Assessment of potential seawater intrusion in a coastal aquifer system at Abomey - Calavi, Benin

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ABSTRACT

Severe sea-water intrusion can be detected several kilometers inland and represents a high risk for coastal region groundwater. The coastal aquifer of the continental terminal of the township of Abomey-Calavi (Benin) has been highly exploited for intensive drinking water capture to supply the most important cities of Abomey-Calavi, Sémé and Cotonou in Benin. During the past 15 years, extracted water quantities for drinking water supply to those cities rose to the point where saline intrusion was suspected. The present study aims at determining the intensity and the extent of saline intrusion, if any, in those regions. Elaboration of Piper diagrams, related graphs and Stiff diagrams resulted in the ascertainment that groundwater in the district of Godomey is probably contaminated by sea water and revealed Togbin to be an 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 previous findings, which had detected an early saline intrusion in this Godomey pumping area.

1. Introduction

Operating a coastal aquifer is generally delicate because of water quantity and quality issues (El Mansouri et al., 2003; Kouzana et al., 2007). Indeed, a prolonged drought can be the origin of the rupture of the seawater–freshwater interface equilibrium, which in turn may cause seawater intrusion (Freeze and Cherry, 1979; Kouzana et al., 2007). Therefore, intensive pumping of coastal aquifer may increase salinity leading to a space-time evolution of the chemical quality of water in this aquifer (Azonsi et al., 2003). Over the past two decades, Benin Republic, like most African countries, has experienced periods of drought. The population growth combined with water scarcity has led to an increased demand on groundwater. Overexploited aquifers, basically in the coastal regions have caused the surrounding seawater to flow towards the aquifer due to created hydraulic gradient differences. This has resulted the groundwater once upon a fresh water to become highly mineralized water and create a limiting factor for its use.

To highlight seawater intrusion, a multidisciplinary approach is required. Several authors, using analytical methods, geophysical and modeling, have studied the phenomenon to locate the position of the interface between freshwater and marine water (Demirel, 2004; El Achheb et al., 2003; Gemal et al., 2004; Grassi and Cortecci, 2004; Paine, 2003; Pulido-Le Boeuf, 2004; Spechler, 1994; Trabelsi et al., 2005; Wilson et al., 2006; Kouzana et al., 2007). Other studies have defined the processes and the chemical reactions that characterize the mineralization that would be responsible for groundwater water chemical elements enrichment or depletion (Grassi and Cortecci, 2004; Hudak, 2000; Martos et al., 2001; Trabelsi et al., 2005; Kouzana et al., 2007).

In this work, we try to demonstrate the presence of the salt wedge and its extension into one of aquifers in Benin experiencing great water demand.

2. Materials and methods

2.1. Geographic location

Abomey-Calavi is located in the southern part of the Republic of Benin in the department of Atlantic, between latitudes 6° 20’23.4’’ and 6 42’6.6’’ North and longitudes 2° 14’13.8’’ and 2° 25’7.8’’ East. Abomey-Calavi include seventy (70) villages and cities grouped in nine (9) counties which are: Abomey-Calavi center, Godomey, Akassato, Zinvié, Osèdo, Togba, Hévié, Kpanroun and Glo-Djigbé (Figures 1 and 2). Abomey-
Calavi, located in the southern part of the Republic of Benin and Atlantic Department, is bordered to the north by the municipality of Zé, south by the Atlantic Ocean, east by the municipalities of So-Ava and Cotonou and west by the municipalities of Tori-Bossito and Ouidah. It is the largest municipality in the Atlantic department. It covers a surface area of 536 km² representing 20% of the surface area of the department of Atlantic and 0.48% of the national surface area of Benin (Freeze and Cherry, 1979; Degbé, 2004). The town of Abomey-Calavi is at the edge of the largest water lagoon of Benin Republic which is the lake Nokoué. Indeed, 20 km long (East-West) and 11 km wide (North-South) lake Nokoué is approximately 160 km², the largest lake of Benin Republic and the most important economically due to its proximity to Cotonou the biggest city of Benin Republic (Dovonou, 2012). Lake Nokoué significantly influences the groundwater pollution close to it (Hounsinou, 2012).

