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Research article

Use of graphical and multivariate statistical methods to show a marine intrusion and salinization of a coastal water table: case study of the township of Abomey-Calavi, Benin

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ABSTRACT

A robust classification scheme for partitioning water chemistry samples into homogeneous groups is an important tool for the characterization of hydrologic systems. In this paper we test the performance of the many available graphical and statistical methodologies used to classify water samples including: Piper diagram and diagram of Schoeller and Berckaloff. All the methods are discussed and compared as to their ability to cluster, ease of use, and ease of interpretation.

The combination of graphical and statistical techniques provides a consistent and objective means to show that groundwater in the district of Godomey in the municipality of Abomey-Calavi is contaminated by sea water. This study reveal Togbin to be the area of intrusion of seawater into groundwater. This study has helped in setting the boundaries where seawater intrusion into groundwater occurs in the township of Abomey-Calavi. These results confirm the findings of Boukari et al., in 1996, who detected an early saline intrusion in this Godomey pumping area.

1. Introduction

The earth's water resources are rainwater, often of good quality, groundwater of fairly good quality and surface water, which is often very polluted (Lee M et al., 2017; Egbueri J. C. et al., 2019). There is a large amount of water on earth, but water resources are very poorly distributed on earth and generally of poor quality. Surface water namely lakes, lagoons, rivers, seas and oceans infiltrate the soil and pollute groundwater. In particular, three quarters of the earth's surface is covered by oceans, the volumes of which increase over the years mainly due to the melting of glaciers due to global warming (Graham S et al., 2010; Li D et al., 2020; Nie Y et al., 2021). So there is an intrusion of seawater into the coastal groundwater and this problem is getting worse over the years. It is therefore important to detect and monitor seawater intrusions into groundwater to alert governments so that they can limit seawater intrusion into groundwater if possible by avoiding among other things, intensive pumping of wells water in coastal regions.

In recent years, the authors have used several methods to study seawater intrusion into groundwater. In particular, the Revelle index has been used to study seawater intrusion into groundwater by several authors (for example, Hounsinou, 2020; Motchemien R et al., 2020 Lappas I et al., 2016; Busico G. et al., 2021; Kazakis N. et al., 2018; Naseem S. et al., 2018). The Stiff diagram has also been used to study the intrusion of seawater into groundwater by several authors (for example, Hounsinou, 2020; Kura N. U. et al., 2014; Bhagat C. et al., 2021; Yidana S. M. et al., 2010; Ghezelsofloo E. et al., 2021; Putra et al., 2021).

The objective of this study is to prove that there is an intrusion of seawater in the groundwaters of the coastal region of the municipality of Abomey-Calavi in Benin by using several graphic methods in particular the spatial distribution of chlorides ions and TDS in groundwater, the correlation between the concentrations of sodium ions and chloride ions in well waters and a rigorous interpretation of the Scholler-Berkaloff diagrams of the water sample studied.

2. Materials and methods

2.1. Geographic location

Benin is a country in West Africa. This country is divided into 77 municipalities. Abomey-Calavi is one of the municipalities of the

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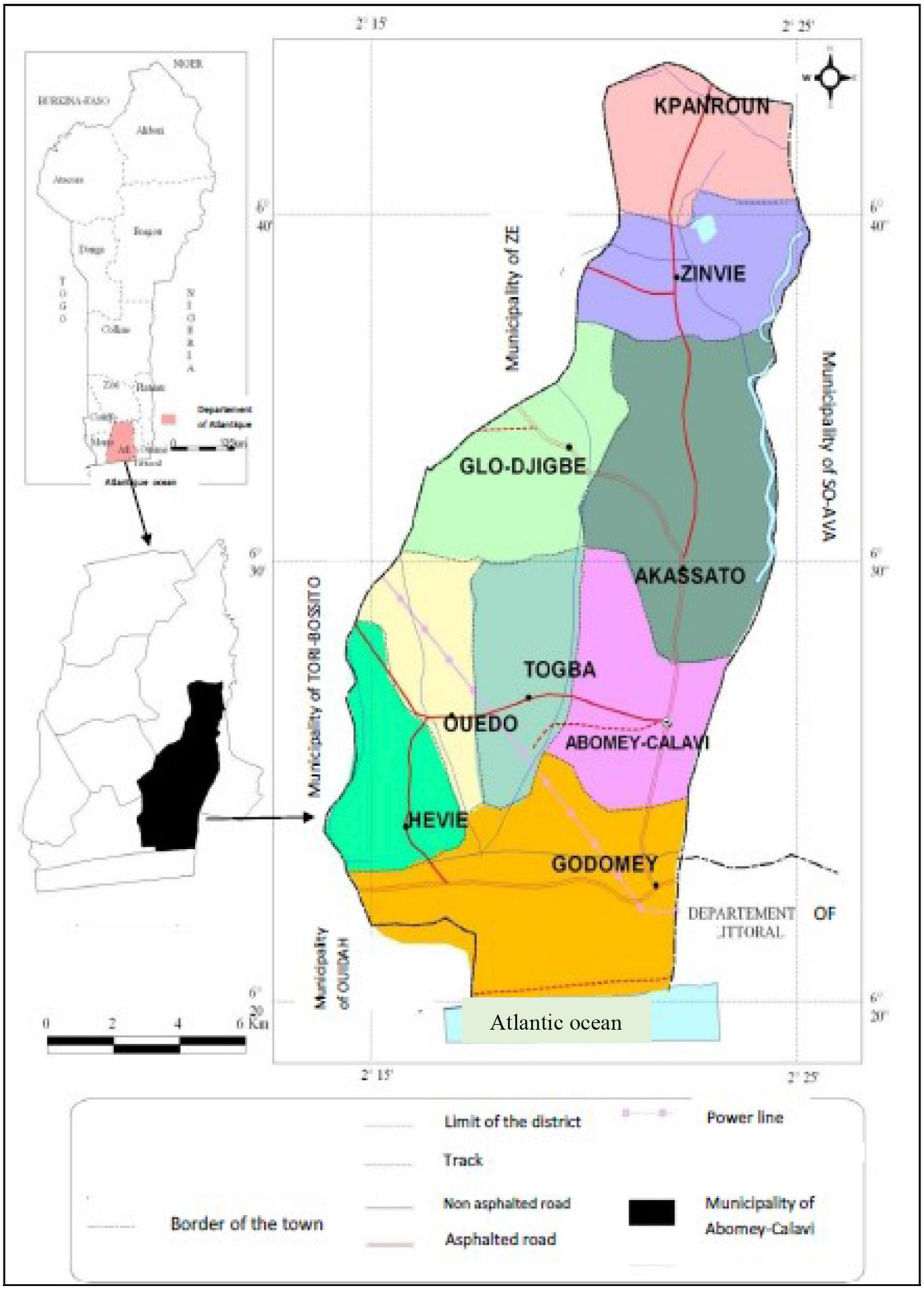

Figure 1. Geographic localization of Abomey-Calavi.

