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Characterizing Arid Soils from Long-Term Use of Brackish Irrigation Waters

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*Abstract***— In arid regions, irrigation is needed to satisfy the crops water requirements. This study examines the impacts of the use of brackish water for 30 years on soil characteristics of the public irrigation zone Zelba 1 of the region of Mahdia (Eastern Tunisia). The monitoring of the evolution of groundwater quality showed a high risk of salinization and alkalization. The monitoring of soil salinity evolution revealed that this salinity increased during the last decade. Indeed, from 1986 to 1993, the electrical conductivity increased slightly throughout the soil profile. It varied with depth from 0.8 to 1.4 dS/m in 1986 and from 0.9 to 3.5 dS/m in 1993. During the period extending from 1993 to 2000, a significant increase in electrical conductivity was recorded throughout the soil profile to reach a maximum value of about 16 dS/m in the layer (60-75 cm). In 2011, the electrical conductivity increased with depth from 5.3 to 11.9 dS/m while it decreased compared to that of the year 2000. The monitoring of soil sodicity evolution showed that the highest values of soluble sodium were observed during the last decade. This led to an increase in the sodium adsorption ratio in the soil to reach a maximum value of 32 at depths (90-105 and 120-135 cm) in 2011. The soil complex enrichment by exchangeable sodium during the last decade proves that this element mainly comes from brackish water. Therefore, the use of the poor-quality water in irrigation increased the risk of soil salinization and sodisation.**
Keywords- **Brackish water; irrigation; soil salinity; temporal monitoring; Tunisia.**

I. INTRODUCTION

Population growth and economic development exert a pressure on water resources, which are often limited and poorly distributed [1]. Arid regions, with high evaporation rates and low precipitation, are the first to face the problem of water scarcity, and especially the consequences of drought. In the regions of the southern Mediterranean, characterized by a semi-arid and an arid climate, the problem of shortage of water resources of good quality has been known for years. In fact, these regions fall below the level of shortage of 500 m^3 of renewable water per person per year [2]. This scarcity of water resources led to the use of non-conventional water resources to satisfy the increasing water demand, especially for the agricultural sector. The use of drainage waters, marginal quality waters with high salinity and wastewaters were valued in developing countries for land irrigation [3]. Nevertheless, the use of this poor-quality water requires monitoring and control of soil salinity [4]. Several anomalies associated with these water resources were noted. These are especially the process of hydromorphy caused by the mismanagement of irrigation and the inefficient drainage system and the process of salinization. The latter is due either to the seawater intrusion or to the rising of the near-surface groundwater often salty [5, 6]. It is also due to the scarcity of water resources used in irrigation and their often poor-quality. According to [7] nearly 100 000 ha of public irrigation zones, located especially in the center and the south of the region, are deeply affected by the problem of salinization. This process constitutes one of the major factors in the decrease of agricultural productivity [8].

Irrigated lands of the region of Mahdia are characterized by progressive soil salinization, mainly due to the use of saline water. This water come from deep aquifers presenting a high salinity (5 < total dissolved solids <

6 g/l) [9]. In such arid climate, the use of saline water in irrigation induces salinization of these soils and over time, the salinization of the aquifer. In order to provide adequate solutions and to use soil and water resources in a sustainable manner, the Tunisian Government implemented monitoring programs of the soil salinity evolution to control this alarming situation.

In this context, the Public Irrigation Zone (PIZ) Zelba 1 of the region of Mahdia was chosen. In fact, this irrigation zone was the subject of several studies of diagnosis and monitoring of the soil salinity evolution. Except for the study of Ben Hassine who studied the soil salinity evolution for about10 years in this irrigation zone Zelba 1, previous studies remain dependent only on a monitoring for 2, 3 or even 4 years. Furthermore, there is no exhaustive study that dealt with all parameters describing the evolution of the soil physical and chemical characteristics since the beginning of irrigation in Zelba 1 zone.

In this case, a temporal monitoring was carried out each decade at the PIZ Zelba 1 based on previous studies [10, 11, 12, 13, 14] and studies carried out in 2011 in order to examine the impact of the use of brackish water over the period of 30 years in the PIZ Zelba 1.

II. MATERIALS AND METHODS

A.Study area

The PIZ Zelba 1 was created in 1986. This area is located in the center of an alluvial plain of the region of Zelba, situated in the South of Sidi-Alouane at about 35 km southwest of the town of Mahdia (Fig.1). The region of Zelba is characterized by an arid climate. Precipitation is highly variable and irregular with an annual average of about 288 mm. The annual average temperature is about 19.3°C [15].

Zelba 1 soils types (isohumic and texture dominated by sand and silt) and crop occupations are considered typical of the region of Mahdia. It covers 60 hectares consisting of 20 lots of 3 ha each. Irrigation water comes from the well Zelba 1 (n°BIRTH 17 796/4) created in 1983, capturing a deep aquifer (depth=400 m) debiting 18 l/s. Adopted crops, irrigated by the furrow method, are mainly: cotton, sorghum, barley, oats, corn, vegetables and fruit trees. The irrigation zone is crossed by two drainage ditches leading to a pit latrine. Currently, no water flows through this network of ditches completely dry.

