Chapter

Multivariate Pollution in the Coastal Aquifer of Lebna area, Northeastern Tunisia

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Abstract

Anthropogenic contamination and excessive water consumption endanger an overexploitation of groundwater, which causes groundwater mineralization in coastal aquifer of Lebna area. Consequently, the salinity of groundwater reserves increases and creates big economic, agricultural, and social problems. Moreover, agricultural activities are the main source of nitrate, sulfate, and potassium ions and contribute to groundwater salinization and contamination with increasing chloride and nitrate concentrations. The objectives of this research are to determine the main source of groundwater salinization in coastal aquifer of Lebna area to not confuse between seawater intrusion and fertilizer effects and to determine the salinity effects on the ecosystem. To reach this goal, several geological tools and hydrogeological data are used in combination with geochemical and geophysical methods.

Keywords: coastal aquifer, seawater intrusion, agricultural contamination, multiple approaches, mineralization, vertical electrical soundings, stable isotopes, molar ratio, ecosystem

1. Introduction

Around the world, the coastal areas contribute most significantly to agriculture, tourist, and demographic activities. However, coastal aquifer areas are threatened by many factors such as population growth leading to increased water demand, changing climatic conditions (longer periods of drought), shoreline retreat, and tidal effect as well as overexploitation (more agricultural production) and anthropogenic activity (pollution by fertilizers, return flow of contaminated irrigation water and hydraulic barriers like dams). All these factors create seawater intrusion, which then contaminates groundwater through mineralization, depletion of groundwater storage, and salinization of soil and crops causing ecosystem changes. Saltwater intrusion is one of the major environmental problems in coastal areas due to the serious and irreversible effects on the quality of the water used for drinking and irrigation purposes.

Actually, there exist several processes and natural mechanisms that can procure the mineralization process in the coastal aquifer; the most important causes are the seawater intrusion [1, 2], the sea-level-rise effect [3, 4], the up-coming of salt groundwater from deep underground layers [5–7], the direct and indirect ion exchange [8, 9], the variable density flow effect [10, 11], and salt water irrigation return flow [12, 13].

Several authors from the world have used several approaches to study and manage the mineralization problem in coastal aquifer such as geophysical and geochemical techniques, conceptual and mathematical modeling, and analytical and numerical methods [1, 2, 14]. Generally, there is confusion between researchers in the determination of the principal origin of groundwater salinization in the coastal aquifer where the coastal area recognizes an intensive use of fertilizers.

In North Africa, coastal aquifers serve as major sources of freshwater supply in many countries, especially in arid and semi-arid zones.

Tunisia, located in eastern North Africa, undergoes the influence of two types of climate: the Mediterranean in the north and the Saharan in the south. Tunisia is known by a spatial and temporal variability of water resources and is menaced by relatively limited renewable water resources. In fact, Tunisia is one of the countries that are facing the problem of marine intrusion in the coastal areas where groundwater is intensively used for irrigation. Furthermore, farming consumes 80% of water resources, especially groundwater resources in the coastal areas. Numerous studies of the salinization processes in Tunisia are elaborated based on several approaches and show the phenomenon of marine invasion may extend over several kilometers inland, jeopardizing coastal groundwater supplies in these areas such as the coastal aquifer of Nabeul-Hammamet in northeastern Tunisia [15], the coastal Teboulba aquifer in the eastern Sahel of Tunisia [16], the shallow coastal aquifer of the Djeffara plain in southeastern Tunisia [17].

The study area is the coastal aquifer of Lebna plain, located in northeastern Cap-Bon, Tunisia. It is characterized by very intense agricultural activities (vegetables and spices), population growth, and a developing economy, all of which have greatly increased freshwater demand. Moreover, in recent years, the study area has seen significant changes in water and land use: some wells have been abandoned due to salty groundwater; new crops and animals have moved closer to the sea, and brackish soil and water have surrounded the river. In addition, groundwater depletion and high electrical conductivity values appeared near the coastal part of the aquifer, suggesting that seawater intrusion may occur [18, 19].

Hence, this work aims to determine the principal sources of groundwater mineralization and to identify the salinity effects to ecosystem in the Lebna area.

2. Study area

The study area, Lebna coastal plain, is part of the Lebna watershed located in northeastern Tunisia (**Figure 1**). It is near the Korba watershed, within the eastern coastal plain of Cap-Bon in northeastern Tunisia. It is surrounded by the Mediterranean Sea along the eastern border, the Djebel Sidi Abdurrahman anticline in the west, and the cities of Menzel Heur and Tafelloune in the northeast and southeast, respectively.

The study area is recognized by an important crop production than industrial production. Consequently, the irrigated areas are extended which increased the water irrigation demand. In addition, Lebna River is the main hydrology network in the Lebna plain, where in the upstream of Lebna River, a big dam was implemented in 1986 with a big water storage capacity to provide water demand. In fact, Lebna River receives water flux only during Lebna dam spill.

The area is also characterized by a semi-arid climate, an annual mean temperature of 22°C, and a highly variable annual average precipitation between 400 and 450 mm, thus resulting in the unsustainability of its water resources [20].

