Scientific Research Publishing

Open Journal of Applied Sciences, 2025, 15(10), 3274-3290
https://www.scirp.org/journal/ojapps
ISSN Online: 2165-3925
ISSN Print: 2165-3917

Mapping Saline Intrusion by Using Electrical Conductivity of the Continental Terminal Water (Northern Limit of the Ebrié Lagoon)

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How to cite this paper: Coulibaly, A., Bouadou, R.A.M. and Kouassi, K.A. (2025) Mapping Saline Intrusion by Using Electrical Conductivity of the Continental Terminal Water (Northern Limit of the Ebrié Lagoon). *Open Journal of Applied Sciences*, **15**, 3274-3290.
https://doi.org/10.4236/ojapps.2025.1510211

Received: September 28, 2025
Accepted: October 25, 2025
Published: October 28, 2025

Abstract

Continental Terminal waters of the Ivorian sedimentary basin are being exploited to supply the population with drinking water. In 2013, the catchment fields extracted around 400.000 m^3/d from the water table, although this production was insufficient to cover the needs. However, one of the consequences of this overexploitation of water is saline intrusion into the aquifer. In order to assess the level of contamination of the "Abidjan water table", a water mineralization study in piezometers located on the northern edge of the Ebrié lagoon was carried out. This study took place in March 2022, during the major dry season and involved twenty boreholes. A piezometric probe was used for this purpose. The study focused on the horizontal spatialization of surface and on the vertical distribution of electrical conductivities. Analysis of the spatial distribution of water indicates that the CT water is generally "fresh water", except those of the piezometer PZ_C2D 9. There, brackish and salty water is recorded. However, brackish water is abundant deeper in the basement at seven piezometers. These piezometers are located respectively along the Ebrié lagoon and around the Aghien lagoon. This study reveals that the Continental Terminal waters on the northern limit of the Ebrié lagoon are not yet affected by marine intrusion.

Keywords

Sedimentary Basin, Continental Terminal, Electrical Conductivity, Spatial Distribution, Saltwater Intrusion, Fresh Water

1. Introduction

Water is essential to life, to natural ecosystems and is an indisputable socio-economic asset. This water is stored in aquifers (continuous and discontinuous), which are more or less exposed to pollution. One source of pollution is marine intrusion in coastal areas. In this area, salinization makes it difficult to use groundwater for domestic purposes. Heavy mineralization of coastal groundwater is generally linked to the intrusion of marine water [1] [2]. This intrusion is marked by high concentrations of certain minerals. In addition, mineral salts are added by sea spray dissolution, cation exchange and anthropogenic pollution [3]. The mineralization of groundwater is often assessed by measuring electrical conductivity [4]. This is because most of the dissolved matter in water is in the form of electrically charged ions.

In the District of Abidjan (Côte d'Ivoire), drinking water is supplied to the population from catchment areas comprising around a hundred boreholes. According to the Ministry of Water, Sanitation, and Hygiene, approximately 06 m^3/s of water is extracted from the Continental Terminal aquifer for this purpose. Although it is already very high, this flow is constantly increasing, due to the high demand for water. Overexploitation of this resource is a threat to the waters of the Continental Terminal [5] [6]. Also, over the last few decades, industrial exploitation of sand in the lagoon has developed to meet the needs of the megalopolis of Abidjan. However, these sands are extracted from geological layers that protect the Abidjan water table beneath the lagoon. Finally, previous studies [7] carried out on this water table have highlighted salinity problems in the water from certain boreholes in Plateau and Adjamé. High levels of dissolved salts (chlorides) and high mineralization (electrical conductivity of between 7000 and 10,500 $\mu S \cdot cm^{-1}$) [8] have been recorded in the water from these boreholes, indicating marine intrusion.

Faced with this challenge, the aim of this study is to analyse changes in the electrical conductivity of the Continental Terminal water at the northern edge of the Ebrié Lagoon, with a view to identifying the wedge.

2. Presentation of the Study Area

2.1. Geographical Location

Located in the south of Côte d'Ivoire, the study area lies on the northern edge of the Ebrié Lagoon, between 4˚15'57.6'' and 3˚45'36'' West and 5˚17'20.4'' and 5˚27'57.6'' North (**Figure 1**). It belongs to the Autonomous District of Abidjan, which comprises ten (10) municipalities and four (04) sub-prefectures covering an area of around 1.160 km^2 and with an estimated population of 29 million [9].

It has three main lagoons. The Ebrié lagoon, the largest, is a vast expanse of navigable water covering 566 km^2 and connected to the Atlantic Ocean via the Vridi canal. It receives water from the Comoé river, the Agnéby and Mé rivers [10]. The Potou and Aghien lagoons are small internal lagoons running north-south. They flow into the Ebrié Lagoon [11] (**Figure 2**).