2.2. Geology and hydrogeology

The hydrographic network of Abomey-Calavi consists essentially of two bodies of water such as Lake Nokoué and Djonou lagoon. In addition,
the town has a coastline juxtaposed to the coastal lagoon (lagoon of Togbin), marshes, streams and wetlands.

The study area covers two main types of geological formations (Figure 3):

- Quaternary formations that are sandy deposits of the coastal strip, the lagoon deposits of clay and sand and alluvial deposits consisted of sand and clay. Coarse sand on the coastline has a thickness of about 6 m with a porosity exceeding 40% (Degbé, 2004). Up coast, marine gray silt fine sand has a thickness of 15 m and a porosity of around 35% (Degbé, 2004). Finally, the clay gravelly sands from the alluvium follow and whose characteristics are fairly similar to the ordinary sands of the coastline.

- The Tertiary formations consist mainly of clay and sand of the Continental terminal.

Two major units can be distinguished in this group:

- The first consists of sandy clay deposit, altered in land facies from the Upper Miocene. In this unit, and a little deeper, we note the presence of an alternating clay and quartz sand and further, gravel with a particle size that is increasing or decreasing upward.
- The second is made of rounded and angular gravel deposit, bathing in a sandy clay matrix generally red and shaped in land facies.

There are three aquifers on the set: the aquifer of shallow continental terminal 120 m deep; the aquifer layer Paleocene at the depth of 320 m; the aquifer of the Maastrichtian 1500 m deep. The drinking water of the municipality of Abomey-Calavi is captured by drilling into the aquifer of the Continental Terminal (Degbé, 2004; Hounsinou, 2012).

There are in the town of Abomey-Calavi, several aquifers more or less well differentiated. They are identified in the first two hundred meters approximately and consist of a shallow aquifer and three lower aquifers separated from each other by discontinuous clay layers (UNESCO, 2004).
2.2.1. Shallow aquifer

The reservoirs of this aquifer consist of:

- A thin layer of coarse-grained sand;
- Yellow sands and gray and brown sands in the coastal plain. Their thicknesses vary from 10 to 20 m.

The shallow aquifer is based on a more or less clayey layer that separates it from the lower aquifer.

2.2.2. Lower aquifer system

It consists of three more or less distinct aquifers. These aquifers are included in layers of sand and gravel whose thickness varies considerably from one place to another. Aquifers are separated by layers of clay more or less sandy to silty who behave in places like semi-porous or porous materials causing hydraulic communication between aquifers (Terrabo, 2010).

Catchment works made in the town exploit the resources contained in two continuous aquifers. From bottom to top we have:
Figure 5. Piezometric map (July 2015) of the district of Godomey in the town of Abomey-Calavi (Koudemekpo, 2015).
The aquifer of sand (fine to coarse), of sandstone and gravel with sandy clay levels (red laterite, many-coloured, black or colored) of Continental Terminal;
- The aquifer of clay, sand and gravelled sandy clayey Quaternary aluvium. It is a shallow aquifer.

The technical characteristics of drilling are (Terrabo, 2010):
- Drilling depth: 30–170 m (average 75 m).
- Operating flow rate: average of 36 m$^3$/h.

The Figure 3 illustrates the geological context of the Abomey-Calavi municipality.

According to Boukari and Alassane (2007), the hydrodynamic parameters of the aquifer are such that the Transmissivity and Storage Coefficient values range from $1.5 \times 10^{-3}$ m$^2$/s and $1.6 \times 10^{-1}$ and $24 \times 10^{-3}$ (aquifer of the Continental Terminal) respectively. Flows are very variable, but their values are often approximately up to 5 L/s.

