

ASSESSMENT AND EVALUATION OF THE GROUNDWATER RESOURCES OF THE MULTILAYER AQUIFER SYSTEM OF SFAX (SOUTH-EASTERN OF TUNISIA) USING ENVIRONMENTAL ISOTOPES

R. TRABELSI, K. Zouari, R. AYADI

Laboratory of Radio-Analysis and Environment
National Engineering School of Sfax,
Route de Soukra, BP 1173, 3038 Sfax, Tunisia

Abstract

In the coastal area, the significant and increasing demand of water has caused an intensive exploitation of groundwater resource. This situation is intensified in the arid and semi arid regions where surface water is scarce or even absent as the region of Sfax, southern part of Tunisia. The Sfax region presents a multi-layer aquifer system composed of a deep confined aquifer, a middle aquifer and shallow aquifers that are delimited by their respective catchment areas. The objective of this Coordinated Research Project (CRP) is to develop and review approaches and methodologies, mostly based on the combined use of conventional hydrogeological techniques and environmental isotopes, to assess the response of groundwater systems to intensive exploitation and groundwater availability. The combined use of these tracers with the geostatistical and modeling tools was very useful in the case of Sfax aquifer system. In fact, the intensive exploitation of this aquifer system has led to lowering of water tables, changing flow patterns in the shallow aquifer and a progressive deterioration of water quality. Hydrochemical and isotopes analyses have been used to identify the geochemical processes that affect the shallow and deep aquifer of Sfax and to delineate groundwater quality evolution under intensive exploitation.

1. INTRODUCTION

Groundwater sustainability constitutes a very sensitive issue in arid and semi arid coastal areas that are densely populated since the lack of permanent surface water due to dry climatic conditions. Both natural processes and human activities may have a significant impact on groundwater quality and further limit its use as water supply. In Tunisia, particularly in the southern part, groundwater is the main water resource and is used by agriculture (80 per cent), industry (10 per cent) and domestically (5 to 10 per cent). Intensive use of groundwater has been a common feature in many area of this part of the country where fossil groundwater (groundwater recharged under different climatic conditions) still constitutes the main source of water supply.

Sfax region is located in Southeastern of Tunisia, it is characterized by a semi-arid to arid climate. Precipitation is rare and irregular and the dry season is pronounced which aggravates the situation of intensive exploitation of groundwater resources. The Sfax basin

belongs to the eastern Tunisian plain, it is especially made up of tertiary and quaternary sediments. The region covers an area of approximately 15,000 km². Topographically, the plain of Sfax is characterized by altitudes rarely exceed 200 m. The hydrogeologic studies have identified three main aquifers: The shallow aquifer, the middle and the deep aquifers.

Since more than three decades, several multidisciplinary studies (hydrogeologic, hydrochimic and isotopic) have been carried out on the Sfax aquifer system [1], [2], [3], [4], [5]. These investigations using chemical and isotopic tracers of the aquifer system of Sfax allowed to identify and to characterize the shallow and the deep aquifer. It has been established that the shallow aquifers show a progressive deterioration of water quality cause by particularly nitrogen pollution and seawater intrusion. Indeed, the combination of chemical elements and oxygen-18 has highlighted that marine contamination, contributes significantly to the mineralization of the shallow aquifer (up to a maximum of 15%) [4].

The study of groundwater residence time in the deep aquifer of Sfax was performed by using carbon-14 on samples taken from about forty boreholes. The low activity values that were measured correspond to high «ages». This confirms that most of this groundwater reserve formed before Holocene and the recent recharge of the Sfax aquifer system is very limited. Until recently, the lack of any synthesis, interpretation and archiving of data concerning these aquifers led to the lack of an accurate description of them. This, in turn, led to an under evaluation of Sfax groundwater resources and hence to difficulties in establishing a suitable management plan.

2. STUDY AREA AND METHODS

The study area is part of the eastern Tunisia. It is limited by the "North-South" axis mountain chain in the west region, by Mahdia to the north and to the south region Skhira (Fig. 1). The region is located between the North parallel 34 ° 12 'and 35 ° 12' and 42 'and the meridian 9 ° 10 ° 54' and forms a coastal plain that is gradually declining to the east towards the Mediterranean Sea. Rainfall in Sfax region is characterized by high variability and irregularity in time and space. The average annual rainfall is around 220 mm. The study area is characterized by a thermal Mediterranean climate with an annual air temperature of about 20 ° C. Evapotranspiration with an annual average value of 1829.4 mm/ year in 2011[6] .

The Sfax basin belongs to the coastal eastern Tunisian plain, the geology is dominated by outcrops of the Mio–Plio–Quaternary deposits, more or less affected by the major tectonic phases [7]. Based on the previous hydrogeological studies [3], [8] ,[9], [10], [11], the aquifer system of Sfax is defined as a multilayered aquifer system, composed of three main aquifers: The shallow aquifer, the middle and the deep aquifers.

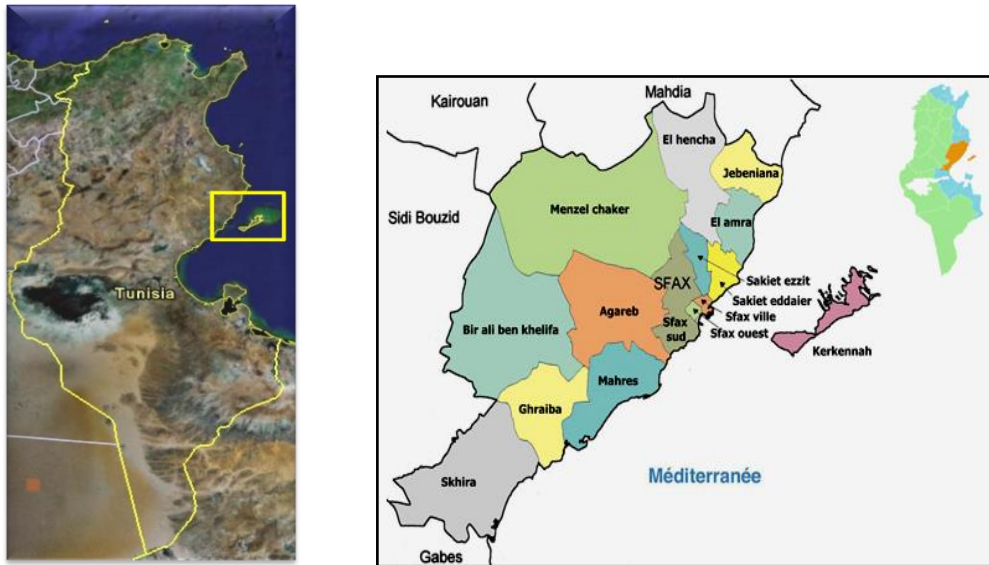


FIG. 1. Location map of Sfax region

-The shallow aquifer is containing in sandy and shally levels of the MPQ deposits. It constitutes a lenticular aquifer with two levels with an average thickness of about 30 m. It represents very significant reserves, about 40 Mm³ in 2012. This unconfined aquifer is easily accessible but very vulnerable to pollution.

-The middle aquifer, recently identified [5], is logged in the sandy clay formations and sandy clay-Mio-Plio-Quaternary. It is characterized by a heterogeneous lithology consisting mainly on clayey sands with interbedded sands and coarse sands. This middle aquifer is made by several levels of abstraction, separated by semi-permeable deposits, allowing a possible hydraulic communication. The groundwater resources of this aquifer are estimated at 12 Mm³ / year.

-The deep aquifer logged in the upper Miocene, is primarily made up of sands and clays with depths going from 220 to 700 m and extends on a surface of about 15000 km². The deep groundwater flows from the North-South axis reliefs in the NW towards the South east (area of Skhira). The exploitation of the deep aquifer is done by drilling, intended for various uses: agriculture (31%), industry (55%) and domestic (14%).

Stable isotopes ($\delta^2\text{H}$ and $\delta^{18}\text{O}$) and radio-isotopes (^{14}C , ^3H) are used in conjunction with chemical analysis and hydrogeologic data to assess the sustainability of intensively exploited aquifer systems of Sfax region. Several sampling campaigns were conducted from December 2012 to March 2015. About 300 water samples were collected from different aquifer levels of Sfax region. Physical parameters of sampled groundwater (temperature, pH, electrical conductivity) were measured in situ. Major elements (Cl^- , SO_4^{2-} , NO_3^- , HCO_3^- , Ca^{2+} , Mg^{2+} , Na^+ , K^+) were analyzed by ion liquid chromatography with an analytical precision of 5%. The ionic balance for all samples is within $\pm 5\%$.

Stable isotope ($^{18}\text{O}/^{16}\text{O}$) contents of the groundwater samples were measured by laser spectrometry (LGR DLT100). The isotope contents are reported in the usual δ notation

relative to the Vienna standard mean ocean water (V-SMOW) standard [12]. Typical analytical uncertainty of the reported values is about $\pm 0.2\%$ for $\delta^{18}\text{O}$ and $\pm 1.5\%$ for $\delta^2\text{H}$ (one-sigma level).

