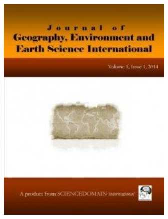


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# Evaluation of a Monitoring Network of Seawater Intrusion in the Coast of El Jadida District, Morocco

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***Authors' contributions***

*This work was carried out in collaboration between all authors. Author MA designed the study, wrote the protocol, and wrote the first draft of the manuscript. Authors AE and AS managed the SaDin project and improved the results. Author SEM participate in the first study of choice of the boreholes site. Author NM participates in campaigns of measurement. Author LB participate in the languages correction. All authors read and approved the final manuscript.*

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## ABSTRACT

The coastal area of El Jadida District contains one of the most important monitoring networks of seawater intrusion along the Moroccan Atlantic coast. This network is constituted of six boreholes lies at about 1km from the coast and arranged with space between 10 and 13km. Boreholes are drilled by the mixed drilling technique using two different methods; the rotary rock bit in the mud and the down the hole hammer drilling. The drilling has allowed us to recognize an unconfined aquifer formed by Quaternary sandstone and two confined aquifers formed by Cenomanian limestone and Paleogenian sandstone. A measurement campaign of the electrical conductivity by multi-parameterics probe had allowed locating a seawater intrusion into each borehole, the high value of

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the electrical conductivity reached its 56 mS/cm allowing concluding that Ghyben-Herzberg relationship was improved. The calibration of the geophysical data by the networks allows us to highlight the seawater extension in the Sahel.

*Keywords: El jadida; Morocco; atlantic coast; sahel; seawater intrusion; electrical conductivity; geophysics.*

## 1. INTRODUCTION

In the international level, several study was treated a relationship between seawater and freshwater of the coast aquifers, in different methods and using hydrogeology and geophysics techniques [1].

Morocco is located in the North West part of Africa continent; it is open to a Mediterranean Sea and oceanic Atlantic (about 3km of coastline). El Jadida District is a coastal city which opens to oceanic Atlantic. The coastal area of El Jadida District between Azemmour and Oualidia localities is currently the headquarters of major socio-economic activities and will be in the near future one of the main industrial zones in Morocco. Its economic structure is based primarily on the chemical industry, pharmaceutical production, candy, dairy production, market gardening and salt production. In spite of this, the groundwater is very requested, as well as all coastal areas of the world. The aquifer of this area shows an increase in salinity that could be related to seawater intrusion.

From 1980, hydrogeologists and public institutions scholars have emphasized the need to consider the risk of seawater intrusion in the coastal aquifers of Doukkala Sahel. Several studies were carried out on salt wedge [2,3,4,5,6] and the state of the aquifer [7,8,9].

### 1.1 Study Area

The study area, called Sahel, corresponds to the coastal zone of El Jadida District lies in western part of Morocco. The North West boundary of Sahel is Atlantic Ocean, and the North East is Oum Rbia River. The South East is natural boundary with Doukkala-Abda plain, and South West is the administrative limit with Safi District (Fig. 1).