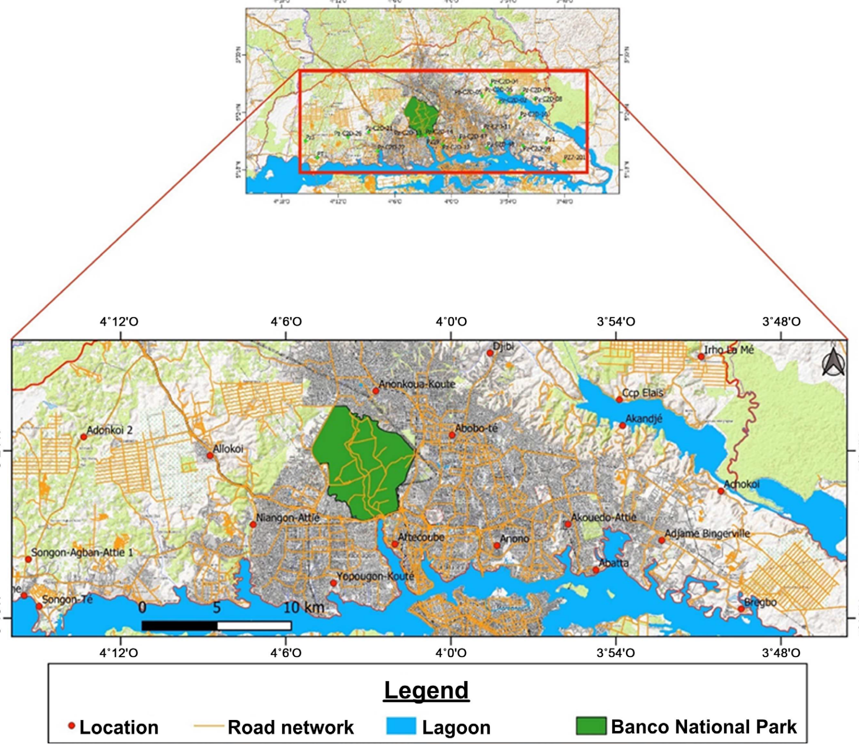

Figure 1. Location of the study area.

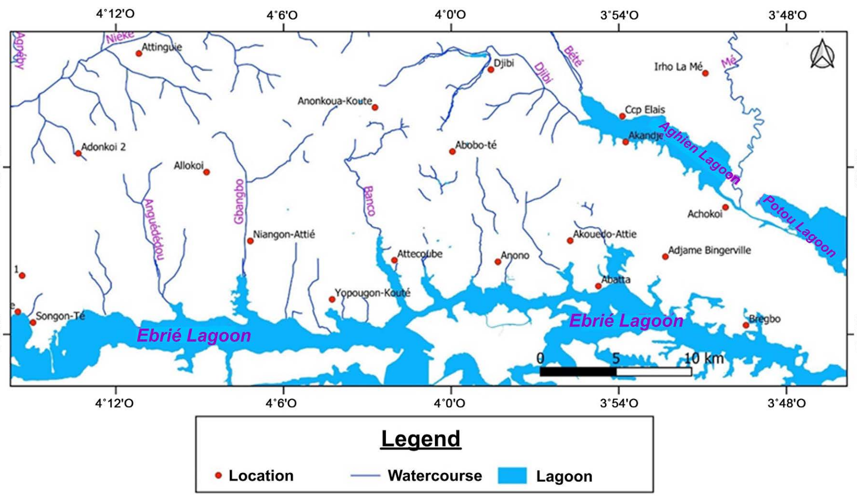

Figure 2. Hydrographic network in the study area.

The most important rivers are [12]:

- the Agnéby is a coastal river that rises in Agoua at an altitude of 250 m. It covers a catchment area of 8900 km^2 and is 200 km long. In its lower reaches, the Agnéby flows through marshland. Its longitudinal profile is fairly irregular, with an average gradient of 1.25 m per km,
- the Anguédédou, Banco and Gbangbo flow in a N-S direction and all empty into the Ebrié lagoon,
- the Niéky, a tributary of the Agnéby, flows NE-SW,

- the Djibi and the Bété, which flow NW-SE and empties into the Aghien lagoon. The Bété drains the clayey sands of the Anyama plateau and erodes part of the metamorphic schists [13].

2.2. Geological Context

The geological context of the study area generally belongs to the sedimentary basin. The sedimentary formations in this basin are grouped into two main formations: the Continental Terminal in the northern part of the lagoon fault and the Quaternary to the south of this fault [14]. The Continental Terminal or Tertiary is made up of sandy-clay sediments, gravels and conglomerates, while the Quaternary is composed of marsh muds and sand (**Figure 3**).

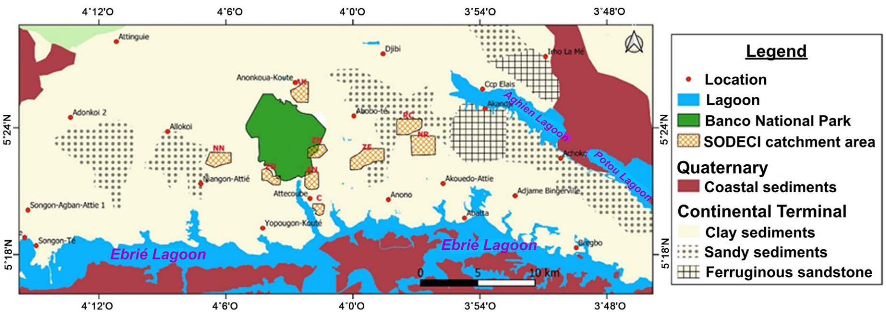

Figure 3. Geological map of the study area.

