Assessment of soil salinization risks under irrigation with brackish water in semiarid Tunisia

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Abstract

The salinity problem is becoming increasingly widespread in arid countries. In these regions, water is the most limiting factor of agricultural production. In semiarid Tunisia, the water resources are largely inadequate for the growing population. For conventional water resources, 50% have a salinity >1.5 and 30% >3 g NaCl g l^{-1}, respectively As fresh water is allocated in priority for drinking purposes, irrigation water is often of poor quality. Because of the risks associated with climatic change, poor water quality as well as poor soil and water management, about 50% of the irrigated land in Tunisia are highly sensitive to salinization. Only about 8% of the Tunisian farmland are irrigated but represent about 35% of the agricultural production. In addition, about 65% of the Tunisian population are associated (directly and indirectly) to the agricultural sector. As a result soil and water degradation in irrigated areas negatively affects farmers' income, environment, and the overall economy. To reduce and avoid the risk of salinization, it is important to control the soil salinity and keep it below plant salinity tolerance thresholds. To reach this goal, field and laboratory measurements of soil and water composition were conducted to establish the causes of irrigated soil salinization. A result of this, functional homogeneous areas (FHA) and soil salinization risk units (SRU) could be determined. Whatever climate of the irrigated areas (semiarid to Saharan), it was found that groundwater constitutes a main soil salinization risk. This paper aims at showing how SRU, which differ by risk salinization levels, can be used to select the appropriate soil and water management strategies (salt tolerant crops, water leaching fraction, irrigation systems et cetera).
Keyword: Salt balance, soil salinity, long term monitoring, shallow ground water, Tunisia

1. Introduction

In arid Tunisia, the combination of water quality and agricultural practices (e.g., cultivation techniques, crop management, irrigation water) has often resulted in significant degradation of soil resources that affected the sustainability of irrigation systems. Nowadays, 50% of the total irrigated areas are considered highly sensitive to salinization, 56% are affected by waterlogging at different levels, and about 50% are affected by a decline in soil fertility (DGACTA, 2007). To avoid or reduce the risk of salinization, it is important to monitor the soil salinity and keep it below the plant salinity tolerance threshold (e.g., CRUESI, 1970; Bahri, 1982; 1993). However, soil and water management are part of the sustainable agricultural knowledge which depend on accurate measurement of soil and water properties (e.g., Persson *et al*., 2002; Corwin and Lesch, 2003). In the Kalâat Landalous irrigated district (Tunisia) Bach Hamba (1992) and Bouksila (1992) found that due to rainfall and the newly installed drainage network, the amount of salt removed from the soil and salt in the drainage water outlet were approximately equal. They concluded that it was possible to estimate and monitor soil salinity indirectly, from salinity input (irrigation) and output (drainage). To keep track of changes in salinity and anticipate further soil degradation, monitoring of soil salinity is essential so that proper and timely decisions can be made. At spatial scale, salinity monitoring allows detection of areas with greatest irrigation impact and delimitation of vulnerable zones where special attention is required for soil conservation (Nunes *et al.*, 2007; Bouksila *et al.*, 1998).

To avoid soil degradation, estimation of salt balance at a range of spatial scales has been used to assess trends in root zone and groundwater salinity levels (Kaddah and Rhoades, 1976; Thayalakumaran *et al.*, 2007; Marlet *et al.*, 2009). The objectives of the present study were thus to analyze methods to predict the risk of soil salinization for irrigated agriculture and to suggest strategies for sustainable irrigation in Tunisia. To reach this goal tools were developed for better prediction and control of soil salinity at different observation scales to help farmers and rural development officers. Experiments were conducted in the semiarid Kalâat Landalous, situated in northern Tunisia in the lower valley of the Medjerda River.