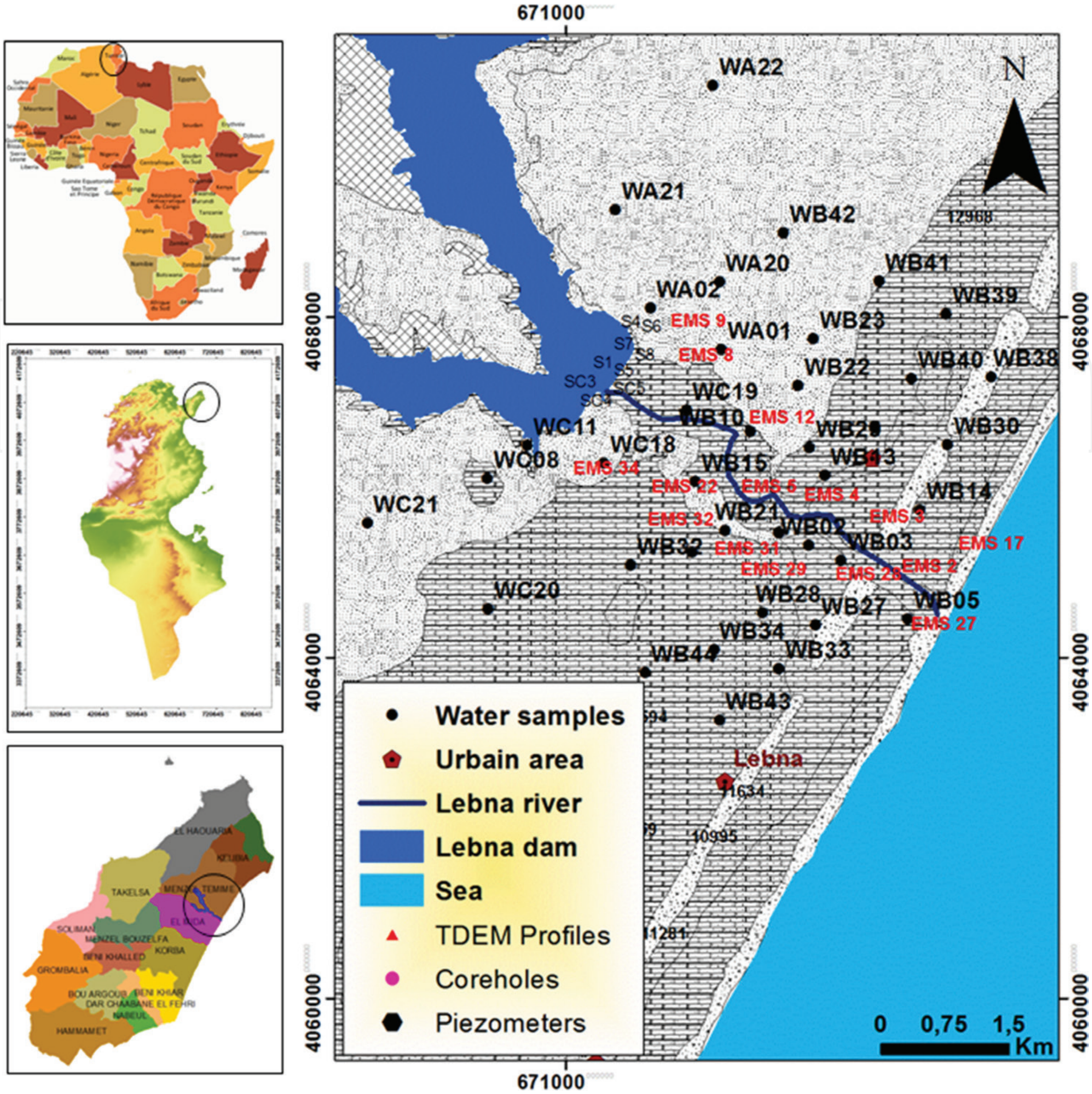

Figure 1.
Geographical location of study area.

The outcropping formations of the coastal area in the Lebna plain contain Mio-Plio-Quaternary sediments as shown in **Figure 2**. The first unit, the lower Miocene, has detrital deposits known as the Fortuna formation. The middle Miocene is composed of lenticular sandstones and marls with lignite levels called the Saouaf Formation. In the study area, the Upper Miocene is absent. The second unit, the transgressional marine Pliocene, which represents the main aquifer and has sandstone facies Astian or Porto Farina, whose outcrops are mainly composed of sandstone-sand-marl alternations topped by sandstone and sand [21]. Finally, the Quaternary deposits are generally formed by crusts, beaches, and consolidated dunes and are usually composed of two units: the lower unit of Quaternary marine facies corresponding to the Tyrrhenian outcrops along the east coast formed by the superposition of two cycles of marine sandstone limestone and sandstone dunes [22]. The upper unit is mainly composed of the Quaternary continental extending along the river which is formed of a crust of white limestone.

The coastal aquifer of Lebna area is typically unconfined aquifer consisting of Quaternary deposits whose thickness exceeds 100 meters and Pliocene sands underlying bedrock, which are composed of marl.

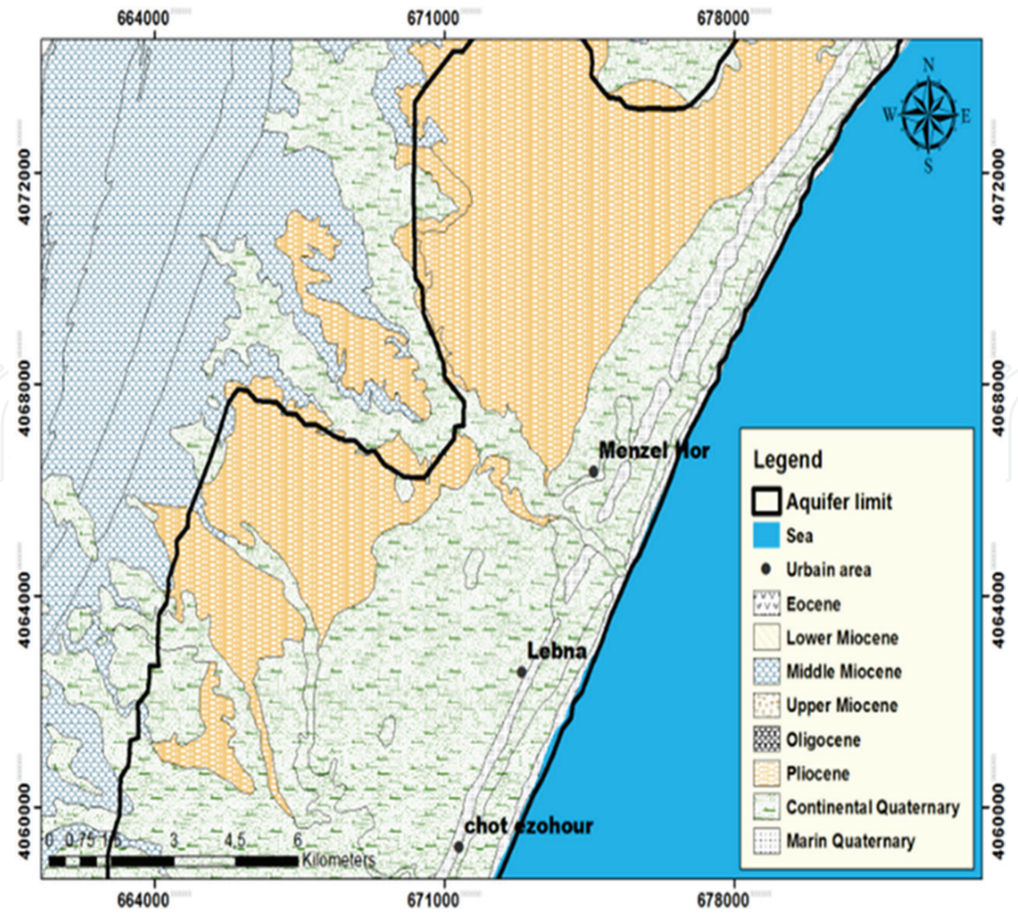

Figure 2.
Geological field of study area.