2.3. Hydrogeological Context

The hydrogeological overview of the Ivorian coastal sedimentary basin at the northern boundary of the Ebrié Lagoon reveals the existence of a Continental Terminal aquifer. It comprises four horizons superimposed from top to bottom [15]:

- horizon 4: discontinuous lateritic cuirass locally capping sandy clays and clayey sands (0 to 70 m),
- horizon 3: coarse fluvial sands (0 to 90 m),
- horizon 2: black clays and clayey sands (0 to 10 m),
- horizon 1: gravelly sands with bands of mottled clays (0 to 20 m).

According to the same authors, horizons 3 and 4 make up the bulk of the Continental Terminal aquifer. Generally unconfined, lenticular clay banks located at the top of horizon 3 make the aquifer captive in some areas. These horizons form a single aquifer when these clay banks are absent. Horizon 2 is a sterile aquifer and horizon 1 contains the water table at the base of the Tertiary period.

Exploitation of the Continental Terminal aquifer, commonly known as the "Abidjan aquifer" accounts for 68% of Côte d'Ivoire's drinking water supply. This water table also feeds the Maestrichtian one at its base [16] because of the thickness of the clay and ferruginous sandstone separating the two aquifers.

2.4. Influence of Environmental Factors on Water Mineralization

The various processes involved in the mineralization of groundwater were determined by studying the spatial and temporal evolution of electrical conductivity, piezometry and correlations between the major elements. Water mineralization is often assessed by measuring electrical conductivity [4]. This is because most of the dissolved matter in water is in the form of electrically charged ions [8].

In this study, electrical conductivity was used as a marker of the mineralization of the Continental Terminal groundwater.

3. Material and Methods

3.1. Data Acquisition

Electrical conductivity measurement campaign was carried out using a sound piezometric probe at twenty (20) piezometers (**Figure 4**) covering the study area. It took place from 02 to 05 March 2022, a month that corresponds to the dry season.

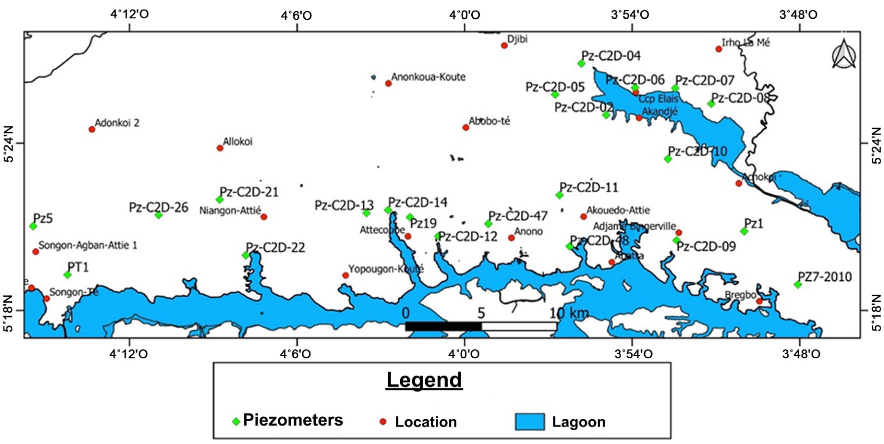

Figure 4. Location of piezometers in the study area.

The piezometric probe used is a Solinst TLC Meter model 107, 300 m long and mounted on a coil. It is ideal for profiling conductivity and temperature in piezometers for saltwater intrusion studies and a general indication of contamination levels. Conductivity and temperature readings are displayed on a rotating LCD screen on the face of the coil The depth of the water and the depth of the readings displayed are read off the tape. Conductivity accuracy is 5% of reading or 100 µS (whichever is greater). A light and buzzer are briefly activated when the zero point of the probe enters the water.

The GARMIN Map64s GPS (Global Positioning System) is used to determine the coordinates (longitude, latitude and altitude) of the measurement points (piezometers).

3.2. Groundwater Electrical Conductivity Measurements

The probe is lowered progressively into the piezometer (vertical profiling) and measurements are taken in steps of approximately two (02) meters. At each depth, the electrical conductivity and the temperature values are displayed on the screen of the coil.

The electrical conductivity of a liquid depends largely on its temperature. That's why these two parameters were measured simultaneously. While standard temperatures such as 20˚C or 25˚C are used for calibrations with conductivity standards, conductivity measurements are generally carried out at different temperatures. Identifying water types from conductivity therefore requires recalculating the conductivity measured at a standard temperature, for example 25˚C. This correction is based on the following equation [17]:

$$EC_{25^\circ C} = EC_T \times F_{25} \quad (1)$$

where: EC_T = the measured electrical conductivity et F_{25} = temperature correction factor.

A classification of electrical conductivity has been established in order to define water types. This is the Milot and Renaud (2020) classification (**Table 1**).

Table 1. Classification of waters according to electrical conductivity [18].

