the dry season, the piezometric level drops and the freshwater aquifer thins; the saltwater wedge then progresses inland, and the saline interface is established at a depth of 25 m;
- During the rainy season, the piezometric level rises, the freshwater aquifer thickens, and the saline interface is pushed back to a depth of 50 m.

Thus, a precarious hydrostatic equilibrium exists in this aquifer, which appears vulnerable to saltwater intrusion in the absence of sufficient rainfall to push back the saltwater wedge (Frissant et al., 2005). Consequently, a thickening of the freshwater layer is observed over nearly 30 m at the Iwosso aquifer. Like the Makouengué aquifer, the Iwosso aquifer is characterized by the alternating influence of freshwater infiltration during the rainy season and an advance of the saltwater wedge during the dry season (Zouhri et al., 2010).The vulnerability of the Makouengué and Iwosso aquifers to salt intrusion can also be explained by a higher transmissivity (T) or hydraulic diffusivity (D) which can be confirmed by carrying out pumping tests or a diffusivity analysis of the coastal aquifer (Bourhane et al., 2024). Furthermore, distance from the sea is not the only factor contributing to saltwater wedge intrusion, as the Iwosso borehole, reaching a depth of 70 m and located 1.5 km from a sea inlet and 6.4 km from the nearest coastline, exhibits the highest electrical conductivity signals. Given the complexity of salinization processes in coastal aquifers, it is therefore important to understand the mechanisms that drive interface dynamics (Bourjila, 2023).

6. Conclusion

This study made it possible to know the impact of the seasons on the limestone aquifers groundwater of the geological groups of Anguille (Makouengué borehole), Sibang (Iwosso borehole) and alluvium formations (Parlementaires borehole), and as well as the salinity spatio-temporal variation in the aquifers of the Akanda commune. The piezometric coasts of these three water layers are low in the dry season and high in the rainy season. The Parlementaires water layer has a lower piezometric coast, therefore close to zero sea level. The thick layers of claystone and marl present at Parlementaires and Makouengué have a delayed effect on the recharge of these two limestone layers, unlike that of Iwosso, which recharges quickly.

The high electrical conductivity values in the Iwosso and Makouengué boreholes indicate increased groundwater mineralization, which could be due to possible seawater intrusion. Thus, we have a possible salt intrusion at Makouengué and a strong suspicion of salt intrusion at Iwosso. However, current electrical conductivity data alone are insufficient to confirm the hypothesis of seawater intrusion or to distinguish it from water-rock interaction, residual saline water, or local contamination.

Therefore, it is recommended to conduct further studies, such as geophysical, hydrochemical, geochemical, and groundwater tests, to either confirm or refute the hypothesis of saltwater wedge influence and to better characterize its seasonality and dynamics.

Acknowledgements

All the authors of this manuscript wish to express their sincere thanks and gratitude to the Gabonese Ministry of Universal Access to Water and Energy for providing the boreholes and to the agro-industrial company Olam Palm Gabon for supplying the measuring equipment and logistical support. We also thank all those who contributed to the improvement of this article.

Author Contributions

This manuscript benefited from the participation of all authors. Boussougou, M.I.S., collected the data in the field, designed the graphic elements, interpreted the data, and wrote the paper. M'voubou, M.M.C., and Bourhane, A., designed the analytical methodology and interpreted the results. M.C.M. and Pemba, L.-P.N., assisted in designing the outline, compiling the bibliography, and analyzing the data.

Conflicts of Interest

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

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