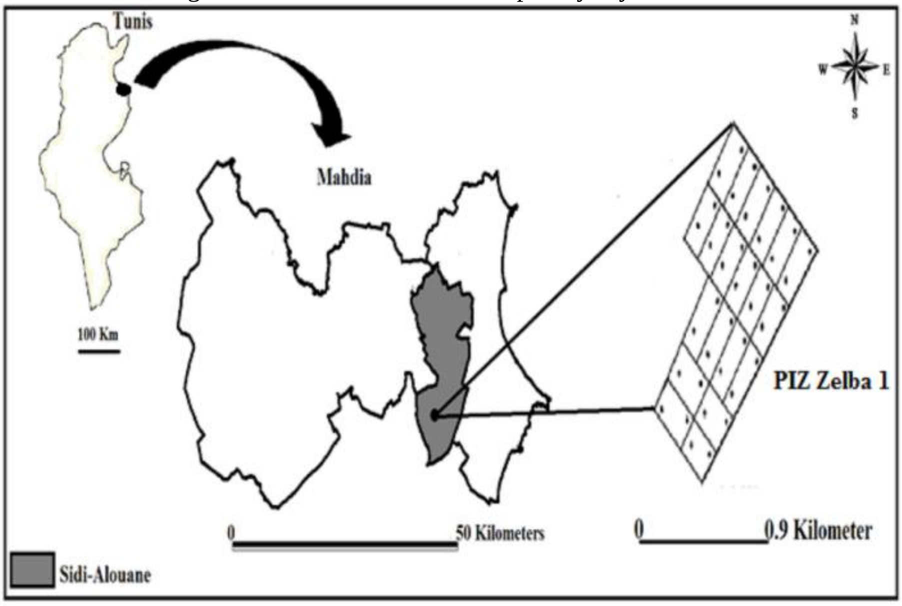

Figure 1. Study area and sampling points' location [16]

B. Field work

Water and soil samples were collected during the summer 2011. Water samples were taken directly from the water well according to the norm ISO 5667-11. They were kept in cold, at very low temperatures (<4°C) for the analysis of chemical parameters.

Soil sampling was carried out to depths of 1.5 m, in 20 lots of the irrigation zone. Indeed, two soil profiles per plot were collected in a systematic manner with an auger in order to have a soil sample for each layer of 0.15 m (Fig.1). About 500 g from each sample was taken in a plastic bag. The collected samples served in the reconstitution of soil profiles in the laboratory of the High Institute of Agronomy of Chott Mariem in order to identify and to characterize different constitutive layers of soil (color, presence of calcareous nodules, presence of plant debris, etc.). Then, a composite sample was taken from each identified layer of the reconstructed profile for analysis in the laboratory. Next, soil samples were air-dried, crushed and sieved at 2 mm. The fraction less than 2 mm was used for analysis of physical and chemical properties.

C. Laboratory work

Irrigation water properties are: pH, electrical conductivity (EC_w), total dissolved solids (TDS), cations (Ca^{2+}, Mg^{2+}, K^+ and Na^+) and anions (SO_4^{2-}, Cl^- and HCO_3^-). pH was measured using a pH meter electrode immersed directly in the irrigation water. The EC was evaluated using a conductivity meter equipped with a temperature correction setup which allowed direct reading at the reference temperature of 25°C. The TDS was measured by drying a total of a volume of 50 ml of the aqueous extract in an oven at 110°C for 24 hours. The ionic composition analysis was determined by volumetric proportioning based on the principle of Mohr for chlorides (Cl^-), carbonates (CO_3^{2-}), bicarbonates (HCO_3^-), calcium (Ca^{2+}) and magnesium (Mg^{2+}). The proportioning of sodium (Na^+), potassium (K^+) and sulfate (SO_4^{2-}) was based on the principle of flame spectrophotometer. Chlorides were determined using a standard solution of silver nitrate ($AgNO_3$, 0.02N) in the presence of potassium chromate ($KCrO_4$). These elements were precipitated in the form of silver chloride (AgCl). Bicarbonate proportioning was conducted by acidimetry using sulfuric acid (0.02N H_2SO_4). The colored indicator used is green bromocresol which gives a blue color. Carbonate ions are absent. Calcium was proportioned by complexometry at pH=10 in the presence of (NaOH). Titration was carried out using tetraacetic ethylene diamine. Magnesium was calculated by the difference of the total hardness and the calcium. Sodium and potassium proportioning was based on the atoms dissociation during their passage through the flame which emit energy to their excitement. Sulfates were analyzed using stabilized Barium Chloride ($BaCl_2$). The proportioning of cations: (Ca^{2+}, Mg^{2+} and Na^+), provides the sodium adsorption ratio (SAR) according to the following relationship:

$$SAR= Na^+ /\sqrt{} [(Ca^{2+} + Mg^{2+})/2] \qquad (1)$$

Where Na, Ca and Mg are expressed in milliequivalents/liter (meq l^{-1}).