The Figure 4 illustrates the hydrogeological context of the Abomey-Calavi municipality.

The Figure 5 shows the isopiezometric contours, the rivers, water bodies and wetland or marshy areas in the district of Godomey in the town of Abomey-Calavi.

2.3. Methodology

The objective of this study encompasses the geochemical characterization of the coastal aquifer and to demonstrate seawater intrusion. The approach is to determine the geochemical properties through measurements and analyzes to characterize the sources.

To get an overall picture of the hydrogeological regime of the aquifer system of the Continental terminal in the town of Abomey-Calavi, we collected data from the Water General Directorate (DG-Eau) concerning some characteristics of wells in the study area and we sampled water from functioning drillings in the municipality. For physical and chemical analyses, a total of seventy-seven samples (77) at seventy-seven (77) wells were collected. The following parameters were measured in July:

| Measuring apparatus and methods | Parameters studied |
|---------------------------------|-------------------|
| Direct measurement by multi parameter PC WATER QUALITY CHECKER HORIBA U-10 | pH, temperature, dissolved oxygen |
| Direct measurement by multi parameter Conductivity WTW 340 i | Conductivity, total dissolved solids |
| HACH colorimeter/890, Method 8025 | Turbidity |
| Chromatographic Method ICS 1000 | Chemical parameters ($\text{NO}_2^-$, $\text{NO}_3^-$, $\text{NH}_4^+$, $\text{Ca}^{2+}$, $\text{Mg}^{2+}$, $\text{Cl}^-$, $\text{CO}_3^{2-}$, $\text{SO}_4^{2-}$, $\text{HCO}_3^-$, total $\text{PO}_4^{3-}$) |

Figure 6. Spatial variation of TDS values (July 2015).

Figure 7. Spatial variation of chlorides contents (July 2015).
Figure 8. $\text{SO}_4^{2-} = f(\text{Cl}^-)$ of well water in the town of Abomey-Calavi.

Figure 9. $\text{Na}^+ = f(\text{Cl}^-)$ of well water in the town of Abomey-Calavi.
2013: TDS, color, hardness, pH, electrical conductivity, temperature, alkalinity, calcium, magnesium, sodium, potassium, total iron, ammonium bicarbonate, chloride, sulfate, nitrate, nitrite, phosphate and turbidity (Table 1). The Piper diagram was used to determine the Abomey-Calavi well water facies. The graphs SO4- = f (Cl) and Na+ = f (Cl/C0), Spatial variation of TDS values, chlorides contents and Revelle Index and Stiff diagram were also used.

3. Results and discussion

3.1. Hydrochemistry

In the study area, the TDS values of the water from the Continental terminal range from 13 mg/L, at well F76 to 2020 mg/L, at F40 well (Figure 6). It should be noted that the water TDS value from F40 drilling
from Godomey county exceeds those of other drillings in the county and in general water TDS from Godomey (F38 to F44) are much higher than those of other counties of the of Abomey-Calavi.

In the study area, the results show that the chloride content of the analyzed waters varies slightly for 76 wells (Figure 7), with a minimum of 6.65mg/L (well F29) and a maximum of 35.5mg/L (F45 well). The chloride content of the water of well F10 (1,224.8mg/L) is much higher than those of the other wells and in general chloride contents of well water throughout Godomey (F38 to F44) are well above those of other areas of Abomey-Calavi.

The distribution maps of TDS and chlorides ions show that the highest values of TDS and chlorides ions are in the wells nearest the ocean: wells of the city of Abomey-Calavi, by their proximity to the Atlantic Ocean, are under the influence of the ocean water.

The Chemical facies of the water in the town of Abomey-Calavi are indicated on the Piper diagram (Figure 10).

The chlorinated facies concerns 93.33% of the water in the region. There are two variants: the chlorinated sodic potassic waters overwhelmingly and chlorinated sulfated magnesia waters.