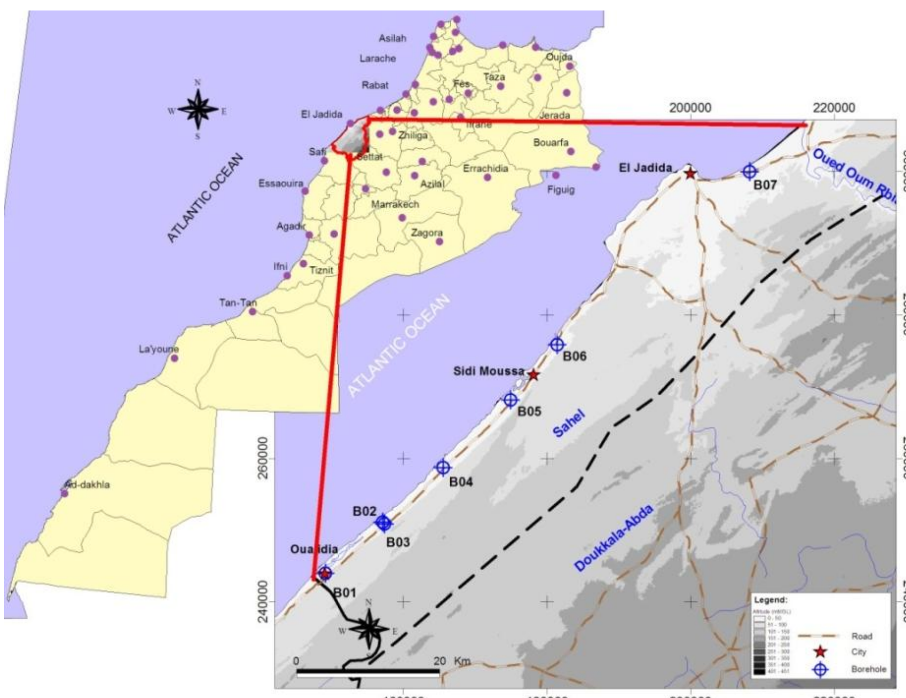



**Fig. 1. Situation of the study area and location of boreholes**

### 1.2 Geological Setting

Dealing with lithostratigraphy, the Sahel is dominated by Cretaceous limestone outcropping in the South of El Jadida city and bedrocks of the Plio-quaternary sandstone at the South west of study area. At the North, the Cretaceous limestone is overlained by Plio-quaternary sandstone, as a result of a system of NW-SE trending faults (Fig. 2), these formations constitute two main aquifers in this area. In the Sahel, in general, five potential aquifers could be distinguished [7]: Plio-quaternay, Cenomanian, Hautervian, Valanginian and Jurassic.

## 2. MATERIALS AND METHODS

The choice of the network boreholes sites was based on the collection of hydrogeological [12,9], hydrochemical [4,6] and geophysical [12] data. Accordingly six potential sites were selected in the most sensitive points along the coast.

The piezometry of Sahel area is characterized in general by a very low hydraulic gradient of approximately 2 ‰ between Sidi Moussa and Jorf Lasfar and 7 ‰ between Sidi Moussa and El Oualidia [2], and the electrical conductivity (EC) values exceed 3 mS/cm. The same trend was observed on other chemical elements, Cl- and Mg++ which illustrate an enrichment of groundwater in these elements nearby the coast too [4,5,6,7].

The boreholes of the network were drilled using the mixed drilling technique. At a point in the continuance of drilling the cutting sample are assured each one meter by filling small plastic bags numbered in the order and then freshened in the laboratory.

At the end of each drilling, and before equipping the borehole by casing, an air lifts' system, is installed in these boreholes for their cleaning properly. The equipment used in these air lift reaches a depth of 53 m.

After drilling, a campaign of quality control is operated at different times by measuring several physico-chemical parameters using a multi-parameters probe brand SEBA Hydrometry kind KLL-Q, equipped by an electrode bar "Steckbare" to which are attached multiple electrodes to measure EC, temperature (T°), dissolved oxygen (DO), pH and red-ox potential (Fig. 3).

The boreholes of the network lie between Sidi Moussa and Oualidia at 1 km on a line parallel from the shore. Respectively the distance between the boreholes B01, B03, B04, B05 change between 10 and 13km, while the seventh borehole (B07) is at about 35 km from (B06). B02 and B03 are aligned perpendicular to the shore (Fig. 1).

Given below are the boreholes characteristics Table 1.