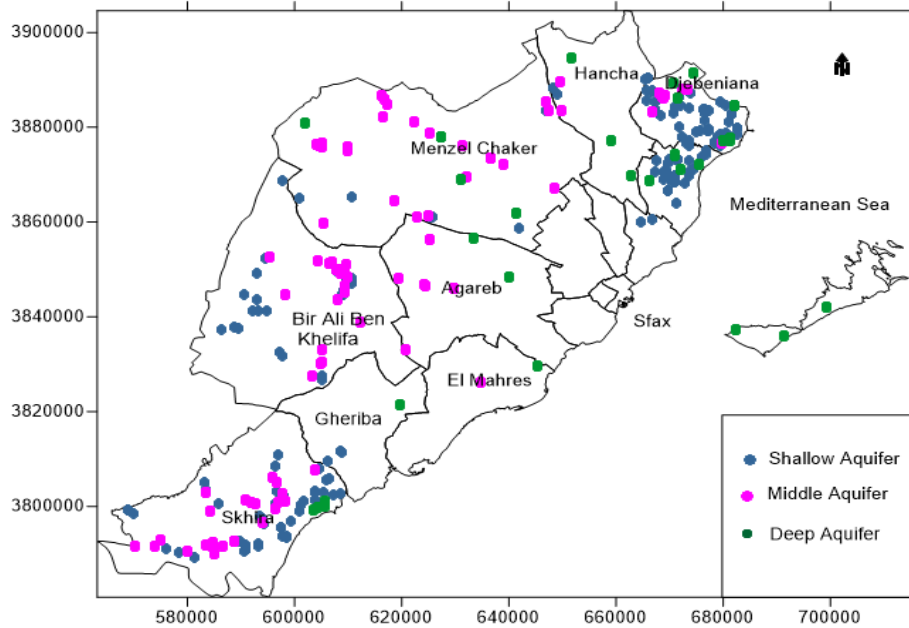


FIG.2: Locations map of sampling points

Radiocarbon analyses were measured through benzene synthesis and liquid scintillation spectrometry [13]. The measured ^{14}C concentrations are expressed as percent of modern carbon (pmC) with uncertainty for each sample as determined from the counting statistics. Chemical and isotopic analysis are undertaken at the Laboratory of Radio-Analysis and Environment of the National School of Engineers of Sfax(Tunisia).

3. RESULTS AND DISCUSSION

3.1 Hydraulic Head Evolution and Exploitation

At the current state, the shallow groundwater is exploited by 9976 equipped shallow wells (6769 Electrical Group authorized in 1253 and 1954 Group Electrical home Diezel Group). The total rate of exploitation was estimated to $53.6 \text{ Mm}^3/\text{year}$. Unfortunately, this intensive exploitation of the Sfax shallow aquifer is significantly higher than available natural resource rate (134%), causing marked lowering of water tables (Fig.3). This phenomenon is observed particularly in the northern part of the basin (Djebeniana region) where the withdrawals in 2014 was estimated at $12.35 \text{ Mm}^3/\text{year}$ which exceeds the exploitable resources valued at $4.58 \text{ Mm}^3/\text{year}$. The calculated drawdown observed from 1993 to 2012 varies between 4 to 8 m. In 2012, the total volume of exploitation from the middle aquifer is only $2.3 \text{ Mm}^3/\text{year}$ corresponding to 20% of available groundwater resources. The exploitation of the deep aquifer is intended for various uses: agriculture (31%), industry (55%) and domestic (14%). The exploited volumes increase from 18 Mm^3 in 1988 to approximately 25 Mm^3 in 2012

which corresponds to 98% of the available resources. The increasing exploitation caused an annual hydraulic head decrease varying between 0.2 and 0.4m (Fig.4).

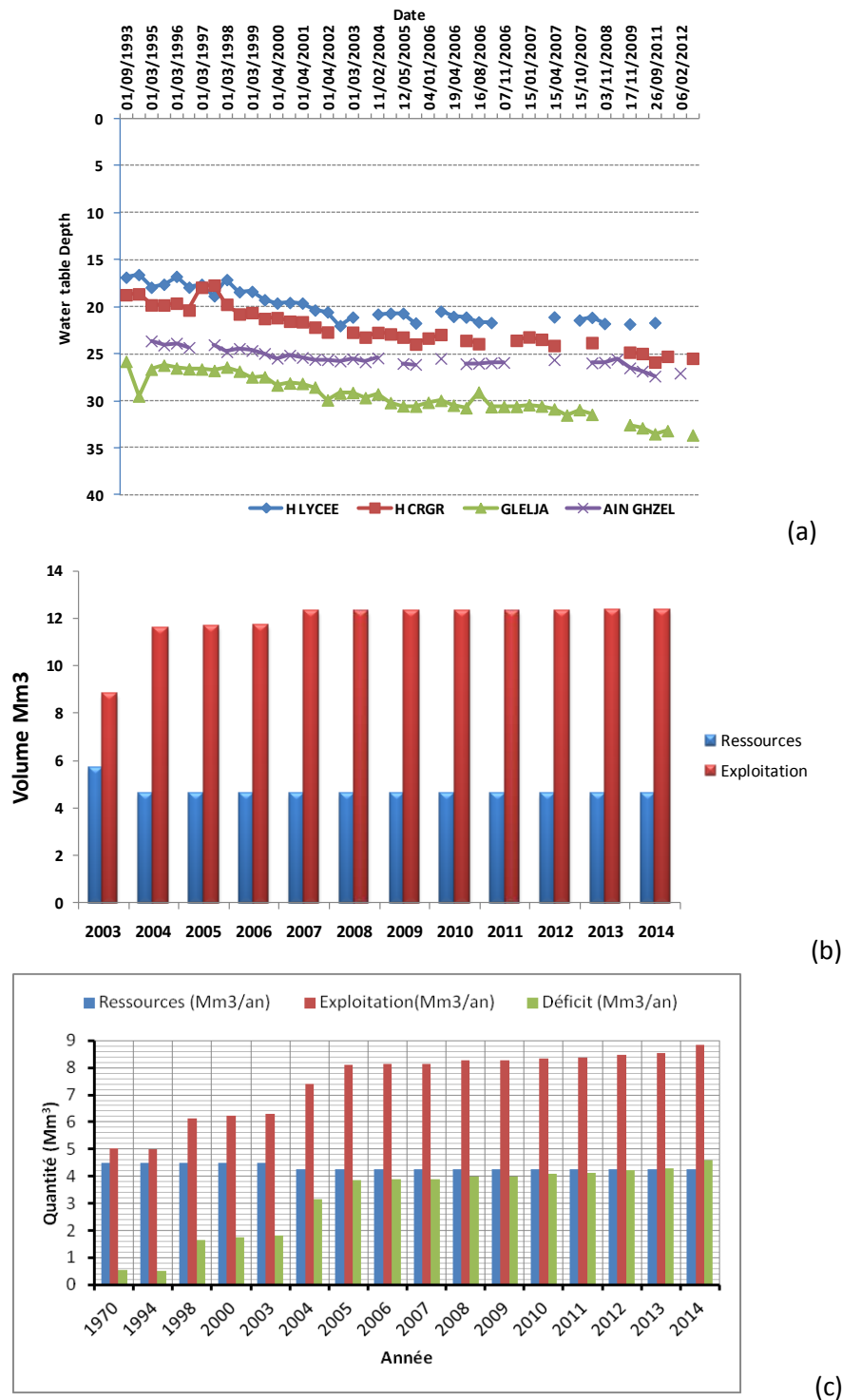


FIG.3: Temporal evolution of the hydraulic head and the exploitation in shallow aquifer of Djebeniana (a,b) and Skhira (c)

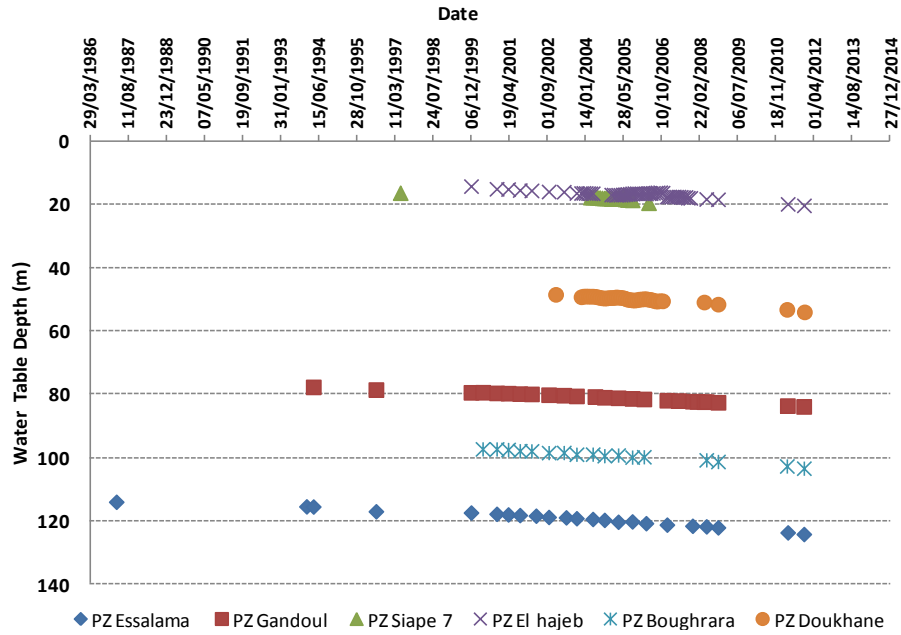


FIG.4: Hydraulic head evolution of Sfax Deep Aquifer

3.2 .Chemical analysis:

3.2.1. Shallow aquifer

Groundwater salinity, which is highlighted by the TDS values, varies largely from 0.5 to 11 g/l. About 71% of the analyzed samples of the shallow aquifer showed TDS higher than 3g/l (Fig.5), and almost of shallow samples were brackish or saline water according to the classification of Freeze and Cherry (1979) with total dissolved solids (TDS) value exceeding 2g/l. The most saline groundwater are located south-western part of the basin in Skhira basin and in the northern part of Sfax (Djebeniana and El Amra aquifer). However, the low values are recorded in some points located mainly in the western part of Sfax basin, in the recharge area. The chemical composition of these points is characterized by HCO₃-Na-Ca water type (Fig.6). The most saline TDS values (TDS>5 g/l) characterize the shallow groundwater of Djebeniana aquifer, in particular in the coastal area where the salinity exceeds 10g/l. In Piper diagram, brackish to saline groundwater show a clear gradation from sulphate mixed type to that of sodium chloride. The alignment is very clear, particularly in the anion triangle. Compared to the chemical composition analyzed in 2003, enrichment in chloride contents can be seen in the most mineralized groundwater (Fig.6). The Cl⁻ content of the groundwater increases to the east, in relation to the proximity to the coastal area.

In order to identify the origin of salinization, bivariate diagrams of major ionic species in solution (Fig.7). Chloride and sodium are closely positive correlated ($r^2 = 0.99$) (Fig. 6). On the bivariate diagram Na⁺ versus Cl⁻, most of the coastal sampled water is placed along the theoretical seawater dilution line characterized by a slope less than 1 indicating marine influence of the salt.

The analyzed groundwater samples have much higher SO_4 and Ca contents than Seawater suggesting that the inputs of sulphate other than seawater must exist. The most likely source of this sulphate is from dissolution of the small amounts of gypsum scattered through the aquifer.

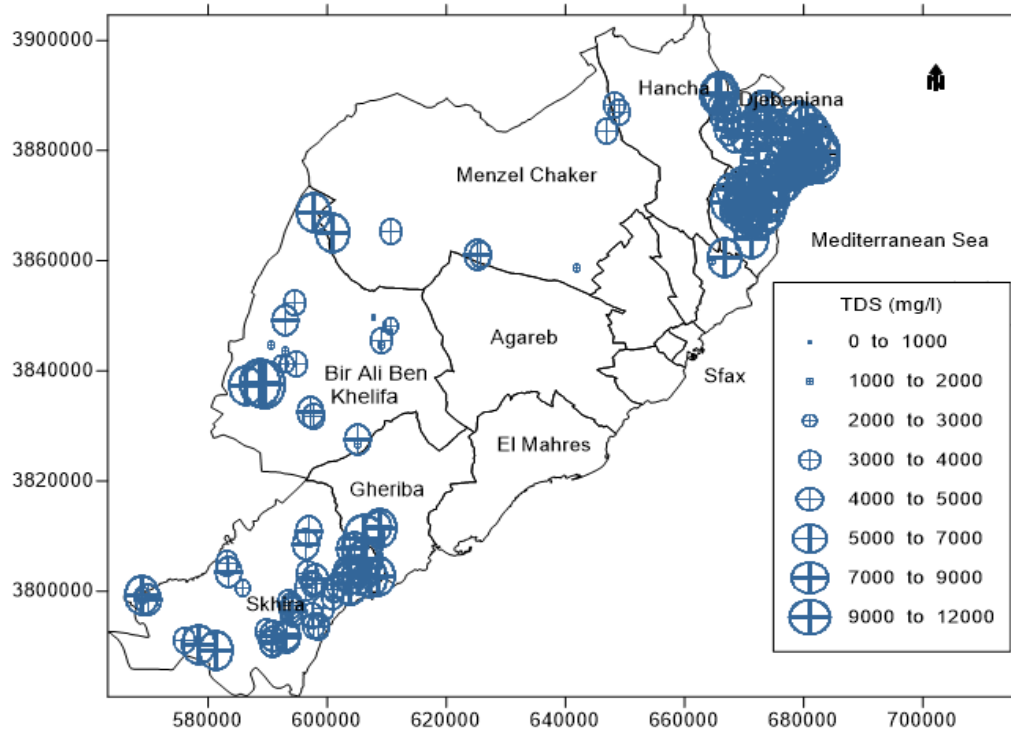


FIG.5: Distribution of groundwater salinity in analyzed samples of Sfax shallow aquifer