Water type	Electric conductivity (μS/cm)
Fresh water	EC < 200
Mineral water	200 ≤ EC ≤ 1000
Salt water	EC ≥ 2000

Water mineralization is assessed by measuring electrical conductivity. It is a good indicator of groundwater mineralization. This is because most of the dissolved matter in water is in the form of electrically charged ions [8].

In this study, Continental Terminal water mineralization is assessed by studying the spatial evolution of the electrical conductivity of water from this aquifer. Electrical conductivity data are acquired at each piezometer and along with six (06) aligned profiles (horizontal profiling) (**Table 2**). The horizontal profiles were defined according to the alignment and orientation of the piezometers.

Table 2. Piezometer profiles.

Profiles	Piezometers
1	PT1, PZ_C2D 26 et PZ_C2D 21
2	PZ_C2D12, PZ_C2D13, PZ_C2D14, PZ19 et PZ_C2D47
3	PZ_C2D 11, PZ_C2D 9 et PZ7_2010
4	PZ_C2D 10, PZ1 et PZ7_2010
5	PZ_C2D5, PZ_C2D10 et PZ_C2D2
6	PZ_C2D4, PZ_C2D6, PZ_C2D7 et PZ_C2D8

This study focuses on the horizontal spatialization of electrical conductivities in the surface part of the water table and on the distribution of electrical conductivities as a function of depth (vertical profiling).

3.3. Data Processing

Data processing was carried out with software. This software is chosen in accordance with the different objectives set. These are:

- Quantum GIS (QGIS 3.16), to generate and digitize the cartographic media;
- Microsoft EXCEL TM 2016, to set up the databases for the study of the spatial distribution of the electrical conductivity of water.

4. Results

4.1. Analysis of Measured Temperatures

Table 3 shows low standard deviations overall. This reflects a high concentration of measured temperatures around their mean values. In fact, the almost zero standard deviation values indicate that the temperatures measured as a whole are similar. Also, the standard deviations of approximately one (01) obtained only at the level of three piezometers (PZ-C2D8, PZ-C2D9 and PZ-C2D12), means that the temperatures measured are distributed more or less uniformly over a range of one (01) unit.

Table 3. It summarizes the temperature statistics measured in the various piezometers.

Piezometers	Mean	Standard deviations
PZ C2D26	26.75	0.11
PZ C2D09	29.29	1.3
PZ C2D06	26.27	0.08
PZ C2D05	26.33	0.06
PZ C2D07	26.62	0.25
PZ C2D10	26.75	0.08
PZ C2D08	25.18	1.56
PZ 01	26.51	0.04
PZ05	26.66	0.12
PZC2D04	26.58	0.29
PZC2D12	27.46	1.19
PZ07-2010	27.33	0.64
PZC2D21	26.01	0.26
PT1	28.5	0.02
PZC2D14	26.27	0.48
PZC2D13	26.43	0.74
PZC2D02	26.26	0.09
PZ19	28.52	0.08
PZC2D48	27.78	0.48
PZC2D47	27.01	0.52

4.2. Spatial Evolution of Electrical Conductivity in the Surface Part of the Water Table

Electrical conductivity measurements are analyzed according to their spatial distribution (mapping) and their behaviour at depth (electrical conductivity logs).

4.2.1. Electrical Conductivity Mapping of the Surface Part of the Water Table

The electrical conductivities measured in the first few meters of the piezometers are all low (less than 200 µS/cm). These values are typical of freshwater. However, their spatial distribution highlights three classes of electrical conductivity (**Figure 5**).

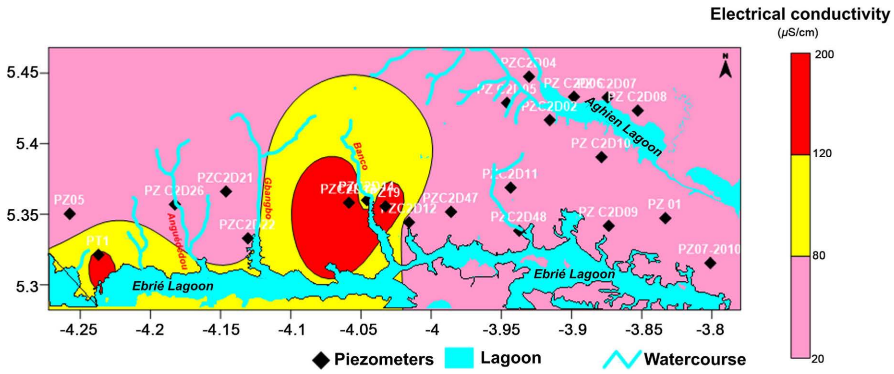

Figure 5. Spatial distribution of electrical conductivity values in the surface part of the aquifer.

The first class, the most important in terms of surface area, is that of water with very low electrical conductivity (between 20 and 80 µS/cm). The second class is characterized by electrical conductivities ranging from 80 to 120 µS/cm and is located along the Ebrié lagoon to the west and between the Banco and Gbangbo rivers. Finally, the third class, comprising water from piezometers PT1, PZ_C2D 13 and PZ 19, is characterized by electrical conductivity values of between 120 and 200 µS/cm. This class is contained within the previous class. The piezometers in these last two classes are located downstream of surface water flows towards the Ebrié Lagoon (PT1) and Banco Bay (PZ_C2D 13, PZ_C2D 14 and PZ 19).

