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RESEARCH ARTICLE

TDEM STUDY OF THE VARIATION OF FRESHWATER LENS MORPHOLOGY BETWEEN RAINY AND DRY SEASON IN THE COASTAL SHALLOW AQUIFER OF SOUTH BENIN

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ABSTRACT

The study was realized with the aim of showing the variation of the freshwater lens morphology in a unconfined coastal aquifer on a site of 360.000m^2 between the Atlantic Ocean and the coastal lagoon. For this study 115Time Domain Electromagnetism (TDEM) soundings were realized in rainy season and in dry season. For two various seasons, the static levels and the electric conductivities of waters in 17 wells were measured. A porosity of 34 % of the aquifer was determined using Archie's law. That has allowed determining the limit of resistivity value of ground containing freshwater lens. At each season 12 TDEM resistivity maps and 7 TDEM vertical sections are been built for mapping the extent of freshwater lens. The obtained results show that under the pressure of sea water intrusion the freshwater lens moves towards the lagoon in dry season. The consequence of this movement is that few wells inside the freshwater lens in rainy season are found outside the freshwater lens in dry season and are thus contaminated. This TDEM study for monitoring the variation of freshwater lens morphology between rainy and dry season can contribute to the choice of wells with sustainability sanitation.

INTRODUCTION

In coastal zones the salt intrusion, is a cleaning phenomenon. (De Marsily, 1986) and (Van Dam, 1983). Freshwater-lens is a primary source of water for water supply for domestic and agricultural purposes (Shirazi *et al.,* 2011) in coastal zones. Density differences between freshwater and saltwater create a lens-shaped body of freshwater overlying saltwater (Fetter, 2010). Seawater entry and other forms of contamination like effluents which may require special attention (Ismail and Bedderi, 2009) in the planning and management of fresh groundwater (Bear, *et al.,* 1999; Boukari, 2002; Boukari, 1998; Boukari, *et al.,* 2009; Cheng, *et al.,* 2000; Darboux-Afouda, *et al.,* 1997; De Marsily, 1986; Descloitres, 1998; Dominique, 2002; El-Kaliouby, 1995; El-Kaliouby, 2001; Everett and Meju, 2005; Fetter, 2010; Fitterman and Stewart, 1986; Goldman, *et al.,* 1988; Goldman, *et al.,* 1991; Ismail and Bedderi, 2009; Kafri and Goldman, 2005; Kaufman and Keller 1983; Keller, 1988; Krivochieva and Chouteau, 2003; Laibi, 2011; Lang, *et al.,* 1988; Le Barbé *et al.,* 1993; Maliki, 1993; McNeill, 1994; Mota and dos Santos, 2006; Nabighian and Macnae, 1991; Oyédé, 1991; Pedersen *et al.,* 2005; Rodier, 1996; Shirazi, *et al.,* 2011). The knowledge of the extension of the salt intrusion and the depth of the fresh water/salty water interface contribute to make decisions of the environment protection and for the users of this resource in water (Yalo, *et al.,* 2012). Ayers and Vacher (Ayers, *et al.,* 1976) used a technique incorporating surface geology, water levels and their variations, surface geophysics and subsurface core samples to determine the freshwater-lens morphology. Within the last decade, classic hydrogeological information has been increasingly complemented with subsurface geophysical information that allows obtaining more accurate images of aquifer systems (Schwinn and Tezkan, 1997), (Unsworth, *et al.,* 2000), (Krivochieva and Chouteau, 2003), (Kafri and Goldman, 2005), (Pedersen *et al.,* 2005) and (Mota and dos Santos, 2006). Geological studies were made in our zone but only two studies in electric resistivity were made on our zone of study. (Darboux-Afouda, *et al.,* 1997; Worthington, 1993). Stratigraphic or aquifer mapping using the TEM method is not new (Sinha, 1990). TEM data have been used widely for groundwater studies (Everett and Meju, 2005); (El-Kaliouby, 1995), (El-Kaliouby, 2001). However, geophysical prospection in TDEM constitutes a first for this aquifer surface coastal. The electromagnetic method of survey in general aim at determining the conductivity (or conversely the resistivity) distributions in grounds and subsoil according to the depth (Fitterman and Stewart 1986), (Dominique, 2002). Also, (Goldman *et al*., 1998), (Goldman *et al*., 1991) charted the extension and the depth of the salt water wedge top on the coastal plain of Israel with a confirmation of the resolution of the method after comparison of the results with existing drillings. The water supply of the Cotonou town (economic capital of Benin) is assured incidentally from the Quaternary aquifer in the littoral sand cords (Boukari, 2002). But proximity of the sea entail problems of salt water invasion accentuated by the intense pumping in this aquifer system since

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1956 (Boukari, 2002). This study presents the variation between dry and rainy season of the limits of the salt water wedge in the Quaternary aquifer by using the geophysical method of the TDEM (Time Domain Magnet-Magnetic).

