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Effects of treated wastewater irrigation on soil salinity and sodicity in Sfax (Tunisia): A case study

Effets de l'irrigation par les eaux usées traitées sur la salinité et la sodicité des sols de Sfax (Tunisie) : Un cas d'étude

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Article abstract

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The fluvisol, irrigated for only four years, is more affected by salinity than the calcisol irrigated for 15 years. In the upper fluvisol layer irrigated by the treated wastewater, ECs reach 8 mS•cm^{-1} and ESP a value of 15% while in all layers of the calcisol, ECs and ESP are lower and rarely exceed 4 mS•cm^{-1} and 6% respectively. This result is due to a combination of factors in the fluvisol treatment area including texture, cation exchange capacity, irrigation procedure and crop management.

RSE

EFFECTS OF TREATED WASTEWATER IRRIGATION ON SOIL SALINITY AND SODICITY IN SFAX (TUNISIA): A CASE STUDY

Effets de l'irrigation par les eaux usées traitées sur la salinité et la sodicité des sols de Sfax (Tunisie): Un cas d'étude

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ABSTRACT

In arid regions such as near Sfax (Tunisia), treated wastewater effluents (TWE) are often applied as agricultural irrigation. Irrigation TWE usually contain large amounts of carbon, nitrogen and sodium. The objective of this study was to evaluate the impact of TWE irrigation on soil salinity and sodicity. In the city of Sfax, two sites were selected with two soil types (fluvisol and calcisol) having been irrigated for 4 and 15 years respectively. Soils were sampled at three different depths (0-30, 30-60 and 60-90 cm) in the TWE irrigated area and in a non-irrigated control area. Irrigated and non-irrigated study soils were analyzed for pH, nitrate and ammonia, electrical conductivity (ECs), exchangeable sodium percentage (ESP), sodium absorption ratio (SAR) and soil organic matter.

The fluvisol, irrigated for only four years, is more affected by salinity than the calcisol irrigated for 15 years. In the upper fluvisol layer irrigated by the treated wastewater, ECs reach 8 mS•cm^{-1} and ESP a value of 15% while in all layers of the calcisol, ECs and ESP are lower and rarely exceed 4 mS•cm^{-1} and 6% respectively. This result is due to a combination of factors in the fluvisol treatment area including texture, cation exchange capacity, irrigation procedure and crop management.

Key words: wastewater, irrigation, calcisol, fluvisol, exchangeable sodium, sodium absorption ratio.

RÉSUMÉ

Dans les régions arides telles que le cas de Sfax (Tunisie), les eaux usées traitées (EUT) sont souvent utilisées en irrigation agricole. Généralement, les EUT sont riches en composés organiques, en azote et en sodium. L'objectif de cette étude est d'évaluer l'impact de l'irrigation par les EUT sur la salinité et la sodicité des sols. Dans la région de Sfax, deux sites ont été sélectionnés, représentant deux types de sols différents (fluvisol et calcisol) irrigués par les EUT, respectivement

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depuis 4 et 15 ans. Des échantillons des sols ont été prélevés systématiquement à trois profondeurs différentes (0-30, 30-60 et 60-90 cm) au niveau des parcelles irriguées et sur des placettes contrôle non irriguées (témoin). Sur chaque échantillon composite de sol, les pH (eau, KCl), teneurs en nitrate et ammonium, capacité d'échange cationique (CEC), conductivités électriques (CEs), taux de sodium échangeable (ESP), ratios d'absorption de sodium et teneurs en matières organiques ont été mesurés.

Le fluvisol, irrigué depuis seulement quatre ans, est plus affecté par la salinité que le calcisol, irrigué depuis 15 ans. Dans les niveaux de surface du fluvisol, la CEs et l'ESP ont atteint les seuils critiques de 8 mS•cm^{-1} et 15 % respectivement, alors qu'au niveau du calcisol, la CEs et l'ESP sont plus faibles et dépassent rarement 4 mS•cm^{-1} et 5 % respectivement. Pour le fluvisol, ce résultat est dû à la combinaison de plusieurs facteurs impliquant la texture, la capacité d'échange cationique, la procédure d'irrigation et la rotation des cultures.

Mots clés: eaux usées, irrigation, calcisol, fluvisol, sodium échangeable, taux d'absorption du sodium.

1. INTRODUCTION

Growing concerns about water scarcity associated with population rise are due to increasing water demands *per capita*, with improvement of standards of living and intensification of agricultural activities. KIZILOGLU *et al.* (2007) point out that consumption of existing water resources has reached its maximum amount. Accelerated urbanization threatens the supply of water for agriculture, and leads to both increases in water consumption and pollution of water resources (BAHRI, 2002). Continuing increases in demand of fresh domestic water by the urban sector have indeed produced greater volumes of wastewater. Therefore, in arid and semi-arid countries such as Tunisia which are facing rising serious water shortage problems, reuse of urban wastewater for non-potable purpose, such as agriculture (BAHRI, 2002; HARUVY, 1997) has become an important concern. Indeed, wastewater reuse for irrigation offers some attractive environmental and socio-economic benefits including: a) reduction of effluent disposal in receiving water bodies, b) supply of nutrients as fertilizer and c) improvement in crop production during the dry season (PESCOD, 1992; YADAV *et al.*, 2002). However, planners are aware of the potential disadvantages of wastewater reuse for irrigation which are, aside from pathogenic contamination of irrigated crops, mainly related to their specific chemical composition being somewhat different from most natural waters used in irrigation (COPPOLA *et al.*, 2004).

Wastewater generally contains high concentrations of suspended and dissolved solids, both organic and inorganic (*e.g.* chloride, sodium, boron and selected heavy metals), that are added to wastewater during domestic and industrial usage (LEVINE and ASANO, 2004). Most of the salts added are only partially removed during conventional sewage treatment (secondary and tertiary), so they remain in the irrigation water (TARCHITZKY *et al.*, 1999). Previous studies related to the changes in soil salinity and sodicity after irrigation with wastewater are mostly based on short-term laboratory experiments with continuous water flow in packed soil columns (JALALI *et al.*, 2008) or on controlled field experiments conducted in small plots (GLOAGUEN *et al.* 2007; HERPIN *et al.* 2007; HULUGALLE *et al.*, 2006). However, little is known about the time needed for soil salinization to appear in real agricultural conditions.

This study focuses on the impact of TWE irrigation on soil salinity and sodicity on a calcisol and a fluvisol which have been irrigated for 15 and 4 years respectively in the irrigated area of the arid region of Sfax (Tunisia). At Sfax (second largest city in Tunisia), signs of extremely low groundwater levels have been recorded over the last three decades due to the increasing number of wells used for crop irrigation (BOURI *et al.*, 2008). The Sfax treated wastewater has been reused for irrigation since 1989. The irrigated area has been extended to an area of 600 ha. A new extension doubling the current wastewater irrigated area is planned.

This study is part of a research program evaluating the impact of wastewater application on both soil and crop properties. The goals of this study are to aid management of crop irrigation by wastewater, to reduce overexploitation of the local groundwater resources and to improve its recharge.

2. MATERIALS AND METHODS

2.1 Study area

The irrigation area is located ten kilometres west of the town of Sfax (approximately one million inhabitants), next to the sewage treatment plant (Figure 1) in crop fields which are irrigated with TWE. The wastewater treatment plant receives domestic effluents and industrial effluents, predominantly from canning factories and textile production. The region has an arid climate with mean monthly air temperatures ranging from 11.3 to 26.7°C, dry summers and annual rainfall of 200 mm mostly occurring from October to December. An average annual potential evaporation of 1,200 mm, combined with the low rainfall and high temperatures, make irrigation essential for crop production.