2. Materials and methods

2.1 Experimental area

The study was carried out at the Kalâat Landalous irrigated area in the Lower Valley of Medjerda, north-east Tunisia (37° 4' 49'' N, 10° 8' 8'' E), close to the Mediterranean Sea (Fig. **1**). The irrigated area covers 2900 ha and the main crops are fodder, cereal, and market vegetables. The climate is Mediterranean semiarid with average rainfall of 450 mm y^{-1}. The potential evapotranspiration (*ET*) is 1400 mm y^{-1}. The soil is an alluvial formation of the Lower Medjerda River (Xerofluent). In 1987, a drainage and irrigation system was constructed. The electrical conductivity of irrigation water *ECiw* was about 3 dS m^{-1}. The drainage system is mainly composed of two primary open ditches (E1 and E2), subsurface PVC pipes, and a pumping station that discharges drainage water to the sea (P4, Fig.**1**). The depth of subsurface drains varied between 1.4 m and 1.7 m before discharging into a secondary open drain. Before the completion of the drainage and irrigation system, the old Medjerda riverbeds (30 to 40 m wide and 1.5 m to 3 m deep) constituted a natural drainage system and the Medjerda water was discharged into these riverbeds allowing farmers to irrigate their land. A 1400 ha area surrounded by two primary open ditches (E1 and E2) was selected within the 2900 ha irrigated area (Fig. **1**) for experimental studies. The experiments were conducted in 1989 and 2005-2006.

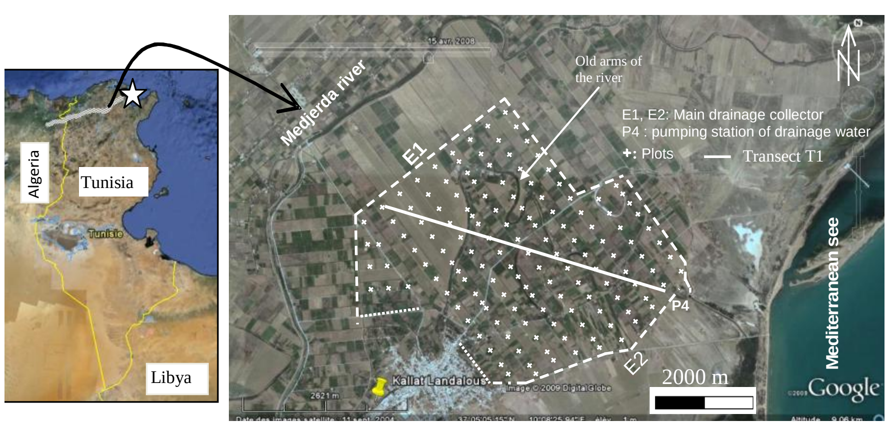


Figure 1. Kalâat Landalous irrigated area and measurement sites.

2.2 Data collection

The soil and groundwater properties were analysed at two different times and spatial scales (1400 ha, transect and soil profiles). In October 1989, at the end of the summer season, before land irrigation, 144 sampling plots were investigated according to a grid of 360 m x 240 m (Fig. 1). In each plot, soil samples were collected at 0.1, 0.5, 1.0, 1.5, and 2.0 m depth for soil analysis (particle size, electrical conductivity of saturated soil paste (*ECe*), exchangeable sodium percentage (*ESP*), etc.) according to USSL (1954) methods. Beside soil samples, the depth to the groundwater table from the soil surface (*Dgw*) and its salinity (*ECgw*) were measured. Plot coordinates (*x, y*) and altitude (z) were measured by GPS. The altitude was used to calculate the piezometric level ($PL = z - Dgw$) of the groundwater table. The overlay of spatial variation of soil particle size at the five soil depths allowed identification of functional homogeneous areas (FHA), for details, see Bouksila (1992). After that, the FHA was used to choose transect and soil profile location for soil properties measurement at smallest scale. In 2005, at the same location as in 1989, soil samples were collected at 8 soils depths (0.2 m depth interval up to 1.2, 1.2-1.8, and 1.8-2.2 m) for ECe analysis and groundwater properties (*Dgw*, *ECgw*) measurements. Because of several constraints, the period of measurement was about seven months from August 2005 to February 2006. The measurements over 1400 ha were performed along a transect T1 upstream-downstream length equal to 5200 m with an interval between the plots equal to 200 m (see Fig. 1). At T1, soil samples were collected at 3 soil depths (0-0.2, 0.2-0.4, and 0.4-0.7 m) for laboratory soil physical and chemical analysis (soil particle size, ECe, pH, SAR, ESP, etc). Also, at the 27 plots of T1, field bulk density (*D*a) and saturated hydraulic conductivity (*Ks*) were estimated with Müntz or double ring (*KsM*), Porchet (*KsP*), and Reynolds *et al.* (1985) methods (for details, see Bouksila, 1992). To estimate water and salt balances, rainfall data were collected at Kalâat Landalous weather station (CTV Kalâat Landalous). Monthly samples of irrigation water (*Viw, ECiw*) and drainage water (*Vdw*, *ECdw*) were collected from the drainage pumping station (P4) and irrigation water (P2), respectively, by SECADENORD (Fig 1).