3. Materials and methods

A total of 38 water samples were collected from the Lebna aquifer as plotted in **Figure 1**. The wells were selected to be uniformly distributed throughout the study area. The groundwater samples are picked from active shallow wells where water depth ranges between 2 and 35 m (after stabilization of the physical parameters), in three similar and rinsed polyethylene bottles of 100 ml.

Then, several physical parameters are measured in situ for each groundwater sample. After that, the samples were filtered using 0.2 μm siring filters while

Parameters	Methods
pH, temperature (T °C), electrical conductivity (EC mS/cm), and oxidation-reduction potential (ORP mV)	Multiparameter probe
Nitrate (NO_3), chloride (Cl), and sulfate (SO_4)	Ion chromatograph analyzer (SHIMADZU Co. Ltd., HIC-SP/VP Super)
Bicarbonate (HCO_3)	The titration method with sulfuric acid (H_2SO_4)
Magnesium (Mg), sodium (Na), calcium (Ca), and potassium (K)	Inductively coupled plasma atomic emission spectrometer ICP-AES (Nippon Jarrel-Ash Co., Ltd. Model ICAP-757)
Stable isotope oxygen (^{18}O) and deuterium (^{2}H)	Mass spectrometry analyzer

Table 1.
Physicochemical analysis method of water samples.

chemical parameters are analyzed in laboratory as described in **Table 1**. Moreover, groundwater samples are kept at 4°C in an ice box with dry ice during the transmission to the Hydrology Laboratory of Tsukuba University, Japan.

During the survey, the edge (cm) and the depth of water-Table W-T (m) were determined for each well.

Quality was ensured by taking and analyzing duplicates and blank samples and by keeping ion balance errors within ±10%.

Meanwhile, geophysical characteristics were investigated in the study area using the vertical electrical sounding (VES) method by SYSCAL RII equipment based on 14 vertical electrical soundings carried out in the study area along and around Lebna River.

4. Results and discussion

4.1 Groundwater geochemistry characterization

A statistical analysis of eight ions and EC values are presented in **Table 2**. At first, we found that the maximum concentrations of the analyzed ions are decreasing in the order Cl > Na > Ca > SO_4 > Mg > NO3 > K > HCO_3. Consequently, the most dominant ion is chloride.

Normally, fresh groundwater is dominated by Ca^{2+}; but under specific conditions, an increase in Cl^- concentration was considered as an indicator of a salinity trend and as a possible seawater intrusion in coastal aquifer [13, 23].

Then, for all groundwater samples, the Cl concentrations exceed the WHO (World Health Organization) value for drinking water. Else, Na, Ca, SO4, Mg, NO_3, K, and HCO_3 ion concentrations in mg/l for most groundwater samples exceed the WHO value except for some well samples. As a result, the groundwater in Lebna area is not suitable for drinking and for irrigation purposes especially for piment and strawberry crops.

Meanwhile, the high NO_3, K, and SO_4 concentrations indicate the pollution of groundwater by these ions, which may be due to an increase of agricultural activities and return flow from water irrigation.

Further, the EC values of the shallow aquifer range between 1.7 and 7.01 mS/cm. They are heterogeneous and depend on their distance from the sea and the pumping rate and the depth of wells.

Parameters	Average	WHO	Max	Min
Cl^- (mg/l)	1063.4	250	1910.5	316.29
Na^+ (mg/l)	436	200	745.99	141.59
Ca^{2+} (mg/l)	332.35	52	550.57	109.07
SO_4^{2+}(mg/l)	304.63	250	544.6	86.65
Mg^{2+}(mg/l)	87.37	0.88	153.25	28.94
NO_3^- (mg/l)	260.07	50	805.30	33.2
K^+ (mg/l)	11.15	10	84.63	0.40
HCO_3(mg/l)	4.45	20.5	9.55	1.58
CE (mS/cm)	268	—	7.01	1.70

Table 2.
Statistical analysis of the hydrochemical parameters of 38 groundwater samples from Lebna aquifer.

In conclusion, we found that for most wells, the water salinity is unsuitable for drinking and irrigation and we identify several origins of salinity and pollution in studying aquifer.

In other parts, several correlation coefficients are established to measures how several parameters can be explained by relationships between themselves and to determine the main contributing elements to groundwater mineralization as shown in **Figures 3** and **4**.

Figure 3 shows that EC has an important correlation coefficient with Na, Cl, Ca, and Mg. Hence, these ions are the main contributors to groundwater salinization, while we note a medium correlation coefficient with SO4 and EC and no significant correlation between EC and NO_3, HCO_3 and K ions.