Study area

The study site is to south of Benin between the Atlantic Ocean and the coastal lagoon insides the WGS 84 UTM co-ordinates of 701 650 and 702 250 of latitudes and 424 550 and 425 150 of longitudes, with a surface of approximately 360 000 m^2 (Figure 1). The South of Benin is characterized by a subequatorial climate in four seasons: a great rainy season from March to the middle of July, a small dry season from the middle of July to September and a short rainy season in September-October followed by a long dry season from November to March (Yalo *et al.,* 2012). The annual pluviometric average is 1300 mm in the south of Benin. The temperature is on average of 27,7°C in dry season and of 26,5°C in rainy season. Average temperature of water in the wells is around 26°C. The climate in the South Benin is of transitional subequatorial type (Lang, *et al.,* 1988). Several authors (Boukari, 1998), (Lang, *et al.,* 1988), (Le Barbé, *et al.,* 1993), (Laibi, 2011), (Maliki, 1993), (Oyédé, 1991), (Tastet, 1977) studied the various sandy bars of the south Benin littoral zone. The intern bars of yellow sand are separated of the median gray sand bars by the Outobo lagoon. The median gray sand bars are separated of the sub actual brown gray sand bars by the coastal lagoon (Figure 2). The Quaternary coastal shallow aquifer, target of this study, is constituted of gray brown sand bar.

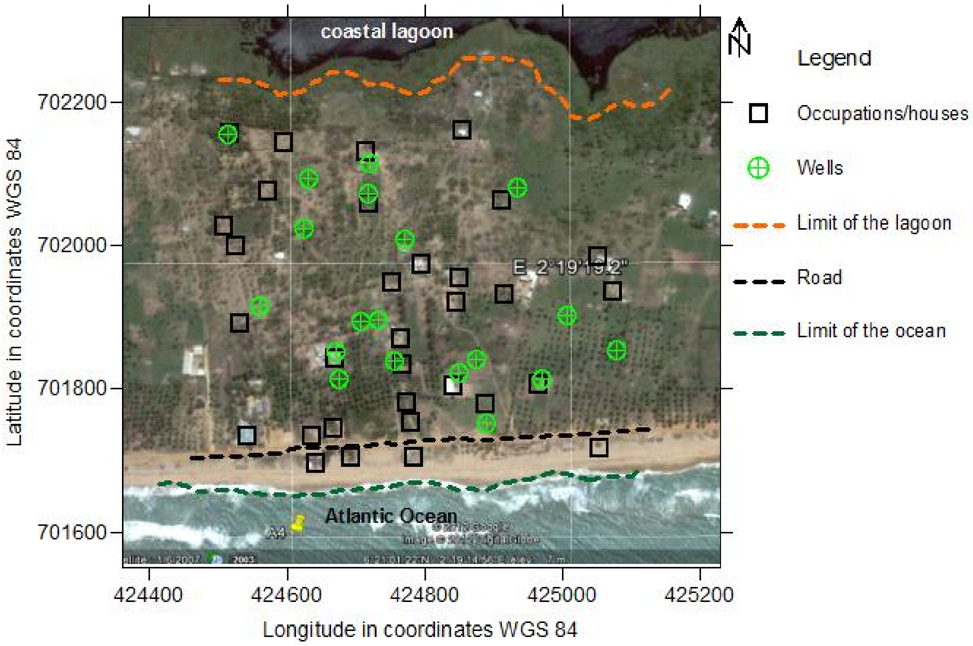


Fig. 1. Localization of study site in the South Benin

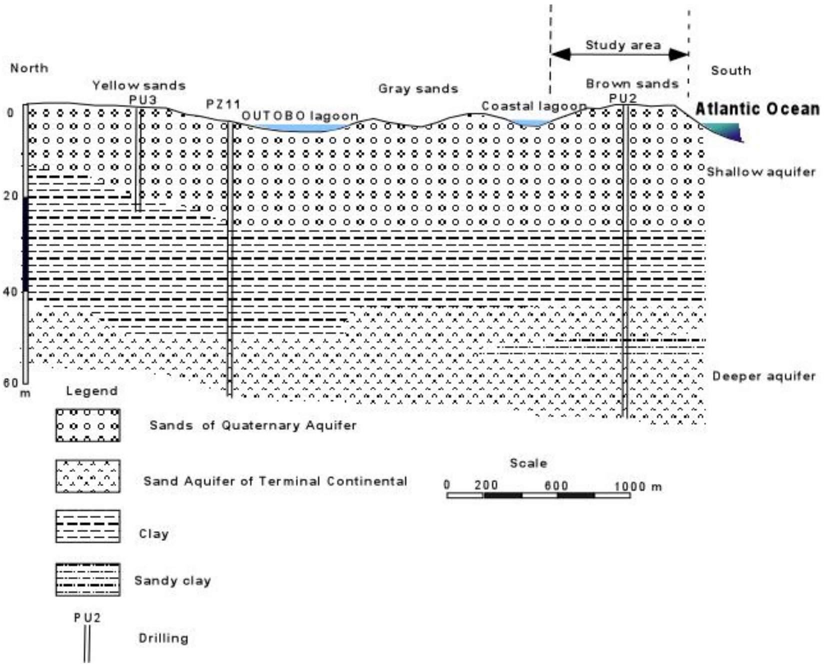


Fig. 2. Hydrogeological section of the Quaternary shallow aquifer (Source: Yalo, 2012)