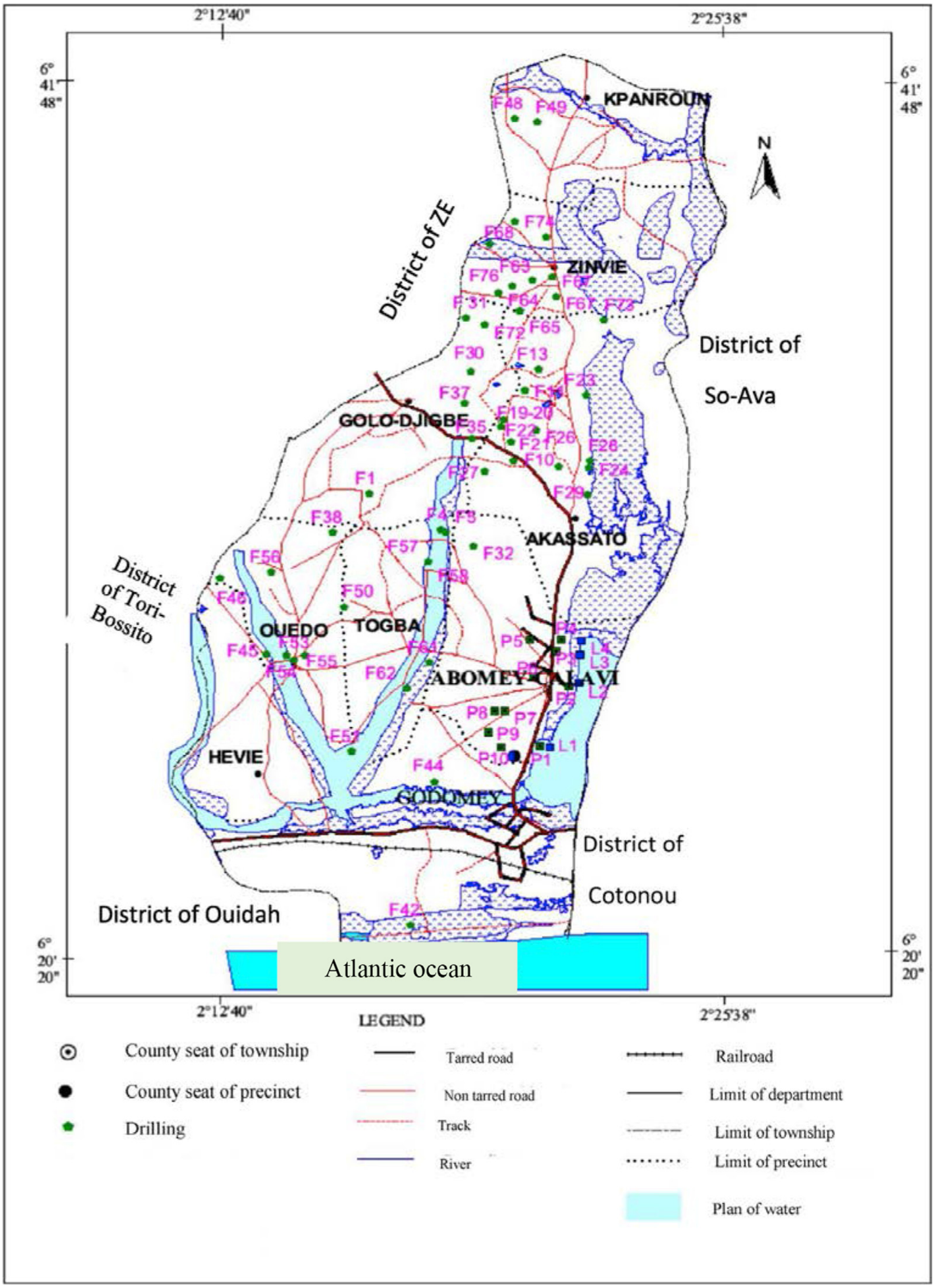

Figure 2. Sites of withdrawal of waters of drilling.

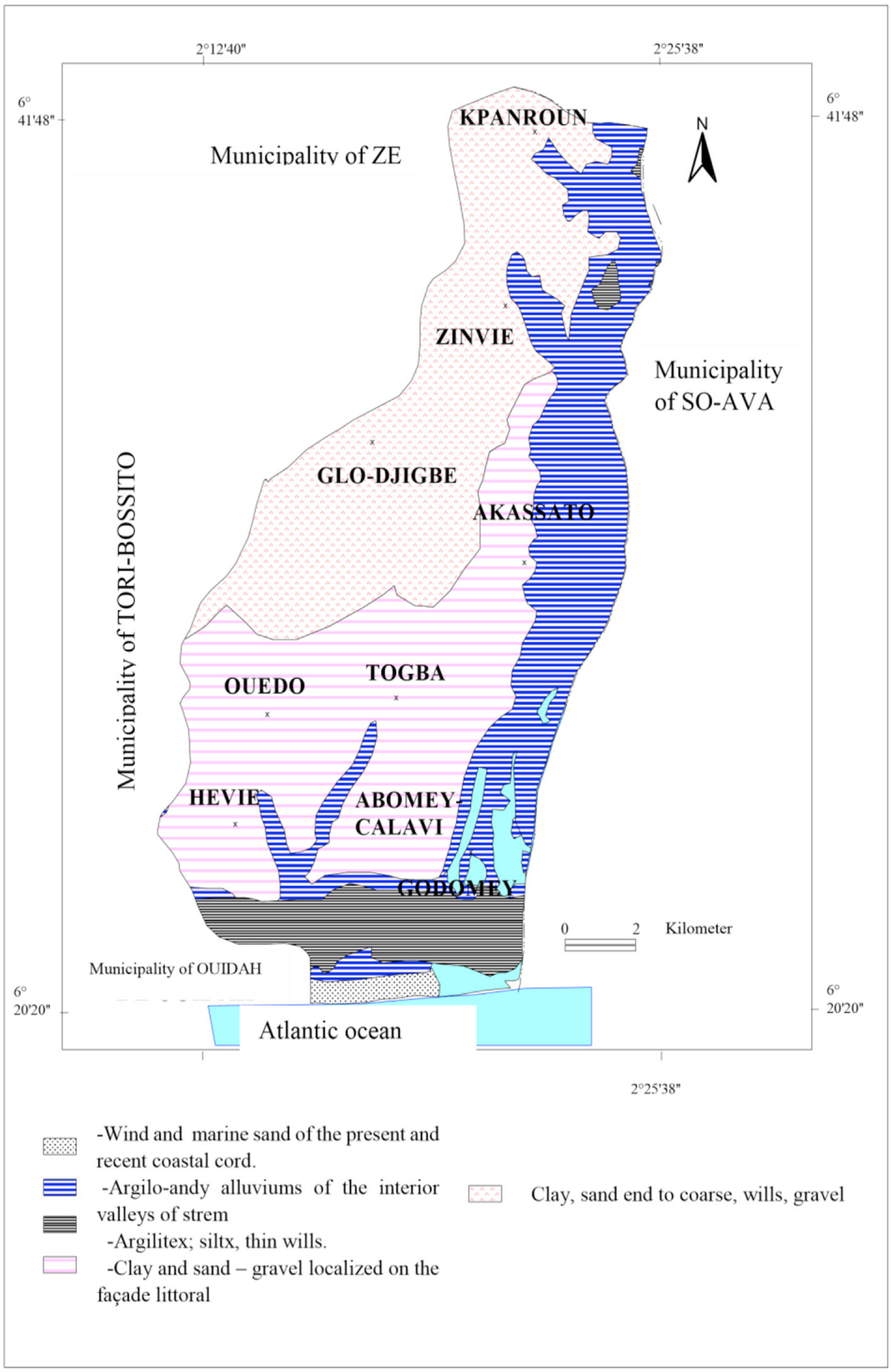

Figure 3. Geological map of Abomey-Calavi.