Physical and chemical soil analysis performed in the laboratory are, soil texture, soil saturated permeability (K_{sat}), pH, saturated-paste electrical conductivity of soil (ECe), SAR and exchangeable cations. Soil texture was carried out on a representative sample for each layer by the Robinson pipette's method [17]. This method consists in separating the mineral portion of the soil in fractions classified according to the size of particles less than 2 mm and to determine the relative proportions of these categories in percentage of the total mass of soil mineral. Soil permeability was determined by the double cylinder method based on the principle of vertical infiltration. Soil pH was measured in a soil/distilled water ratio of 1/2.5 by the electrometric method using a pH meter equipped with a glass electrode. ECe was measured in the saturated paste extract and corrected for a temperature of 25°C [18]. Ionic composition analysis was carried out using the same proportioning technique as for the irrigation water for the Ca^{2+}, Mg^{2+} and Na^+. This analysis was carried out in order to determine the soil SAR. The proportioning of the exchangeable cations (Ca^{2+}, Mg^{2+}, Na^+ and K^+) was determined using an atomic absorption spectrometry.

III. RESULTS AND DISCUSSION

A. Chemical composition of the groundwater

Results of monitoring of the evolution of the groundwater quality Zelba 1 over the period 1986-2011 are shown in Table 1.

TABLE 1. MONITORING OF THE IRRIGATION WATER QUALITY

Year	pH	EC_w (dS/m)	TDS (g/l)	Ionic composition							SAR
				Cations (meq/l)				*Anions (meq/l)*			
				Ca^{2+}	Mg^{2+}	Na^+	K^+	SO_4^{2-}	Cl^-	$HCO3^-$	
2011	7.90	7.20	5.00	14.00	9.87	54.00	0.61	28.00	50.00	4.00	15.60
2000	8.00	7.20	4.90	19.00	6.91	53.00	0.56	19.00	54.15	5.00	14.72
1990	7.30	6.90	4.80	13.00	12.83	52.00	0.64	23.00	50.14	5.00	14.44
1986	7.70	6.90	4.83	11.00	10.86	50.00	0.64	22.00	48.64	2.90	15.10

The pH varied from 7.7 to 7.9 with an average of 7.76. EC_w values varied from 6.9 to 7.2 dS/m, with an average of 7.04 dS/m. TDS varied from 4.8 to 5.0 g/l, with an average of 4.88 g/l. This water is characterized by the abundance of sulfates and sodium chlorides and the presence of potassium, calcium and magnesium and it is devoid of carbonates. Cations and anions are therefore distributed according to following order: $Na^+>Ca^{2+}>Mg^{2+}>K^+$ and $Cl^->SO_4^{2-}>HCO3^-$. Thus, this water has a chlorinated and sodic sulfated geochemical facies. The SAR value varied from 15.10 in 1986 to 15.6 in 2011, with an average of 14.77. These data classify the irrigation water in the C5S4 class according to the diagram of Riverside waters classification [19]. Therefore, this water has a very high risk of salinization and alkalization. Consequently, this water can cause degradation of soil structure by alkalization, if necessary precautions were not taken into consideration [20].

The homogeneity of the water quality observed from 1986 to 2011 is explained with the fact that the used aquifer was not exposed to natural and/or anthropogenic constraints, such as over-exploitation during this time.

B. Description and analysis of the reconstructed profiles

The soil profiles reconstitution showed that the soil of the PIZ Zelba 1 is a deep isohumic brown soil evolving on a silt spreading material with calcareous nodules. It is an homogeneous soil, due to the land geomorphology characterized by a flat surface which the slope is less than 3%. Soil particle size analysis showed that the clay content increased with depth ranging from 13 to 30%, while the content of coarse particles decreased from 37 to 20% for fine sand and from 8 to 6% for coarse sand.

Indeed, the soil, which consists mainly of silt, presents a sandy-silt texture and a fine angular polyedric structure with the presence of shells, many plant debris and clods of small and medium size in the first 30 cm layer. It presents a silty-sand texture and a mean polyedric structure with the presence of medium-size clods, clusters and calcareous spots at depths varying between 30 and 135 cm. Finally, this soil is characterized by a clay-silt texture and a net angular polyedric structure with the presence of spots, clusters and calcareous nodules at depths beyond 135 cm.

C. Impact of the use of brackish water on soil permeability

Results of monitoring of the evolution of the saturated permeability (K_{sat}) at the soil surface over the period ranging from 1986 to 2011 are indicated in Table 2. Indeed, the soil permeability of the irrigation zone decreased slightly from 1986 to 2011, but it kept values greater than 5 10^{-6} m s^{-1} indicating a permeable soil. According to [21], many factors affect the permeability of the soil such as: texture, presence of cracks and holes made by roots, worms or animals, tillage, water quality used in irrigation, etc. In this case, soil surface permeability was slightly affected by the poor-quality of water used in irrigation.