4.2.2. Electrical Conductivity Logs for Piezometer Water

The vertical variation of electrical conductivity was characterized using conductivity logs. The results are summarized in the appendix. These were analyzed using (6) aligned piezometer profiles (**Table 4**).

Table 4. Characteristics of the conductivity profiles.

Profile	Number of piezometers	Direction
1	3	SW-NE
2	5	W-E

Continued

3	3	NW-SE
4	3	NW-SE
5	3	NW-SE
6	4	NW-SE

✓ Profile 1

It comprises piezometers PT1, PZ_C2D 26 and PZ_C2D 21. The electrical conductivity logs are shown in the appendix. Its values range from 30 to 1900 µS/cm. Piezometers PT1 and PZ_C2D 21 have very low electrical conductivity ranging from 30 to 200 µS/cm (PT1: 30 < EC < 74 µS/cm and PZ_C2D 21: 31 < EC < 250 µS/cm). It's the same for the electrical conductivities of the CT sands at PZ_C2D 26, which range from 58 < EC < 66 µS/cm. However, there is a sudden jump in conductivity from 140 m corresponding to the depth of the bedrock. These electrical conductivities reach 1900 µS/cm, indicating the presence of brackish water.

✓ Profile 2

It includes piezometers PZ_C2D12, PZ_C2D13, PZ_C2D14, PZ19 and PZ_C2D47. The electrical conductivities range from 34 to 1600 µS/cm and the logs of electrical conductivity are shown in the appendix.

The electrical conductivities of the water in the CT sands define two classes of water. "Fresh water", relatively low (CECT < 200 µS/cm), is found in all the piezometers except PZ19. Slightly higher conductivity values (200 < CECT < 1000 µS/cm) corresponding to "mineralized water" class were measured in piezometers PZ_C2D13, PZ19, PZ_C2D14, PZ_C2D12 and PZ_C2D47. This class is marked by significant and sudden variations of conductivity at 23 m and 80 m, 40 m, 80 m, 100 m and 138 m respectively.

In the basement, brackish water is found in piezometers PZC2D12 and PZ_C2D13, at 120 m and 100 m respectively. These depths correspond to those of the basement.

✓ Profile 3

Three piezometers (PZ_C2D 11, PZ_C2D 9 and PZ7_2010) make up this profile. The electrical conductivity logs are shown in the appendix. Piezometers PZ_C2D 11 and PZ7_2010 record very low electrical conductivity values ranging from 33 to 200 µS/cm with depth. As for piezometer PZ_C2D 9, three (03) electrical conductivity classes are defined. These are:

- the class of electrical conductivities below 200 µS/cm representing fresh water. These waters are marked between 0 m and 60 m and between 100 m and 160 m.
- the class of electrical conductivities between 200 and 1000 µS/cm. This is the class of mineralized water located between 60 m and 100 m.
- finally, the class of electrical conductivities between 1000 and 3600 µS/cm. This includes brackish and salty waters. These waters are located at a depth of between 160 m and 180 m.

To sum up, the water in the CT for this profile is made up of fresh water, mineralized water and brackish and saline water.

✓ Profile 4

It comprises piezometers PZ_C2D 10, PZ1 and PZ7_2010. The electrical conductivity logs are shown in the appendix. The water in the CT is characterized by low electrical conductivity (29 to 94 µS/cm) and is classified as freshwater.

✓ Profile 5

It consists of piezometers PZ_C2D5, PZ_C2D10 and PZ_C2D2. The electrical conductivity logs are shown in the appendix. The water in the CT has very low electrical conductivity (30 - 62 µS/cm) to a depth of around 120 m. This electrical conductivity is characteristic of 'fresh' water. However, 'weakly and moderately mineralized' water, with electrical conductivity values of less than 1000 µS/cm, is encountered in PZ_C2D 5 and PZ_C2D2.

Brackish water was also detected in piezometer PZ_C2D5 at a depth of 126 m. At this depth, the bedrock is found. Relatively high electrical conductivity values (1400 µS/cm) were measured from this depth.

✓ Profile 6

This profile consists of piezometers PZ_C2D4, PZ_C2D6, PZ_C2D7 and PZ_C2D8. The electrical conductivity logs are shown in the appendix. Low electrical conductivities were measured at depths of 32 m, 98 m, 47 m and 116 m. These depths correspond to those of the CT. We therefore conclude that at the level of this profile, the water in the CT is 'fresh water'.

Below, in the basement, the electrical conductivity values of the water indicate 'moderately mineralized water' and 'brackish water'.

Analysis of all the electrical conductivity logs indicates high electrical conductivity values (greater than 1000 µS/cm) in seven (07) piezometers (**Table 5**). These are piezometers PZ_C2D 26 (profile 1), PZ_C2D 12 and PZ_C2D 13 (profile 2), PZ_C2D 9 (profile 3), PZ_C2D 5 (profile 5), PZ_C2D 6 and PZ_C2D 7 (profile 6).