Hydrogeologic setting

The PU2 drilling data well in the study zone between the Atlantic Ocean and the coastal lagoon show that the upper sand aquifer thickness does not exceed 30m (Figure 3). This upper aquifer is collected by wells and drillings, with depth less than 30m, in which the water level is between 1m and 9 m. The water flow is between 1 and 15m^3/h (Boukari, 1998). It is an unconfined aquifer in which thickness of unsaturated area makes approximately 0 to 3m. (Boukari, 2009). On the study site, freshwater duckweed floats on salted water: water of the Ocean in the south and water of the brackish lagoons in north (Worthington, 1993), (Figure 1). According to (Maliki, 1993), the permeability of sands is raised enough, between 10^{-2} and 10^{-4}m/s. the water table varies between 2.5 and 3.5 m with 1 m of annual variation. In practice, the freshwater can be exploited by wells or not very deep drillings far away from the offshore bar limits. According to SRHAU/BURGEAP (Serhau-Burgeap, 1987), the total porosity of littoral sands is around 35%.

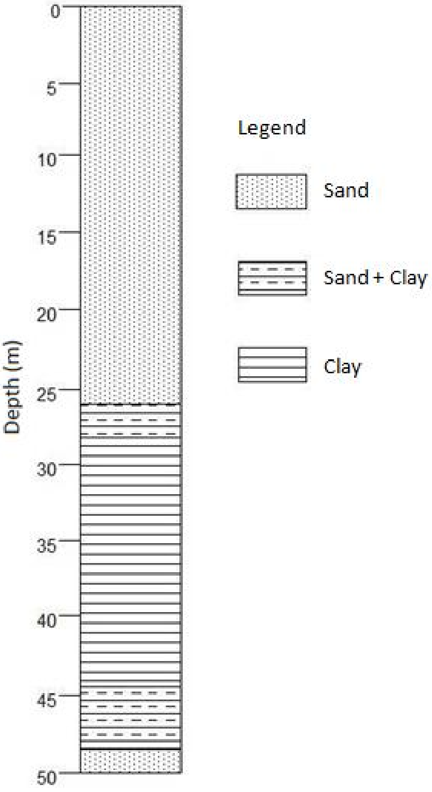


Fig. 3. Stratigraphy of PU2 well in the south Benin (Source: Maliki, 1993)

MATERIALS

The TEMfast 48 is a device portable geophysics called Transient ElectroMagnetic (TEM). The equipment was originally developed for the international Mars-94 project. The equipment was developed by the Russians in the Company of research in applied Electromagnetism (AEMR LTD) (AEMR, 2002a). The intention was to include the equipment in a module to land on Mars and perform TEM soundings, but this project was never completed. However the result of this project is the very compact and light TEMfast 48. The complete TEM-fast 48 set, including cables, battery and pc. The TEM-fast 48 device (Figure 4) itself includes transmitter, receiver, controller and battery assembled in a single case.

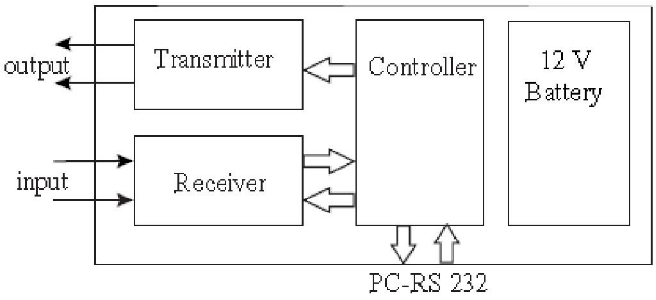


Fig. 4. Block diagram of the TEM-fast 48 device. Modified AEMR (2002a) (AEMR: 2002a)

This equipment can be used with one of these two configurations namely: the device of cable power plant of reception or dispositive coincide, but the experience showed that the coincident dispositive, at the same time as it is practical he allows to have also good results with this device. The internal battery of 12 V of the device is not rather powerful to realize more than 50 soundings with a configuration of I=4A and stacks. 10 it is thus the reason why, an external battery of 12V is useful to realize more than 50 soundings. All soundings have been realized with the TEMfast 48 associated by an external battery and by a size of cable 12.5 X 12.5m in coincident dispositive. The curves of resistivity calculated from the apparent resistivity were obtained according to time of decrease of the signal after cut of the current (Kaufman and Keller, 1983; Fitterman and Stewart, 1986).