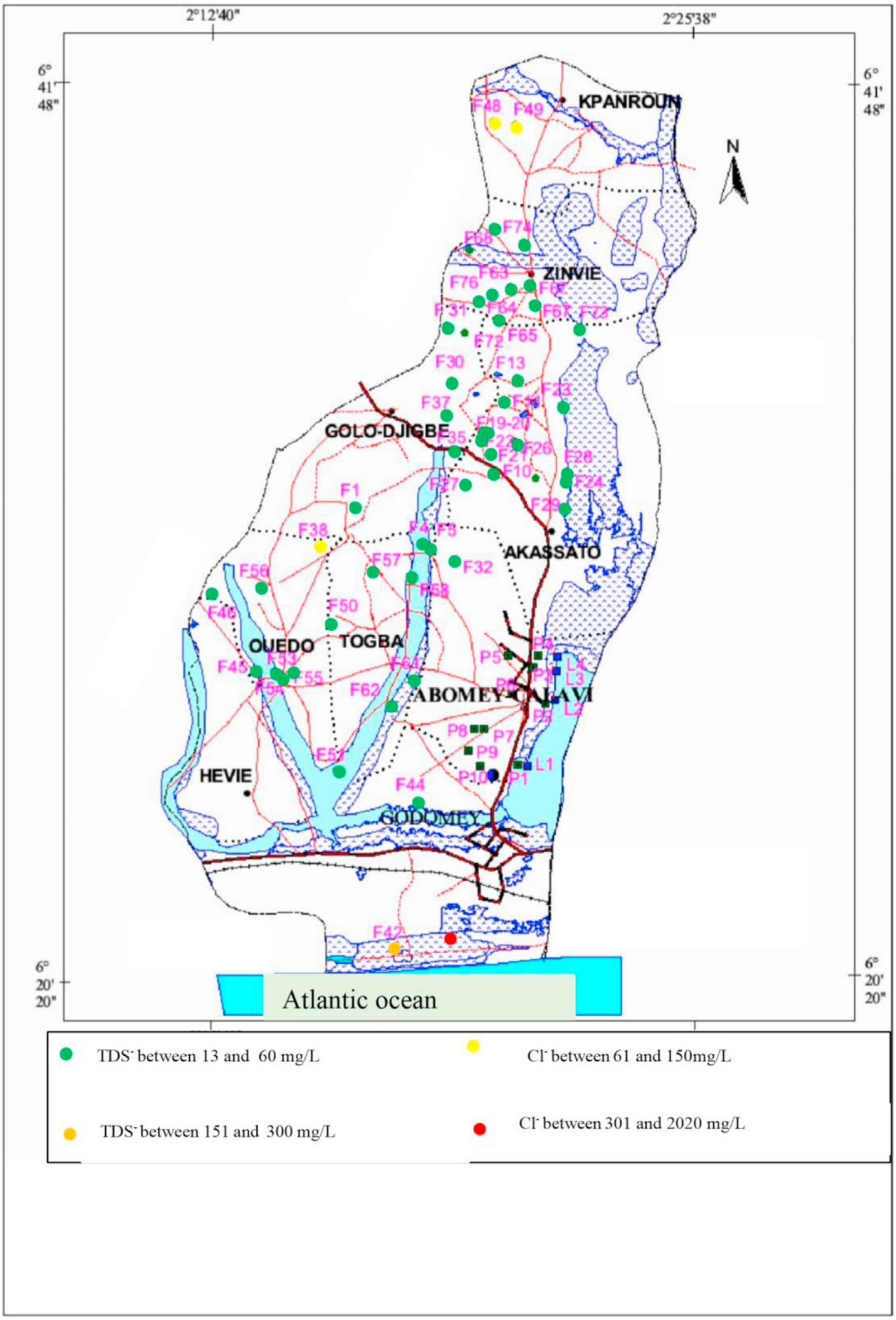

Figure 4. Spatial variation of TDS values of wells water in the municipality of Abomey-Calavi.

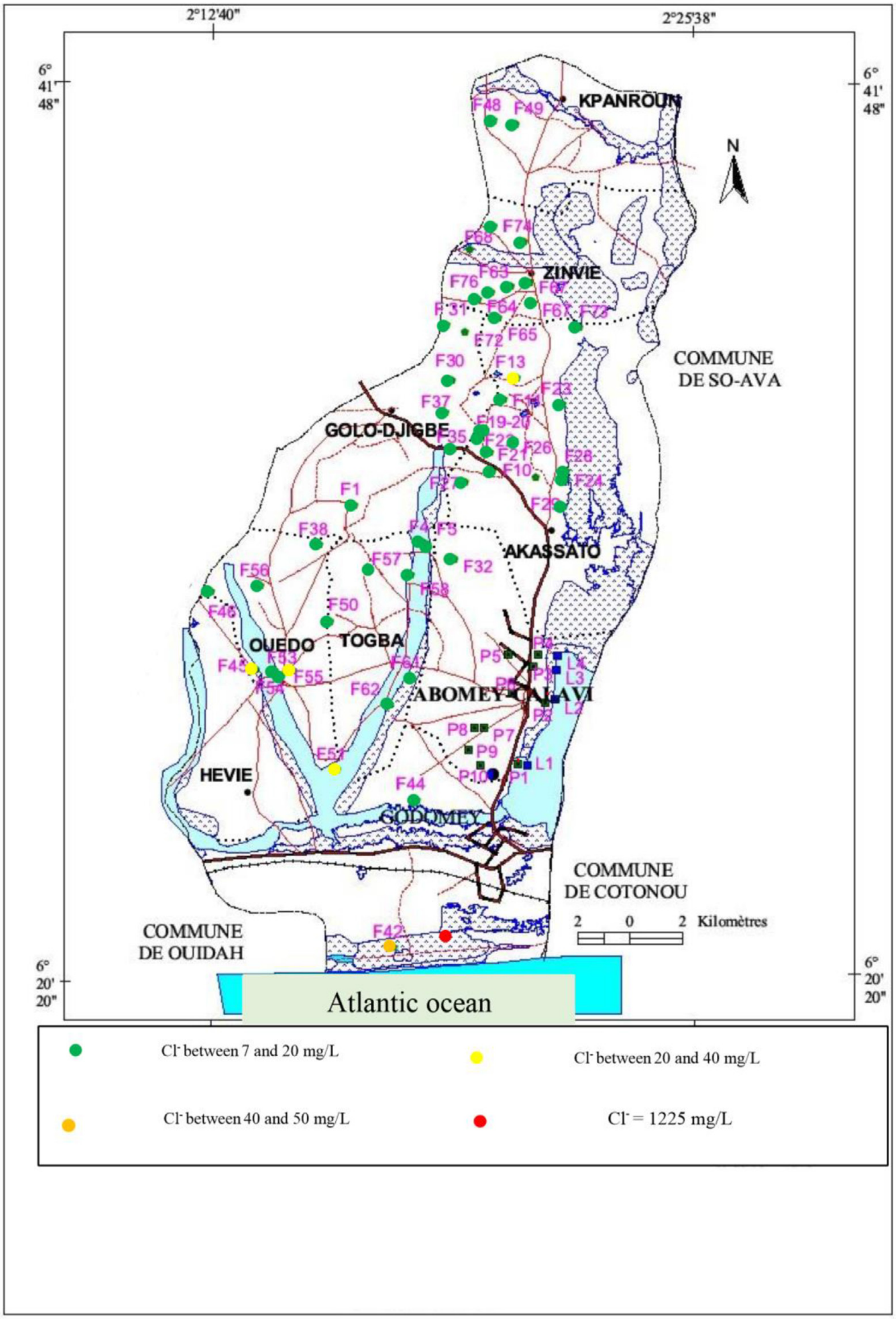

Figure 5. Spatial variation in chloride content in wells water in the municipality of Abomey-Calavi.

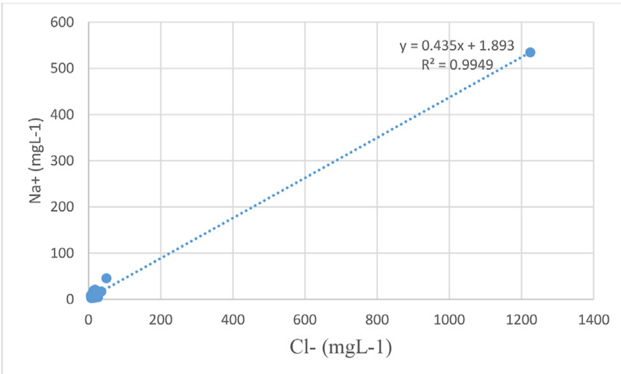

Figure 6. $Na^+ = f(Cl^-)$ of wells water in the municipality of Abomey-Calavi.