Table 5. Summary of piezometers where saline intrusions have been observed.

Piezometers	Electrical conductivity range (µS/cm)	Base depth (m)	Intrusion zone	Water category
PZ_C2D 26	1000 à 1971	142	Basement	Brackish
PZ_C2D 13	1000 à 1609	100	Basement	Brackish
PZ_C2D 12	1000 à 1639	120	Basement	Brackish
PZ_C2D 9	1000 à 3612	191	CT	Brackish and salty
PZ_C2D 5	1000 à 1418	126	Basement	Brackish
PZ_C2D 6	1000 à 1744	98	Basement	Brackish
PZ_C2D 7	1000 à 1264	50	Basement	Brackish

The CT waters have not yet been affected by the marine intrusion, the effects of which are perceptible at basement level with the presence of brackish waters. Only the CT waters at piezometer PZ_C2D 9 are brackish and saline.

5. Discussion

The first electrical conductivity values were measured at the static level and are all less than or equal to 200 µS/cm. These values are characteristic of freshwater [18]. Although these waters are "fresh waters", relatively high electrical conductivity values were measured in piezometers PT1, PZ_C2D 13, PZ_C2D 14 and PZ 19. These piezometers are located in the Banco bay and to the west of Songon Té village. They are also located downstream of groundwater flows. The piezometric levels in these piezometers are relatively low (between 2 and 38 m). Also, horizon 4 of the Continental Terminal also outcrops in the Banco valley [19]. All this creates favourable conditions for the exchange of water flows between surface water and the Continental Terminal aquifers and exposes the latter to organic pollution linked to wastewater discharges (ammonium, nitrate, etc.). The North-South conceptual model of the Continental Terminal aquifer in Abidjan indicates a hydrogeological relationship between the CT aquifer and the underlying crystalline and crystallophyllian basement [19]. This relationship is reflected by an interconnection of these two aquifers through a contact formation composed of clays, limestone, and sands. The presence of this horizon, particularly the clayey one, limits water exchanges between these aquifer levels.

Brackish water is present in some piezometers. This could be explained by intrusions of water from the Ebrié and Aghien lagoons into these piezometers. These piezometers are located either near (less than 500 m) the Aghien lagoon (PZC2D 6 and PZC2D 7), or in the bays of the Ebrié lagoon (PZC2D 12, PZC2D 13 and PZC2D 9). In addition, the significant changes in electrical conductivity indicate an increase in the input of dissolved substances into the water in the piezometers. These substances are thought to be the result of anthropogenic pollution from wastewater draining into coastal rivers. Indeed, the work of [20] revealed that the mineralization of waters is due to the intrusion of lagoonal waters and/or to the infiltration of the streaming waters. That infiltration of superficial waters in the wells brings several minerals ions notably Cl^-, Na^+, K^+ and Mg^{2+} and H^+ protons, as well as the organic matter. The addition of these ions contributes to the increase of their concentration in the groundwater.

These cumulative effects may explain the brackish nature of the water in piezometer PZ_C2D 9 located in Adjamé-Bingerville village. Unlike the other six (06) piezometers, brackish water was found in the CT aquifer. The water quality in this locality will have to be better studied in order to determine the level of contamination caused by this pollution.

6. Conclusions

At the end of this study, it was concluded that the surface water in the piezometers was fresh and generally of very low electrical conductivity (between 20 and 80 µS/cm). However, the piezometers located downstream of the surface water flows towards the Ebrié Lagoon (PT1) and Banco Bay contain water with increasingly high electrical conductivity (≈ 200 µS/cm). This is due to exchanges between surface water and groundwater, which expose the water in the piezometers to anthropogenic pollution.

Depending on the depth, all the water in the CT is "fresh water", except for that in piezometer PZ_C2D 9 located in Adjamé-Bingerville, where brackish and salty water is recorded. Also in the basement, brackish water was found in seven (07) piezometers (PZ_C2D 26, PZ_C2D 13, PZ_C2D 12, PZ_C2D 9, PZ_C2D 7, PZ_C2D 6 and PZ_C2D 5), located respectively along the Ebrié lagoon (Ayewahi-Anguédédou, western zone, Gourou downstream) and around the Aghien lagoon (Adjamé-Bingerville, Yacé, Elais, Bahouakoi).

This study provides information on the quality of the waters of the Continental Terminal on the northern edge of the Ebrié Lagoon. These waters have not yet been affected by marine intrusion. However, the presence of brackish water found at greater depth (at the level of the bedrock) in some piezometers requires increased vigilance in the ongoing monitoring of the quality of these waters.

Acknowledgements

This research was supported by the Hydrogeology and geophysics Research Group of the Geosciences and Environment Laboratory at Nangui Abrogoua University in Abidjan, Ivory Coast. The constructive and valuable comments of the anonymous readers and the Editor-in-Chief of the Journal are greatly appreciated.