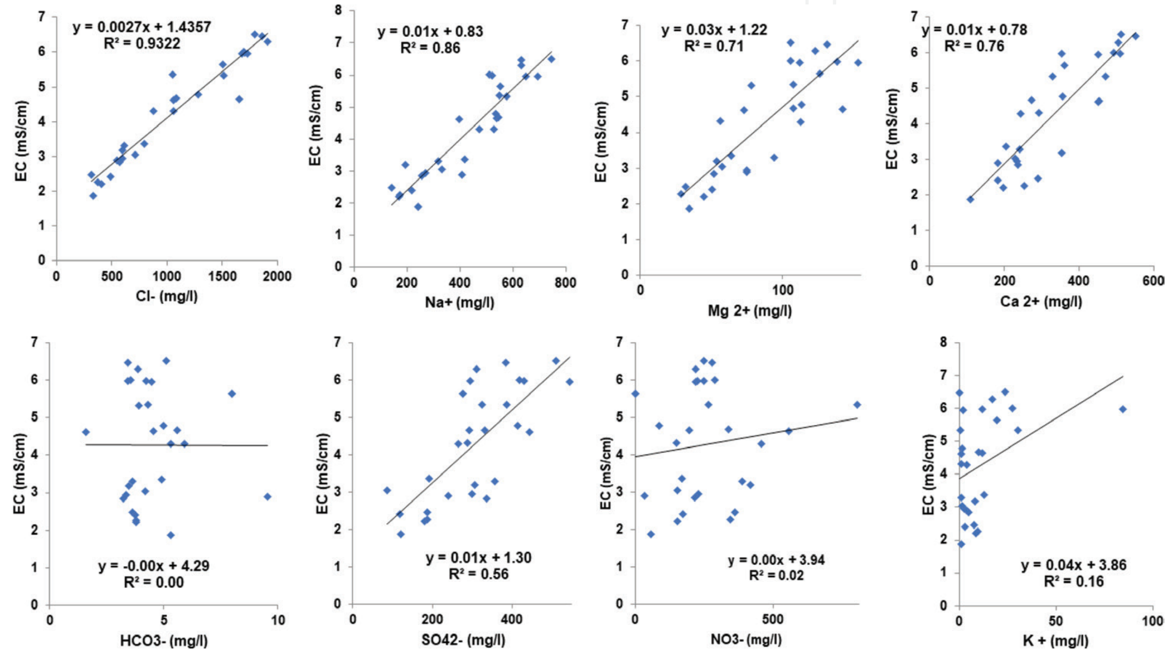

Figure 3.
Correlation between EC and eight chemical parameters.

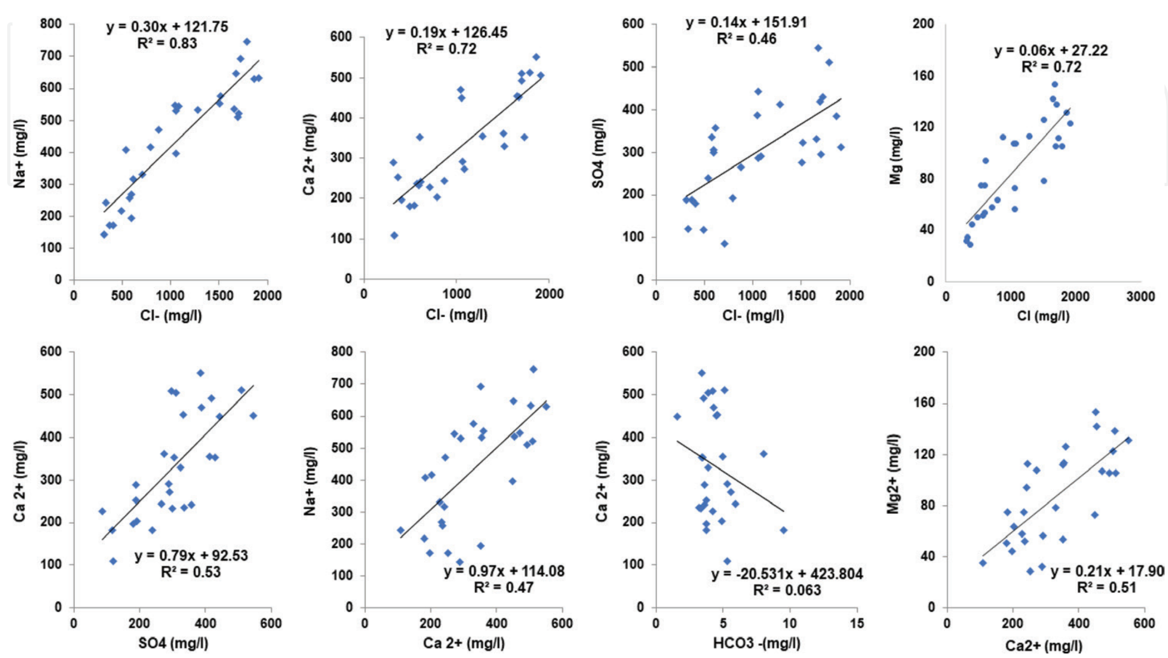

Figure 4.
Correlation between eight chemical parameters.

Further, **Figure 4** shows a high correlation coefficient between Na-Cl, Mg-Cl, and Ca-Cl, and a moderate correlation between SO_4-Ca and Mg-Ca. At this step, the result proof of the main origin of Cl, Na, Mg, and Ca is the seawater intrusion and water-rock dissolution by groundwater and/or cation exchange.

Whereas, the presence of K, SO_4, and NO_3 ions is probably related to the use of mineral fertilizers.

4.2 Groundwater mineralization processes

There exist several methods and tools to provide the groundwater mineralization processes but, in this work, we choose to use the Na/Cl molar ratio and the stable isotope analysis to determine the principal source of groundwater salinization in coastal aquifer of Lebna area.

4.2.1 Geochemistry analysis

The Na/Cl ratio and Cl concentration (mg/l) diagram is presented in **Figure 5**. From this figure, we note that no samples have Cl concentrations lower than 230 mg/l, which means that all water samples are salinized by several sources. Moreover, the water samples are divided in two groups: the first is characterized by Na-Cl water type as well as high Na/Cl ratios above the corresponding seawater dilution ratio R = 0.53 and a higher increase of Na concentrations than Ca. In the literature, these results reflect a flushing of seawater by fresh water (freshening process). This process is generated by a reverse cation exchange or/and from anthropogenic contamination sources like the irrigation by salt or brackish water [1, 24, 9, 25].

The reverse cation exchange indicates that Ca is taken up by the sediment exchanger and Na is released in the aquifer; X is the soil exchanger. The reverse cation exchange equation was explained by [9]:

$$\frac{1}{2}Ca^{2+} + NaX \rightarrow \frac{1}{2}CaX_2 + Na^{+} \quad (1)$$

The second group G2 of water samples was located below the seawater dilution line (R = 0.53) and characterized by Na/Cl ratios lower than 0.53, the existence of