Republic of Benin and is located in the south of the country. The municipality of Abomey-Calavi is bounded to the south by the Atlantic Ocean, to the north by the municipality of Zè, to the west by the municipality of Ouidah and the municipality of Tori-Bossito and to the east by the municipality of Cotonou and the municipality of Sô-Ava (Figures 1 and 2). The municipality of Abomey-Calavi covers an area of 536 km^2 and is divided into 9 districts, one of which is called the district of Abomey-Calavi. The 8 other districts of the municipality of Abomey-Calavi are the districts of Akassato, Hêvié, Glo-Djigbé, Godomey, Kpanroun, Ouèdo, Togba and Zinvié. The municipality of Abomey-Calavi is located on the shores of lake Nokoué, a large lake which has an area of approximately 160 km^2. Lake Nokoué and the Atlantic Ocean have a significant influence on groundwater pollution (Hounsinou, 2020; Hounsinou, 2021).

2.2. Geology

They are in the Atlantic Department three types of geological formations namely:

2.2.1. Secondary geologycal formation

The formations of this era are made up of facies of white, fine to coarse sands and greenish brown clays of the Marine Cretaceous.

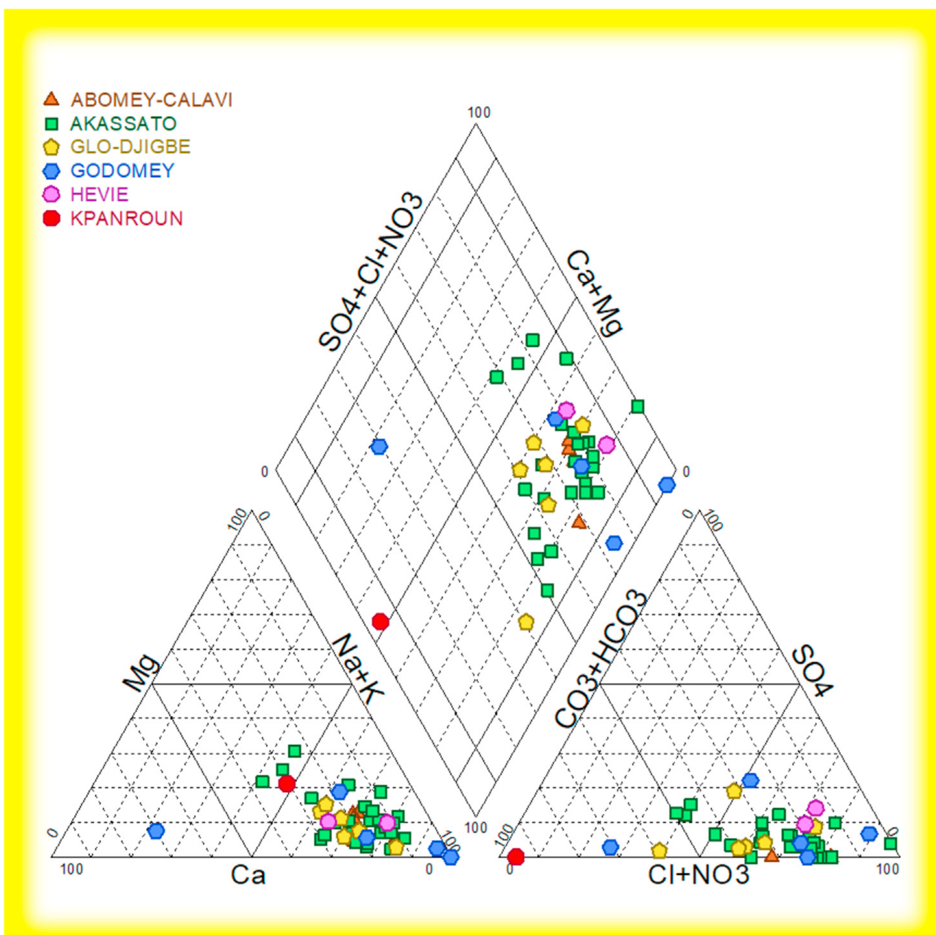

Figure 7. Piper diagram of wells water from the municipality of Abomey-Calavi.

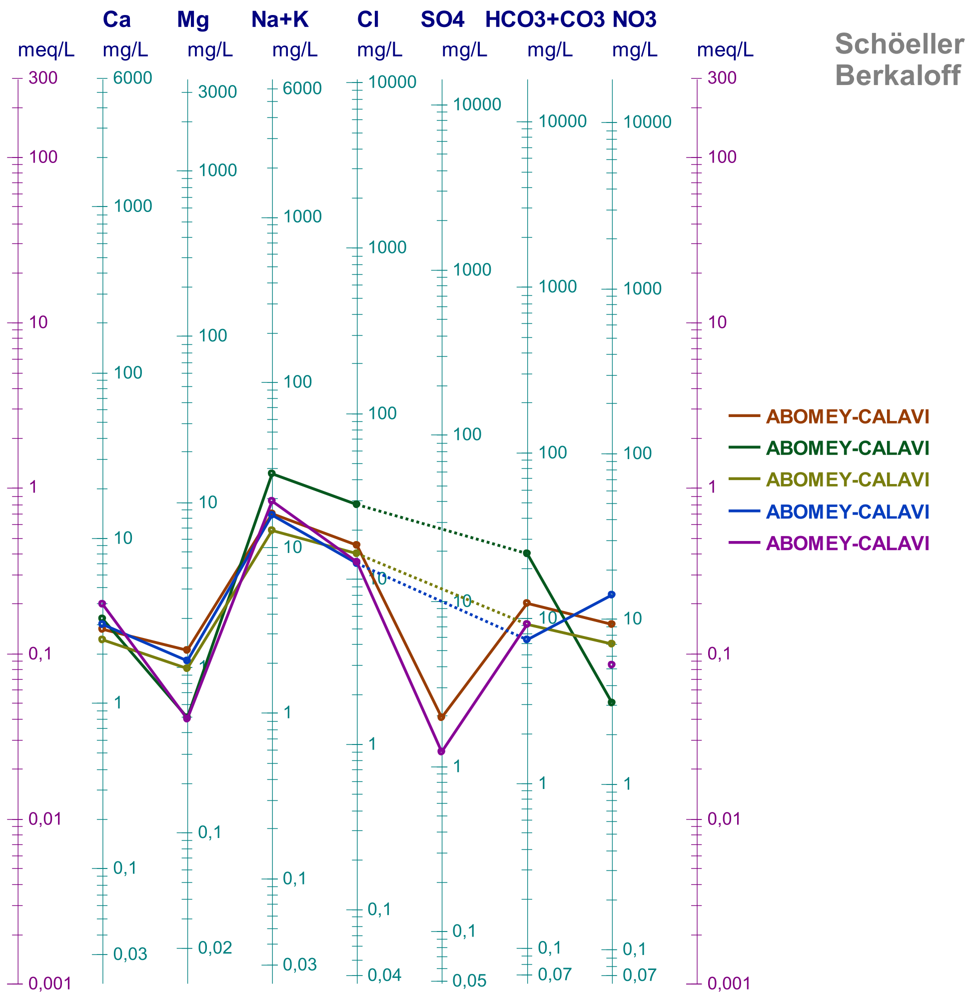

Figure 8. Scholler-Berkaloff diagrams of drilling water in the Abomey-Calavi district.

2.2.2. *Tertiary geologycal formation*

These are formation of:

- Paleocene: mainly clayey-marly with some intercalations of limestone levels;
- Eocene: made up of mainly marly facies with gray clays sometimes containing quartz pebbles. There are also some levels of fine sands and phosphate limestones difficult to distinguish from those of the Paleocene;
- Continental Terminal: made up of lateritic, variegated, black or colored sandy clays and fine, coarse sands, soft sandstones and gravels at the base.

2.2.3. *Quaternary formations*

These formations consist of fundamentally alluvial and sometimes clayey facies of the current and recent shoreline of the Holocene.

The geological substratum over which the municipality of Abomey-Calavi extends consists of sands and even clayey from the Continental Terminal and Quaternary alluvium.

Indeed, the sands of the Continental Terminal date from the Upper Miocene and the Pliocene-Pleistocene (Boukari et al., 1996; Boukari and Alassane 2007). They cover the bar earth (homogeneous formation of kaolinic argillites and fine to medium quartz sands) and the sometimes conglomerate silty argillites of the Lower Miocene as the substratum.