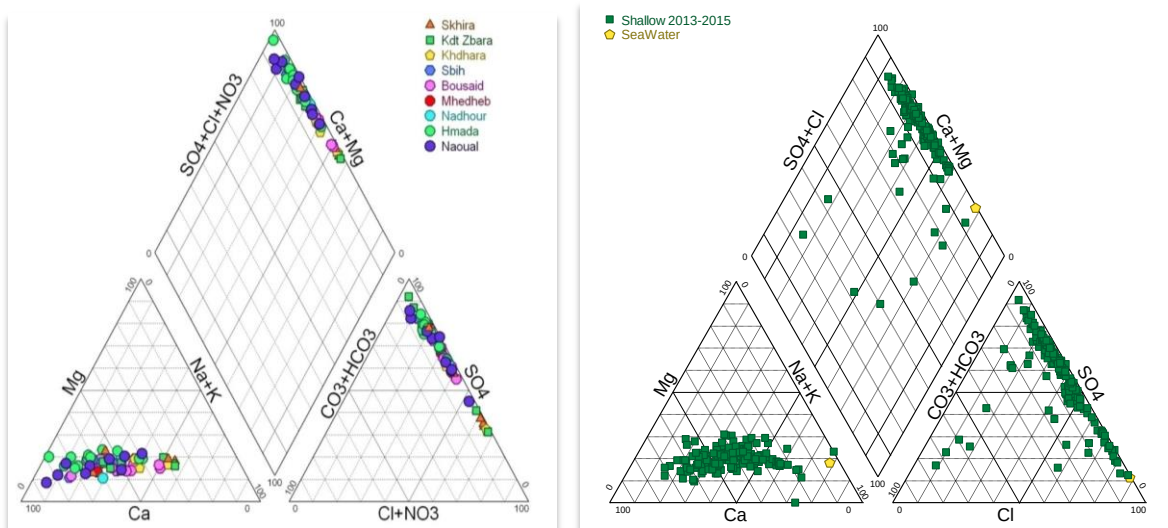


FIG.6: Piper Diagram of analyzed samples of the Shallow aquifer of Sfax

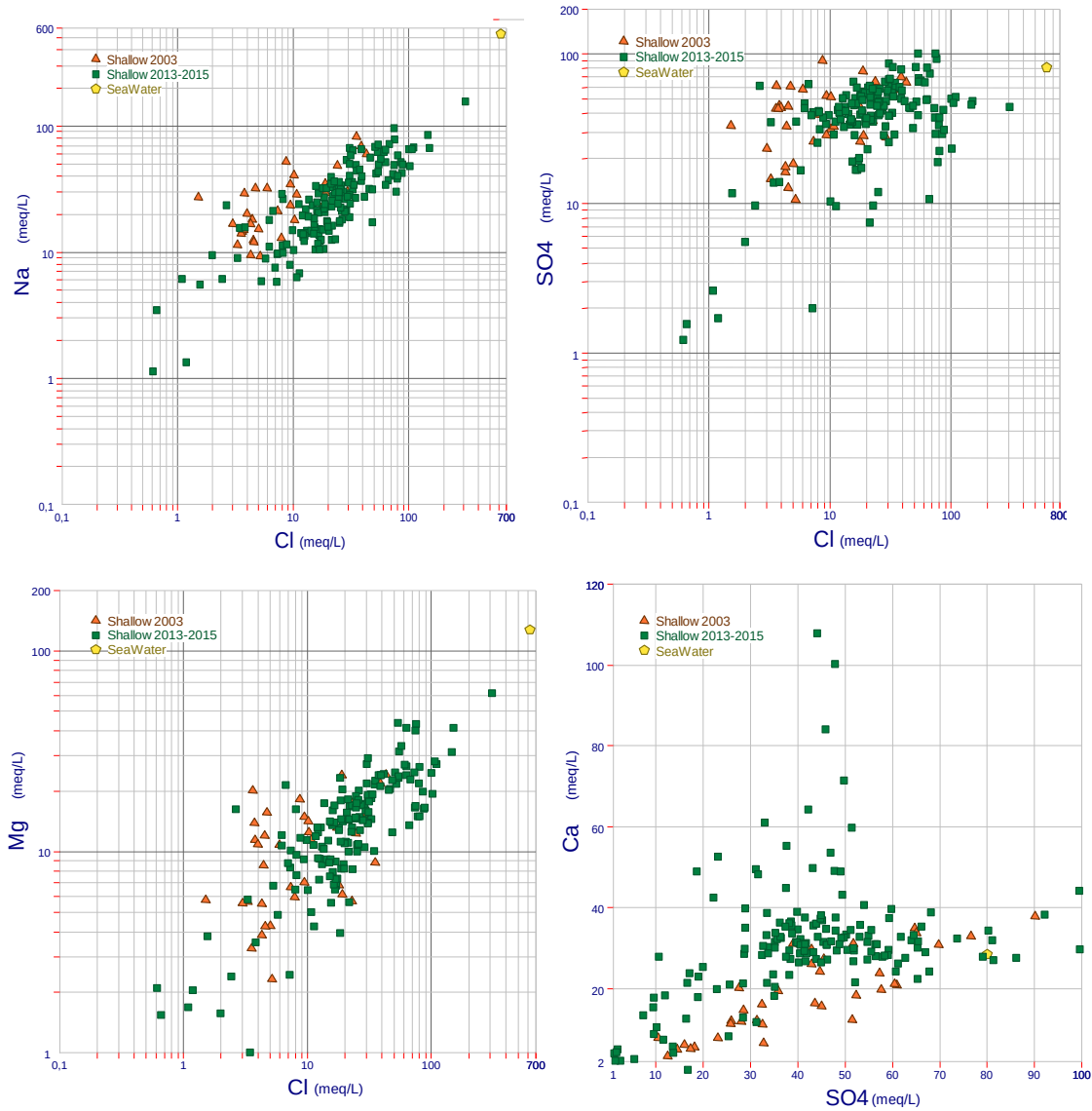


FIG.7: Bivariate diagrams of major ions species in shallow groundwater

3.2.2. Deep aquifer

The total dissolved solids values (TDS) of the deep aquifer are very heterogenous varying between 2,860 and 9,170 mg/L with an average of 4,237 mg/L. Exceptionally for coastal boreholes in the southern part of the basin particularly in Skhira region, the salinities are high and comprising between 8,535 and 9,170 mg/l, likely originated from halite dissolution. The deep aquifer of Sfax is characterized mainly by Na-Cl water type, this hydrochemical facies is generated by the dissolution of halite (NaCl) (Fig.8). Comparing to the previous geochemical studies [3] there is no change in the chemical composition of the deep groundwater of Sfax.

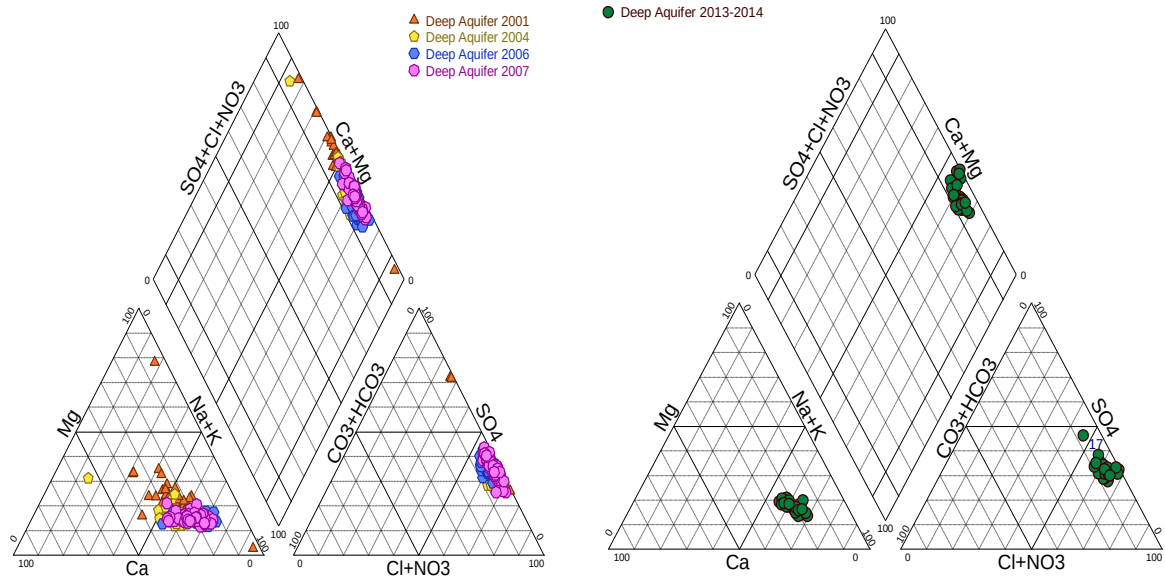


Fig. 8: Piper diagram of deep aquifer.

3.3 . Isotopes results:

The measured stable isotope ratios were used as conservative tracers of water origin. The $\delta^{18}\text{O}$ and $\delta^2\text{H}$ values of the shallow aquifer are plotted on Fig. 9 in relation to the Global Meteoric Water Line (GMWL) [14] and the Regional Meteoric Water Line of Sfax (LMWL). The measured stable isotope composition of the samples representing Sfax aquifer is quite variable; $\delta^{18}\text{O}$ changes from -1.6 to -5.62‰ with corresponding $\delta^2\text{H}$ values changing from -14.2 to -38.4‰.

The $\delta^{18}\text{O}$ / $\delta^2\text{H}$ diagram shows that the Sfax groundwater plots on or slightly below the GMWL and the LMWL. The first group of point plots along the LMWL represents fresh groundwater collected from western part of Sfax basin. Most likely, they represent recent infiltration water.

Other samples plot along mixing line between seawater and groundwater. Most of samples plotting near this line are characterized by high mineralization and are located in the coastal area.

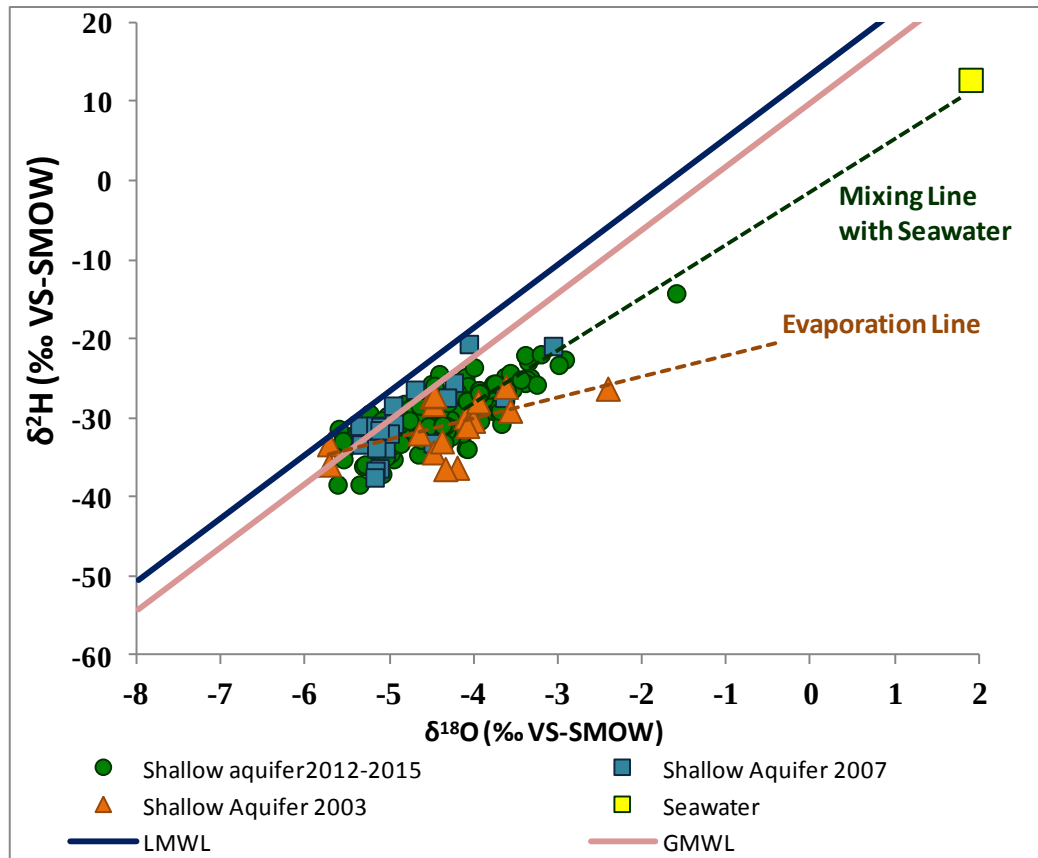


FIG.9. $\delta^{18}\text{O}/\delta^2\text{H}$ diagram of the shallow aquifer of Sfax

The mixing trend between fresh groundwater and seawater is clearly confirmed by the $\text{Cl}/\delta^{18}\text{O}$ relationship (Fig.10). It can be seen that the groundwater samples are distributed around three trend lines (i) an evaporation line, (ii) mixing line with seawater and (iii) dissolution Line.