2.3 Soil salinity prediction

Covering 1400 ha of Kalâat Landalous soil, soil particle size at various soil depths, groundwater properties, and plot coordinates sampled in 1989 were used to predict the soil salinity *ECe* at the 5 soil depths (0.1 to 2.0 m). Two statistical methods were explored to predict the soil salinity, the first was a multiple linear regression (MLR) and the second was a non linear model, artificial neural networks (ANN) (for details, see Bouksila *et al.*, 2010a)

2.4 Multiscale assessment of soil salinization risk

2.4.1. Water and salt balances

Due to the nature of subsurface drainage collector lines, the subsurface drainage collected and discharged is a mix of deep percolation from the root zone and intercepted shallow groundwater. If steady-state conditions are assumed for waterlogged soils, the salt balance (SB) equation can be reduced to (FAO, 2002):

$$SB= (Viw \times Ciw+Vgw \times Cgw)-(Vdw \times Cdw) \quad (1)$$

where *Viw*= volume of irrigation water [L^3], *Vgw*= volume of groundwater [L^3], *Vdw*= volume of drainage water [L^3], *Ciw*= salt concentration of irrigation water [$M\ L^{-3}$], *Cgw* = salt concentration of groundwater [$M\ L^{-3}$], *Cdw*= salt concentration of drainage water [$M\ L^{-3}$], and ΔMss = mass of change in storage of soluble soil salts [M].

According to Bach Hamba (1992) and Bouksila (1992), in Kalâat Landalous district, *Vgw x Cgw* can be omitted and Eq. (1) reduces so that the salt balance (SB) can be considered as:

$$SB= Viw \times Ciw-Vdw \times Cdw \quad (2)$$

2.4.2 Soil salinization risk unit (SRU)

The soil particle size constitutes the soil skeleton. The fine soil fraction (clay and fine silt) is the colloidal part of soil which largely affects the water and solute transfer. The overlay of spatial variation of fine particle size fractions at the 5 soil depths (0 to 2 m) allows the identification of functional homogeneous areas (FHA). After that, the overlay of FHA and temporal and spatial variation at of soil salinity at different depths and groundwater properties (*Dgw*, *ECdw*), soil properties measured at the transect T1 and at the soil profiles were used for delimitation of the soil salinization risk unit (SRU). The SRU was different according to the cause of secondary salinization and to the soil salinization risk level.

3. Results and discussion

3.1 Soil and groundwater properties

In 1989, before irrigation, the average *ECe* at all soil depths (0.1 to 2 m) was higher than 6 dS·m^{-1}. The average *Dgw* was 2.2 m (below the PVC drains) and it varied from 1.1 to 2.9 m and the *ECgw* varied from 4.1 to 59.6 dS m^{-1} (Table 1). In 2005-2006, soil desalinization was accompanied by an significant dilution of the groundwater. The average *ECe* at the different soil depths had decreased and varied from 2.0 to 3.6 dS m^{-1}. At the soil surface, *ECe* was characterized by a large variability (Coefficient of variation CV= 92%) which could be explained especially by the differences in soil management and drainage efficiency (Bouksila and Jelassi, 1998; Mekki and Bouksila, 2008). In spite of irrigation intensification, the drainage network allowed the groundwater table depth to be kept below the drain pipes. The average *Dgw* was about 1.7 m and varied from 0.6 to 2.5 m. The average *ECgw* was 6.6 dS m^{-1} and varied from 1.8 to 22.5 dS m^{-1}. The exceptional rainfall observed before the measurement campaign in 2005-06, about 372 mm which corresponds to 80% of the annual rainfall, could have generated major soil leaching. According to Thayalakumaran *et al.* (2007), heavy rainfall events flush out salt laterally and vertically causing large changes in the salt balance and extreme climatic events can cause large changes in the salt balance at all spatial scales.