The Quaternary formations are made up of three lithological levels, namely:

- Aeolian and marine sand facies of the current and recent coastline, the summit of which corresponds to terraces of 5–7 m;
- clay-sandy alluvial facies of the lower river valleys and;
- a terrace made of clay, sands (white, brown and gray) and gravel; located on the coastline. The coarse sands on the coastal front are about 6 m thick with a porosity exceeding 40%. Coming up from the coast, the fine, grayish marine silty sands are 15 m thick and have a porosity of around 35% (Figure 3).

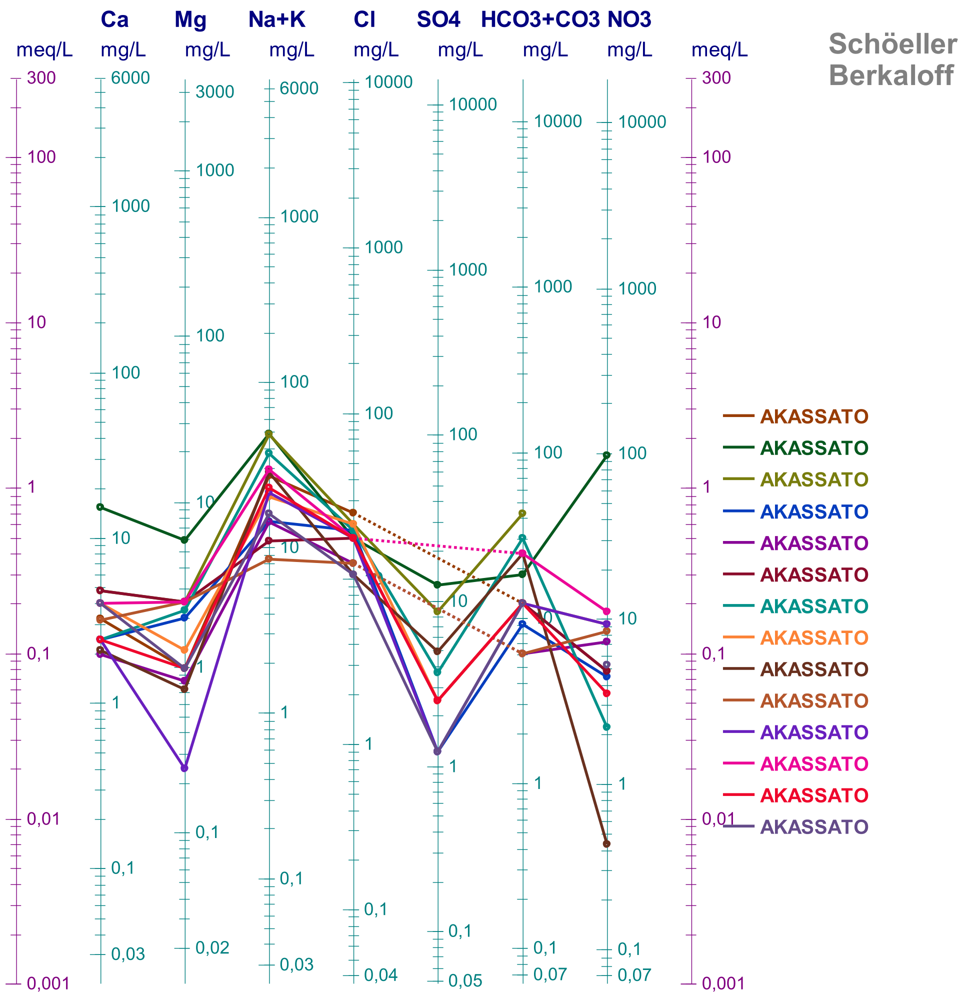

Figure 9. Scholler-Berkaloff diagrams of drilling water from the Akassato district (first part).

2.3. Hydrogeology

The municipality of Abomey-Calavi is crossed by the Djonou lagoon and the Togbin lagoon. The municipality of Abomey-Calavi is located to the east by Lake Nokoué and to the south by the Atlantic Ocean.

In the municipality of Abomey-Calavi there are two aquifers separated by a more or less clayey layer. These are the superficial aquifer and a lower aquifer system (UNESCO, 2004).

The superficial aquifer is made up of a mixture of clay and sand, then coarse sand, followed by yellow sand, then gray sand and brown sand (Figure 3).

The lower aquifer system consists of gravel and sand. The lower aquifer system is made up of several horizons that communicate with each other because they are separated by layers of clay and sand that are permeable in places.

The depth of the wells we have studied varies from 30 m to 170 m. In these wells, the transmissivity varies from 1.5 and 8.10^{-3} m^2/s and the storage coefficient varies from $1.6.10^{-11}$ and 24.10^{-3} (Boukari and Alassane, 2007).

2.4. Methodology

We measured 20 physico-chemical parameters and 3 microbiological parameters of water from 65 wells varying in depth from 30.91 m to 103.21 m (Figure 2). The study of the spatial distribution of the values of the measured parameters and the graphs produced from the values of the measured parameters made it possible to prove the intrusion of seawater into the groundwater of the municipality of Abomey-Calavi.

The wells water samples were collected using standard sampling procedures (APHA 1985; ISO 1993; Hounsinou, 2021).

At each wells, the groundwater was purged for several minutes (Aullón Alcaine et al., 2020), a sample of groundwater for the cation analyzes was taken in a polyethylene bottle, and it was taken from a second polyethylene bottle a sample of groundwater to which was added a nitric acid solution intended for anion analyzes and then a sample of groundwater intended for microbiological analyzes was taken from a sterilized bottle. The water samples taken from the 68 wells were stored at 4 °C and transported to laboratories for physico-chemical and microbiological analyzes.

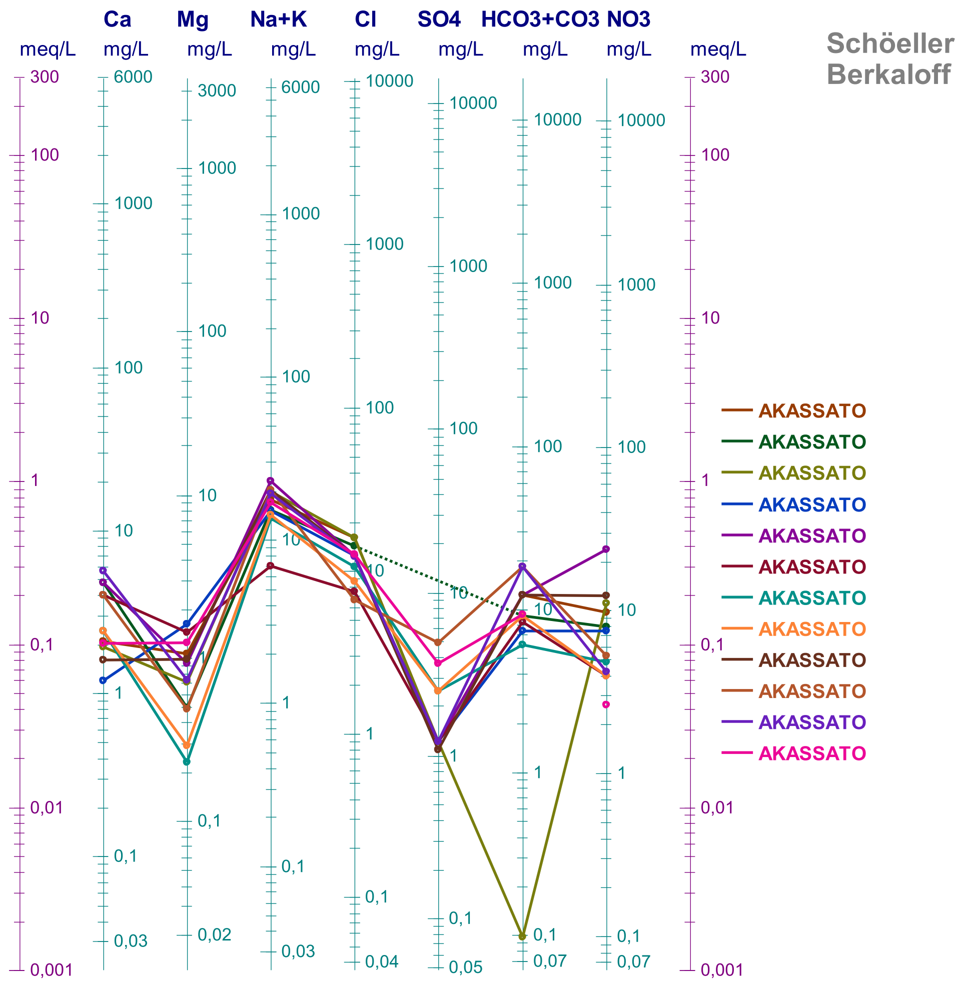

Figure 10. Scholler-Berkaloff diagrams of drilling water from Akassato district (second part).