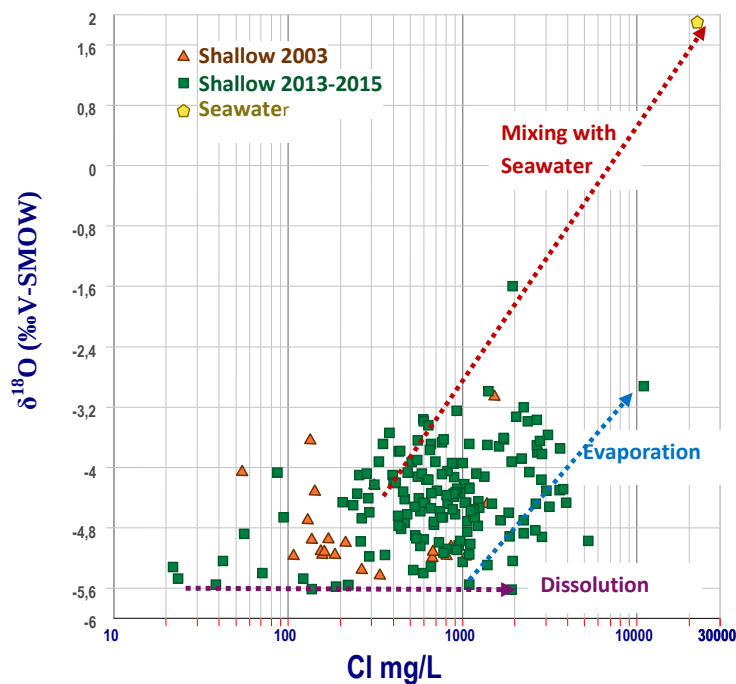


FIG.10. $\delta^{18}\text{O}/\text{Cl}$ diagram of the shallow groundwater of Sfax

An estimation of seawater intrusion rate is made using ^{18}O mass balance. The calculated seawater intrusion rate is ranging between 3 and 18% in Djebeniana Shallow aquifer. The tritium values of the shallow aquifer range from 0.3 to 5.82 TU clearly indicating the recent recharge signature particularly in northern and western parts of Sfax basin. Stable isotope contents of deep groundwater of Sfax are depleted comparing to the weighted mean values of $\delta^{18}\text{O}$ and $\delta^2\text{H}$ for precipitation, indicating either recharge at higher altitudes or a palaeoclimatic effect (recharge under colder climatic conditions than at present) (Fig.11). Based on the low ^{14}C activities and tritium contents, the difference between the isotopic composition of deep groundwater and that of present precipitation is likely to result from a palaeoclimatic effect. The low ^{14}C contents in the deep aquifer indicate old groundwater, corresponding to ages greater than 10000 years. Although the deep aquifer of Sfax is intensively exploited, the stables isotopes contents measured during different sampling campaign since 1996 does not show any significant variations (Fig.11).

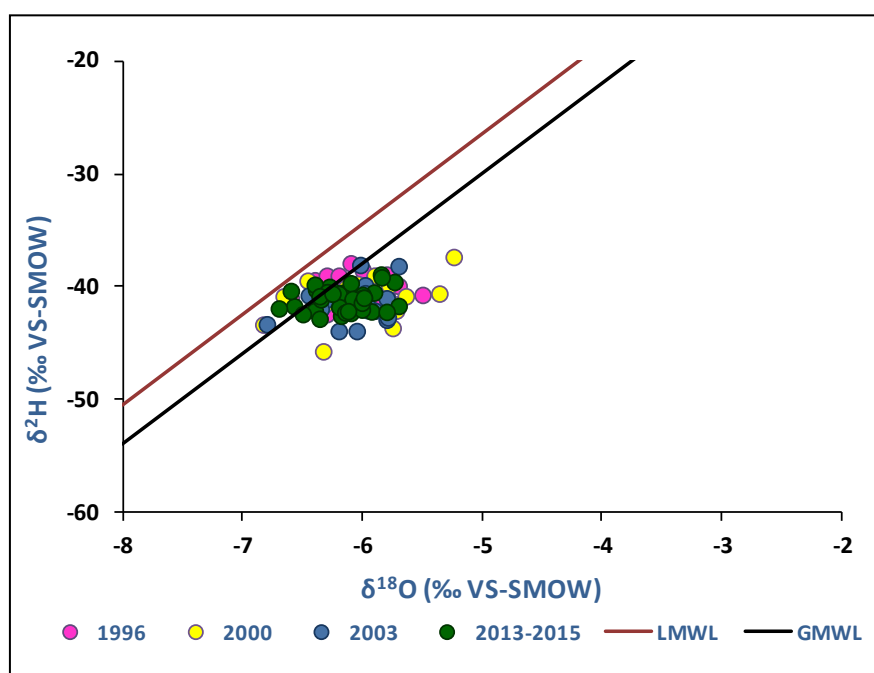


FIG.11. $\delta^{18}\text{O}/\delta^2\text{H}$ diagram of Sfax deep aquifer

3.4 Noble gases:

Dissolved atmospheric noble gases (i.e., Ne, Ar, Kr, and Xe, but not He which often contains radiogenic components) in groundwater provide information on the conditions during groundwater recharge, in particular the recharge or noble gas temperature (NGT). While temperature is the traditional main result of the noble gas thermometer, as implied by the name of the method, more recent research has shown that additional information can be derived from the so-called "excess air" [15]. All this information nicely complements the stable isotope data, which also indicate the origin of the groundwater and the climatic conditions under which it was formed. One important application of noble gas isotopes concerns age dating of groundwater, where tritium and ^{14}C are the classical methods. The

combination of noble gas temperatures and stable isotopes from groundwater is therefore a powerful approach to paleoclimate reconstruction. Under this project a total of eleven samples were collected of deep groundwater of Sfax in order to measure the noble gases concentrations. Samples for noble gas analysis are typically collected by flushing the water sample through annealed copper tubes, which are then pinched off at either end to prevent atmospheric contamination. The analyses were performed in Isotopes Hydrology Laboratory in IAEA and noble gas concentrations are reported as cm^3 STP per mass of sample (g).

The noble gases concentrations are analysed by a non-parametric statistical method and visualized using box-and-whisker plots (Fig.12).

Measured values were identified as outliers if the distance from the top or bottom 25th percentile was larger than 1.5 times the interquartile range. The box in box-whisker plots represents the interquartile range; the median is represented by a square mark. The whiskers extend to 1.5 times the interquartile range from the 25th and 75th percentile or the extreme value, whichever is closest to the median. Outliers as identified by this method are plotted separately. Differences between measured concentrations in replicate samples are noted which could be caused by sampling artifacts. The measured neon concentrations are similar ($2.8\text{--}3.4 \times 10^{-7} \text{ cm}^3 \text{ STP/g}$) for 7 samples and contain a few outliers. Argon, krypton and xenon concentrations show larger variations comparing to the median value with few outliers and extreme values.

Based on these data the different outliers were removed in order to investigate recharge temperature and to estimate the amount of excess air. The used model was provided by the IAEA and it is fitted to three noble gases (Xe, Ne and AR), the preliminary interpretations show a mean recharge temperature of $14.4 \pm 3^\circ\text{C}$ and an excess air value of 6.5 ± 1 .