The facies bicarbonate calcium and magnesium concerns 6.66% of samples.

The bicarbonated sodic potassic facies of a well in GLO-DJIGBE is a singular case.

Wells from the town of Abomey-Calavi, by their proximity to the Atlantic Ocean, are under the influence of the water from the ocean. This fully justifies the facies of chlorinated waters. Based on the current observations, we have refined our reasoning, considering the Stiff diagram.

The representation of Stiff is to build, for each sample, a diagram as a polygon which geometry depends on the content of chemical elements under investigation (Figure 11). The distinction between samples is based on the geometry of the polygon which gives an idea of the dominant species, and the chemical relationships. The three axes of Stiff diagram are respectively, up-down, Na\(^+\), Cl\(^-\), Ca\(^{2+}\), HCO\(_3\)\(^-\), Mg\(^{2+}\), SO\(_4\)\(^{2-}\).

Godomey is a coastal city of Abomey-Calavi county. This justifies the high values of TDS and chloride ion contents in Godomey well waters. It is in Godomey that probable zone of seawater intrusion into groundwater using the Stiff diagram should be identified and addressed.

Stiff diagrams of the samples from the town of Abomey-Calavi wells are (Figures 12, 13, 14, 15, 16, 17, 18, 19, and 20):

- The first group, group I (36.76%) is related to the water sample F38 from Cococodji, a village near Godomey. This village is not on the coast of the Atlantic Ocean. The geometric shape of the Stiff diagram is that of fresh water. This shows, in principle, that there is no saline water intrusion. This group is also related to the water of the wells of the districts of Togba, Ouedo, Kpanroun and Zinié. These districts are not on the coast of the Atlantic Ocean. These geometrics shapes of the Stiff diagrams show that there is no saline water intrusion.
- The second group, Group II (60.29%) encompasses 2 wells in 2 villages of Godomey. These villages are not on the coast of the Atlantic Ocean. The shape of this group Stiff diagram shows a mixture of freshwater and seawater. This group encompasses also the wells of the districts of Abomey-Calavi, Akassato, Glo-Djigbé and Hevié. The shape of this group Stiff diagram shows a mixture of freshwater and seawater.
- The third group, Group III (2.9%) is formed by the waters of Togbin, a coastal part of the district of Godomey (wells F43 and F44). The shape of the Stiff diagram of this group is similar to that of sea water.

The spatial distribution of different groups from Stiff diagram gives an idea about the origin of the salinization of water in the region. This study has revealed Togbin to be an area of intrusion of seawater into groundwater of Abomey-Calavi.

The evaluation of groundwater salinization with the Revelle index confirm the results obtained by using the Stiff diagrams.

Evaluation of groundwater salinity was executed applying Revelle Index (R) (Zaharin et al., 2009; Revelle, 1941):

\[
R = \frac{r\text{Cl}^-}{(r\text{HCO}_3^- + r\text{CO}_3^{2-})}
\]

where:
- R < 0.5 (unaffected),
- 0.5 < R < 6.6 (slightly affected)
- R > 6.6 (strongly affected)

The computed Revelle index varied from 0 and 19.5 (Figure 21).

Revelle index obtained allow dividing the groundwater samples in 3 homogeneous chemical groups. These 3 groups are identical to the 3 groups previously obtained by using the Stiff diagrams.

3.2. Hydrogeochemistry

The determination of the origin of the salinity of the groundwater of interest has been based on the study of the spatial evolution of the TDS, chlorides and the major chemical elements.

![Stiff diagrams of chemical analysis of groundwater samples from monitoring wells in Abomey-Calavi (July 2015).](image-url)
- The first group, group I (36.76%) is related to the water sample F38 from Cococodji, a village near Godomey. This group is also related to the water of the wells of the districts of Togba, Ouedo, Kpanroun and Zinvié. These districts are not on the coast of the Atlantic Ocean. For these samples: \( R < 0.5 \). These samples were unaffected by seawater. It shows that there is no saline water intrusion in these wells.