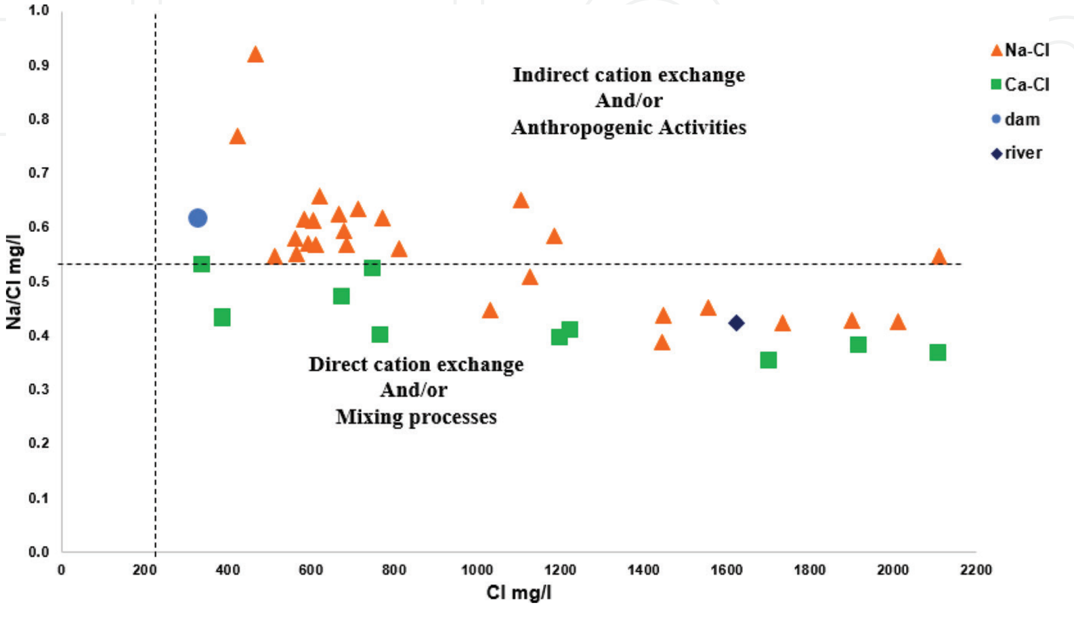

Figure 5.
Diagram plot of Na/Cl (mg/l) ratio and Cl (mg/l) concentrations for groundwater and surface water samples.

both Ca-Cl, Na-Cl water types, as well as an important increase of Cl concentrations and an increase of Ca and Mg ions. All these indicators proved that a cation exchange took place while seawater intrusion flushed fresh groundwater. In this case, sediment in contact with seawater adsorbed Na and released Ca in the aquifer [9, 26, 1]. These samples of G2 indicated that a large proportion of groundwater was affected by diluted seawater. The direct cation exchange reaction is demonstrated in the following equation [9]:

$$Na^{+} + \frac{1}{2}Ca - X_2 \rightarrow Na - X + \frac{1}{2}Ca^{2+} \quad (2)$$

Furthermore, some groundwater samples had an Na/Cl ratio close to the seawater diluted line, which indicated a recent mixing of groundwater with seawater [13].

4.2.2 Stable isotopes

Stable isotopes of oxygen $\delta^{18}O$ and deuterium $\delta^{2}H$ are commonly used in the local groundwater of Lebna Plain studies to identify the sources of recharge and to describe the mixing process between saline and freshwater.

Fresh groundwater is generally depleted in both ^{18}O and ^{2}H (deuterium) relative to seawater [1].

The delta diagram of oxygen 18 and hydrogen isotopes ($\delta^{18}O$ and $\delta^{2}H$) is plotted in **Figure 6**. The regional meteoric water line (RMWL) was calculated from the weighed annual means of precipitation in Tunis-Carthage station, the nearest global network for isotopes in precipitation (GNIP) station. RMWL follows the linear regression [27]:

$$\delta^{2}H = 8 * \delta^{18}O + 12.4 \quad (3)$$

The global meteoric water line (GMWL) equation is described by [28] as:

$$\delta^{2}H = 8 * \delta^{18}O + 10 \quad (4)$$

From **Figure 6**, we conclude that stable isotope composition of the analyzed groundwater samples from the study area revealed a large variability in the

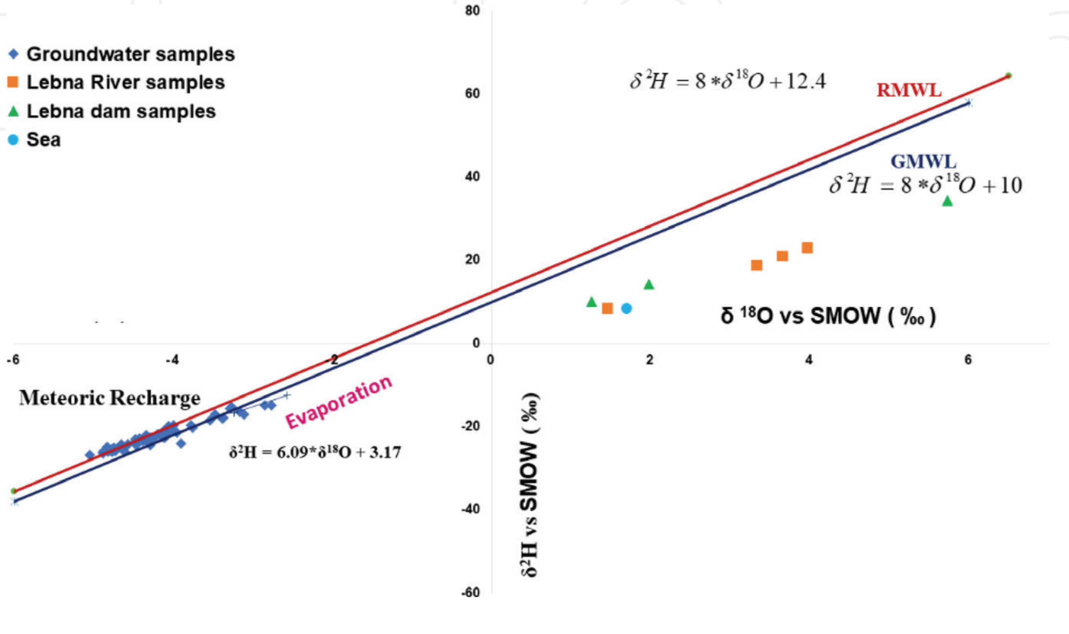

Figure 6.
Delta diagram (δ^2H vs. $\delta^{18}O$).

Plio-Quaternary aquifer, suggesting significant differences in the origin as well as in the groundwater evolution.

Further, the $\delta^{18}O$ and $\delta^{2}H$ contents of groundwater of the Plio-quaternary aquifer in Lebna plain vary from −5.1 to −2.6% and from −26.46 to −12.51%, respectively. This variation is controlled by local climatic parameters, including the origin of the vapor mass, the re-evaporation during rainfall and the seasonal and monthly precipitation [29–31].

In addition, the most important number of groundwater samples was falling between the regional meteoric water line (RMWL) of Tunis Carthage station and the global meteoric water line (GMWL) and were characterized by a depletion in oxygen 18 and deuterium contents. This may confirm the hypothesis of an important contribution of the meteoric water to the recharge from recent rains that would be rapidly infiltrated into the saturated zone in the study aquifer. This rapid infiltration is consistent with the relatively high hydraulic conductivity that characterizes the natural recharge zones of the aquifer [31, 32].