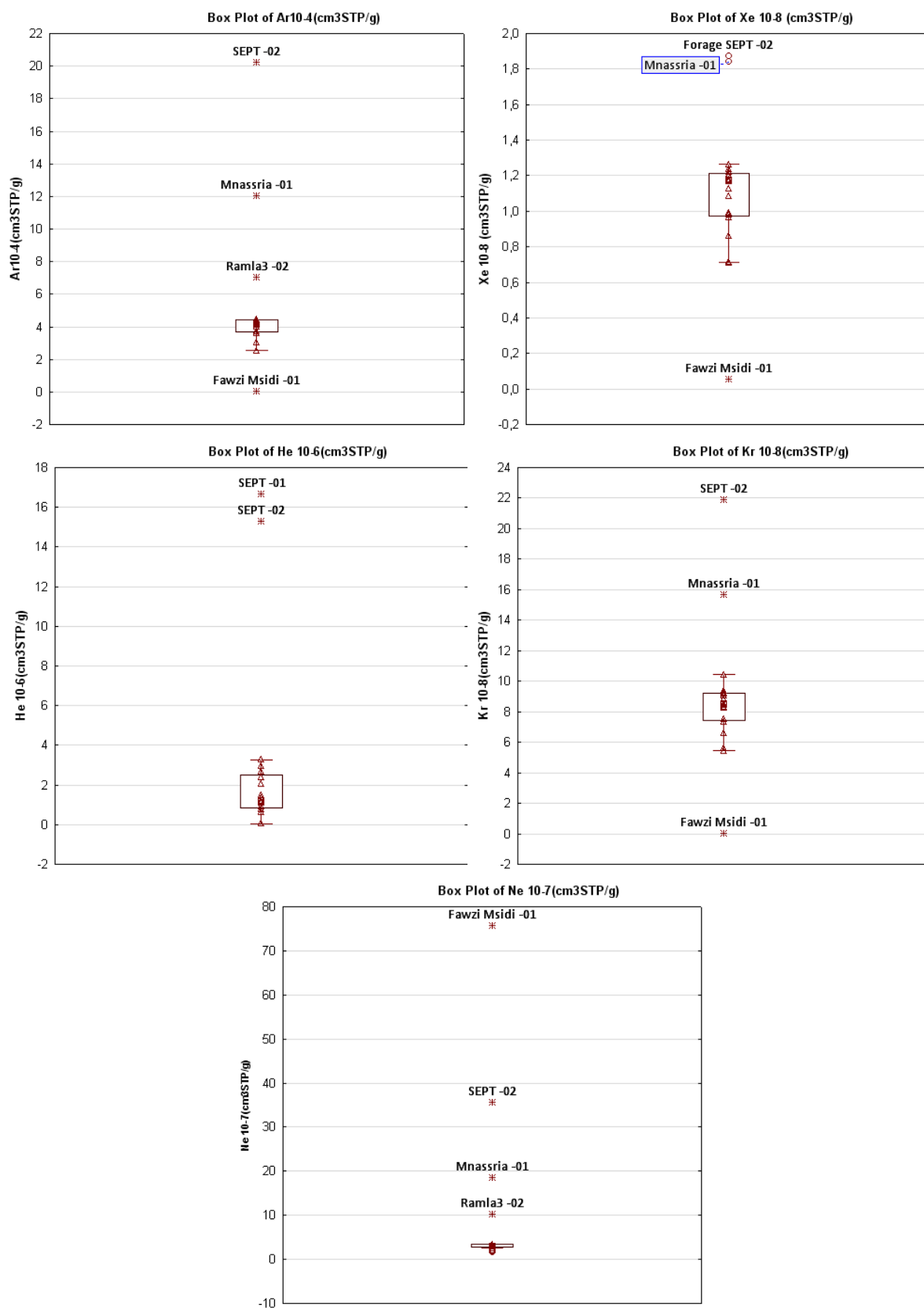


FIG.12. Box-whisker plots for noble gases concentrations of Sfax groundwater

3.5 .Multivariate statistical analysis (ACP):

Multivariate statistical analyses, such as Cluster analysis (CA) and principal component Analysis (PCA) combined with conventional hydrochemical and isotopic methods were applied to identify the main geochemical process controlling groundwater quality. Two factors are extracted to statistically represent the contributions influencing chemical composition of groundwater samples. These components all describe 73% of the total variance of the data. It suggests that all hydrogeochemical process in the study area could not be completely explained by PC1 and PC2 (Fig.13).

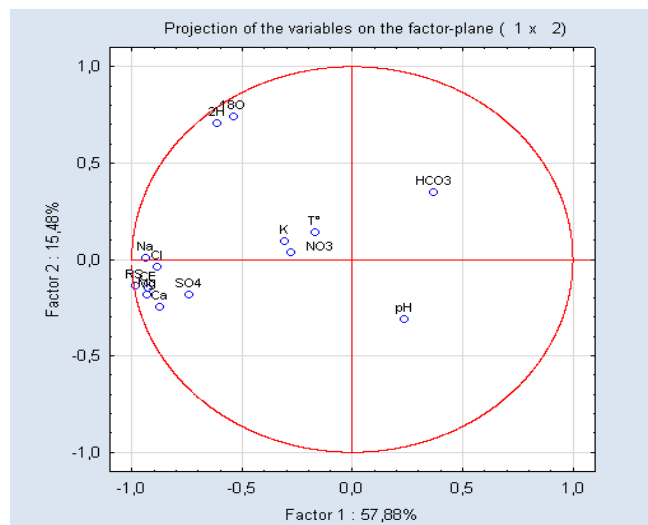


FIG.13. Projection of the variables on the factor plan (1x2) of the shallow aquifer of Sfax

The first principal component (PC1) shows strongly and high negative loading related to EC, TDS, Mg, K, Na, $\delta^2\text{H}$ and $\delta^{18}\text{O}$ which have dominant contribution to groundwater salinization. The second principal component (PC2) has a high positive factor loading for $\delta^2\text{H}$, $\delta^{18}\text{O}$, NO_3 , T° and K which are related to agricultural return flow and evaporation process. The projection of the samples according PC1/PC2 (Fig.14) confirms the obtained geochemical results where three group could be identified: (i) the first is composed by fresh groundwater samples located mainly in the western part of Djebniana area, (ii) the second group plots along PC1 in its negative part and it is composed by high saline water samples related to water-rock interaction and (iii) the third group is characterized by high salinity and elevated stable isotope contents representing groundwater samples affected by seawater intrusion.

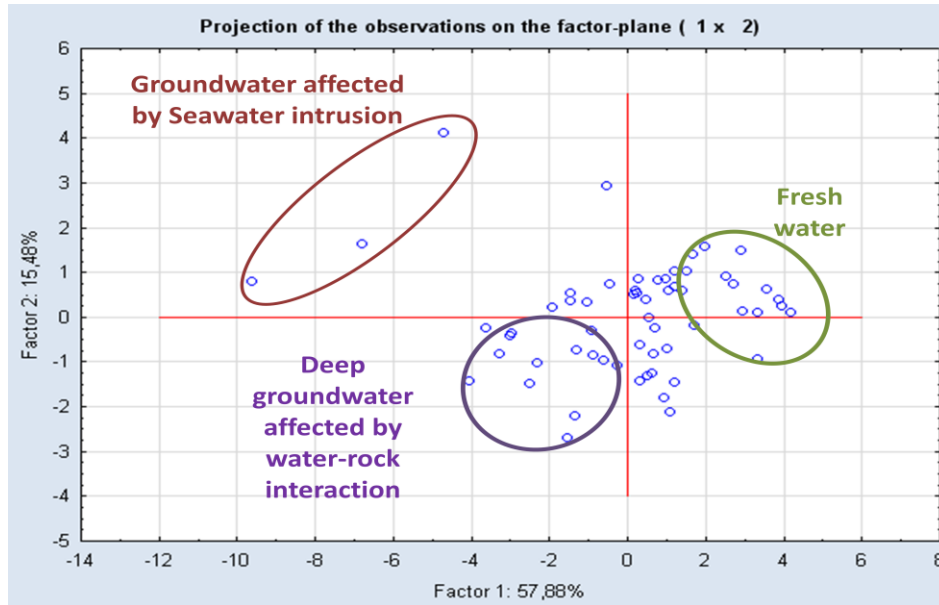


FIG.14. Projection of the observations on the factor plan (1x2) of the shallow aquifer of Sfax

The Cluster analysis using the Ward's method and Squared Euclidean distances shows that the shallow aquifer of Sfax groundwater could be classified into four groups (Fig.15):

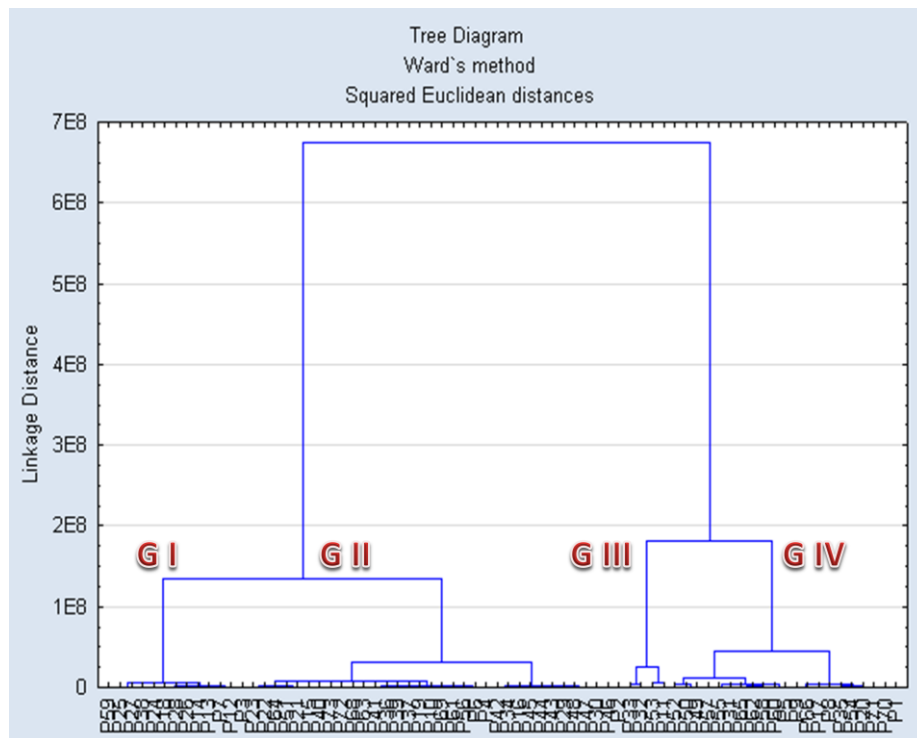


FIG.15. Tree Diagramm of the shallow aquifer of Sfax

- The first group (G I) is composed by Fresh groundwater which are located mainly in the recharge area western part of the basin.
- The Second group (GII) is represented by brackish groundwater affected by evaporation and irrigation return flow.
- The group G III is composed by saline groundwater affected by seawater intrusion