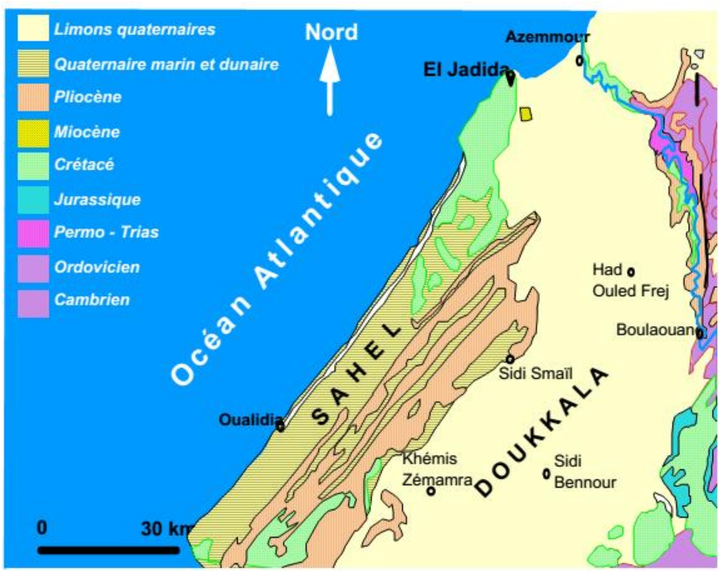



**Fig. 2. Simplified geological map [8]**

**Fig. 3. Multi-parameters probe**

**Table 1. Boreholes characteristics**

| Code | X(m) | Y(m) | Z(m) | Landmark (m) | Level of the water (m) | Total depth (m) |
|---|---|---|---|---|---|---|
| B02 | 167968 | 250485 | 18 | 0,50 | 9.80 | 70 |
| B03 | 167708 | 250720 | 30 | 0,10 | 27 | 80 |
| B04 | 176132 | 258355 | 16 | 0,40 | 9.50 | 74 |
| B05 | 185524 | 267772 | 12 | 0,40 | 6.90 | 61 |
| B06 | 192056 | 275460 | 15 | 0,20 | 4.90 | 60 |
| B07 | 218840 | 299602 | 24 | 0,30 | 5.90 | 68 |

The cuttings were described in the Laboratory, of Geosciences and Environment Technology of the Faculty of Sciences of Chouaib Doukkali University, after freshening, using the eyepiece observation and sometimes the optical microscope and using the existing literature on the region, and the stratigraphic logs were combined with hydrogeological field.

The EC of water is the parameter that most readily distinguishes the freshwater from seawater it represented as logs in order to visualize the changes in salinity with depth. EC logs presented above have been prepared taking into account the hydraulic load.

## 3. RESULTS AND DISCUSSION

The geological description of cutting allow to define lithostratigraphic formations that characterize the study area, silts, sands, sandstones (coquina) and clay of Plio-quaternary with intercalation of Cenomanian yellow marly limestone.

### 3.1 B02

B02 is made by hammer borehole until a depth 68 m and recovered only 9 m of cuttings corresponding to the Quaternary deposits (Fig. 4) Hydrogeological column of boreholes B02 captures a shallow aquifer with a static level of 9.8 m corresponding to an elevation of 4.8 mMGL (Morrocan General Level). The air lift test exceeded 3 hours and the EC during this test reached 7.77 mS/cm.

### 3.2 B03

B03 is drilled by down-hole hammer drilling up to a depth of 80 m with recovering only 33 m of cuttings corresponding to Quaternary deposits (Fig. 4) Hydrogeological column of boreholes. B03 captures a phreatic aquifer, and the depth to water from the ground is 27.3 m corresponding to an elevation of 5.7 mMGL. The air lift test exceeded 2 hours and the EC during this test reach to 4 mS/cm.

### 3.3 B04

B04 is made by rotary with a Tricne until a depth of 74 m with entire recovering of cuttings ((Fig. 4) highlighting a Cenomanian limestone deposit, and the Quaternary deposit dominated by sand. All of these formations constitute two types of aquifers; shallow and confined aquifer. The piezometric level is 9.50 m corresponding to an altitude of 3.8 mMGL. The air lift test exceeded 2 hours 30 minutes and the EC during this test reached to 14 mS/cm.

### 3.4 B05

B05 is drilled by down-hole hammer drilling up to a depth of 61 m with recovering only 25 m of cuttings (Fig. 4). Hydrogeological column of boreholes revealed a Cenomanian limestone and the Quaternary deposits dominated by sand, and all of these formations constitute a shallow aquifer. The piezometric level is found at 6.40m corresponding to an altitude of 2 mMGL. During 2 hours of air lift test the EC reach to 10.61 mS/cm.