Taking into account the nature of the soil of the study area with sandy-silt texture in the surface layers (0-30 cm), this water characterized by very high risks of salinization and alkalization, has little impact on the physical properties evolution of these soils. In fact, the good permeability could be explained by the presence of a sandy-silt texture at the soil surface and/or the creation and the multiplication of macropores just after tillage and backcrossing operations which improved the water infiltration rate. Permeability could be also enhanced by the presence of cracks and the organic matter intake in the surface layers, which resulted in improving soil porosity.

TABLE 2. MONITORING DATA OF SOIL K_{SAT} AT THE PIZ ZELBA 1

Year	**1986**	**2000**	**2011**
Mean K_{sat} (m/s)	13.4 10^{-6}	9.7 10^{-6}	9 10^{-6}

D. Impact of the use of brackish water on soil pH

The profile analysis of soil pH was carried out since the creation of the PIZ Zelba 1 in 1986 as can be seen in Fig. 2.

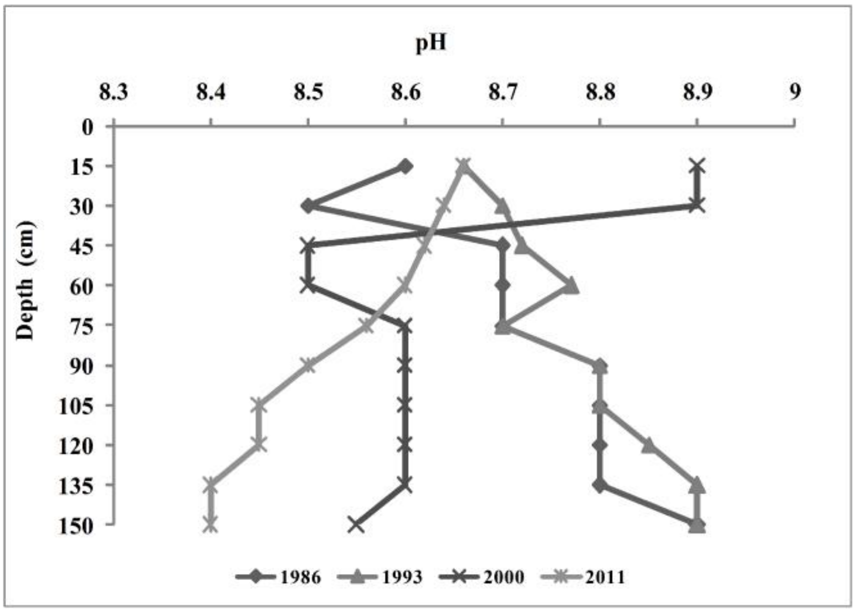

Figure 2. Soil pH evolution monitoring

Referring to previous works carried out each decade and those performed in 2011, soil pH varied with depth but generally the observed values are comparable with an average of about 8.7 indicating an alkaline soil. Indeed, mean values of pH increased with depth from 8.6 to 8.9 in 1986 and 1993 and decreased from 8.9 to 8.5 in 2000 and from 8.6 to 8.4 in 2011. The low standard deviation of about 0.15, showing almost no significant effect of brackish water irrigation on pH. Therefore, the pH was not affected considerably over time by the brackish irrigation water. This could be due to the buffering capacity of the soil which allowed it to resist to pH variations and to support the modifications in the soil solution concentration during irrigation.

E. Impact of the use of brackish water on soil salinity

The monitoring of soil salinity evolution was the subject of several studies in Tunisia and in the world. Indeed, it was treated in Tunisia by [22, 23, 24]; in Algeria by [25]; in Spain by [26, 27, 28]; in China by [29, 30]; in Senegal by [31], etc. In this work, soil salinity monitoring was studied in the public irrigation zone Zelba 1 during the period passing from 1986 to 2011. In fact, a fluctuation of the soil salinity was observed during this period (Fig.3). The ECe measured in 1986 was very low. It increased slightly with depth from 0.8 to 1.4 dS/m. In 1993 the ECe increased slightly throughout the soil profile to vary between 0.9 and 3.5 dS/m compared to that of the year 1986. A significant increase in the ECe was recorded from 1993 to 2000, including from the layer 45 cm until 135 cm depth. Indeed, the observed values of the ECe are between 5 and 16 dS/m. During the year 2011, the ECe increased gradually with depth ranging from 5.3 to 11.9 dS/m while it decreased compared to that of the year 2000, especially from the layer 45 cm to 135 cm depth. Based on [18] classification, the soil is considered saline with ECe values exceeding 4 dS/m. Fig. 4 showed that 50% of the studied soil samples are considered non-saline where the major parts of soil salinity (F=35%) is in the interval of 0-2 dS/m. This figure also showed that 50% of the studied soil is characterized by a relatively high salinity (ECe>4 dS/m), where 32% are greater than 8 dS/m.This is observed during the last decade.