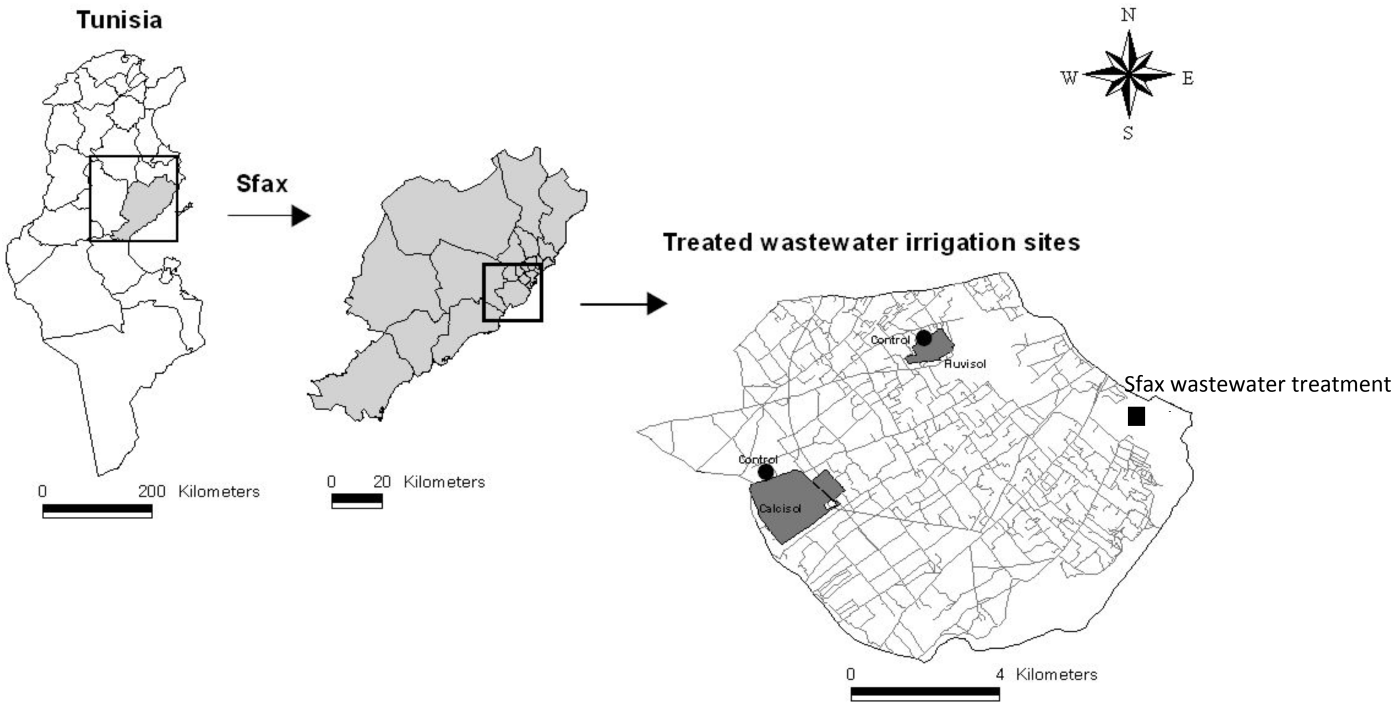

Figure 1. Map of study area with location of the Sfax water treatment plant and of calcisol and fluvisol fields within the TWE irrigation perimeter.
Carte de localisation de la station d'épuration de Sfax et des parcelles du calcisol et du fluvisol au niveau du périmètre irrigué par les eaux usées traits (EUT)

The present survey was carried out at two selected sites chosen to represent both the soil type diversity and the variety of local agricultural practices and irrigation systems. Two main soil types occur in the study area (Table 1): calcisols and fluvisols (according to the FAO World reference base for soil resources, 1998). The calcisols have a homogeneous sandy to sandy loam texture, whereas the fluvisols present a clayey sand texture at the soil surface and a fine sandy texture below 0.5 m depth. As shown in table 1, the two selected areas produce alternate cycles of crops with successive winter and summer harvests of annual crops (oat, sorghum) separated every ten years by a three year-long cropping of alfalfa. However, due to differences in soil properties, the selected study fields are subjected to different agricultural practices. The calcisol field is used for production of successive winter and summer forage crops in association with permanent harvesting of olives. This kind of cropping system requires irrigation by open surface furrows distributed every 24 m in between each row of olive trees. For the fluvisol field, irrigation is performed by direct surface submersion for the summer crops and by sprinkler aspersion for the winter crops. The two study areas also differ in their irrigation duration (Table 1). The fluvisol study field has been irrigated with TWE for only four years whereas the calcisol has been subjected to TWE irrigation for 15 years. In order to assess the effect of the wastewater, non-irrigated fields of both soil types (i.e. control) were selected near each irrigated field. Relative areas of irrigated and non-irrigated fields are indicated in table 1.

2.2 Sampling, preparation and analyses

Treated effluents were sampled at the outlet of the Sfax wastewater treatment plant at different times and conserved at a -4°C before characterization. Effluent samples were analyzed for pH and electrical conductivity using a pH meter (AFNOR standard method N° NF T 90-008, see AFNOR, 1997) and a conductimeter (AFNOR N° NF EN 27888) respectively. Chemical oxygen demand (COD), suspended solids (SS), biochemical oxygen demand (BOD) and total phosphorus were measured according to standard methods (AFNOR N° NF T 90-018, NF EN 872, NF T 90-103, NF EN 1189). Cations and anions were measured using ion chromatography and trace metals by using Furnace Atomic Absorption Spectrometry after aqua regia acid digestion (AFNOR N° NF EN ISO 15587-1). Carbonates and bicarbonates were estimated by titration with HCl of an aliquot of the effluent samples (AFNOR N° NF EN ISO 9963-2).

Soil sampling was performed in October 2006 after the harvest of summer crops and before seeding of winter crops. Sampling was carried out with an Edelman-type auger on summer crops plots only. At each sampling point, samples were taken from three layers: 0-30, 30 60 and 60-90 cm depth. In order to account for spatial variation of soil texture and soil depth, all soil samples correspond to a composite sample collected at the tips of an equilateral triangle of sides of 8 to 10 m long. Seven composite samples were collected at the irrigated

Table 1. Main characteristics of study sites

Tableau 1. Principales caractéristiques des sites étudiés

Characteristics	**Calcisol**	**Fluvisol**
Soil taxonomy [a]	Light texture isohumic calcimagnesic soil	Fine texture slightly developed soil
Soil depth	Moderately deep soil laid over a limestone crust approximately 60 cm deep (the crust was dismantled in most of the irrigated area).	Very deep (> 150 cm)
Soil texture	Sandy to sandy-loam with calcareous nodules in subsurface	Fine sandy to clayey in surface layer (0-60 cm); fine sandy in subsurface
Soil bulk density (surface layer)	1.4 $g{\bullet}cm^{-3}$	1.54 $g{\bullet}cm^{-3}$
Total $CaCO_3$	5 to 35%	5 to 13%
CEC [b] ($cmol^+{\bullet}kg^{-1}$)	5 to 10 (all depths)	11 to 25 (surface layer) 7 to 16 (subsurface layer)
Cultural system	Associated cultivars (olives trees and forage crops)	Single cultivar (forage crops) with regular incorporation of organic matter
Crop rotation	Winter (oats, ray grass) summer (sorghum) annual (alfalfa)	Winter (oats, ray grass) summer (sorghum) annual (alfalfa)
Irrigation rate	1000 $mm{\bullet}yr^{-1}$	1000 $mm{\bullet}yr^{-1}$
Total area of irrigation perimeter	270 hectares	70 hectares
Area of irrigated summer crops	90 hectares	30 hectares
Area of neighbouring control field	1.5 hectares	0.7 hectares
Irrigation system	Surface irrigation by furrows	Surface and/or sprinkle irrigation
Irrigation time	15 years	4 years
Number of composite samples collected in irrigated fields	8	3

[a] Tunisian pedologic map; [b] cation exchange capacity measured by the cobaltihexamine method

calcisol site, three at the fluvisol site and only one composite sample in the non-irrigated fields (control sites), according to the respective areas of each field (Table 1). This sampling took place in the central part of each field, so as to avoid boundary effects. At the calcisol control site, only two soil layers could be sampled because of the occurrence of a concreted carbonate crust at a depth of 60 cm. This crust, of sedimentary origin, is irregular and has been generally dismantled in the irrigated field in order to help infiltration of the treated wastewater.