### 3.5 B06

B06 is drilled by rotary with a Tricne until a depth 60 m with recovering only 8 m of cuttings corresponding to the Quaternary sand. Following this depth, 9 m of total loss of cuttings was recorded (Fig. 4). From 17 m to 33 m the Neogen cuttings were recovered, then, the remaining of the cuttings was lost at a maximum depth of 60m (Fig. 4). The aquifers captured by the borehole are isolated by a semi-permeable layer. Then, semi-confined and phreatic shallow aquifers were distinguished. The piezometric level is found at 4.9 m corresponding to 0.3 mMGL. The test of air lift exceeds 3 hours and the EC during this test reached to 13.50 mS/cm.

### 3.6 B07

B07 is drilled by rotary with a Tricne until a depth of 68 m with recovering all cuttings (Fig. 4) by:

- Cenomanian limestones and marl;
- Paleogen sandstone and the clay;
- Quaternary sandstone.

From hydrogeological point of view we distinguish phreatic shallow and confined aquifers:

- two confined aquifers, one in Cretaceous layers and the second in the Paleogen layers;
- an unconfined aquifer in the Quaternay deposits.

The depth of the water from the ground is 6m corresponds to a height of 18 mMGL.

The test of air lift exceeds 2 hours and the EC during this test reached 5.80 mS/cm.

## 4. ELECTRICAL CONDUCTIVITY (EC) LOGS (Fig. 5)

### 4.1 B02

B02 log shows two levels indicating a passage of the transition zone (TZ) then, to the seawater. At first, the EC was stabilized around an average of 3.43 mS/cm and the height of freshwater was 15 m (from the altitude 4.8 to -10 mMGL). The thickness of a TZ is more than 20 m (from the altitude -11 to -42 mMGL) presented by three levels where the EC increases up to 49 mS/cm, below the TZ the sea water began to individualize a EC slightly exceeding 50 mS/cm. This borehole is located at 750 m from the shore. At this point, the freshwater of the Quaternary karsts aquifer constituted by coquina sandstone directly interacts with marine seawater influenced by tidal movements.

### 4.2 B03

B03 illustrates a single step of EC stabilized around an average of 03.39 mS/cm and the freshwater height reached 37 m (from the altitude 5.7 to -30 mMGL). The drilling of B03 is limited at the altitude of 33 mMGL (total depth is 75 m) and hit the roof of the TZ.

### 4.3 B04

B04 revealed a sudden increase in the EC in the first meter of freshwater (3.89 to 5.46 mS/cm), and then stabilized around 5.6 mS/cm. The freshwater thickness reached at 14m (from the altitude 3.4 to-8.6 mMGL). From the altitude -10 mMGL appears a step in the EC that starts with 7 mS/cm, then reached 11 mS/cm before declining to 9 mS/cm and then, ends by 13 mS/cm at the altitude -34 mMGL.

An examination of the lithology shows that drilling captures unconfined and confined aquifers which are both influenced by the slightly salty waters. However, in the first unconfined aquifer, the salinity is due to contamination by other salt sources than seawater.

The freshwater/seawater interface, materialized by a TZ, is located only in the confined aquifer at -35 mMGL. The EC began in this TZ by 16 ms/cm and reached 34 mS/cm at the altitude -52 m corresponding to maximum depth of the borehole (74 m).

### 4.4 B05

EC of B05 shows two main bearings that limit a TZ. At first, the EC was stabilized around 2.3 mS/cm with 18 m of thickness of freshwater (from altitude 2 to -16 mMGL), then it increased to 6 mS/cm before reaching 10.4 mS/cm at -20 mMGL. Then, a first step of EC increasing stabilized around 35 mS/cm for 11 m of thickness (from altitude -20 to -31 mMGL), corresponding to the TZ. The EC continues then to increase until reaching and stabilizing around 43.6 mS/cm for 10 m of thickness corresponding to the seawater intrusion. The stabilization around these EC values is due to the fact that this borehole contains a confined and an unconfined aquifer. The altitude -31 mMGL corresponding to the passage from TZ to SW corroborates with the substratum altitude of the phreatic aquifer observed in the borehole B04.