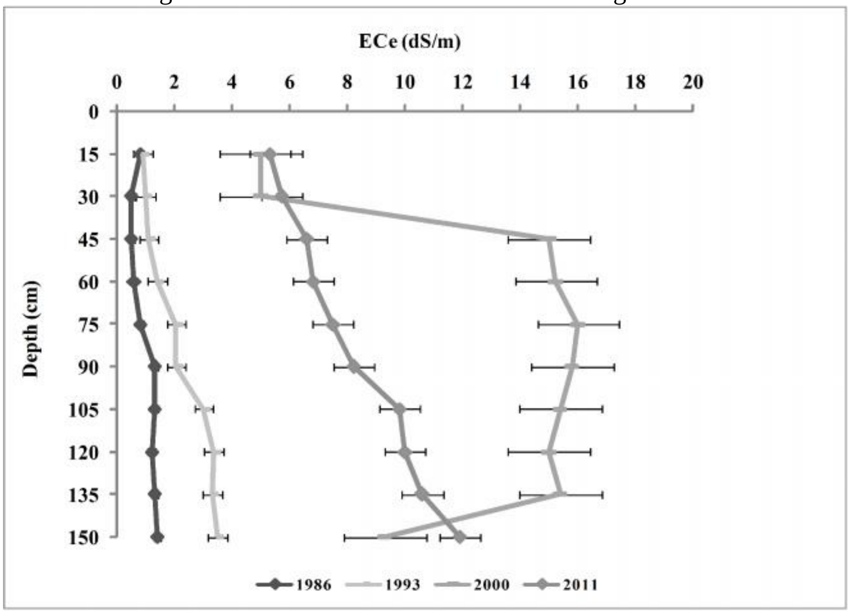

Figure 3. Soil ECe evolution monitoring

The fluctuation of soil salinity observed over time, either by salt leaching or by salt concentration, may be explained, among other factors, by climatic conditions such as precipitation. Indeed, from 1986 to 1993, the irrigation zone has known a significant activity, which facilitated the monitoring of the control program and the surveillance of the soil salinity. The low salinity recorded along the soil profile, could be explained by the phenomenon of salt leaching to deeper layers induced by irrigation water and the relatively high rainwater especially registered in (1989-1990), reaching 502 mm (Fig. 5). Furthermore, over the period extending from 1991 to 1993 the PIZ Zelba 1 did not function and was considered as an abandoned zone. The non-irrigation during this period marked by a relatively good precipitation (the total amount of rain was 341.4 mm) contributed significantly to the decrease in the soil salinity in the irrigation zone [12]. By 2000, soil salinity increased dramatically. Indeed, the increase in the fine fraction with depth led to salts accumulation and consequently an increase of the ECe from depths of 45 to 135 cm followed by a gradual decrease in the deepest layers. This reflects the difficulty of rainwater infiltration and irrigation in depth and thus soil desalinization. The significant increase in soil salinity during this period has led some farmers to abandon their lots due to unprofitability.

The comparison of the current results to those obtained in 2000 revealed a decrease in ECe values, except for the deep layers. This easily explains the phenomenon of soluble salts leaching induced by irrigation waters and by rainfall recorded in 2011 (the total amount of rain was 307.5 mm) and their accumulation in depth. These results are in agreement with the findings of [27] indicating that soluble salt were leached by the rainfall irrigation operations of soil located in the southern province of Cordoba, Spain.