After air-drying, the soil samples were sieved at 2 mm. Soil pH was measured in a 2:5 soil: water slurry using a glass electrode. Soil sample CEC was determined at actual soil pH by the cobaltihexamine method (ORSINI and REMY, 1976), to avoid influence of soluble salts in the quantification of the soil CEC. Exchangeable cations were measured after exchange with the cobaltihexamine at actual soil pH and also at pH 7 by the buffered Metson method, after exchange with 1 M ammonium acetate solution (METSON, 1956). Exchangeable cations were extracted with 1 M ammonium acetate with a 1:4 soil-to-extractant ratio, shaken for 2 h. Determination of exchanged Ca^{2+} and Mg^{2+} was performed by Atomic Absorption Spectrophotometry (AAS) whereas exchanged Na^+ and K^+ concentrations were determined by Flame Atomic Emission Spectrometry (FAES). Salinity of wastewater and soil was first estimated by measurements of the electrical conductivity (ECw and ECs for water and soil respectively). The electrical conductivity of the soil samples (ECs) was determined on saturated paste extracts of soils (U.S. SALINITY LABORATORY STAFF, 1954). The soil sodicity was also assessed by the exchangeable sodium percentage (ESP, calculated as:

$$\mathrm{ESP}(\%) = \frac{\mathrm{Na}^{+}_{\mathrm{exch}}}{(\mathrm{Ca}^{2+}_{\mathrm{exch}} + \mathrm{Mg}^{2+}_{\mathrm{exch}} + \mathrm{K}^{+}_{\mathrm{exch}} + \mathrm{Na}^{+}_{\mathrm{exch}})} \times 100 \quad (1)$$

(Na^+ exch, Mg^{2+} exch, Ca^{2+} exch and K^+ exch are the concentrations of exchangeable cations extracted from soil samples by the Metson method, expressed in $cmol^+{\bullet}kg^{-1}$).

Potential risk of sodification of water and soils has also been estimated by the sodium absorption ratio (SAR); SARs and SARw are respectively the sodium absorption ratio for soil and water samples:

$$\mathrm{SAR} = \frac{\mathrm{Na}^{+}_{\mathrm{exch}}}{\sqrt{0.5(\mathrm{Ca}^{2+}_{\mathrm{exch}} + \mathrm{Mg}^{2+}_{\mathrm{exch}})}} \qquad (2)$$

(Na^+ exch, Mg^{2+} exch and Ca^{2+} exch are either the concentration of exchangeable cations in soils as determined by extraction with the Metson method, expressed in $\mathrm{cmol}^+ \bullet \mathrm{kg}^{-1}$, or the concentrations in wastewater, expressed in $\mathrm{mEq} \bullet \mathrm{L}^{-1}$).

NO_3 and NH_4 concentrations were measured in water soluble extracts using ion chromatography (DIONEX DX-120) after water extraction using a 1:5 soil: water for 2 h. Soil organic matter (SOM) was determined by the Walkley and Black dichromate oxidation method (JACKSON, 1958; WALKLEY and BLACK, 1934).

2.3 Statistical analysis

For each soil type, one-sample T-test was used for comparing mean values obtained from replicates of measurements at an irrigated site to the values measured at the corresponding non-irrigated control site. All measured values correspond to average composite samples. However, due to the limited area of the control sites, and since the sampling was limited to the central part of these control sites in order to avoid any influence of the neighbouring irrigation, no replicate control samples were collected, and thus no variance is associated with the control value. Hence, we have assumed that the value from the control site represents an exact mean to be compared within the variance of the replicated mean values measured at the corresponding irrigated site. Variance is expected to be larger in the irrigated zone than in the corresponding control zone, so that the following one sample T-tests can be considered as conservative:

$$T = \frac{\textit{(mean of TWE irrigated replicated values - control value)}}{\textit{standard deviation of TWE irrigated replicated values}} \qquad (3)$$

A unilateral T-test was calculated for the parameters which clearly increase or decrease after the irrigation by the treated wastewater (ECs, ESP, NO_3 and NH_4). For parameters presenting no obvious response to the irrigation (pH, CEC, SOM), a bilateral T-test was chosen. The global risk increases with the number of simultaneous tests performed. Therefore, we have also adopted a more severe individual rule than the usual one to minimize the increase of the global risk: the differences are considered significant when $p < 1\%$ instead of $p < 5\%$. In case of p ranging between $1\% < p < 5\%$, we conclude that the differences have to be confirmed. The T-tests were performed using SYSTAT Software version 13.

3. RESULTS

3.1 Treated wastewater characteristics

Characteristics of treated wastewater effluents (TWE) used for irrigation varied within and among the years of application (Table 2). Therefore, only ranges of variation of parameters

Table 2. Minimum and maximum values of water quality parameters in the treated wastewater effluents (TWE) generated by the wastewater treatment plant of Sfax, as characterized since 1984.

Tableau 2. Valeurs minimales et maximales des paramètres de la qualité des eaux usées traitées de la station d'épuration de Sfax, caractérisés depuis 1984.

Parameter	Sfax effluent	Standards*
pH	(7.1-8.7)	6.5 – 8.5
ECw $\mathrm{mS} \bullet \mathrm{cm}^{-1}$	(4-7.7)	7
TDS $\mathrm{g} \bullet \mathrm{L}^{-1}$	(3.56-5.13)	-
SS $\mathrm{mg} \bullet \mathrm{L}^{-1}$	(29-275)	30
COD $\mathrm{mg} \bullet \mathrm{L}^{-1}$	(123-700)	90
BOD_5 $\mathrm{mg} \bullet \mathrm{L}^{-1}$	(37-220)	30
Pt $\mathrm{mg} \bullet \mathrm{L}^{-1}$	(2.9-12.5)	-
NO_3^- $\mathrm{mg} \bullet \mathrm{L}^{-1}$	(0.35-50)	-
Cl^- $\mathrm{mg} \bullet \mathrm{L}^{-1}$	(903-2580)	2000
SO_4^{2-} $\mathrm{mg} \bullet \mathrm{L}^{-1}$	(508-1950)	-
HCO_3^- $\mathrm{mg} \bullet \mathrm{L}^{-1}$	(490-732)	-
Na^+ $\mathrm{mg} \bullet \mathrm{L}^{-1}$	(780-2100)	-
K^+ $\mathrm{mg} \bullet \mathrm{L}^{-1}$	(17-105)	-
Mg^{2+} $\mathrm{mg} \bullet \mathrm{L}^{-1}$	(129-209)	-
Ca^{2+} $\mathrm{mg} \bullet \mathrm{L}^{-1}$	(103-521)	-
NH_4^+ $\mathrm{mg} \bullet \mathrm{L}^{-1}$	(61-73)	-
Cd $\mathrm{mg} \bullet \mathrm{L}^{-1}$	(0.001-0.07)	0.01
Cr $\mathrm{mg} \bullet \mathrm{L}^{-1}$	(0.007-1.1)	0.1
Cu $\mathrm{mg} \bullet \mathrm{L}^{-1}$	(<0.01-0.06)	0.5
Fe $\mathrm{mg} \bullet \mathrm{L}^{-1}$	(<0.013-1.69)	5
Mn $\mathrm{mg} \bullet \mathrm{L}^{-1}$	(0.04-0.17)	0.5
Ni $\mathrm{mg} \bullet \mathrm{L}^{-1}$	(0.02-0.13)	0.2
Pb $\mathrm{mg} \bullet \mathrm{L}^{-1}$	(0.001-0.37)	1
Zn $\mathrm{mg} \bullet \mathrm{L}^{-1}$	(0.01-0.27)	5
SARw	(9.7-15.6)	-

EC: electric conductivity; TDS: total dissolved solids; SS: suspended matter; COD: chemical oxygen demand; BOD: biochemical oxygen demand; Pt: total phosphorous; SARw: sodium absorption ratio.