### 4.5 B06

The EC log shows three increasing steps. The EC was stabilized in the first step around 3.5 mS/cm for 11 m of thickness, and then it increases to 10mS/cm (from altitude 0.3 to -12 mMGL). After that, the three increasing steps of EC reflected a TZ, around 26 mS/cm and seawater around 48 and 56 mS/cm. The thickness of this TZ is 18 m (from altitude -12 to -30 mMGL). In the SW height, two stationary steps of EC were observed; one around 50 mS/cm (12 m height) and the second around 56 mS/cm (4 m height). This variation is due probably to the passage from the semi-confined aquifer to the confined aquifer formed by the cenomanian limestones.

### 4.6 B07

In B07, The investigation by the multi-parametric probe is blocked by the heavy vegetation intensity. Nevertheless, at the depth of 12 m we could measure the EC. From the first meters, the EC is higher up to 6.9 mS/cm (Table 2). Then, it drops to 6.6 mS/cm and this allows us to conclude that this excess in salinity is related to the salty silt levels observed in geology drilling.

Between El Jadida and Azemmour cities, the high salinity water in the phreatic aquifer is due to the nature of the basement and most likely to the anthropogenic activities contamination. The water is quite contaminated by the effect of salty silt leaching induced by the strong agricultural activities in the surrounding area. The EC values measured during the air lift test did not exceed 6mS/cm; in this borehole the freshwater-seawater interface was not reached.

## 5. DATA ANALYSIS

Ghyben-Herzberg relationship (Fig. 6) based on the hydrostatic balance between freshwater and seawater contact:

$$h=\left[\frac{\rho s}{(\rho s - \rho f)}\right]hf \qquad [10]$$

avec :

- $\rho s$ : Density of salt water (1025 kg/m3);
- $\rho f$ : Density of the fresh water (1 000 kg/ m3) ;
- h : height from salt / fresh water interface;
- hf : piezometry coasts zero sea level

Where h=40h*f*

This means that the position of the interface of fresh / sea water is located at a depth of 40 times the hydraulic load of the water. Ghyben-Herzberg's relationship is valuable only in the sixths borehole (B06). In this borehole, from the coast piezometry to zero sea levels we have hf=0.3m (Fig. 7) and h=12 m. Therefore, at -12mNGM the EC exceeds 10 mS/cm.

The borehole B02, B03, B05 and B05 captured a karstic aquifer characterized by high dynamicity of the water circulations. This characteristic doesn't exist in the aquifer captured by B06. Those results is correlated with Ognjen and Tanja (2009)'s results, indicating that's the Ghyben-Herzberg's relationship is formulated exclusively on the basis of hydrostatic equilibrium, and its use under dynamic conditions is limited [11].