- The last group G IV is represented by saline groundwater affected by water rock interaction

3.6 . Modelling : 2D Thematic maps (case of Djbeniana aquifer):

Geostatistical approach is used for the analysis of spatial variations of groundwater hydraulic head and salinity of Djbeniana aquifer. The basic assumption in using geostatistics is that the properties in the earth have some spatial continuity up to a certain lag distance. The geostatistical concepts and its applications are reported by different researchers around the world [16]. Kriging method considers the spatial correlation between the sample points and is mostly used for mapping spatial variability. Kriging is distinguished from IDW and other interpolation methods by taking into consideration the variance of estimated parameters [17]. It is recognized that the statistical approach (geostatistical methods or Kriging), has several advantages over the deterministic techniques [18]. The fact of giving unbiased predictions with minimum variance and taking into account the spatial correlation between the data recorded at different locations is an important advantage of Kriging. Structural analysis of data: Spatial correlation or dependence can be quantified with semivariograms (or variograms). Furthermore, ordinary kriging makes the assumption of normality among the data points. When performing ordinary kriging, semivariogram values for any distances may be required. The variogram properties were proved to be efficient in characterizing the spatial variability. Therefore a mathematical model must be fit to the semivariogram values to provide a semivariogram value for any distance. A variogram consists of two parts: an experimental variogram found by calculating the variance for each point, and a model variogram. In this study, to elaborate thematic map of the hydraulic head and the salinity in Djebeniana shallow aquifer, the spatial distribution of each parameters was studied using the variogram and ordinary Krigage methods in geostatistical extension in ARCGIS.

The corresponding sill, nugget, range values and the best fitted variogram models are shown in table 1. Subsequently, thematic maps for groundwater hydraulic head and TDS are generated using ordinary Kriging (Fig 16, Fig 17 and Fig 18). The obtained hydraulic head maps confirm the existence of hydraulic depression near the coastal area which exceeds 12m below the sea level. At the same time the TDS map show a gradual increase of the salinity values in the direction of the sea. The TDS values are high in the hydraulic head depression due to the sea water intrusion process.

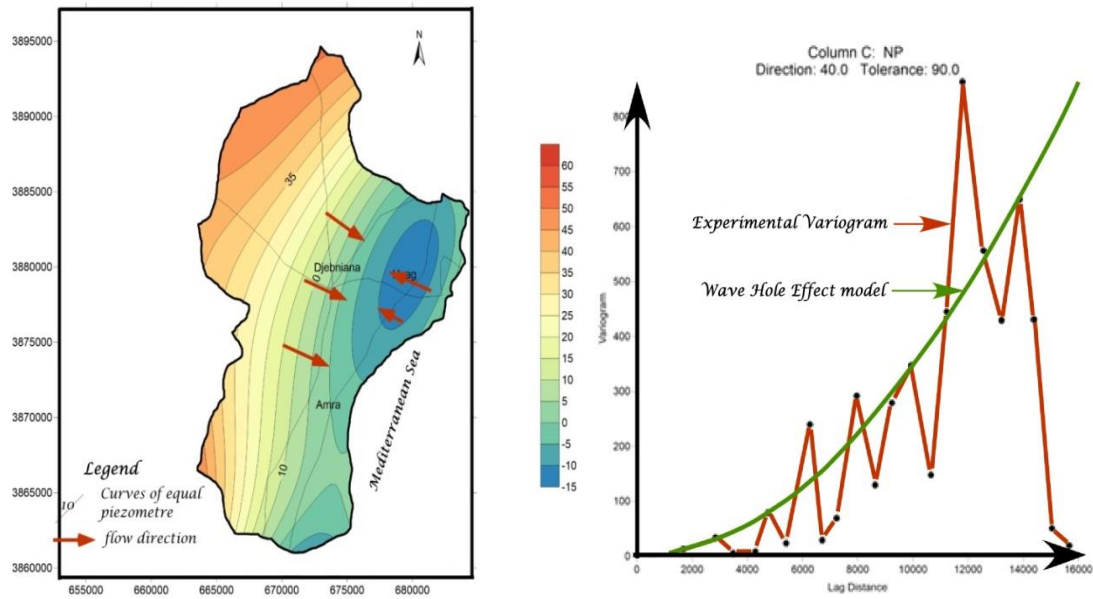


FIG.16.: Best-fitted semivariograms models and Hydraulic head map for 2009 of Djebenaian Shallow aquifer

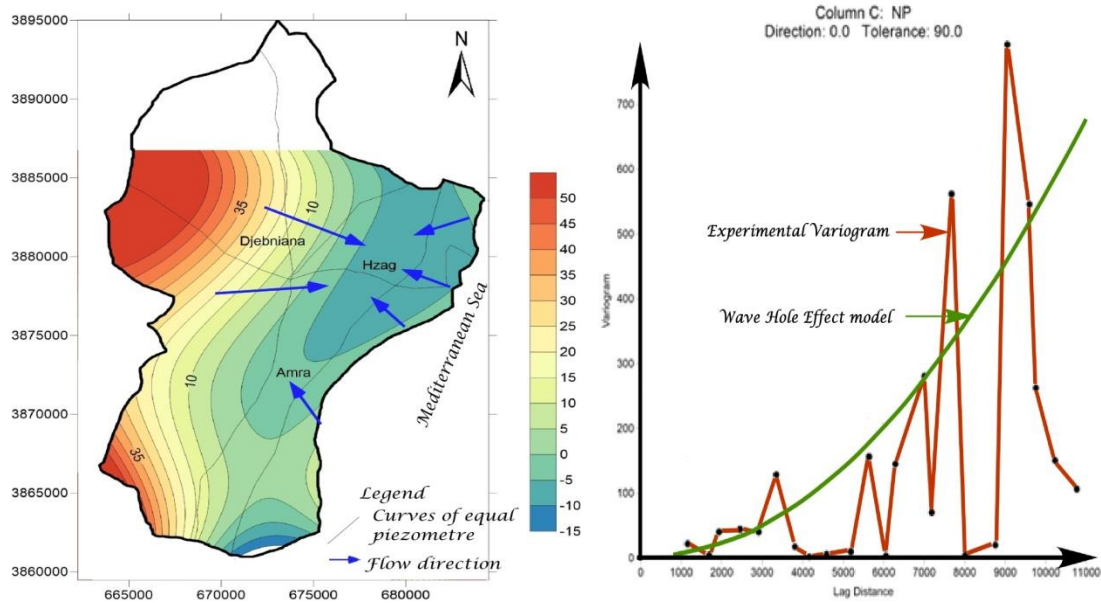


FIG.17: Best-fitted semivariograms models and Hydraulic head map for 2015 of Djebenaian Shallow aquifer

The experimental variogram has an irregular shape (Fig.16 and 17). After adjustment, the variogram piezometry and salinity have a Wave Hole Effect model type.

The equation of this model is:

$$\gamma(h) = 0 \text{ if } h = 0$$

$$\gamma(h) = C_0 + C \left(1 - \frac{\sin\left(\frac{\pi h}{a}\right)}{\left(\frac{\pi h}{a}\right)} \right) \text{ if } h > 0$$

with :

C_0 : The effect nugget

C: The sill
a: The range
h: The distance

TABLE 1: VARIOGRAM CHARACTERISTIC

	Sill C	Range a (m)	Nugget Co
Hydraulic head 2009	800	30900	0
Hydraulic head 2015	600	11000	0
Salinity 2015	12	20000	2