Moreover, the Lebna dam sea sample and the Lebna river sample were isotopically enriched in oxygen 18 and deuterium. The stable isotope contents of the Mediterranean Sea water were taken from the result published by [33], which was close to the GMWL.

Indeed, some groundwater samples were located under GMWL according to a trendline with an equation.

$$\delta^{2}H = 6.09 * \delta^{18}O + 3.17 \tag{5}$$

and $R^2 = 0.95$. This low slope (inferior to 8) in the evaporation equation might be an indicator of evaporation processes of the infiltrated water [34]. On the other part, some groundwater samples closer to the Standard Mean Ocean Water SMOW pole ($\delta^{18}O$ SMOW = 0% and $\delta^{2}H$ SMOW = 0%) indicated a probable seawater intrusion. However, other groundwater samples were close to the first group, in which differentiating between the mixture with salt water and that with the evaporated water was difficult.

The plot of $\delta^{18}O$ versus Cl^- can be used to identify the seawater mixing with the groundwater [35]. Most of the wells that have a large isotopic composition have high levels of chloride ion concentrations [30]. Indeed, the ^{18}O isotope provides a direct means to identify and study the marine intrusion dynamics. Its relation to changes in salinity is unambiguous.

In fact, the plot of $\delta^{18}O$ versus Cl^- of groundwater in the Lebna plain is presented in **Figure 7**. From this figure, we distinguish four water groups in the study area:

- Samples in the left bottom with chloride concentration less than 1000 mg/l and $\delta^{18}O$ less than −4‰ were interpreted as groundwater recharged from direct meteoric water.
- Samples in the left top were characterized by an increasing level of Cl concentration in the groundwater with no significant change in $\delta^{18}O$ content (still less than −4‰). It could be attributed to the leaching of surface salt and the irrigation water return flow.
- Samples in the right bottom with chloride concentration less than 1000 mg/l and enriched in $\delta^{18}O$ more than −4‰ resulted from evaporation processes.
- Samples at the right top of the diagram with enriched contents in $\delta^{18}O$ values (more than −4‰) and high chloride content (more than 1000 mg/l) might be due to the infiltration of salt water into the wells located along the Lebna River and in the wells close to the coastal part of the seawater intrusion.

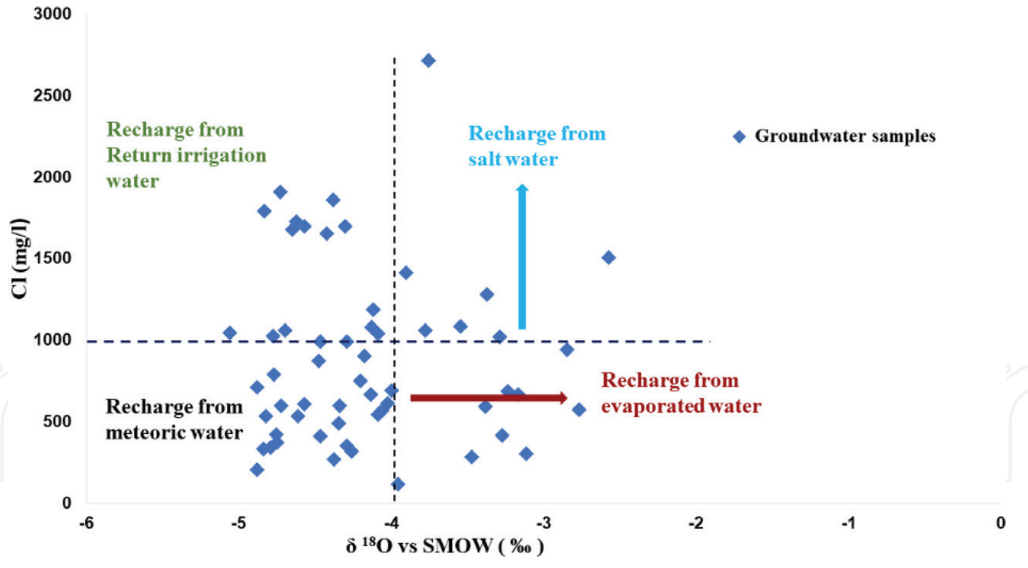

Figure 7.
The plot of $\delta^{18}O$ versus Cl^- of the groundwater in the Lebna plain.

Consequently, the groundwater in Lebna plain is recharged by seawater intrusion and surface water (direct meteoric water, evaporated water and the irrigation water return flow), which brings fertilizers during infiltration.

The seawater contribution to groundwater mineralization is determined by the end-member mixing analysis EMMA method and varies between 1 and 10% [36], while the contribution of fertilizers to groundwater mineralization is not yet determined.

4.3 The extent of seawater intrusion

The geophysical method is used in this work to determine the freshwater-saltwater interface and to prove the extent of seawater intrusion from the Mediterranean into the aquifer. This method is used by several authors from the world [37–39].

In this chapter, 14 vertical electrical soundings (VES) as shown in **Figure 8** were carried out along Lebna River and perpendicular to coastal line. The field measurements were carried out using direct current resistivity meter called SYSCAL R II,

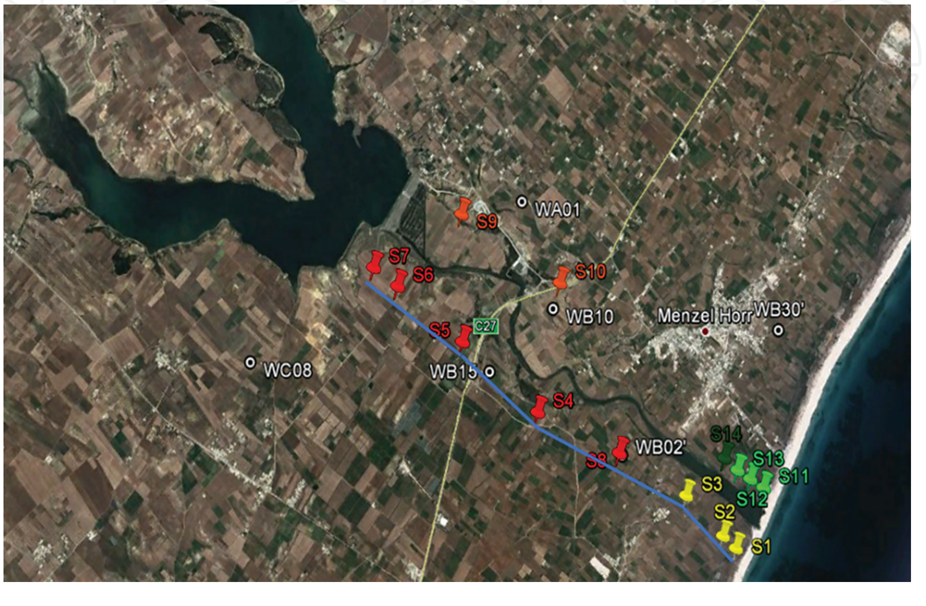

Figure 8.
Geographical location of 14 vertical electrical soundings (VES) in the Lebna area.

using Schlumberger array with AB/2 ranging from 0.5 to 400 m in successive steps. Moreover, the lithology of the existing boreholes in the study area was collected and the water table level for closer wells to electrical soundings was measured to calibrate the geophysical results.