The methods and/or equipment used to perform the physico-chemical analyzes and references for previous use of these methods are as follows: The hardness was measured by titrimetry (Sunitha, 2014). Temperature, pH, electrical conductivity (EC) are measured by a portable multi-parameter meter with probe WTW340i (Nakhaei et al., 2015; Amiri et al., 2017; Hounsinou, 2021). Turbidity was measured by a colorimeter, TDS was measured by a conductimeter (Hounsinou, 2020; Hounsinou, 2021). The major ions namely calcium ions, magnesium ions, sodium ions, potassium ions, nitrates ions, chloride ions and sulfate ions were measured by the chromatographic method (APHA, 1985). Minor ions namely total iron, nitrites ions, phosphates ions, fluorides ions and ammonium ions were measured by ionic spectrophotometry (Roy et al., 2011; Hounsinou, 2021). Carbonates ions and alkalinity were measured by acidimetry (APHA, 1985).

3. Results and discussion

3.1. Multivariate statistical techniques

3.1.1. Spatial variation of the chemical parameters of groundwater in the municipality of Abomey-Calavi

The graphs are used to analyze the parameters of the water. The analysis of these graphs makes it possible to assess the quality of the water and to classify the water samples by hydrogeochemical facies. Graphical analysis of water parameters was successfully used to classify lake water samples into geochemical facies (for example, Jaquet et al., 1975). Graphical analysis of water parameters was used (for example Alther, 1979, Williams, 1982 and Farnham et al., 2000) to classify data in water chemistry.

In the municipality of Abomey-Calavi, the TDS value and the concentration of chloride ions in groundwater in the coastal district of Godomey are much higher than the TDS and the concentration of chloride ions in groundwater in the other districts of the municipality of Abomey-Calavi (Figures 4 and 5). These high values of TDS and chloride ion concentration are due to the contamination of groundwater by seawater.

The variation in the concentration of sodium ions as a function of the chloride ions contained in the groundwater of the municipality of Abomey-Calavi is an function (Figure 6) such that $Na^+ = 0.6699 \times Cl^- + 0.1409$. The coefficient of determination ($R^2 = 1$) indicates that these ions are of marine origin.

The municipality of Abomey-Calavi is located on the edge of the Atlantic Ocean. In this municipality, there is heavy precipitation consisting of precipitating vapors rich in sodium ions and chloride ions from seawater. This rainwater rich in sodium ions and chloride ions reaches underground aquifers by infiltration.

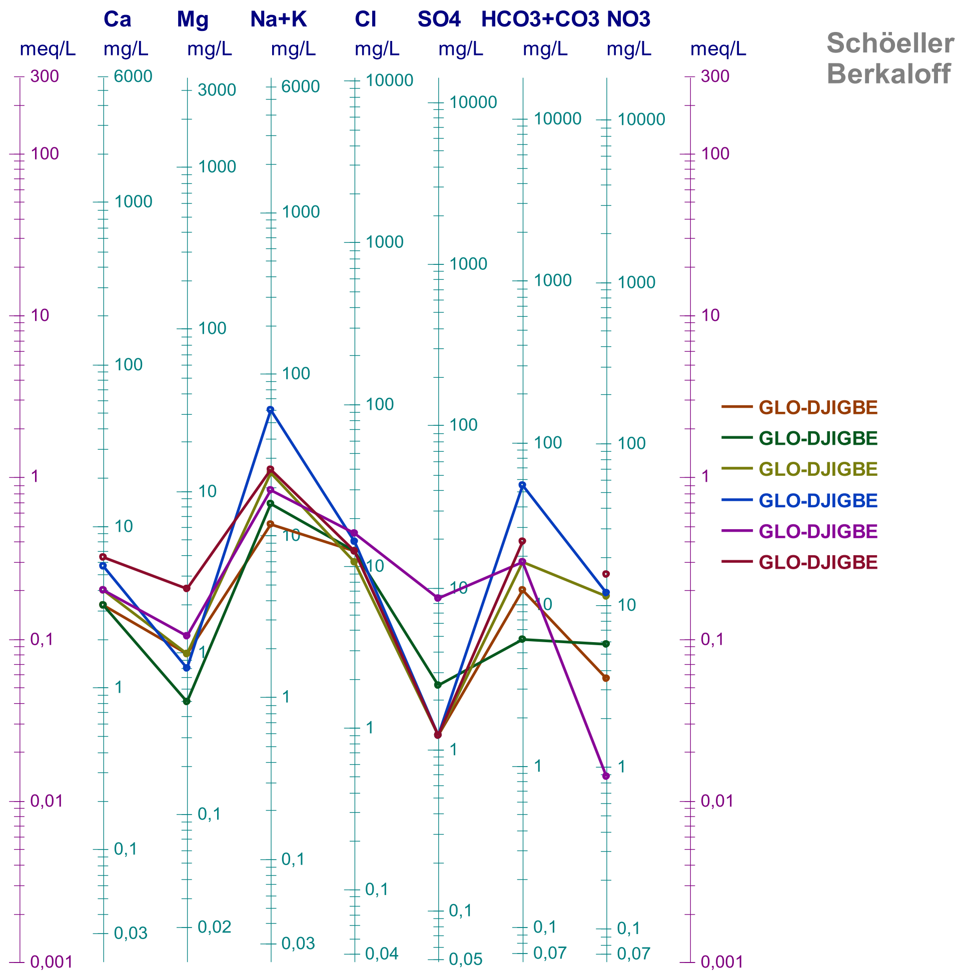

Figure 11. Scholler-Berkaloff diagrams of the drilling water in the Glo-Djigbé district.

3.1.2. Characterization of ion exchange between groundwater and aquifer

In the municipality of Abomey-Calavi, the basic groundwater exchange indices are all non-zero and vary from −3.7 to 0.37 (Hounsinou Sagnon Parfait, 2020)). 87% of the basic groundwater exchange indices have negative values. This indicates a basic exchange linked to clay minerals which fix calcium in the water after the release of sodium.

Three reasons for this abundance of sodium and chloride ions, namely marine intrusion, precipitating vapors of marine origin and base exchange linked to clay minerals which fix calcium in the water of the groundwater after release of sodium.

3.2. Graphic methods

Most graphical methods simultaneously represent the total concentration of dissolved solids and the relative proportions of major ionic species (Hem, 1989). The Piper diagram (Piper 1944, Figure 7) is the most widely used diagram and it is quite similar to the diagram proposed by Hill (1940 and 1942). Piper's diagram consists of a central lozenge and two triangles. Back (1961) and Back and Hanshaw (1965) defined subdivisions of the Piper diagram, which represent categories of water types that form the basis of a common classification system for natural waters (Güler et al., 2002).

In this study, the water facies are determined by the Piper diagram (Figure 7) and the diagram of Shoeller-Berkalof (Figures 8, 9, 10, 11, 12, 13, and 14) that we carried out using the computer program "Diagram 2" (Smiler, 2007) from the Laboratory of Hydrogeology of Avignon (France).

Using the Piper diagram, it was found that 93% of the groundwater in the municipality of Abomey-Calavi has a chlorinated facies. There are two chlorinated variants of groundwater in the study area: chlorinated sodic potassic water predominantly and chlorinated magnesium sulphated water. About 7% of the groundwater in the study area has a calcium magnesian bicarbonated facies.