Conflicts of Interest

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

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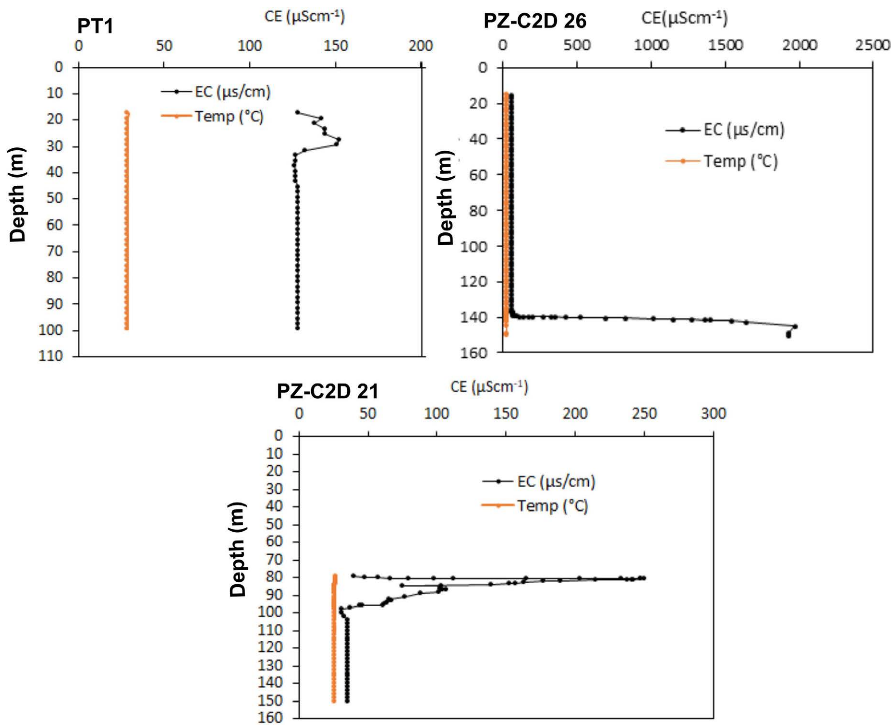
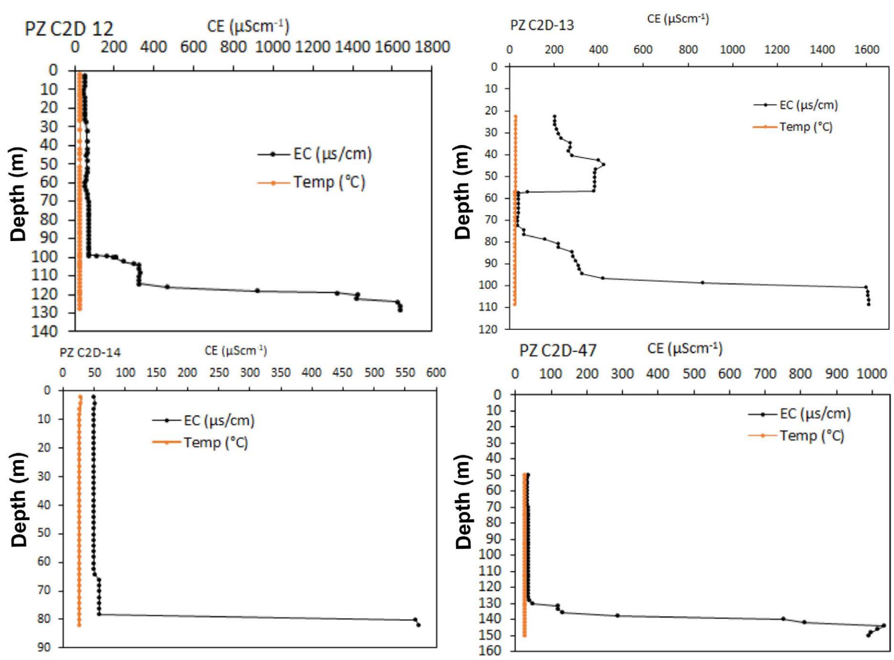
Appendix: Conductivity Log Results for the March 2022 Campaign

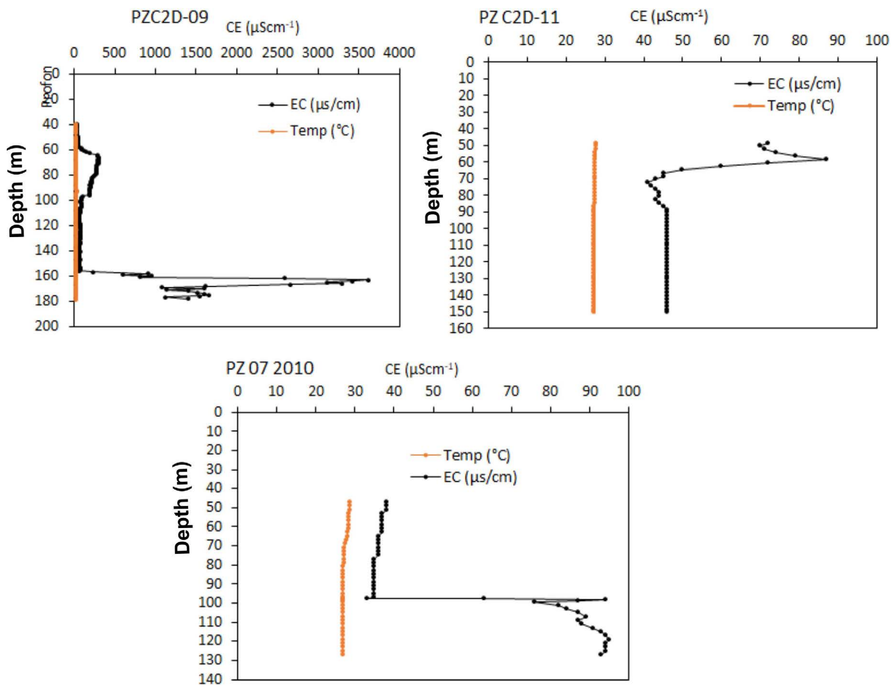
Vertical trend in electrical conductivity values for piezometers in profile 1.