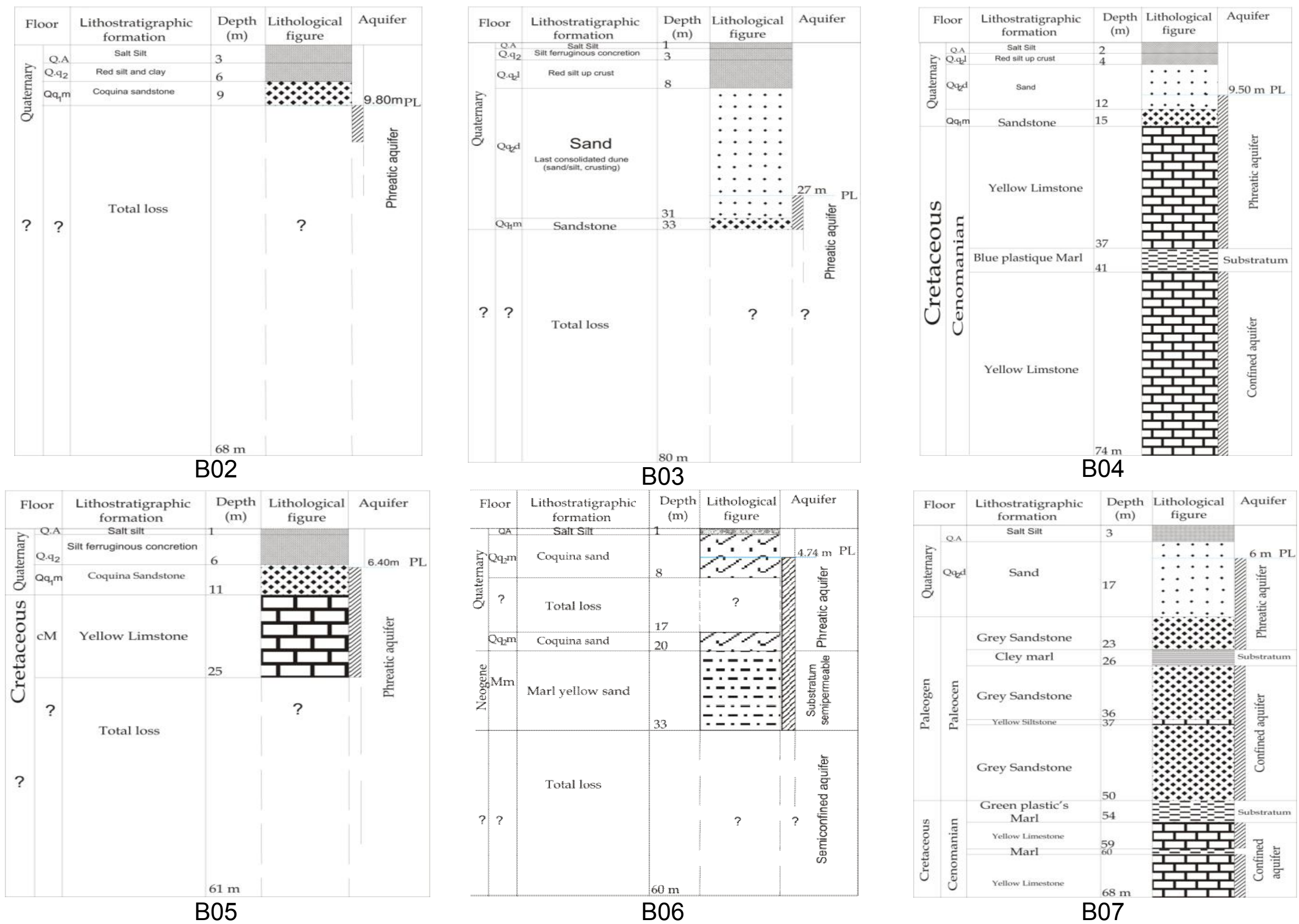


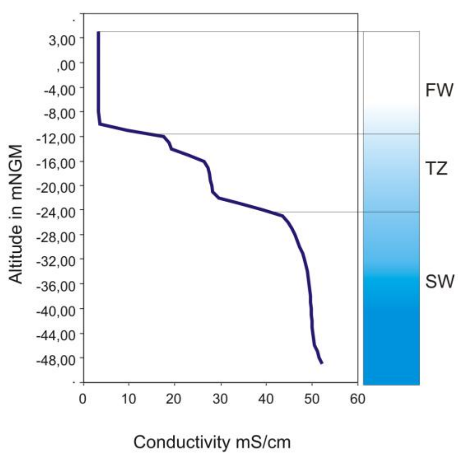

**Fig. 4. Hydrogeological column of boreholes**

The geophysical study, using the electrical method, was done by Direction of Hydraulic Region of Tensift (DHRT) in the Sahel of Doukkala in order to define the seawater extension [12,13]. The boreholes of the network allowed us to calibrate the geophysical data of this study and give the present model (Fig. 8).

Generally the seawater intrusion in the coast area of El Jadida District is located between -2 and -129 mMGL, and is penetrate more in the East and South of Oualidia.