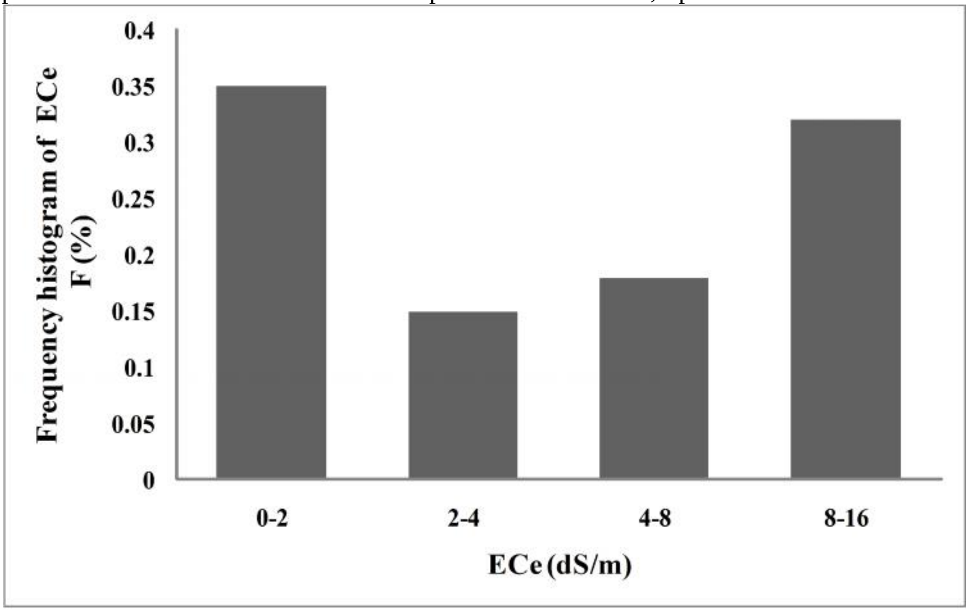

Figure 4. Frequency histogram of the soil salinity evolution from 1986 to 2011

The salt leaching in the irrigation zone PIZ Zelba 1 may also be explained by the fracturing of the calcareous crust in depth which enhanced the water circulation in the soil. The absence of deep drainage systems, explained by its high cost and especially by the small size of lots, is a major reason for the salt accumulation in depth. Most farmers are complaining about this situation.

In spite of the observed fluctuation of the soil salinity over time (salinization and desalinization), the soil of the irrigation zone evolves in a saline way especially in the last decade with ECe values exceeding 4 dS/m. This salinity depends largely on the poor-quality of water used in irrigation. Therefore, the use of brackish water in irrigation could in the long term, aggravate soil salinity and even soil structure degradation, if certain precautions are not taken into consideration.

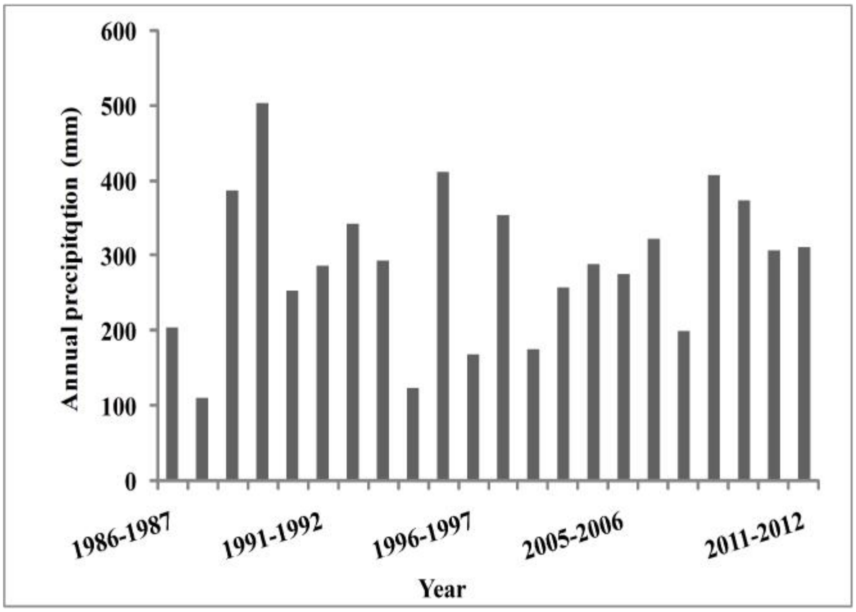

Figure 5. Variation of the average annual precipitation from 1986 to 2011

F. Impact of the use of brackish water on soil sodicity

A fluctuation of the cationic composition of the soil solution (Fig. 6) and the soil adsorbent complex (Fig. 7) was observed over time along the soil profile as did the ECe. The soluble sodium content (Fig. 6A) is largely higher than that of the soluble calcium (Fig. 6B) and the soluble magnesium (Fig. 6C). The highest values were observed during the last decade (2000-2010). These values, which initially ranged from 3.8 to 1.3 meq/l from the surface to the deepest layers, increased significantly to reach values ranging from 110 meq/l on the surface to 94 meq/l in deep layers in 2000 and values ranging from 65 meq/l on the surface to 30 meq/l in deep layers in 2011. This led to an increase in the SAR value in the soil (Fig. 6D). The largest increase in the SAR was also observed during the last decade when it exceeded largely 10 to reach a maximum value of the order of 32 at depths (90-105 and 120-135 cm) in 2011.