METHODS

TDEM measurements

115 surveys TDEM were carried out on a surface of 600 by 600 m thus, approximately 360 000 m^2. These 115 measures were been valid at the end of June (at the end of the great rainy season (9)) and the second time in the first week of the month of Mars (at the end of the great dry season (9)). On the study site, these surveys are divided into 8 profiles of 15 surveys on average (Figure 5). The profiles are spaced of 60 m in the North-South direction perpendicular to the shore line. On each profile, the surveys are spaced of at least twice and half the loop dimension, so approximately 30m. According to the objectives of study, several configurations can be applied with the TEMfast (Descloitres, 1998). Nabighian and Macnae (Nabighian and Macnae, 1991) and (McNeill, 1994) have made an in-depth study on the application of the TDEM method. The maps of resistivity were represented for the two season using values of resistivity, calculated by intervals of depth and interpolated on the entire study area. The sections of resistivity, calculated after inversion of field data, are built also for the two seasons

Estimation of aquifer porosity and freshwater lens resistivity

Archie (1942) introduced the following relation based on his works on the petrophysics of brine-filled rocks under clay-free condition:

$$\rho_f = a\rho_w \emptyset^{-m} \quad (1)$$

where,

- ρ_f : is the bulk resistivity in Ω, (measured resistivity)
- ρ_w : is the fluid (pore water) resistivity in Ω.m,
- $\emptyset$: is the porosity of the medium,
- a: is a coefficient associated with the medium,
- m : is known as the cementation factor although it is interpreted as grain-shape or pore shape factor.

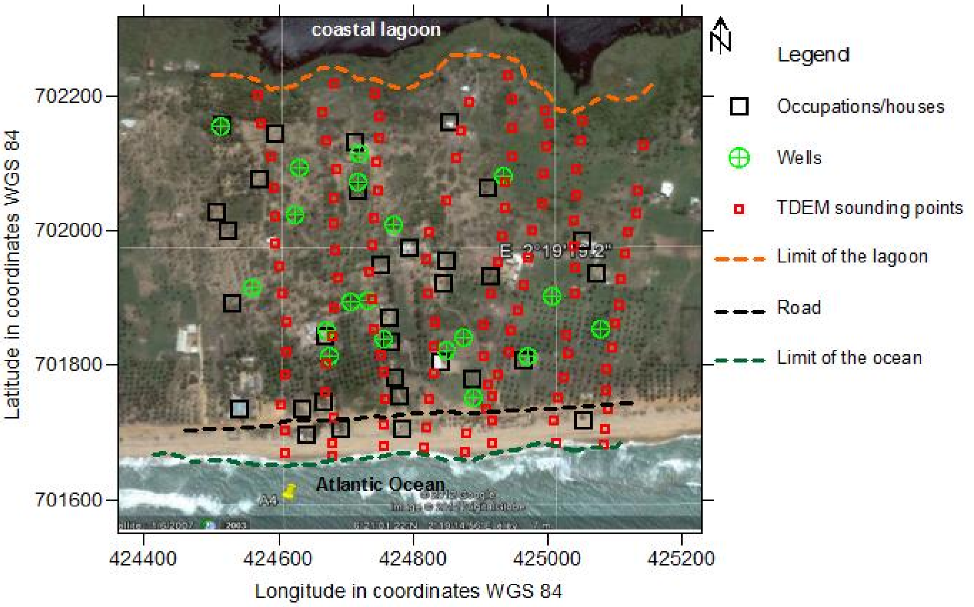


Fig. 5. TDEM soundings on the study area

Table 1. Archie law coefficients (Keller, 1988)

Types of grains or rocks	Coefficient m	Coefficient a	Porosity in %
Slightly cemented detrital rocks (sand, sandstone)	1.37	0.88	25 à 45
Moderately cemented sedimentary rocks (sandstone and limestone)	1.72	0.62	18 à35
Strongly cemented sedimentary rocks	1.95	0.62	5 à 25
Very porous volcanic rocks	1.44	3.50	20 à 80
Crystalline and metamorphic rocks	1.58	1.40	< 4

Due to lack of core data from which the estimated values of "m" and "a" should, ideally, be examined for each site under investigation, an alternative approach reported in literature was adopted for porosity estimations (Worthington, 1993). Keller (1988) suggests Table 1 for the choice of "m" and "a" different values. Knowing that the aquifer is primarily sandy on a thickness of approximately 26m, according to the log of drilling (Figure 4), the values of 1.37 and 0.88 have been chosen respectively for "m" and "a" and the weak variation of porosity could be neglected. The first measurements of static levels and electric conductivities were made in June, at the end of the great rainy season. Water conductivity in the wells has a significant variation of conductivity and thus of the resistivity (16 to 95 ohm.m for rainy season) and makes it possible to deduce that ρ_f would be related basically to ρ_w.

$$\rho_f = F(\rho_w) \qquad (2)$$

With "a", "m", and Φ = Constant

The value of porosity Φ was estimated on a ground saturated with sea water. The measured conductivity ρ_w of sea water being of 50,700 µS/cm or 0.2 ohm.m and the measured resistivity of ρ_f= 0.8 ohm.m, porosity were calculated according to the following equation:

$$\emptyset = \left(\frac{a\rho_w}{\rho_f}\right)^{1/m} \qquad (3)$$

This estimation gives a value of 34% for the total porosity of sands. That value of total porosity closed to the 35% is obtained by SERHAU/BUGEAP (1987) for the salty fine sea sands of the littoral plain. Knowing the porosity $\emptyset$ of the aquifer we calculated the limit of resistivity ρ_f in the equation (1) for grounds with freshwater. According to the WHO standard (2004) the upper limit of freshwater conductivity (lower limit of resistivity) ρ_w is of 1100µS / cm with 25°C. Resistivity values below 30 ohm.m are supposed to represent grounds containing some brackish water or salt water (Yalo, *et al.,* 2013) and thus defined the limit between the freshwater lens and the salt water. Sections and maps of calculated resistivity were realized at different depths with an aim of showing the variation of freshwater lens depth. These variations according to the latitude, to the longitude and to the depth allowed us to observe the variation freshwater lens morphology between a rainy and dry season.