**Table 2. Physico-chemical characteristics of B07**

| Depth (m) | EC (mS/cm) | EC corrected (mS/cm) | pH | Temperature (°C) | Dissolved oxygen (mg/l) | Oxydo- reduction potential (mV) |
|---|---|---|---|---|---|---|
| 6.26 | 6.95 | 6.51 | 6.8 | 22.8 | 2.2 | 99.1 |
| 7 | 6.93 | 6.49 | 6.8 | 22.8 | 1.6 | 102.7 |
| 8 | 6.93 | 6.49 | 6.8 | 22.7 | 1.5 | 105.2 |
| 9 | 6.73 | 6.31 | 6.9 | 22.7 | 1.8 | 109.4 |
| 10 | 6.68 | 6.26 | 6.9 | 22.7 | 2 | 113 |
| 11 | 6.68 | 6.26 | 6.9 | 22.7 | 2.1 | 115.8 |

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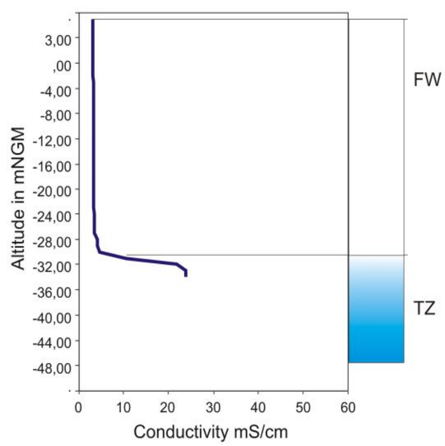
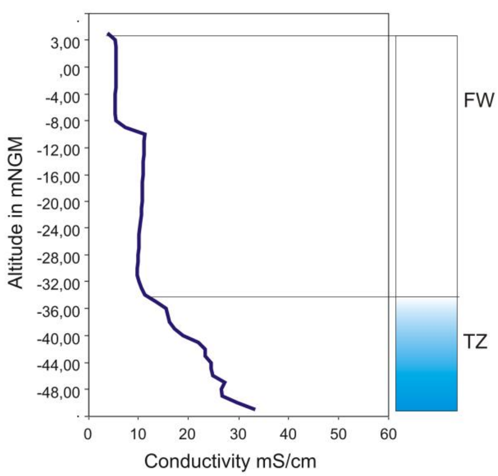
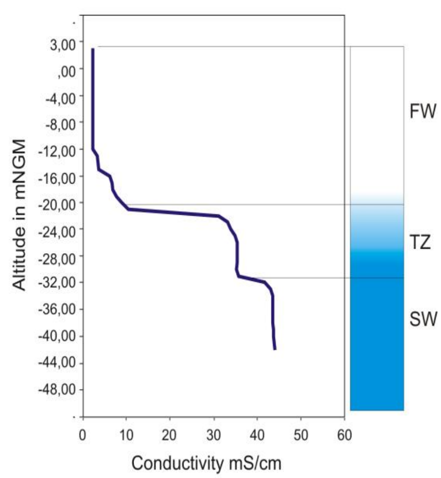