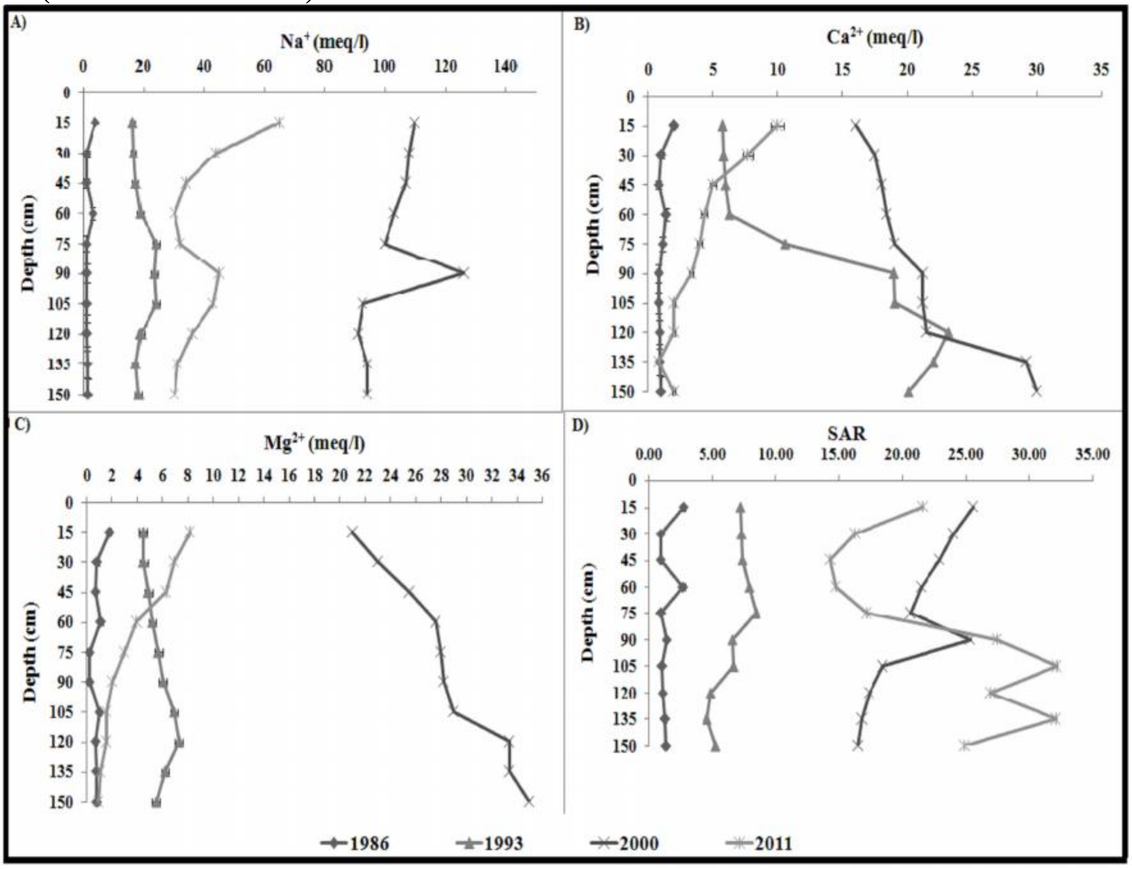

Figure 6. Evolution monitoring of soluble elements over time

In order to show the effect of brackish water on the soil adsorbent complex composition, an analysis of exchangeable cations (Ca^{2+}, Na^+, Mg^{2+} and K^+) was carried out. In fact, the evolution of cationic composition showed a soil complex enrichment by exchangeable cations especially Na^+ (Fig. 7A), Ca^{2+} (Fig. 7B), and Mg^{2+} (Fig. 7C) during the last decade. Globally, exchangeable Ca^{2+} is the major cation. It decreased with depth from 5.9 to 3.6 meq/100 g in 1986 and then it increased in 2000 to reach maximum values especially in layers (30-45 and 45-60 cm). In 2011, exchangeable Ca^{2+} increased gradually with depth ranging from 6 to 8.8 meq/100 g while it decreased compared to that of the year 2000. The exchangeable Na^+, increased with depth from 0.3 to 1.6 meq/100 g in 1986 and then it increased throughout the soil profile in 2000 to vary between 2.7 and 4 meq/100 g compared to the initial state. It increased from 1.3 to 7.5 meq/100 g from the surface to the deep layer in 2011. The exchangeable Mg^{2+} increased during the last decade. It varied with depth from 3.4 to 2.8 meq/100 g in 2000 and from 2 to 2.3 meq/100 g in 2011. The echangeable K^+ is present in relatively small quantities. In 2011, it decreased slightly throughout the soil profile from 1.1 to 0.3 meq/100 g compared to that of the year 1986 (Fig. 7D).

The soil complex enrichment by exchangeable cations (Na^+, Ca^{2+} and Mg^{2+}) during the last decade proves that these elements mainly come from brackish water and their fixation in depth especially for the case of exchangeable Na^+. In fact, the increase in the exchangeable Na^+ with depth tends to alkalize the soil complex by the phenomena of exchange and therefore conduct the irrigation zone to fail if certain precautions are not taken into consideration. Beside the brackish water effect, the dominance of exchangeable Ca^{2+} compared to other cations is related to its natural origin (calcareous crust). For the exchangeable K^+, the observed comparable contents allow concluding its natural origin. Its low content may weaken the soil fertilizing capacity. Additional contributions of this element would be needed to fill the deficit.