4.3.1 Principle of VES

The principle of the vertical electrical sounding method using SYSCAL RII equipment is schematized in **Figure 9**. We conclude that the SYSCAL resistivity-meter is placed in the central part of the sounding. Then, the metallic electrodes have to be plugged into the ground as deep as possible to decrease the ground resistance, for both the transmitting electrodes A and B and the receiving electrodes M and N [40].

A current I_{AB} is transmitted between two grounded electrodes A and B, while a voltage V_{MN} is measured between the other ones: M and N electrodes. Finally, the apparent resistivity R_{AB} is computed automatically by the SYSCAL RII resistivity-meter using the following formula and we move the electrodes to the next station and start a new reading:

$$R_{AB} = K \times V_{MN}/I_{AB} \tag{6}$$

$$\text{Where } K = 2^{*}\,Pi/(1/AM - 1/AN - 1/BM + 1/BN) \tag{7}$$

The apparent resistivity values have to be plotted on a logarithmic paper sheet, to check how the new reading compares with respect to the previous ones, before moving the A, B electrodes to the next measuring point. This step is done during the survey. Then, the data are stored in the internal memory of the equipment after each reading.

The sounding starts by small values of the AB line. For some values of the AB/2, two readings for different values of MN/2 have to be taken to check the lateral variations of the resistivity of the surface. Ideally, both resistivity values are identical.

In other part, the depth of investigation varies from about 1/3 to 1/10 of the length of the AB line. The variation of the depth of investigation is obtained by increasing the length of the current line AB: small lines: shallow and long lines: deep.

The last step is the data transferred to a PC to process them, and run an inversion model using PROSYS and Winsev software to interpolate the results and get layer depths with resistivity. The resistivity values are correlated with the geological layers.

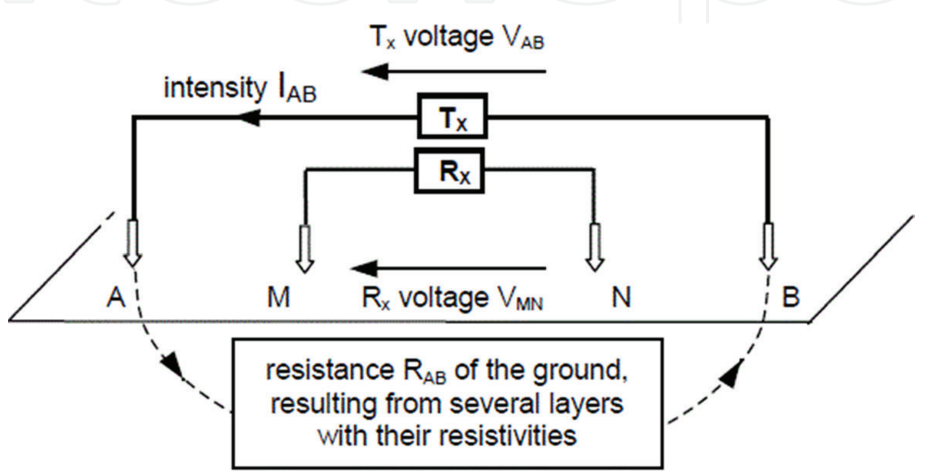

Figure 9.
The vertical electrical sounding principle for Schlumberger disposal.

4.3.2 The 2D pseudo section

The result of the inverted resistivity values from the vertical electrical soundings method is two 2D longitudinal pseudo-section of resistivity model along the Lebna River. We focus our attention on one of these profiles as shown in **Figure 10**. Further, the interpretation of resistivity profile is according to resistivity-water-rock converted table, as well as water table level and EC measurement in the nearer wells and borehole lithostratigraphic and geological fields.

The 2 D longitudinal pseudo section is based on the interpolated results from seven VES (VES1, VES2, VES 3, VES4, VES5, VES 6, and VES7) and is oriented to SE-NW from the sea to Lebna dam, perpendicular to the coastal line and parallel to Lebna River. **Figure 10** shows a heterogeneity of resistivity values along the pseudo-section, which varies from 1 to 95 Ω.m.

- We conclude that for all the VES from VES 1 to VES 7, the resistivity starts with a resistant layer (R > 25 Ω.m), which corresponds to the unsaturated zone. Moreover, the variability of values depends on geological formation. The highest resistivity values in the southeastern part correspond to the wet Tyrrhenian limestone (from marine Quaternary deposits), and in the northwestern part, they correspond to the highlighted crust and encrusting (from continental Quaternary) as well as to the wet sand (from Pliocene deposits).

- Whereas, more in depth, the resistivity value decreases (R < 15 Ω.m), and we found a very conductive layer which corresponds to the aquifer.

- The lowest resistivity values varying between 10 and 1 Ω.m are located in the VES nearer to the coast (500 m distance to the coastal line), especially for VES1, VES2, VES3, and VES 4. Else, this result is combined with high electrical conductivity values measured in the nearer wells to these electrical soundings which prove the intrusion of seawater to the aquifer.