* Tunisian standards for wastewater reuse in irrigation (NT 106.03)

that are regularly measured were reported in Table 2. The applied wastewater always remained alkaline with an average pH of 7.7 (Table 2). It always presented a high level of total dissolved solids (TDS) of 3.7 g•L^{-1} and a high level of suspended matter (SS). Levels of biochemical oxygen demand (BOD) and chemical oxygen demand (COD) indeed always largely exceeded the Tunisian standards for wastewater reuse in irrigation (NT 106.03). The mean electrical conductivity (ECw) of the effluents reached 5.7 mS•cm^{-1}, which places the Sfax TWE in the class of high salinity according to the FAO legislation (AYERS and WESTCOT, 1985). The sodium absorption ratio (SARw) of the treated wastewater ranged between 9.7 and 15.6. According to the FAO guidelines (AYERS and WESTCOT, 1985), TWE presenting similar SARw and as high values of electrical conductivity (i.e. ECw > 2 mS•cm^{-1}) falls into the moderate to severe category for inhibiting infiltration. The elevated ECw and SARw values of the studied effluent are mainly explained by the abundance of free ions such as Na^+, Cl^- and SO_4^{2-} (Table 2).

Although most of the previously mentioned parameters exceed the Tunisian or FAO standards for wastewater reuse in agriculture, the Sfax TWE also contain large amounts of nitrate, phosphate and potassium, which are crucial nutrients for plant growth and soil fertility. Moreover, with the exception of Cr, concentrations of micronutrients and metals in the applied wastewater are relatively low and always met the Tunisian standards.

3.2 Calcisol response to the 15-year long TWE irrigation

The calcisol soil water extract was alkaline at all three depths and at all sampling points (Figure 2a). There are no significant differences in soil pHw (Table 4) between the wastewater irrigated calcisol (IWC) and the control calcisol (NIC). This indicates that 15 years of TWE irrigation has not affected the pH of the calcisol, a result that can be explained by the buffer capacity of this soil. Calcium represents the most abundant exchangeable base cation (Table 3) and therefore calcium is the major cation, despite the relatively low total exchange capacity of cations (< 10 cmol$^+$•kg^{-1}, Table 2). Calcium remains constant in the different soil layers, both in the irrigated calcisol and in the non-irrigated control calcisol (Table 3). In contrast, exchangeable Mg^{2+}, K^+ and Na^+ contents are generally higher in the irrigated calcisol, at all depths.

Soil CEC was determined with the cobaltihexamine method, which minimizes carbonate and salt dissolution (OLIVIER, 1984). Comparing the Metson method with the cobaltihexamine method (Table 3), higher values of exchangeable cations were systematically obtained by the Metson method, suggesting salt and carbonate dissolution in the latter method. With the exception of Ca^{2+}, there are significant linear correlations ($p < 0.05$) between the CEC obtained by the two methods for Na^+ (R = 0.94), K^+ (R = 0.79) and Mg^{2+} (R = 0.99). These results confirm the natural inorganic origin of Ca^{2+}. Calcium content certainly reflects the presence of Ca^- carbonates, whereas Mg^{2+}, K^+ and Na^+ can be attributed largely to the relatively high concentrations of soluble salts in the TWE used for irrigation.

Examination of the electrical conductivity of the saturation paste soil extracts (ECs) confirms that the 15-year long irrigation period by the Sfax TWE led to a significant supply of ions into the calcisol (Table 4; Figure 2b), even in the deepest layers. As a consequence, soil salinity is up to 4 mS•cm^{-1} at all depths, and sometimes exceeds this level such as at point IWC1 (Figure 2b).

The calcisol field irrigated by TWE displays ESP values significantly higher than those of control field at all depths (Table 4). Compared to the control calcisol, the sodicity of the irrigated calcisol increased from 90% to 360% in the first soil layer and from 226% up to 663% in the second soil layer. The ESP even reaches the value of 5.7% at site IWC1 (Figure 2c). However, this sodicity is still of lesser amount than that of sodic soils (ESP < 15%).

Analyses of the ammonium and nitrate concentrations in the soil water extract and the soil organic matter also reveal the impact of the irrigation by the Sfax TWE. In the irrigated calcisol, the NH_4^+ contents remain low and never exceed 0.1 cmol$^+$•kg^{-1} of dry soil (Figure 2d). However, as with the other base cations originating from the applied wastewater, the NH_4^+ content of the calcisol generally increases with depth and is significantly higher in the irrigated calcisol compared to the non-irrigated one (Table 4). Similar to NH_4^+ and other base cations, nitrate is also found in the deepest 60-90 cm soil layer, confirming drainage of the added TWE in the calcisol (Figure 2e). Although much more variable than NH_4^+, the NO_3^- content of the soil water extracts is also systematically higher in the irrigated calcisol than in the non-irrigated calcisol (Table 4). Soil organic matter content (Figure 2f) follows a similar trend with values decreasing with depth in the irrigated calcisol. However, the SOM contents are not significantly different between the irrigated and the control calcisol (Table 4).

3.3 Fluvisol response to the 4-year long TWE irrigation

In the fluvisol, irrigated for four years, soil pHw is alkaline but lower than in the calcisol (Figure 3a). In contrast to the calcisol, the fluvisol pHw is significantly higher in the control field (NIF) than in the irrigated fluvisol (IWF) in the subsoil layers (Table 4). In addition, pHw of the control fluvisol increases from 8.4 up to 9 with depth, whereas pHw