**B03**




**B04**




**B05**

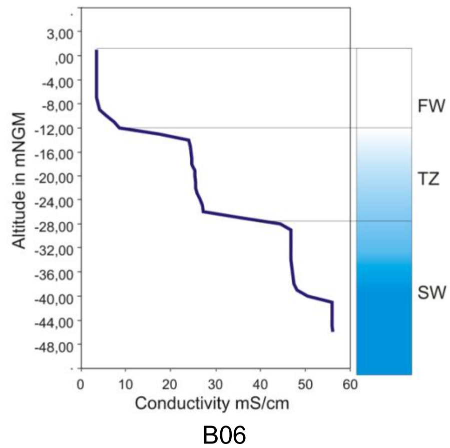



**Fig. 5. Electrical conductivity logs**

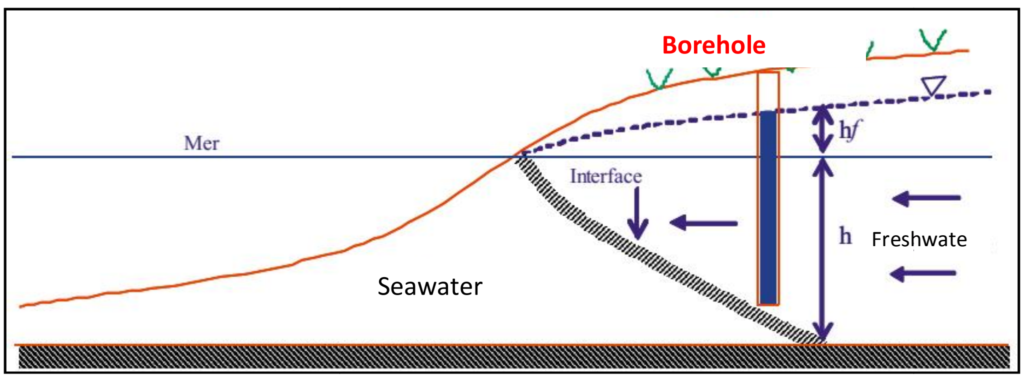



**Fig. 6. Freshwater and seawater relationship**

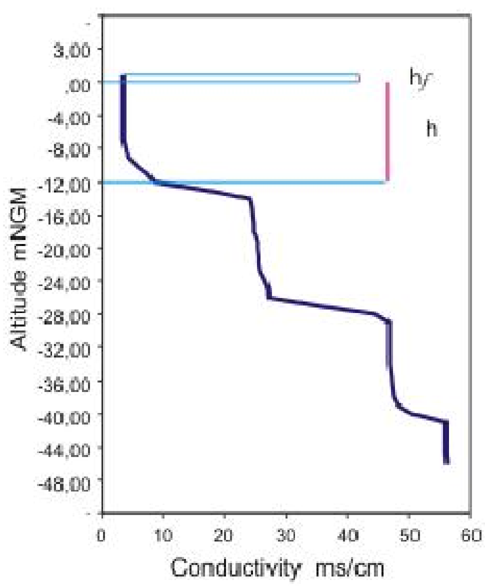



**Fig. 7. Ghyben-herzberg explication in B06**

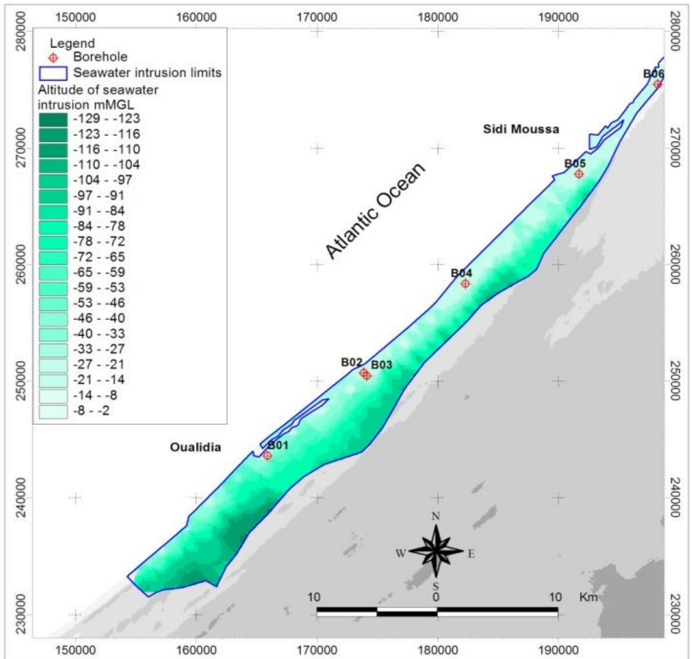



**Fig. 8. Seawater intrusion in the coast area of El Jadida District**

## 6. CONCLUSION

This work allowed highlighting the seawater intrusion in the various aquifers of the coast of El Jadida District through boreholes drilled. The seawater intrusion is located in the confined and unconfined aquifers of the coast region between El Jadida and Oualidia localities. Along the coast, the Ghyben-Herzberg's relationship can be applied only in the Neogen aquifers, prospected by the sixth borehole, because the aquifer captured by this borehole is formed by the homogeneous sandy marl of Neogen. Other boreholes capture the heterogeneous karstic aquifers dominated by limestone and sandstones characterized by high dynamicity of the water circulation.

The boreholes of the network can be used to control and calibrate all the futures studies about the underground water in the coast of El Jadida.

Furthermore, between El Jadida and Azemmour localities, the increasing in the salinity of the water is due to the anthropogenic activities contamination than the seawater intrusion.

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## COMPETING INTERESTS

Authors have declared that no competing interests exist.

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