4.4 Mineralization and nitrate pollution effect on ecosystem

The surface water level of the Lebna River decreased as a result of limited rainwater. Moreover, water quality is deteriorated due to multiple factors: water losses

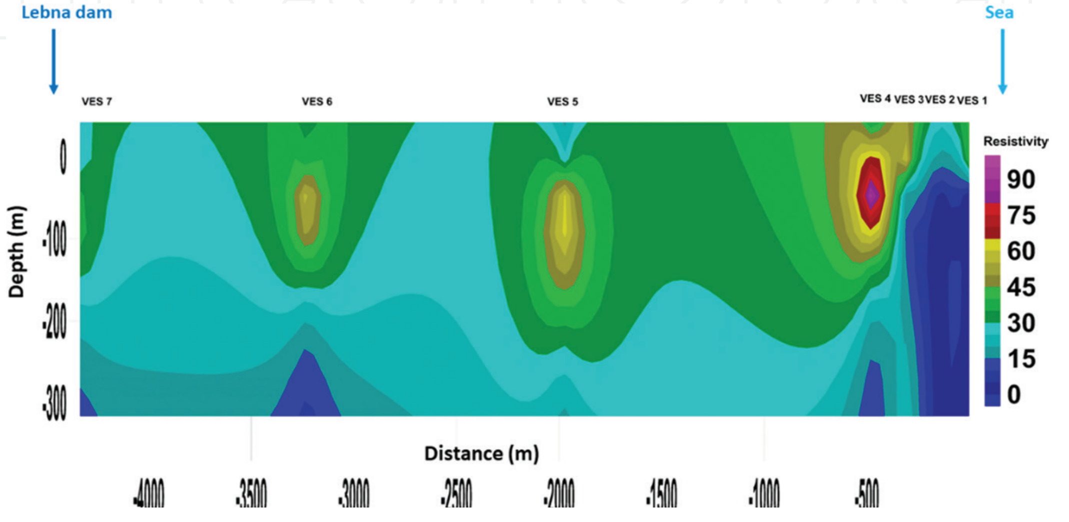

Figure 10.
Longitudinal pseudo-section along Lebna River of interpolated resistivity values from VES results.

Figure 11.
The pollution effect by the industrial discharges in the middle part of the Lebna River in winter season.

Figure 12.
The pollution effect by the industrial discharges in the middle part of the Lebna River in summer season.

from the Lebna dam, upstream of the Lebna River, and industrial discharge from two factories located in the middle part of the Lebna River, as well as tidal effects.

Figures 11 and **12** show the pollution effects on Lebna River by the industrial discharge in winter and summer seasons, respectively.

The effect of seawater intrusion to the ecosystem appeared in the downstream part of Lebna River, where the downstream measurements showed an electrical conductivity value of 45.3 mS/cm as opposed to a value of 54.1 mS/cm in the sea. Furthermore, the EC value measured in the estuarial zone in 2011 was higher than the electrical conductivity value of the sea [18]. Moreover, some halophyte crops and crabs were also depicted in the estuarial zone. Else, crustacean species from marine origins such as "Gammarus aequicaudata," "Palaemonetes varians," and "*Carcinus mediterraneus*" were observed during survey [41]. All these indicators show the salinization effect on ecosystem.

However, the fertilizer pollution effect to the ecosystem appeared also in the estuarial zone on Lebna River. Furthermore, the runoff brings nitrate, phosphate, chloride, and some pesticides which create a change in water, in soil quality, and in ecosystem behavior [42]. Moreover, some new animal species have appeared in the estuarial zone, such as "oligochaetes," "Naïs," and "Paranais" indicating the existence of nitrate pollution which comes from fertilizers.

The observations and results described above confirm the transformation of the estuarial zone to a lagoon.

5. Conclusion

The aquifer chapter is very important because it can include several kinds of aquifers from the world such as ALLUVIAL AQUIFER, karst AQUIFER, coastal aquifer, etc. Our study is a part of Aquifer chapter, which describes some problems that can be found and threatened the coastal aquifers in the world.

The study area is a local coastal aquifer of Cap-Bon in the north-east of Tunisia. The area has witnessed an over-exploitation by the irrigation demand which created a quantitative and qualitative deterioration of the groundwater resources caused by the mixing of salt and fresh waters. Furthermore, high chloride content as well as high electrical conductivity values and low resistivity values have appeared near the coastal part of the aquifer, suggesting that a seawater intrusion may occur.

Unfortunately, we found that the groundwater in Lebna plain was unsuitable for drinking and agricultural purposes.

In this study, the use of statistical analysis and correlation between nine chemical parameters and Na/Cl molar ratio proved that a seawater intrusion as well as a reverse cation exchange between Ca, Mg, and Na and water-rock dissolution had influenced the groundwater salinity. Moreover, we showed that the agricultural activities contributed to the groundwater mineralization in the Lebna area and were the main source of NO_3, SO_4, and K ion concentrations.

In addition, the isotopic study showed that the Plio-Quaternary aquifer was recharged directly by the infiltration of the meteoric water from the Tyrrhenian consolidated dunes the sand deposits, the return of the water irrigation flow, the evaporated surface water, and the seawater intrusion from the coast.

Moreover, the existence of crustacean species of marine origins in the downstream according to the high EC value of the Lebna River confirmed the transformation of the estuarial zone to a lagoon.

Moreover, with the geophysical vertical electrical sounding (VES) method, we could note that the salinization in the coastal aquifer of the Lebna plain was due to the seawater intrusion.

Acknowledgements

We would like to thank the Regional Commissariat for Agricultural development from Nabeul (CRDA) for providing us with borehole information from the area of investigation. We would like to thank Dr. Maki Tsujimura, and Dr. Atsushi Kawachi from Tsukuba University-Japan and Mr. Fathi Lachaal, assistant professor at the Center for Research and Water Technologies (CERTE) for their collaboration. Special thanks for Miss. Emna Trabelsi, INAT member and laboratory technician LRSTE for all her efforts.

Notes and thanks

This paper is a part of my thesis research and a part of my research results of 5 years. I would thank my supervisors Professor Najla Hariga Tlatli and Professor Jamila Tarhouni for their help, scientific advices, and monitoring during the years of my thesis.

Abbreviations

mg/l	milligrams per liter
Ω.m	ohm meter
R	apparent resistivity
V	voltage

DOI: http://dx.doi.org/10.5772/intechopen.84712

I	current
SMOW	standard mean ocean water
R2	correlation coefficient
GMWL	the global meteoric water line
GNIP	global network for isotopes in precipitation
RMWL	the regional meteoric water line
R	seawater dilution ratio
X	the soil exchanger
WHO	World Health Organization
2H	deuterium
18O	stable isotope oxygen
ORP	oxidation-reduction potential
mV	milli volt
EC	electrical conductivity
mS/cm	milli siemens per centimeter
T°	temperature
VES	vertical electrical sounding
W-T	water-table
HCO_3	bicarbonate
Cl	chloride
Ca	calcium
Na	sodium
Mg	magnesium
K	potassium
SO_4	sulfate
NO_3	nitrate

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