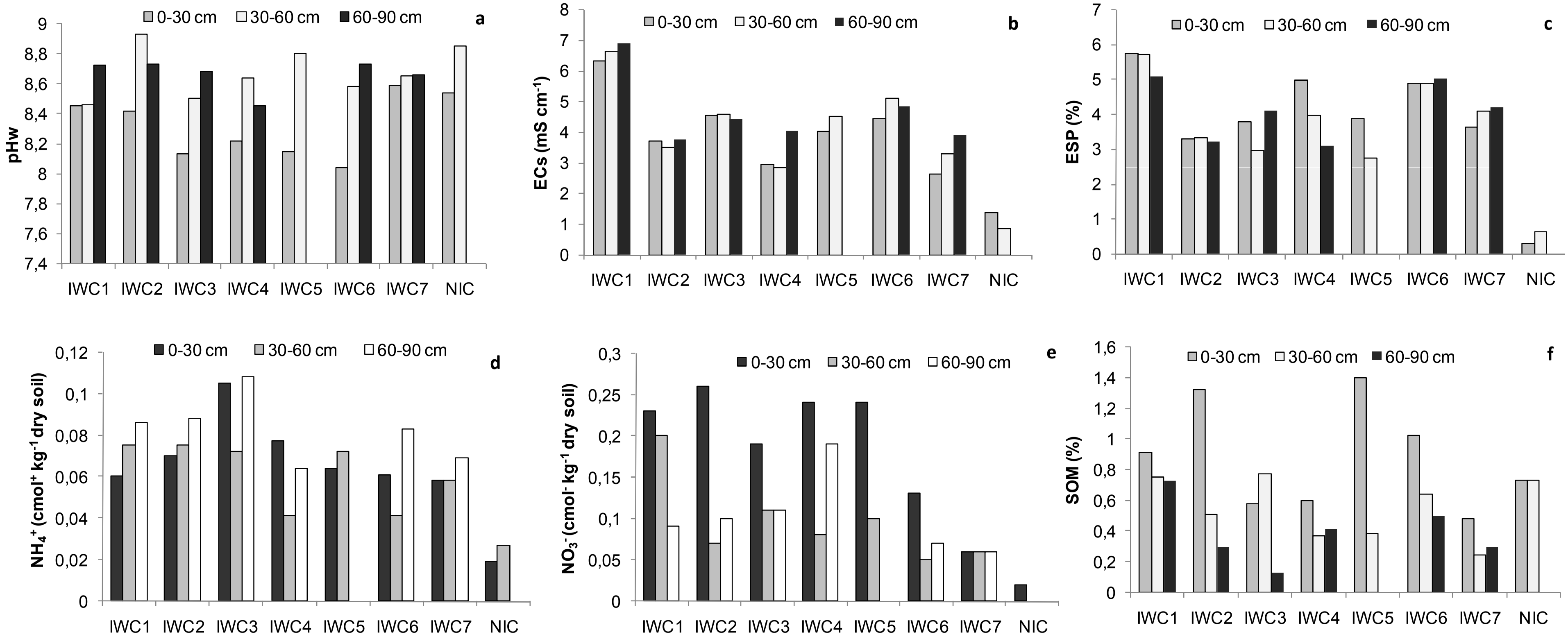

Figure 2. **Calcisol properties in irrigated (IWC) and non-irrigated (NIC = control) field. a) pH in soil-water extract; b) electrical conductivity of extract paste (ECs); c) exchangeable sodium percentage (ESP); d) NH4$^+$ content in water extract; e) NO_3^- content in water extract; f) soil organic matter content (SOM).**

Propriétés du calcisol irrigué (IWC) et non irrigué (NIC = control). a) pH de l'extrait aqueux du sol; b) conductivité de la pâte saturé du sol (ECs); c) pourcentage du sodium échangeable (ESP); d) teneurs en NH_4^+ soluble; e) teneurs en NO_3^- soluble; f) teneur en matière organique du sol (SOM).

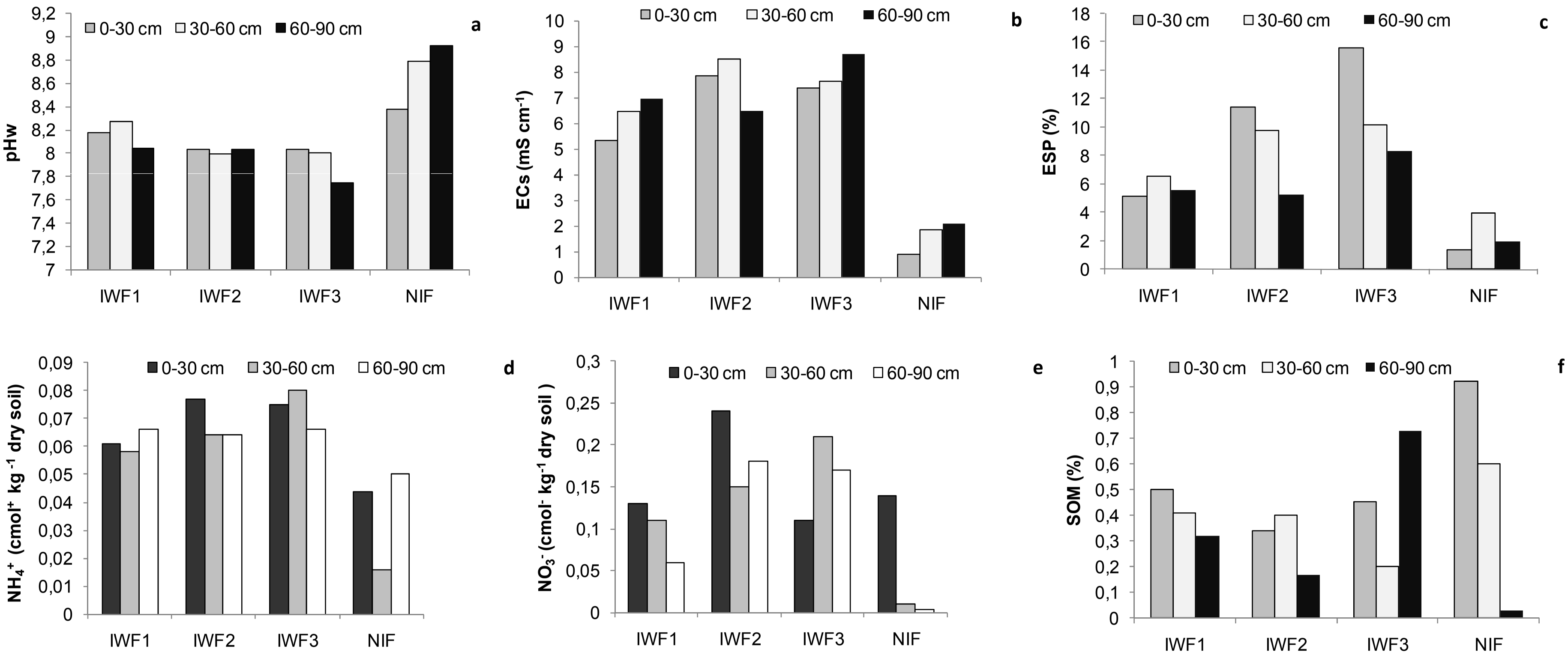

Figure 3. **Fluvisol properties in irrigated (IWF) and non-irrigated (NIF = control) soil. a) pH in soil-water extract; b) electrical conductivity of extract past (ECs); c) exchangeable sodium percentage (ESP); d) NH_4^+ content in water extract; e) NO_3^- content in water extract; f) soil organic matter content (SOM).**
Propriétés du fluvisol irrigué (IWC) et non irrigué (NIC = control). a) pH de l'extrait aqueux du sol; b) conductivité de la pâte saturé du sol (ECs); c) pourcentage du sodium échangeable (ESP); d) teneurs en NH_4^+ soluble; e) teneurs en NO_3^- soluble; f) teneur en matière organique du sol (SOM).

Table 3. **Contents in exchangeable base cations and SAR of irrigated and non-irrigated soils, obtained respectively by the Metson method (bold) and by the cobaltihexamine method (in brackets).**

Tableau 3. ***Teneurs en bases échangeables et valeurs du SAR des sols irrigués et non irrigués, obtenues respectivement par la méthode de Metson (en gras) et la méthode de cobaltihexamine (entre parenthèses)***