These findings indicate that the use of water with a very high risk of salinization and alkalization has a significant effect on the evolution of the sodium content either in the soil solution or on the adsorbent complex. The sodium accumulation may degrade the soil physical properties and affects its structural stability causing, a clay deflocculation and soil destruction by sodisation in the long terms and reducing soil fertility, resulting in reduced crop yields. According to [32] all studied soils manifest the same risk structural behavior when the rate of sodicity exceeds accepted thresholds.

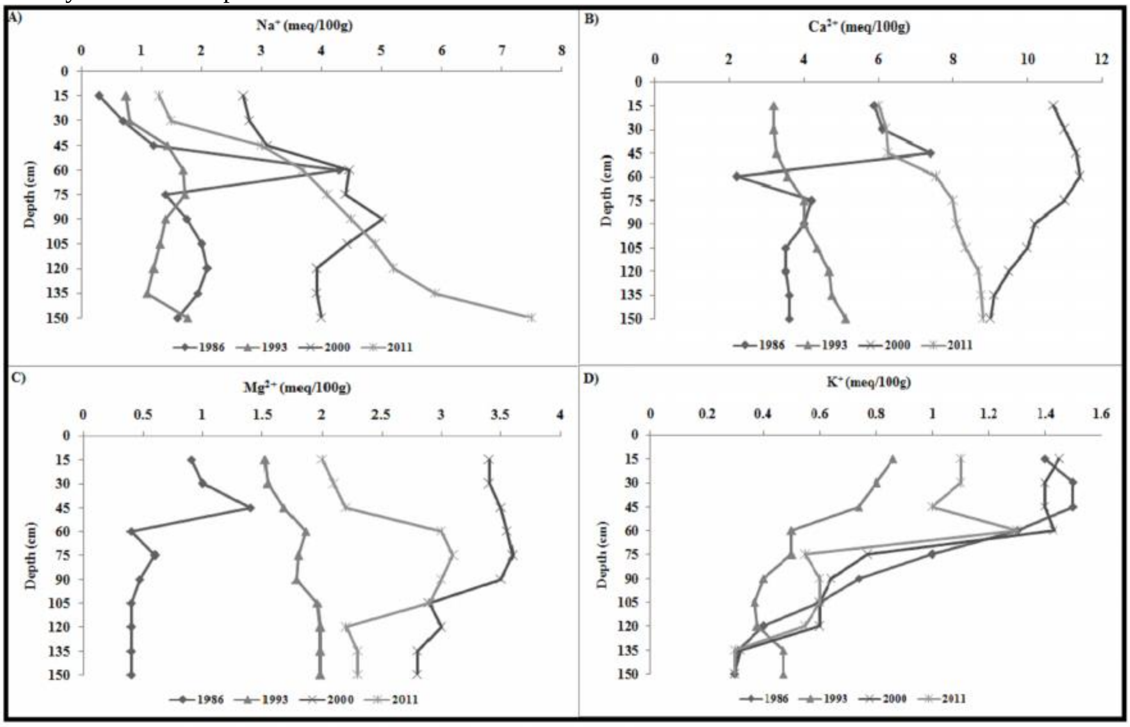

Figure 7. Evolution monitoring of exchangeable cations over time

IV. Conclusion

The fluctuation of soil salinity observed during the period extending from 1986 to 2011, either by salt leaching or by salt accumulation, is mainly due to climatic conditions such as precipitation. During the last decade (2000-2011), the soil of the irrigation zone Zelba 1 evolves in a saline way with ECe values exceeding 4 dS/m. This largely explains the poor-quality of water used in irrigation. In fact, this water, characterized by the abundance of sulfates and sodium chlorides, has a very high risk of salinization and alkalization where the mean value of EC is about 7 dS/m and the mean value of SAR is about 15.

Regarding soil sodicity, a fluctuation of the cationic composition of the soil solution and the soil adsorbent complex was observed along the soil profile as did the soil salinity. The soil enrichment by soluble and exchangeable sodium during the last decade compared to the initial state (1986) proves that this element mainly come from brackish water. Moreover, this enrichment can degrade the soil physical properties causing clay deflocculation and soil destruction by sodisation in the long term, either by the decrease of its permeability or a reduction of its infiltration rate, etc.

These findings indicate that the use of water with a very high risk of salinization and alkalization has a significant effect on soil salinity evolution and on the evolution of the sodium content either in the soil solution or on the adsorbent complex. In this regard, it would be necessary to study soil salinization by multiplying the methods of monitoring of the salinity, set up a drainage system to prevent the concentration of salts and introduce modeling in order to simulate the soil salinity evolution. The use of crops varieties that tolerate soil salinity is essential in order to overcome soil salinization. It would be also necessary to push the works of control and surveillance in this irrigation zone by studying soil sodisation, its current status and its evolution before predicting possible soil structure degradation. Furthermore, chemical amendment including gypsum ($CaSO_4, \cdot 2H_2O$), is a good solution in order to reduce soil sodisation, improve physical and chemical soil properties and finally provide good productivity.

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