RESULTS

According to a previous study (Tastet, 1977), the salted wedge thickness was estimated to 8m at the center of the study area. This thickness decreases towards north closer to the lagoon and towards south closer to the sea. This thickness varies according to that of freshwater lens.

Lateral extent variation of freshwater lens between rainy and dry season

On the study site the freshwater lens extends more towards the sea in rainy season than in dry season (Figure 6 and Figure 7). In the south, on the side of the sea, the freshwater lens lateral extent is reduced of 20m (section 1 of Figure 7) to 140m (section 7 of Figure 7). On seven of the eight sections, the freshwater lens moves away from the sea in dry season. In the north, on the side of lagoon, the freshwater lens widens of one meter to a few tens of meters. With the exception of section 1, this widening of the lens towards the lagoon is observed on all the other sections. The freshwater lens morphology has just moving from the south towards the north between rainy and dry season. It seems that the intrusion of denser sea water pushes back the freshwater lens towards the lagoon.

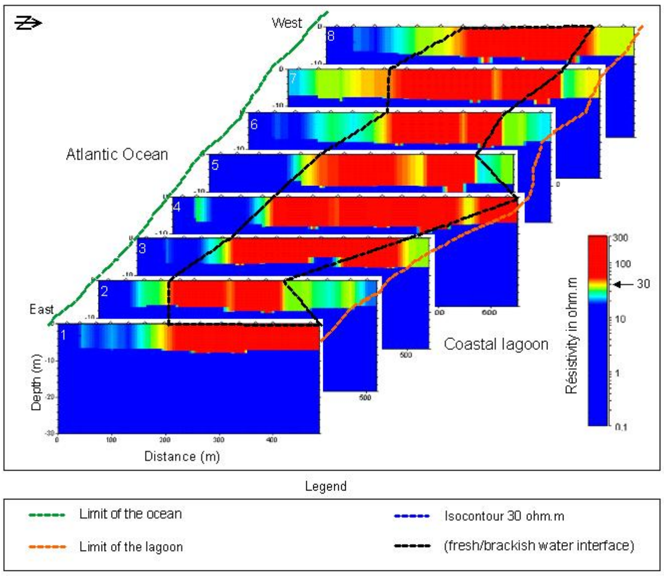


Fig. 6. Lateral extent of freshwater lens (in red) in rainy season

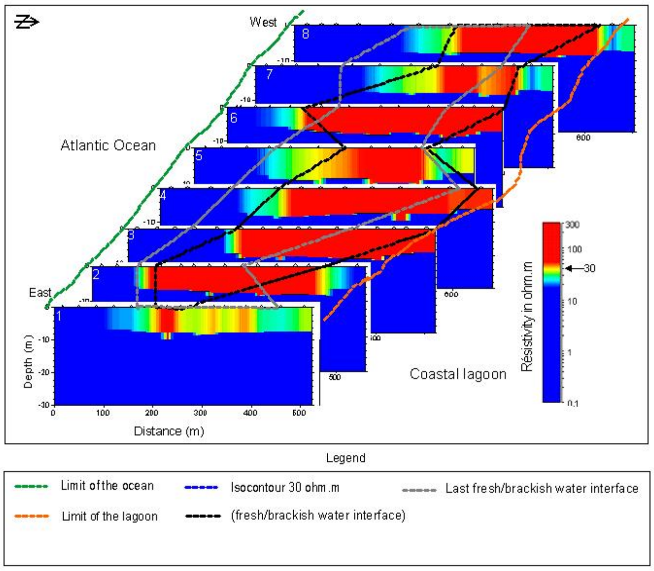


Fig. 7. Lateral extent variation of freshwater lens in dry season

Variation of the freshwater lens depth between rainy and dry season

For the entire study area, twelve maps of resistivity were charted at different depths for the rainy season (Figure 8) and dry season (Figure 9). Maps of resistivity were carried out from a depth of 3 to 10m with an interval of one meter. Then the same maps of resistivity were carried out from a depth of 15 to 30m with an interval of depth of 5m (Figures 8 and 9). On the maps of resistivity, the grounds with a resistivity higher than 30 ohm.m are colored in green, yellow and red. The purple color bounded represents grounds with the salt water. On the maps of resistivity, the depth of sea water intrusion is of 7m in rainy season (Figure 8) and 5m in dry season (Figure 9). Thus, in southern part of study area near the sea, the depth of freshwater lens decreases of 2m between rainy and dry season. In the south, the intrusion of denser sea water pushes up the freshwater lens. In the northern part of study area, the brackish water intrusion from the lagoon started at 9m depth in rainy season (Figure 8) and at 8m depth in dry season (Figure 9). Thus, in the north, the depth of freshwater lens decreases of 1m between rainy and dry season. In dry season the intrusion of denser brackish water from the lagoon pushes up to 1m the freshwater lens. Salted water being denser than brackish water, the increase of the lens is more accentuated in the south close to the sea than in north close to the lagoon. The freshwater lens is compressed as well in north as in south during the dry season. During the dry season, the evaporation of the freshwater lens implies a reduction of its volume and a decreasing of the pressure which it exerts on salted wedge. On the contrary, the evaporation of the sea and the lagoon makes their water denser and thus increase their pressure on the freshwater lens. The freshwater lens is then compressed on the two sides and its morphology changes. As the density of sea water is higher than the density of brackish water, the pressure coming from the sea is higher than that coming from the lagoon and freshwater lens moves towards north in dry season.

DISCUSSION

The values of water conductivity in the wells were converted into resistivity to obtain a map of resistivity (Figure 10) in order to facilitate the comparison between the direct results of measurement in situ and geophysical measurements. The maps of water conductivities in the wells are compared with the maps of TDEM resistivities. In conformity with the maps of TDEM resistivities, those of the water conductivity show in dry season, a sea water intrusion in the south and brackish water intrusion in north of study area. Moreover, the resistivities of water in the wells vary between 16 and 97 ohm.m in rainy season and from 7 to 53 ohm.m in dry season. this reduction of water resistivities in dry season can be explained by sea water intrusion in few wells. Knowing that a water conductivity of 1100 µS/cm with a temperature of 25°C corresponds to a resistivity of 9.1 ohm.m, one can conclude that all sampled water contains fresh water in rainy season. However, the samples containing water with resistivity lower than 30 ohm.m, have an accentuated mineralization and the others with resistivity upper than 30 ohm.m, have a middle or low mineralization (Rodier, 1996). Among the 17 analyzed wells of the study area in rainy season, 9 wells (2, 3, 4, 7, 13, 14, 15, 16 and 17) contain fresh water with accentuated mineralization and the 8 remaining wells collect fresh water with middle and low mineralization. In dry season, there are no wells with low mineralization. They have medium and accentuated mineralization. Moreover in dry season, the well number 4 in the south is polluted with sea water intrusion.