- The second group, Group II (60.29%) encompasses 2 wells in 2 villages of Godomey. This group encompasses also the wells of the districts of Abomey-Calavi, Akassato, Glo-Djigbé and Hévié. These districts are not on the coast of the Atlantic Ocean. For these samples: \( 0.5 < R < 6.6 \). These samples were slightly influenced by salinity showing a mixture of freshwater and seawater.

- The third group, Group III (2.9%) is formed by the waters of Togbin, a coastal part of the district of Godomey (wells F43 and F44). For these samples: \( R > 6.6 \). These samples were strongly influenced by salinity showing a seawater intrusion in the groundwater of Togbin.

The computed Revelle index confirm the results obtained by using the Stiff diagrams. Figure 22 shows the spatial variation of the extent of the groundwater salinization in the town of Abomey-Calavi.
There are samples of water from the coastal zone that are characterized by low salinity and low concentrations of chlorides. These low values are due to the infiltration of meteoric water and the presence of clay layers acting as a barrier against the intrusion of seawater.

These results confirm the findings of Boukari et al., who detected in 1996 an early saline intrusion in this Godomey pumping area. Boukari et al. studied the mineralization and the quality processes of Quaternary to Mio-Pliocene gypsum aquifers in the Cotonou region of Benin using sample drilling in May 1991, August 1991 and April 1992. They reported that the anthropogenic pollution was marked in particular by high levels of nitrate. P and K had been detected in the upper aquifer. On the other hand, the lower aquifer had acceptable levels of dissolved elements, except for the Godomey pumping region, where an early saline intrusion is detected. Boukari et al. reported in 1996 that the rapid growth of catchment points in the Godomey recharge area, to meet growing demand, led for the first time to a major seawater invasion to one of the wells exploration, which had be abandoned. Today, the pumping of the Godomey aquifer is intensive and the saline and marine

Figure 14. Stiff diagrams of chemical analysis of groundwater samples from monitoring wells in GLO-DJIGBE (July 2015).

Figure 15. Stiff diagrams of chemical analysis of groundwater samples from monitoring wells in Godomey (July 2015).

Figure 16. Stiff diagrams of chemical analysis of groundwater samples from monitoring wells in HEVIE (July 2015).
Figure 17. Stiff diagram of chemical analysis of groundwater samples from monitoring well in Kpanroun (July 2015).

Figure 18. Stiff diagrams of chemical analysis of groundwater samples from monitoring wells in OUEDO (July 2015).

Figure 19. Stiff diagrams of chemical analysis of groundwater samples from monitoring wells in Togba (July 2015).
Figure 20. Stiff diagrams of chemical analysis of groundwater samples from monitoring wells in ZINVIE (July 2015).
intrusion of this groundwater is no longer in doubt. What this study has shown.

4. Conclusion

The peculiarity of this study, is that by using only the concentrations of the groundwater major ions of a vulnerable coastal area, many interpretation techniques have all confirmed a seawater intrusion into the groundwater of this area. The aquifer of the continental terminal of the town of Abomey-Calavi has high TDS and chloride ions values in the coastal district of Godomey. 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 Stiff diagrams of these waters. The various diagrams from Group II obtained from samples near Godomey and its surroundings give an additional proof of seawater intrusion zone existing at the coastal district of Godomey. The samples of group III revealed Togbin, a coastal village of the district of Godomey to be an area of intrusion of seawater into groundwater. The computed Revelle index confirms the results obtained by using the Stiff diagrams. We recommend that the intensive groundwater withdrawal has got to be stopped in the district of Godomey for water supply in the most important cities of Abomey-Calavi, Semè and Cotonou in Benin.

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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The authors declare no conflict of interest.

Additional information

No additional information is available for this paper.

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