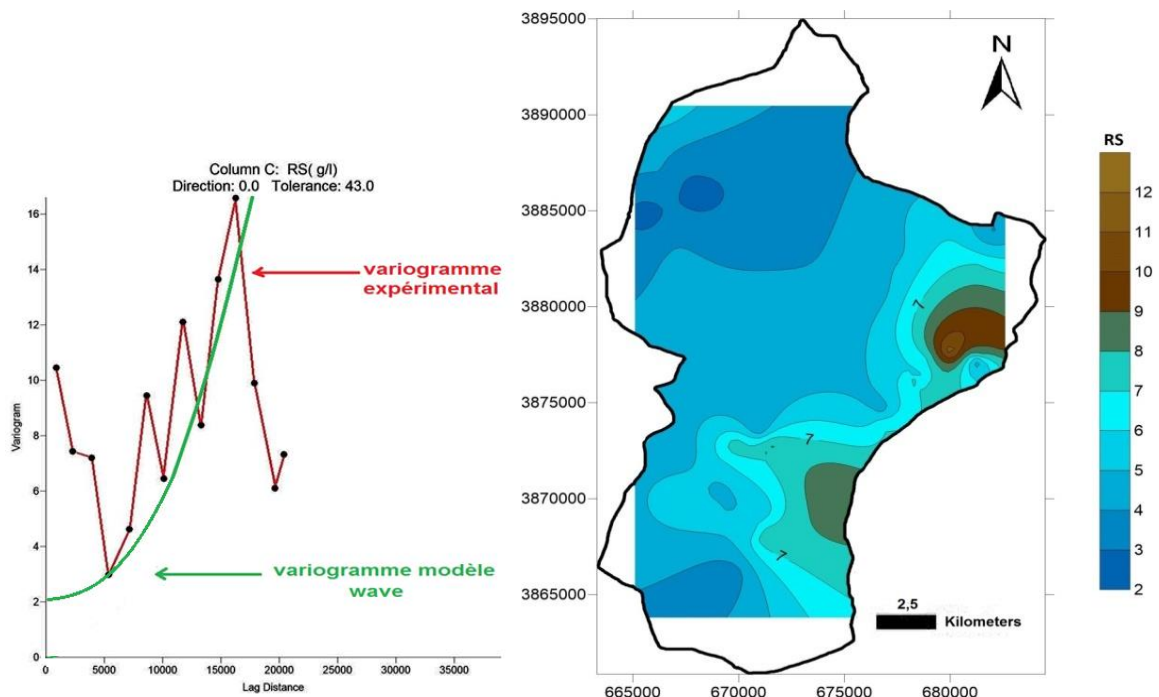


FIG.18: Best-fitted semivariograms models and TDS map for 2015 of Djebenaian Shallow aquifer

4. CONCLUSIONS

The hydrogeologic studies of Sfax have identified three main aquifers: The shallow aquifer, the middle and the deep aquifers. In this CRP project, hydrogeological, hydrochemistry and isotopic tools were used in combination with geostatistical and modelling methods to (i) to conduct an integrated investigation of the multilayer aquifer system of the Sfax region (ii) To identify, characterize and quantify the exchanges between different aquifer levels using isotopic balance (iii) assess the response of groundwater systems to intensive exploitation.

The hydrogeologic investigation show that the intensive exploitation of the Sfax shallow aquifer is significantly higher than natural recharge rate (136.5%), causing marked lowering of water tables and an enhanced seawater intrusion process. This phenomenon is observed particularly in the northern part of the basin (Djebeniana region). Indeed, the current exploitation largely exceeded the available reserves, causing a general drawdown varying

between 4 to 8 m. The elaborated hydraulic head thematic maps confirm the existence of hydraulic depression near the coastal area which exceeds 12m below the sea level. At the same time the TDS map show a gradual increase of the salinity values in the direction of the sea which reach 11g on the depression. The direct effects of the sea water intrusion are the increase of sodium and chloride contents and enrichment on stable isotopes composition. The sea water intrusion rate estimated 18O mass balance is variable and could reach 18 % in Djebeniana area.

The exploited volumes of the deep groundwater increase from 18 Mm³ in 1988 to approximately 25 M m³ in 2008. The increasing exploitation caused an annual decrease of about 0.3m, which considered as acceptable regarding the potential resources of the aquifer. Although this aquifer is intensively exploited, there are no changes in the chemical and stables isotopes contents of deep groundwater. The study of groundwater residence time in the deep aquifer of Sfax was performed by using carbon-14. The low activity values that were measured correspond to high «ages». This confirms that most of this groundwater reserve formed before Holocene and the recent recharge of the Sfax aquifer system is very limited.

Under this CRP project, it has been established that the use of stable isotopes was very important tools for assessing the effects of intensive exploitation of the shallow aquifer. The use of these isotopes with the Hydraulic head data and the salinity values allow to quantify the sea water intrusion process and to localize the area affected by this process. However, although that the deep aquifer is intensively exploited, no significant changes in isotopes composition (18O, 2H and 14C) and chemical quality are noted over 20 years. Under this CRP, noble gases tracers were used to investigate groundwater residence time and recharge conditions of this deep aquifer. Nevertheless, further investigations are recommended using groundwater residence time of the deep groundwater based He-4 and noble gases results to assess the sustainability of this aquifer.

REFERENCES

- [1] Hajjem A., (1980). Etude hydrogéologique de la région de Sidi Abid. Rapport interne, DRES, Tunis.
- [2] Jeribi L., (1995). Contribution à l'étude hydrogéologique, hydrochimique et isotopique de la nappe profonde de Sfax. Projet fin d'étude. Ecole nationale d'ingénieurs. Sfax.
- [3] Maliki MA., (2000). Etude hydrogéologique, hydrochimique et isotopique du système aquifère de Sfax (Tunisie), Thèse Doctorat, Univ. de Tunis II, Tunisie.
- [4] Fedrigoni L., Krimissa M., Zouari K., Maliki A., Zuppi G M., (2001). Origine de la minéralisation et comportement hydrogéochimique d'une nappe phréatique soumise à des contraintes naturelles et anthropiques sévères : exemple de la nappe de Djebeniana (Tunisie), Earth and Planetary Sciences 332 (2001) 665–671.

- [5] Hchaichi Z., (2008). Etude hydrogéologique géochimique et isotopique du complexe intermédiaire de Sfax et sa relation avec le système phréatique du bassin Nord de Sfax. Mastère, Ecole Nationale des Ingénieurs de Sfax, 116p.
- [6] INM (2011). Données météorologiques, Institut National de la Météorologie de Sfax, Tunisie.
- [7] Ben Akacha A., (2001). Etude géologique de la région d'Agareb-Sfax: évolution géomorphologique néotectonique et paléogéographique. DEA, Fac. Sc. Sfax.
- [8] El Batti J. and Andrieux, (1977). Etude hydrogéologique et géophysique du secteur Wadrane. Rapport interne.
- [9] Zebidi H., (1989). Hydrogéologie de la nappe profonde de Sfax. Rapport D.G.R.E. Tunis, pp. 27.
- [10] Beni Akhy R., (1994). Evolution et modélisation de la nappe phréatique urbaine de Sfax. Mémoire de DEA, Fac. Sc. Tunis.
- [11] Hchaichi Z., Abid K., Zouari K., (2013). Use of hydrochemistry and environmental isotopes for assessment of groundwater resources in the intermediate aquifer of the Sfax basin (Southern Tunisia). Carbonates Evaporites. 1-16.
- [12] Coplen, T. B., (1996). New guidelines for reporting stable hydrogen, carbon, and oxygen isotope-ratio data. *Geochim. Cosmochim. Acta* 60, 3359–3360.
- [13] Fontes J.CH., (1971). Un ensemble destiné à la mesure de l'activité du radiocarbone par scintillation liquide. *Revue Géographie Physique et Géologie Dynamique* 13(1), 67e86
- [14] Craig H., (1961). Isotopic variation in meteoric water. *Science* 133, 1702–1703.
- [15] Heaton T. H. E., Vogel J. C. , (1981). Excess air" in groundwater. *J Hydrol* 50 (1981): 201-216.
- [16] Kumar D., Ahmed S., 2003). Seasonal behaviour of spatial variability of groundwater level in a granitic aquifer in monsoon climate. *Current Science* 84: 188–196.
- [17] Buttner O., Becker A., Kellner S., Kuehn S., Wendt- Potthoff K., (1998). Geostatistical analysis of surface sediments in an acidic mining lake. *Water, Air, and Soil Pollution* 108: 297– 316
- [18] Goovaerts P., (1997). Geostatistics for natural resources evaluation. *Geostatistics for natural resources evaluation*. Oxford University Press, Applied Geostatistics Series.

PUBLICATIONS RESULTING FROM THE CRP

- [1] Trabelsi R. , Zouari K., Ayadi R. (2015) The use of stables isotopes and chemicals tracers to assess groundwater quality evolution of intensively exploited aquifer. The example

of Sfax shallow aquifer (South-East Tunisia), International Symposium on Isotope Hydrology: Revisiting Foundations and Exploring Frontiers, IAEA Headquarters, Vienna, Austria, 11–15 May 2015

[2] Trabelsi R. , Ayadi R. , Zouari K. (2014) Characterization of Shallow Groundwater Quality Through Geochemical Investigation And Multivariate Statistical Analysis: Case of Sfax Coastal Aquifer, 41st IAH International Congress "*Groundwater : Challenges and Strategies*" - Marrakech, September, 15-19, 2014

[3] Ayadi R., Trabelsi R., Zouari K., Khanfir H., Itoi R., Saibi H., (2014) Determination of Recharge Sources of Sfax Aquifer System (Southeastern Tunisia) Using Environmental Isotope Tracers International Symposium on Earth Science and Technology 2014, Kyushu University, Fukuoka, Japan; 12/2014.

[4] Ayadi R., Zouari K., Trabelsi R., Khanfir H., Itoi R., Saibi H., (2014) Hydrochemical Evaluation of Groundwaters from the Shallow Aquifer System of Sfax, Southeastern Tunisia. International Symposium on Earth Science and Technology 2014, Kyushu University, Fukuoka, Japan; 12/2014.