The underground waters of the municipality of Abomey-Calavi, by their proximity to the Atlantic Ocean, are under the influence of ocean water. This fully justifies the facies of chlorinated water. On the basis of current observations, we have refined our reasoning, by considering the Schoeller–Berckaloff diagram (Figures 8, 9, 10, 11, 12, 13, and 14).

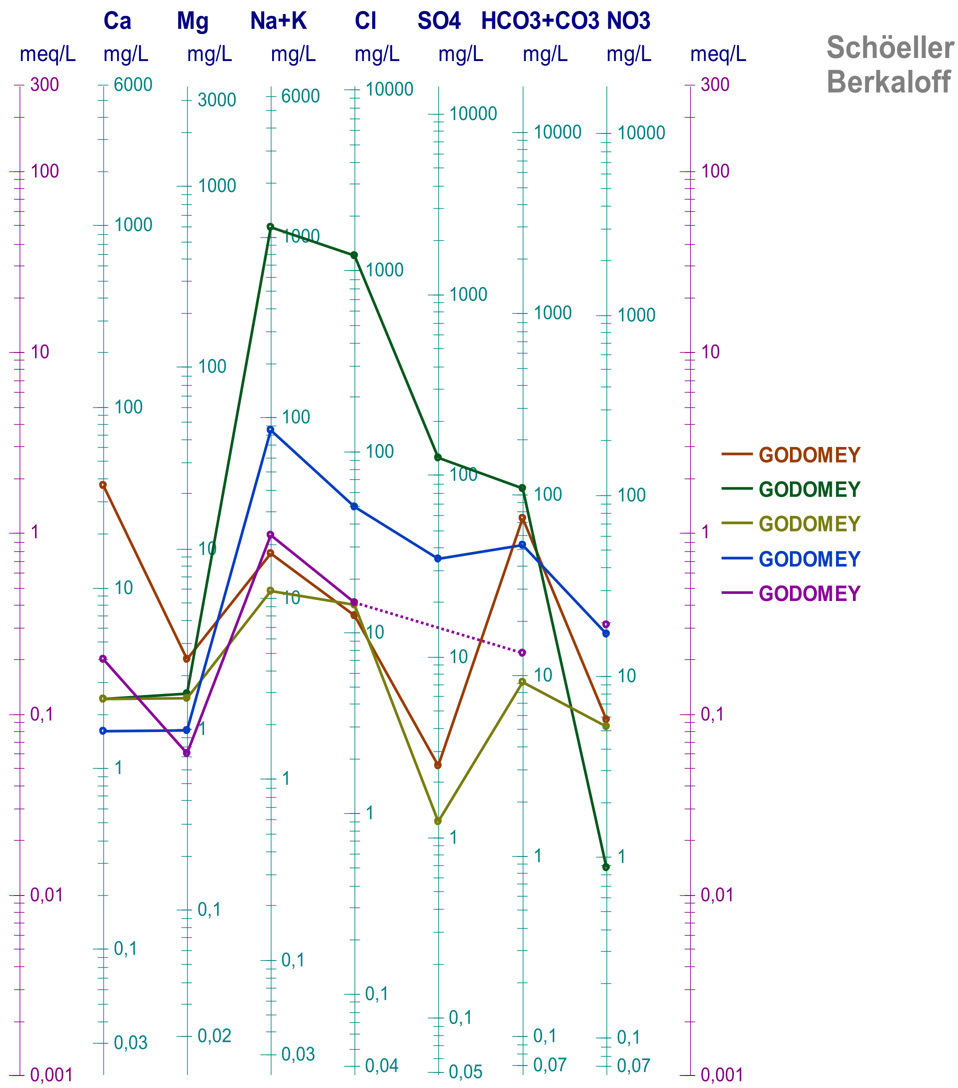

Figure 12. Scholler-Berkaloff diagrams of drilling water in the Godomey district.

According to the Schoeller–Berckaloff diagram, the wells waters of the Abomey-Calavi district have a chlorinated sodic potassic facies (Figure 8).

84.61% of wells water from Akassato district has a chlorinated sodic potassic facies, 7.69% of wells water from Akassato district has a bicarbonated sodic potassic facies and 7.69% of wells water from Akassato district have a nitrated sodic potassic facies (Figures 9 and 10).

67% of the wells water from the Glo-Djigbé district has a chlorinated sodic potassic facies, 33% of the wells water from the Glo-Djigbé district has a bicarbonated sodic potassic facies (Figure 11).

80% of the wells water in the Godomey district has a chlorinated sodic potassic facies and 20% of the well water in the Godomey district has a bicarbonated sodic potassic facies (Figure 12).

All the wells water in the Hêvié district exhibits a chlorinated sodic potassic facies (Figure 13).

The well water from the Kpanroun district exhibits a bicarbonated sodic potassic facies (Figure 14).

In general, the Na^+ contents increase with the salt load in the water, as does the Cl^-; however, the SO_4^{2-}, HCO_3^- and NO_3^- contents play a significant role in increasing the salt load. When there is seawater intrusion into groundwater, $Cl^- \rangle SO_4^{2-} \rangle HCO_3^-$ and $Mg^{2+} \rangle Ca^{2+}$.

Thus, by observing the graph of the Scholler-Berkaloff diagram of a groundwater sample, if, at the cation level, $Na^+ + K^+ \rangle Mg^{2+} \rangle Ca^{2+}$ and at the anions level $Cl^- \rangle SO_4^{2-} \rangle HCO_3^- + CO_3^{2-}$, there is a marine intrusion. By observing the graph of the Scholler-Berkaloff diagram of a

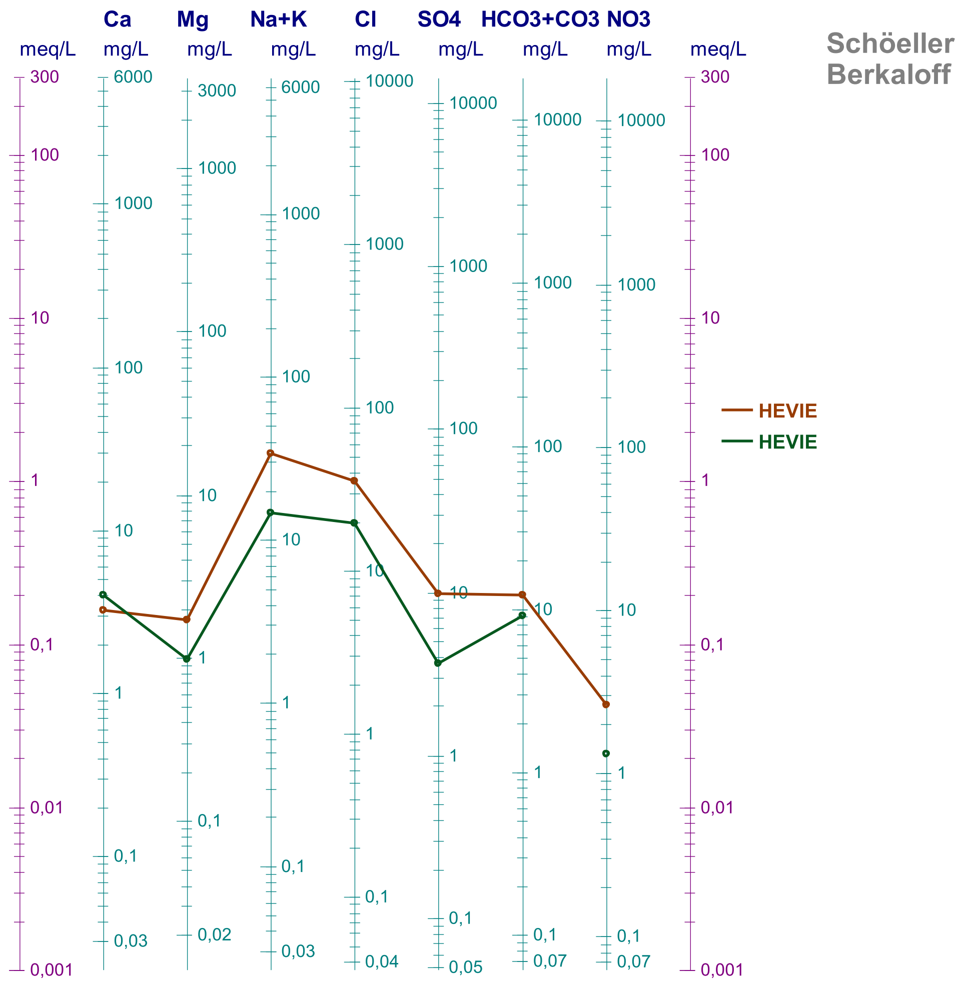

Figure 13. Scholler-Berkaloff diagrams of drilling water from the Hêvié district.