Soil depth (cm)	Ca^{2+} (cmol^{+}•kg^{-1})			Mg^{2+} (cmol^{+}•kg^{-1})			K^{+} (cmol^{+}•kg^{-1})			Na^{+} (cmol^{+}•kg^{-1})			SARs		
	0-30	**30-60**	**60-90**	**0-30**	**30-60**	**60-90**	**0-30**	**30-60**	**60-90**	**0-30**	**30-60**	**60-90**	**0-30**	**30-60**	**60-90**
Calcisol															
IWC1	**44.3**(3.8)	**43.5**(4.0)	**47.8**(4.0)	**6.6**(2.07)	**5.8**(1.87)	**5.4**(1.77)	**11.9**(0.64)	**10.9**(0.52)	**8.6**(0.52)	**3.8**(1.14)	**3.7**(1.1)	**3.3**(1.14)	0.75	0.73	0.64
IWC2	**47.3**(6.2)	**41.3**(5.4)	**50.0**(3.9)	**6.4**(2.07)	**5.0**(1.77)	**5.4**(1.77)	**15.2**(0.86)	**14.3**(0.77)	**13.0**(0.67)	**2.3**(0.83)	**2.1**(0.72)	**2.3**(0.73)	0.45	0.43	0.43
IWC3	**42.5**(3.7)	**45.5**(3.7)	**46.3**(3.4)	**5.3**(1.77)	**5.4**(1.58)	**5.1**(1.68)	**7.4**(0.55)	**5.9**(0.43)	**7.6**(0.43)	**2.2**(0.88)	**1.7**(0.73)	**2.5**(0.78)	0.44	0.34	0.49
IWC4	**31.8**(4.3)	**42.0**(4.02)	**36.8**(4.3)	**7.1**(2.37)	**5.8**(1.97)	**5.9**(1.97)	**10.9**(0.64)	**10.9**(0.55)	**8.9**(0.49)	**2.6**(0.67)	**2.4**(0.83)	**1.7**(0.88)	0.59	0.49	0.35
IWC5	**45.5**(4.9)	**48.0**(3.6)	-	**7.2**(2.27)	**5.7**(1.87)	-	**7.6**(0.58)	7.7(0.46)	-	**2.4**(0.83)	**1.7**(0.88)	-	0.47	0.33	-
IWC6	**38.8**(3.7)	**44.3**(3.5)	**44.8**(3.6)	**6.5**(2.07)	**5.8**(1.77)	**5.0**(1.58)	**10.7**(0.89)	**9.2**(0.49)	**8.0**(0.43)	**2.9**(0.99)	**3.0**(0.93)	**3.0**(0.99)	0.60	0.60	0.61
IWC7	**36.8**(3.4)	**41.8**(3.9)	**50.8**(3.7)	**5.8**(1.68)	**5.9**(1.87)	**5.6**(1.87)	**7.9**(0.49)	**9.3**(0.49)	**9.0**(0.49)	**1.9**(0.36)	**2.4**(0.83)	**2.9**(0.88)	0.41	0.49	0.54
NIC	**39.6**(5.0)	**49.5**(6.7)	-	**1.0**(0.69)	**1.3**(0.89)	-	**5.0**(0.34)	**3.9**(0.12)	-	**0.3**(0.1)	**0.7**(0.1)	-	0.07	0.13	-
Fluvisol															
IWF1	**46.0**(7.14)	**44.3**(5.7)	**39.8**(4.9)	**9.7**(3.45)	**8.7**(3.06)	**6.6**(2.27)	**9.4**(0.74)	**8.0**(0.4)	**4.9**(0.3)	**3.5**(1.25)	**4.3**(1.14)	**3.0**(1.1)	1.82	1.55	0.59
IWF2	**44.0**(16.14)	**49.0**(4.02)	**43.3**(6.1)	**8.0**(6.32)	**16.3**(6.32)	**6.2**(2.27)	**20.3**(1.04)	**17.0**(0.89)	**3.9**(1.97)	**9.3**(2.3)	**8.9**(2.13)	**2.9**(1.99)	3.03	1.5	1.13
IWF3	**53.5**(16.32)	**50.3**(18.36)	**59.0**(19.9)	**16.3**(6.62)	**13.2**(5.23)	**7.3**(2.66)	**27.1**(1.04)	**11.5**(0.67)	**5.3**(0.34)	**17.9**(2.34)	**8.4**(2.24)	**6.5**(1.77)	0.23	0.76	0.46
NIF	**55.1**(17.28)	**48.9**(15.84)	**34.6**(4.0)	**5.7**(4.44)	**4.7**(4.54)	**1.2**(0.99)	**19.9**(1.01)	**7.6**(0.64)	**2.3**(0.15)	**1.3**(0.46)	**4.0**(1.25)	**1.9**(0.57)	0.75	0.73	0.64

IWC : Irrigated Wastewater Calcisol ; NIC = control : Not Irrigated Calcisol
IWF: Irrigated Wastewater Fluvisol ; NIF = control : Not Irrigated Fluvisol
SARs: sodium absorption ratio of soil

Table 4. **Effects of TWE irrigation on some soil parameters (soil parameters affected by irrigation compared to control soils showing a $p<0.01$).**

Tableau 4. ***Effets de l'irrigation par les EUT sur quelques paramètres du sol (les paramètres du sol affectés par l'irrigation, comparés au sol témoin montrant un $p<0,01$).***

Parameter	Depth	Control value	Values for irrigated sites			One-sample T-test	
			N	Mean	SEM	T	P (%)
Calcisol							
pH	0-30	8.54	7	8.28	0.0764	-3.32	1.581
	30-60	8.85	7	8.65	0.0626	-3.17	1.924
SOM	0-30	0.73	7	0.90	0.1388	1.23	26.311
	30-60	0.73	7	0.52	0.0772	-2.68	3.638
ECs	0-30	1.38	7	4.09	0.4608	5.89	0.053*
	30-60	0.87	7	4.35	0.4881	7.14	0.018*
ESP	0-30	0.32	7	4.31	0.3359	11.89	0.001*
	30-60	0.65	7	3.96	0.4036	9.20	0.008*
NH_4^+	0-30	0.02	7	0.07	0.0062	8.29	0.008*
	30-60	0.03	7	0.06	0.0058	5.98	0.048*
NO_3^-	0-30	0.02	7	0.19	0.0276	6.26	0.038*
	30-60	0.00	7	0.09	0.0191	5.00	0.122*
Fluvisol							
pH	0-30	8.38	3	8.08	0.0500	-6.00	2.667
	30-60	8.79	3	8.08	0.0917	-7.66	1.658
	60-90	8.92	3	7.94	0.0950	-10.31	0.927*
SOM	0-30	0.92	3	0.43	0.0473	-10.36	0.917*
	30-60	0.60	3	0.33	0.0684	-3.85	6.131
	60-90	0.03	3	0.40	0.1674	2.25	15.329
ECs	0-30	0.92	3	6.86	0.7758	7.66	0.830*
	30-60	1.87	3	7.54	0.5998	9.46	0.549*
	60-90	2.07	3	7.38	0.6701	7.92	0.777*
ESP	0-30	1.30	3	10.69	3.0608	3.06	4.589
	30-60	3.96	3	8.79	1.1353	4.25	2.552
	60-90	1.95	3	6.39	0.9802	4.52	2.272
NH_4^+	0-30	0.04	3	0.071	0.0050	5.36	1.651
	30-60	0.01	3	0.067	0.0066	7.81	0.798*
	60-90	0.05	3	0.065	0.0007	23.00	0.094*
NO_3^-	0-30	0.14	3	0.160	0.0404	0.49	33.485
	30-60	0.01	3	0.157	0.0291	5.04	1.854
	60-90	0.00	3	0.137	0.0384	3.45	3.733

N : number of samples ; T : observed student statistic (T = mean-control) / SEM); SEM: mean standard error for measurements in irrigated field; p %: significant differences ($p<0.01$ indicated with asterisks..

of the irrigated fluvisol remains around 8 at all depths. This observation suggests that the 4-year long TWE irrigation has induced a slight decrease of the soil pHw. Compared to the calcisol, the impact of TWE irrigation on the pHw, ammonium, nitrate and SOM of the fluvisol is less obvious (Figures 3d and 3e). However, in contrast to the calcisol, the SOM content is significantly lower in the upper layer of irrigated fluvisol than in the control fluvisol (Table 4; Figure 3f).

To date, the irrigation by the sodic-saline TWE has mainly affected the upper fluvisol layer. In the topsoil layer of the fluvisol, cation base saturation is not only dominated by the bivalent cations (Table 3) but also includes K^+ in the control fluvisol and Na^+ imported by irrigation water in the irrigated fields. The electrical conductivity of the saturation paste soil extract (ECs) indicates increased soluble salt concentrations in the irrigated fluvisol (Figure 3b). The ECs is significantly higher at all depths in the irrigated fluvisol than in the control (Table 4). Still, in the control profile as well as in the irrigated fluvisol, salinity decreases with depth. The ESP, SARs and ECs values indeed confirm that soluble salts supplied by the TWE are retained in the upper layer of the fluvisol.