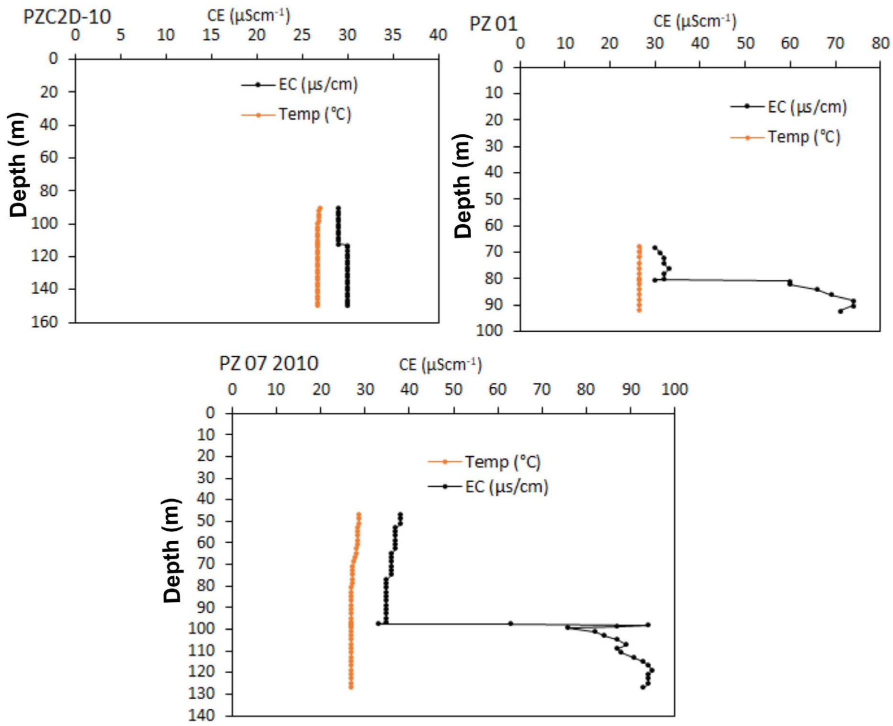
Vertical trend in electrical conductivity values for piezometers in profile 2.



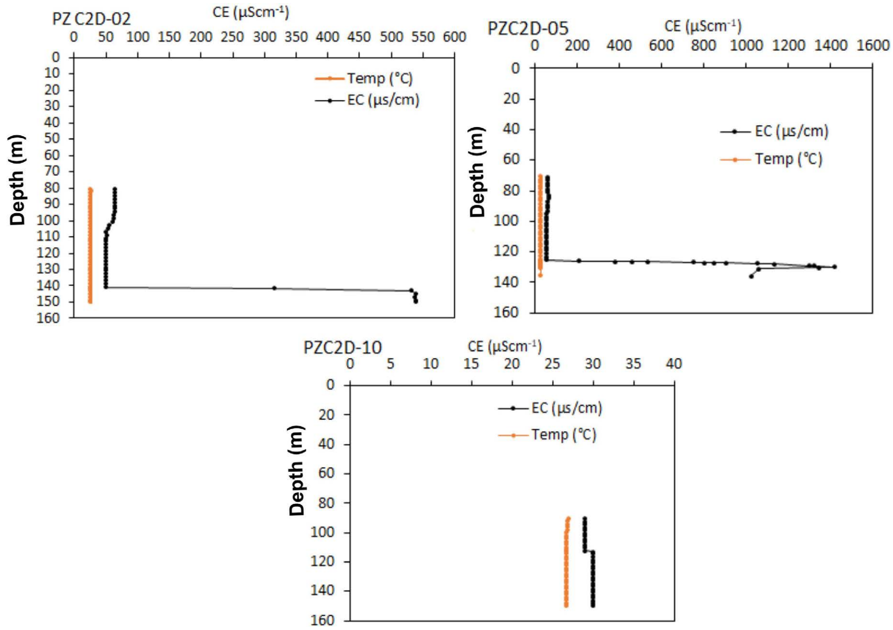
Vertical trend in electrical conductivity values for piezometers in profile 3.



Vertical trend in electrical conductivity values for piezometers in profile 4.



Vertical trend in electrical conductivity values for piezometers in profile 5.



Vertical trend in electrical conductivity values for piezometers in profile 6.