groundwater sample, if, Ca^{2+} is the most abundant major cation and $HCO_3^- + CO_3^{2-} \rangle Cl^-$ and $HCO_3^- + CO_3^{2-} \rangle SO_4^{2-}$ then this groundwater sample is soft water. These relationships concerning groundwater are verified on the Stiff diagram (Hounsinou, 2020).

Scholler-Berkaloff diagrams obtained allow dividing the waters in three homogeneous chemical groups (Table 1).

The district of Godomey is a special case in which, part of the groundwater is fresh water, part of this groundwater is a mixture of fresh water and saline water and there is water intrusion of sea in part of these groundwaters of this district of Godomey. This is due to the type of permeable soil in places in this district and the fact that this district is limited to the south by the Atlantic Ocean. And it is at the coastal village of Godomey district called Togbin that there is an intrusion of seawater into the groundwater.

The districts of Togba, Ouedo, Kpanroun, Zinvié are the furthest from the Atlantic Ocean and Lake Nokoué in the municipality of Abomey-Calavi. The water from the wells in these districts is fresh water. On the other hand, the salinity of water from wells in the districts of Abomey-Calavi, Akassato, Glo-Djigbé and Hêvié is influenced by their relative proximity to the Atlantic Ocean and the lake Nokoué.

The novelty of this study is that we have used the most often used parameters namely major ions and TDS and we have combined the commonly used analytical methods but, this study emphasizes a rigorous

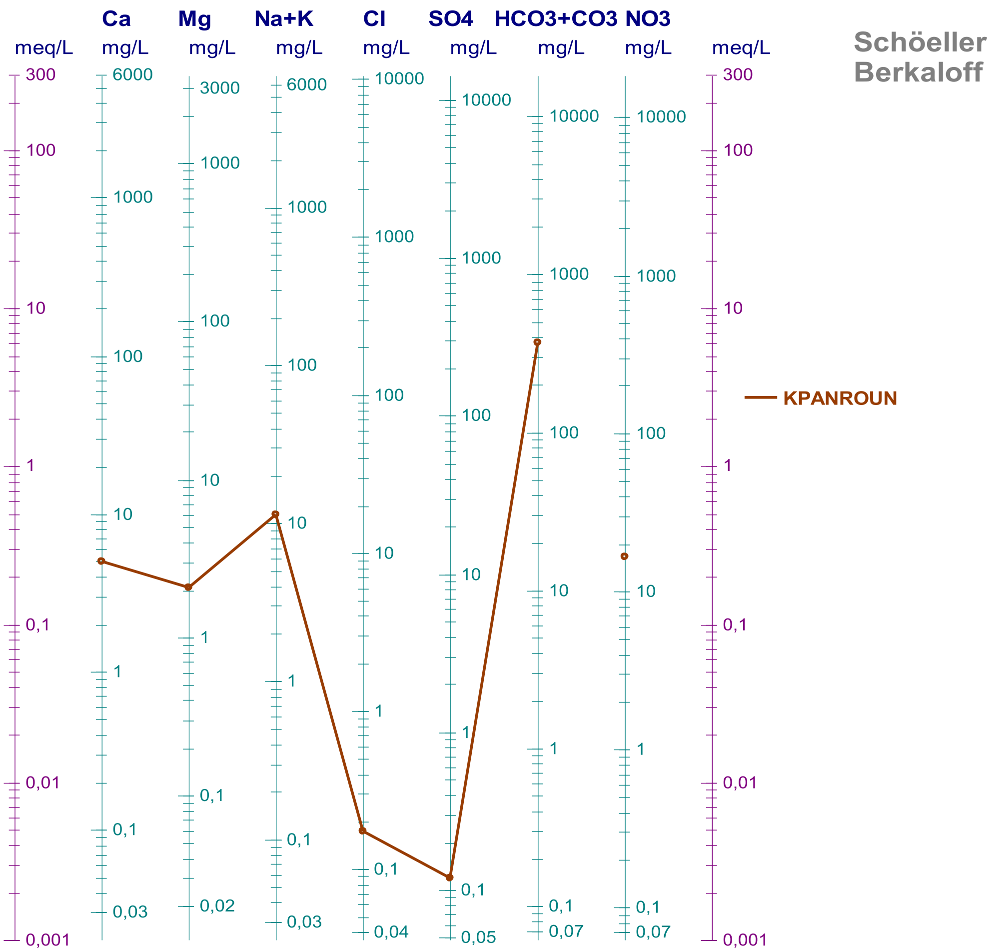

Figure 14. Scholler-Berkaloff diagram of the drilling water from the Kpanroun district.

Table 1. The groundwater homogeneous chemicals groups obtained using the Scholler- Berkaloff diagrams in the municipaty of Abomey-Calavi.

Area	Description or feature of the geometric shape of Scholler-Berkaloff diagram of the groundwater.	Intrusion or not of salt water in the groundwater studied
Districts of Togba, Ouedo, Kpanroun, Zinvié and a part of the district of Godomey (village of Cococodji).	Ca^{2+} is the most abundant major cation and (HCO_3^- + CO_3^{2-})⟩ Cl^- and (HCO_3^- + CO_3^{2-})⟩ SO_4^{2-}	There is no saline water intrusion. There is freshwater
A part of the district of Godomey (coastal village of Togbin, wells F_{43} and F_{44})	(Na^+ + K^+)⟩ Mg^{2+} ⟩ Ca^{2+} and Cl^- ⟩ SO_4^{2-} ⟩ (HCO_3^- + CO_3^{2-})	There is a marine intrusion in the groundwater.
Districts of Abomey-Calavi, Akassato, Glo-Djigbé and Hêvié and a part of the district of Godomey.	The geometrics shapes of the Scholler-Berkaloff diagram is not seawater shapes or freshwater shapes.	There is a mixture of freshwater and saline water

interpretation of these methods analysis makes it possible to prove marine intrusion into groundwater.

4. Conclusion

The groundwater of the continental terminal of the municipality of Abomey-Calavi has high TDS and chloride ions values in the entire coastal region, particularly in the district of Godomey that opens up to the ocean. The high TDS and chloride values are due probably to contamination by seawater. This assumption is justified by the facies of these chlorinated water and the geometric shapes of Scholler-Berkaloff diagrams of these waters. The samples of Togbin shows that are a marine intrusion. The coastal aquifer consists of wind and marine sands and coastal coastline cord current recent. The aquifer is vulnerable and helps for the seawater intrusion. These results confirm the findings of Boukari et al., who detected in 1996 an early saline intrusion in this Godomey pumping area. The novelty of this study is that we have used the most often used parameters namely major ions and TDS and we have combined the commonly used analytical methods but, this study emphasizes a rigorous interpretation of these methods analysis makes it possible to prove marine intrusion into groundwater.

Declarations

Author contribution statement

Parfait Sagnon HOUNSINOU: Conceived and designed the experiments; Performed the experiments; Analyzed and interpreted the data; Contributed reagents, materials, analysis tools or data; Wrote the paper.

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Data availability statement

We want to use the data to publish on another article.

Declaration of interest's statement

The authors declare no conflict of interest.

Additional information

No additional information is available for this paper.

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