4. DISCUSSION

4.1 Factors controlling soil salinity and sodicity

Use of wastewater for irrigation has been recognized to be hazardous with regard to soil salinity as well as soil sodicity. In our case, the applied treated wastewater contains several anionic species (chlorides, sulfates) that are mostly associated with sodium (Table 2). Soils are generally classified as saline when they present an ECs of 4 $mS \bullet cm^{-1}$ or more and are classified as sodic when they present a SARs greater than 13 or an ESP greater than 15% (SUMNER, 1995). Using these guidelines, the control fluvisol as well as the irrigated fluvisol (Figure 3b) are both saline, with ECs values exceeding the level of 4 $m \bullet Scm^{-1}$, whereas the control calcisol is not saline. The irrigated calcisol (Figure 2b) is of moderate salinity (TEDESCHI and DELL' AQUILA, 2005). The calcisol is not sodic whether irrigated for 15 years by the Sfax TWE or not. In contrast, the fluvisol irrigated for only four years is sodic with an ESP ranging between 5 and 15% whereas the control fluvisol is not sodic. Compared to the control, the sodicity is significantly higher in the calcisol irrigated by the Sfax TWE, but not in the irrigated fluvisol (Table 4). It appears that irrigation by the same saline-sodic Sfax wastewater impacted salinity and sodicity in different manners, depending on the soil properties, the irrigation procedure used and the type of crop management.

The studied calcisol and fluvisol mostly differ by their texture. Soil texture strongly influences the soil permeability, the rate of water infiltration and the ability of soil particles to adsorb or desorb chemical ions (exchange capacity) such as Na^+ (BAUDER *et al.*, 2008). Consequently, a clay textured soil of relatively high CEC, such as the studied fluvisol, presents the greatest risk for binding the excess of sodium supplied by the wastewater. The fluvisol is also likely to better retain the salty TWE. For this reason, the studied fluvisol samples present higher contents of exchangeable Na^+. The sandy calcisol has a good permeability and a low CEC (few exchange sites), retains less water and naturally loses water as well as soluble salts from the root zone.

4.2 Factors controlling the extent of salt leaching

Leaching of water and soluble salts occurred in the two studied soil types. Both soil types have been irrigated with TWE containing a high level of TDS and were subjected to high rates of evapotranspiration in the summer growing season. In such contexts, the extent of salt leaching in soils is known to relate to the salt solubility (sodium salts are the most soluble), the irrigation rate (i.e., water quantity), the ion migration rate (controlled by the soil CEC) and the soil permeability (LEVY *et al.*, 2003; TEDESCHI and DELL' AQUILA, 2005). Previous studies (SAIDI *et al.*, 2004; TEDESCHI and DELL' AQUILA, 2005) showed that the soil ESP value is directly related to the rate of NaCl addition by the TWE compared to the ECs. Indeed, the ECs value is more subject to seasonal changes than the ESP value. The ECs of the soil surface layers decreases with the leaching of salt by the TWE and by the autumn-spring rainfalls and increases during the crop season in-between periods of irrigation, due to rise of saline water by evaporation or by root uptake. In our case study, for both the calcisol and the fluvisol, the correlation between ECs and ESP is significant with $r = 0.77$ ($p < 0.05$) for all depths, which suggests that the ECs value is not affected by such seasonal changes.

In the present case, the main factors governing the soil salinization and sodification are the irrigation procedures and choice of crop management. Rate of irrigation during the crop season is regular enough to prevent the rise of salt from the deeper layers. Because crops only remove small amounts of salt (NAKAYAMA and BUCKS, 1986), vertical distribution of salt in soil is directly related to the water movements, which are directly governed by the rate of irrigation. In the studied calcisol, water movement is enhanced first by the good permeability due to the sandy to sandy loam texture and secondly by the dismantlement of the deep calcareous crust that has been performed in the irrigated fields only. In addition, drainage of wastewater is favoured by the density of the permanent irrigation network and finally by the intensive rate of irrigation. Indeed, 1,000 mm of treated wastewater are applied by a furrow irrigation system during the summer in the calcisol fields. This irrigation rate largely exceeds the amount of water required for plant growth, enabling the leaching of salts. Conversely, the irrigation procedure used in the fluvisol mostly led to the salinization of the surface soil layer. Because of its clay texture, its higher CEC and thus its higher water retention capacity, the fluvisol retains more Na^+ and is less permeable than the calcisol. Nonetheless, the fluvisol is permeable enough to enable the leaching of soluble salts. This can be explained by the agricultural practice used at the fluvisol site. Organic matter manure and deep soil tillage are temporarily applied within the annual crop rotation. In other words, the surface soil permeability is improved in periods that are not concerned by the TWE irrigation.

4.3 Risk of structural degradation of the soils over the long term

Research dealing with the environmental impacts of wastewater applications has mostly focused on short-term effects on plant growth and has usually been conducted in experimental plots in open fields (GLOAGUEN *et al.*, 2007; HERPIN *et al.*, 2007; HULUGALLE *et al.*, 2006). Studies examining indirect effects of various TWE qualities (CHOUDHARY *et al.*, 2006; MINHAS *et al.*, 2007; TEDESCHI and DELL' AQUILA, 2005; VAN HOORN *et al.*, 2001) are also generally based on short-term laboratory experiments, sometime using continuous water flow in packed soil columns (JALALI *et al.*, 2008; SUAREZ *et al.*, 2006). In the present study, the impact of the TWE irrigation on soil properties was studied under normal cropping conditions. As a consequence, agricultural practices and irrigation times are not strictly the same for the two studied soil types in contrast to controlled experiments. However, the irrigation times (4 and 15 year-long) correspond to a mid- to long-term period, which is longer than those of most previous field or laboratory experiments.

Since it is not affected by seasonal variations, the ESP value is a more accurate index of the soil aggregate stability than is the ECs (SAIDI *et al.*, 2004; TEDESCHI and DELL' AQUILA, 2005). Following this previous result, the calcisol should present more risks of soil degradation than the fluvisol. Indeed, compared to the control site, the ESP value is significantly higher in the irrigated calcisol only (Table 4). However, assessment of the impact on soil aggregate stability and clay swelling remains complex since many other factors have to be taken into account, as shown by LEVY *et al.* (2003). PESCOD (1992) has reported that irrigation by saline water that presents high SARw does not affect the structure of the irrigated soil when the corresponding ECw is high. Indeed, a relatively high concentration of sodium and high ECw can display antagonistic effects toward the structural stability of soils. Wastewater salinity can cause flocculation and bind fine particles of soil together into aggregates, so that the dispersive effect of the free sodium can be mitigated by the flocculating effect induced by the high electric conductivity. GUPTA and ABROL (1990) have reported that, in calcareous salt-affected soils, Na^- compounds are relatively insoluble in water but soluble in 1 M ammonium acetate, so that they appear in the exchangeable Na^+ fraction. Therefore, in both studied soils, present values of exchangeable Na^+ (Table 3) are probably more related to the presence of salts than to effective sodium saturation of the soil absorption complex. Compared to the calcisol, the amount of exchangeable Na^+ in the fluvisol is much higher and largely exceeds the total CEC. This could explain the high ESP value of the irrigated fluvisol surface layer. In the fluvisol, the build-up of adsorbed Na^+ may induce dispersion of the soil aggregates and cause reduction of the soil permeability, with subsequent crust formation, runoff generation and soil erosion (MINHAS *et al.*, 2007). If the crop management and the irrigation rate are not favourably changed to aid salt dissolution and leaching out of the root zone, more Na-salts will accumulate in the fluvisol surface layer than in the calcisol, which not only exhibits different chemical and physical patterns but also is subjected to more intensive rates of irrigation. In summary, the studied fluvisol, which is inherently more prone to structural dispersion than the calcisol, is also managed in such a way that the risk of structural degradation is enhanced.

5. CONCLUSIONS

Irrigation by the Sfax saline-sodic treated wastewater effluents (TWE) has significantly increased the soil salinization and sodification of both studied soil types, particularly in the study area of Sfax characterized by limited rainfall and high evaporation. Generally, wastewater irrigation management aims at ensuring leaching of salts below the root systems (MOHAMMAD RUSAN *et al.*, 2007). Here, this is not the case either for the calcisol or the fluvisoil, which both display elevated SARs and ESP in the deepest soil layers.