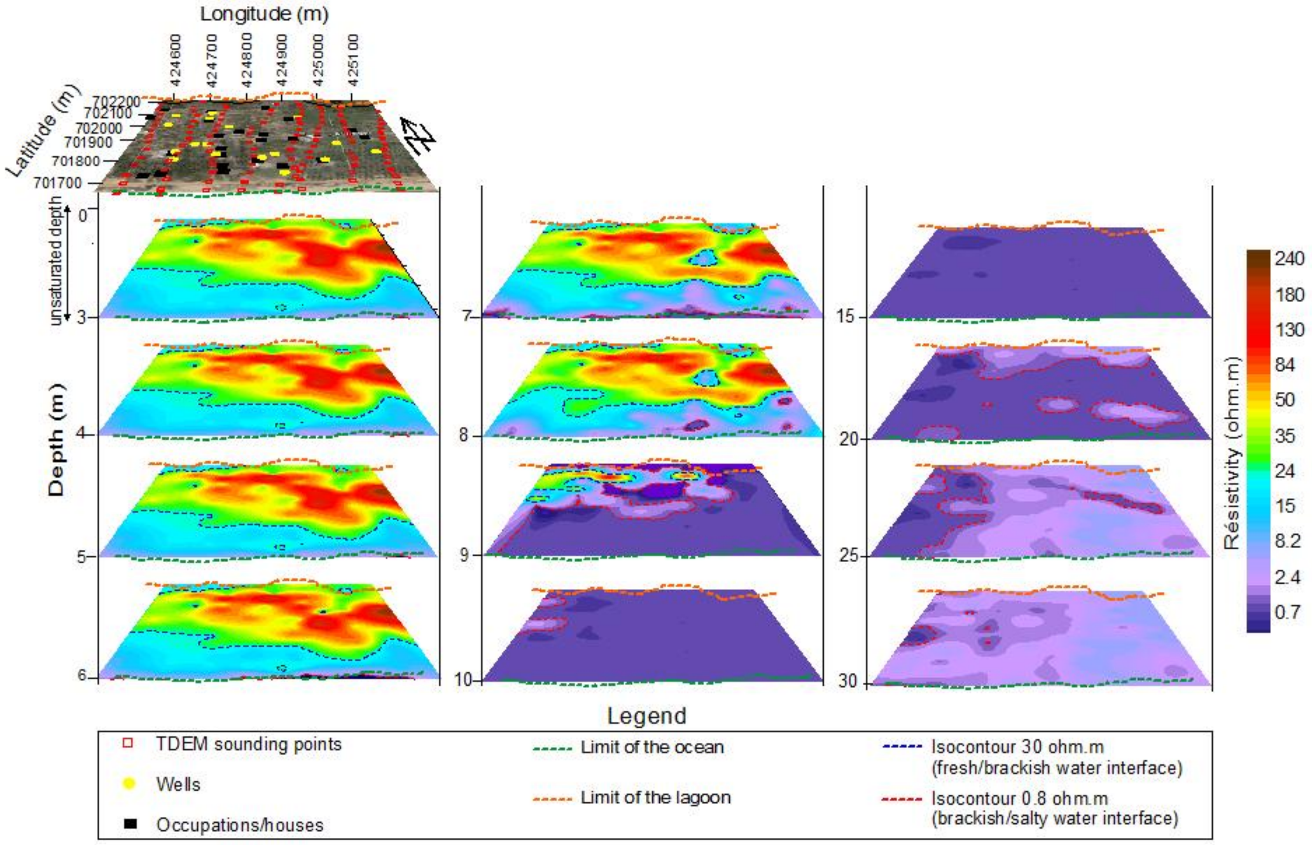


Fig. 8. Depht of freshwater lens (red, yellow and green) in rainy season

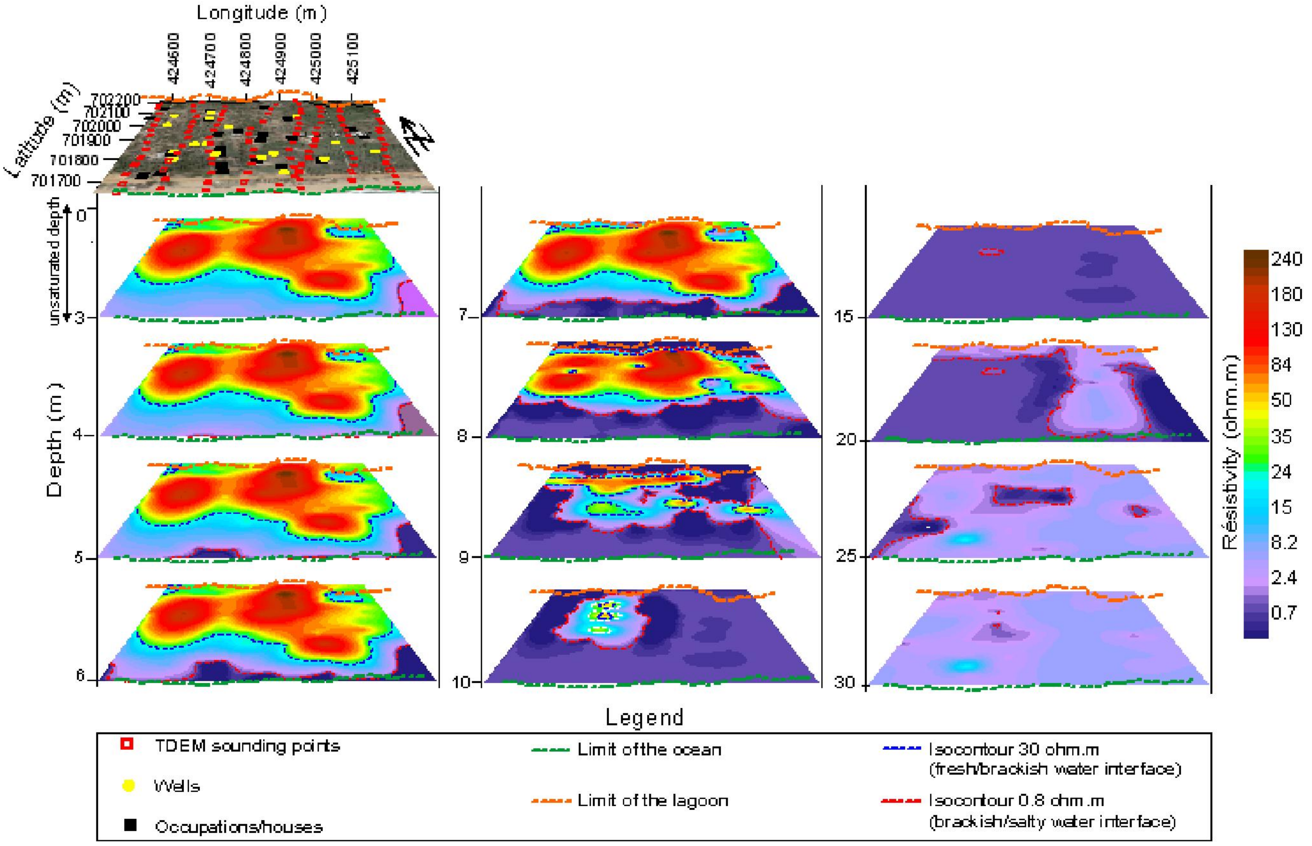
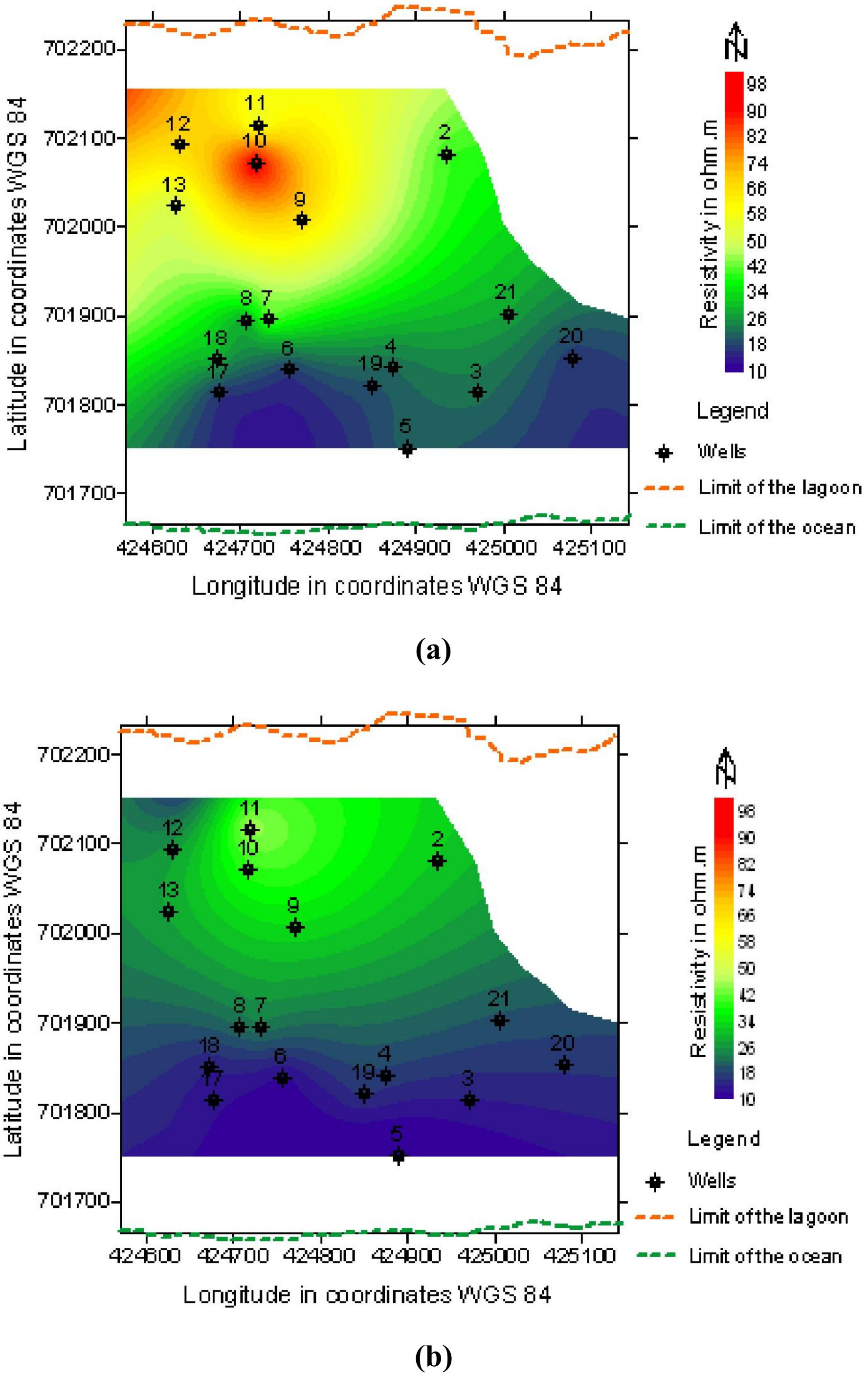


Fig. 9. Depth of freshwater lens (red, yellow and green) in dry season



(a)

(b)

Fig. 10. Map of water conductivity in the wells in the rainy (a) and dry season (b)

Conclusion

The application of the method Time Domain Electromagnetism TDEM in prospecting geophysics allowed us to study at first the extent and the depth of the freshwater lens and in the second, the variation of the same freshwater lens morphology between the rainy season and the dry season. For Vouillamoz *et al*. (Vouillamoz, 2012), a change in rainfall patterns will probably not impact the fresh water resource but a rise of the mean sea level will both reduce the freshwater reserve and the net recharge. Between the rainy and dry season, the freshwater lens morphology changes. Because of evaporation during the dry season, the reduction of freshwater lens volume implies a decreasing of the pressure which it exerts on salted wedge when the pressure of denser water coming from the sea and the lagoon increases. As the density of sea water is higher than the density of brackish water, the pressure coming from the sea moves the freshwater lens towards the lagoon. The consequence of this movement is that few wells inside the freshwater lens in rainy season are found outside the freshwater lens in dry season and are thus contaminated. This study shows that using TDEM for monitoring the variation of freshwater lens morphology between rainy and dry season is possible and useful for the choice of wells with sustainability sanitation.

Acknowledgments

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