Irrigation by the Sfax TWE has affected the salinity, sodicity and SOM content of the two studied soils in different manners, not only because of the different soil properties, but also due to the different crop management and irrigation procedures. Soil CEC and buffer capacity as well as initial soluble carbonate and salt contents are the main factors controlling the extent of soil salinization and salt leaching. Organic matter addition, soil tillage and rate of irrigation are the human factors determining the risk of further permanent structural degradation of the soil.

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7. BIBLIOGRAPHICAL REFERENCES

AFNOR (1997). *Qualité de l'eau, méthodes d'analyses 3*. AFNOR (Editor), tome 4, 296 p.

AYERS R.S. and D.S. WESTCOT (1985). *Water quality for agriculture*. Irrigation and Drainage Paper, 29, FAO, Rome, 174 p.

BAHRI A. (2002). Water reuse in Tunisia: stakes and prospects; In: *Actes de l'Atelier du PCSI*, 28-29 mai, Montpellier, France, 11 p.

BAUDER J.W., K.R. HERSHBERGER and L.S. BROWNING (2008). Soil solution and exchange complex response to repeated wetting–drying with modestly saline–sodic water. *Irrig. Sci.*, 26,121-130.

BOURI S., H. ABIDA and H. KHANFIR (2008). Impacts of wastewater irrigation in arid and semi-arid regions: case of Sidi Abid region, Tunisia. *Environ. Geol.*, 53, 1421-1432.

CHOUDHARY O.P., B.S. GHUMAN, A.S. JOSAN and M.S. BAJWA (2006). Effect of alternating irrigation with sodic and non-sodic waters on soil properties and sunflower yield. *Agric. Water Manage.*, 85, 151-156.

COPPOLA A., A. SANTINI, P. BOTTI, S. VACCA, V. COMEGNA and G. SEVERINO (2004). Methodological approach for evaluating the response of soil hydrological behavior to irrigation with treated municipal wastewater. *J. Hydrol.*, 292, 114-134.

FAO (1998). *World reference base for soil resources, by ISSS–ISRIC–FAO*. World Soil Resources Report N°. 84. Rome, 88 p.

GLOAGUEN T.V., M. CRISTINA FORTI, Y. LUCAS, C.R. MONTES, A.B. GONCALVES ROBERTA, U. HERPIN and A.J MELFI (2007). Soil solution chemistry of a Brazilian oxisol irrigated with treated sewage effluent. *Agric. Water Manage.*, 88, 119-131.

GUPTA R.K. and I.P. ABROL (1990). Salt-affected soils: their reclamation and management for crop production. *Adv. Soil Sci.*, 11, 223-288.

HARUVY N. (1997). Agricultural reuse of wastewater: nation-wide cost-benefit analysis. *Agri. Ecosyst. Environ.*, 66, 113-119.

HERPIN U., T.V. GLOAGUEN, A.F. DA FONSECA, C.R. MONTES, F.C. MENDONÇA, R.P. PIVELI, G. BREULMANN, M.C. FORTI and A.J. ET MELFI (2007). Chemical effects on the soil-plant system in a secondary treated wastewater irrigated coffee plantation - a pilot field study in Brazil. *Agri. Water Manage.*, 89, 105-115.

HULUGALLE N.R., T. B. WEAVER, H. GHADIRI and A. HICKS (2006). Changes in soil properties of an eastern Australian vertisol irrigated with treated sewage effluent following gypsum application. *Land Degrad. Develop.*,17, 527-540.

JALALI M., H. MERIKHPOUR, M.J. KALEDHONKAR and S.E.A.T.M. VAN DER ZEE (2008). Effects of wastewater irrigation on soil sodicity and nutrient leaching in calcareous soils. *Agric. Water Manage.*, 95, 143-153.

JACKSON M.L. (1958). *Soil chemical analysis*. Englewood Cliffs, N.J., Prentice-Hall, 498 p.

KIZILOGLU F.M., M. TURAN, U. SAHIN, I. ANGIN, O. ANAPALI and M. OKUROGLU (2007). Effects of wastewater irrigation on soil and cabbage-plant (*Brassica olerecea* var. capitate cv. yalova-1) chemical properties. *J. Plant Nutri. Soil Sci.*, 170, 166-172.

LEVINE, A. and T. ASANO (2004). Recovering sustainable water from wastewater. *Environ. Sci. Technol.*, 38, 201A-208A.

LEVY G.J., A.I. MAMEDOV and D. GOLDSTEIN (2003). Sodicity and water quality effects on slaking of aggregates from semi arid soils. *Soil Sci.*, 168, 552-562.

METSON A.J. (1956). *Methods of chemical analysis for soil survey samples*. Soil bureau, Bull. N° 12, Wellington, DSIR, New Zealand, 207 p.

MINHAS P.S., S.K. DUBEY and D.R. SHARMA (2007). Comparative effects of blending, intra/inter-seasonal cyclic uses of alkali and good quality waters on soil properties and yields of paddy and wheat. *Agric. Water Manage.*, 87, 83-90.

MOHAMMAD RUSAN M.J., S. HINNAWI and L. ROUSAN (2007). Long term effect of wastewater irrigation of forage crops on soil and plant quality parameters. *Desalination,* 215, 143-152.

NAKAYAMA F.S. and D.A. BUCKS (1986). *Trickle irrigation for crop production: Design, operation and management*. Elsevier, New York, NY, 383 p.

OLIVIER R. (1984). Étude comparative de deux méthodes d'extraction et de dosage des bases et de la capacité d'échange sur les sols du Sénégal. *Agron. Trop.*, 39, 14-21.

ORSINI L. and J.C. REMY (1976). Utilisation du chlorure de cobaltihexamine pour la détermination simultanée de la capacité d'échange et des bases échangeables des sols. *Sci. Sol*, *Bull. de l'AFES*, 4, 269-279.

PESCOD M.B. (1992). *Wastewater treatment and use in agriculture*. Bull. FAO, 47, Rome, Italy, 125 p.

SAIDI, D., Y. LE BISSONNAIS, O. DUVAL, Y., DAOUD et A. HALITIM (2004). Effet du sodium échangeable et de la concentration saline sur les propriétés physiques des sols de la plaine du Cheliff (Algérie). *Étude Gestion Sols*, 11, 81-92.

SUAREZ D.L., J.D. WOOD and S.M. LESCH (2006). Effect of SAR on water infiltration under a sequential rain–irrigation management system. *Agric. Water Manage.*, 86, 150-164.

SUMNER M.E. (1995). Sodic soils: new perspectives. In: *Australian Sodic Soils: Distribution, Properties and Management*. NAIDU, R., SUMNER, M.E. and RENGASAMY, P. (Editors.), CSIRO, Melbourne, 351 p.

TARCHITZKY, J., Y. GOLOBATI, R. KEREN and Y. CHEN (1999). Wastewater effects on montmorillonite suspensions and hydraulic properties of sandy soils. *Soil Sci. Soc. Am. J.*, 63, 554-560.

TEDESCHI A. and R. DELL' AQUILA (2005). Effects of irrigation with saline waters, at different concentrations, on soil physical and chemical characteristics. *Agric. Water Manage.*, 77, 308-322.

U.S. SALINITY LABORATORY STAFF (1954). *Diagnosis and improvement of saline and alkali soils*, USDA Handbook 60. U.S. Government Printing Office, Washington, DC, USA, 160 p.

VAN HOORN J., W. KATERJI, N. HAMDY and M. MASTRORILLI (2001). Effect of salinity on yield and nitrogen uptake of four grain legumes and on biological nitrogen contribution from the soil. *Agric. Water Manage.*, 51, 87-98.

WALKLEY A. and C.A. BLACK (1934). An examination of the Degtjareff method for determining soil organic matter and a proposal modification of the chromic acid titration method. *Soil Sci.*, 37, 29-38.

YADAV R.K., B. GOYAL, R.K. SHARMA, S.K. DUBEY and P.S. MINHAS (2002). Post-irrigation impact of domestic sewage effluent on composition of soils, crops and groundwater - A case study. *Environ. Internat.*, 28, 481-486.