Table 1. Statistical analysis of the soil saturation extract electrical conductivity (*ECe*, dS.m^{-1}) at various soil depths and groundwater properties (*Dgw, PL* and *ECgw*) observed October 1989 and August 2005-February 2006.

		1989						2005- 2006					
		Min	Max	Mean	Median	SD	CV	Min	Max	Mean	Median	SD	CV
Soil depth (m)	*ECe*												
	0.1	1.1	21.5	6.1	5.0	4.2	69	0.6	14.2	2.7	1.9	2.5	92
	0.5	1.7	18.1	6.1	5.7	3.4	55	0.5	13.5	2.0	1.9	1.5	76
	1.0	1.6	23.0	7.1	6.1	4.1	57	0.6	14.8	2.8	2.4	1.9	67
	1.5	2.1	23.0	8.2	7.0	4.5	55	0.9	9.6	3.4	3.1	1.6	47
	2.0	2.1	27.6	8.4	6.8	4.9	58	0.9	9.6	3.6	3.2	1.7	48
Ground water	*Dwg*	1.14	2.90	2.15	2.20	0.31	14	0.60	2.50	1.76	1.60	0.51	29
	PL	0.35	4.05	1.92	1.90	0.79	41	0.63	4.15	2.34	2.38	0.71	30
	ECgw	3.9	59.6	18.3	15.6	10.1	55	1.8	22.5	6.6	5.9	3.3	50

Dgw, depth (m); PL, piezometric level (m); ECgw, electrical conductivity (dS.m^{-1})

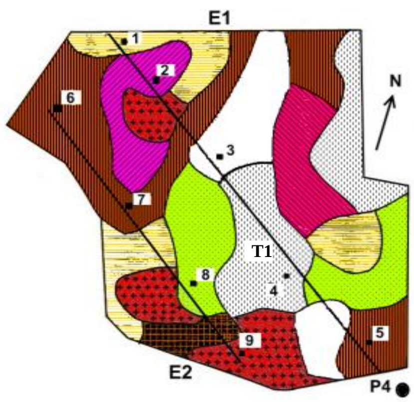
3.2. Soil salinity prediction

The best input for the ANN model contained five variables (*x, y*, *Dgw*, *PL*, and *ECgw*) for 0.1 m and three variables for 0.5 m soil depth (*x*, *Dgw*, and *ECgw*). The overall R^2 varied from 0.85 to 0.88 and the RMSE from 1.23 to 1.80 dS m^{-1}. For the validation subset, the R^2 varied from 0.58 to 0.87 and the RMSE from 1.21 to 3.17 dS m^{-1}. For all depths, in spite of using fewer input variables than in the MLR, the performance of ANN was better than MLR, especially when the ANN best input was used (for details, see Bouksila *et al.*, 2010a).

3.3 Spatial and temporal variation of soil and groundwater properties

Determination of functional homogeneous areas (FHA)

For the area of 1400 ha, statistical and geostatistical analysis of soil properties reveals heterogeneity and anisotropy (Bouksila, 1992). The fine particle size equal to 60% was chosen to distinguish the FHA. This property has a soil scientific and statistical significance. According to the fine textural classification triangle (Chamayou and Legros, 1989), this limit separates the very fine textural soils and other soil textural classes. Also, it corresponds to about the average silt and clay of the different soil depths (58%). On the basis of the fine soil fraction (clay + fine silt), nine homogeneous functional units were identified (Fig. 2). After that, the FHA was used to choose the transect T1 and the soil profiles.



FHA	Soil depth(cm) 10	50	100	150	200
I	+	+	+	+	+
II	-	-	-	-	-
III	+	+	-	+	-
IV	+	+	+	-	-
V	+	+	-	-	+
VI	-	+	+	-	-
VII	-	-	+	-	-
VIII	+	+	+	-	-
IX	+	+	-	-	-

+ Clay + fine silt ≥ 60 %
-: Clay + fine silt < 60 %
■ 6 : Soil profile
T1 : Transect

Figure 2. Spatial delimitation of the functional homogeneous area (FHA).

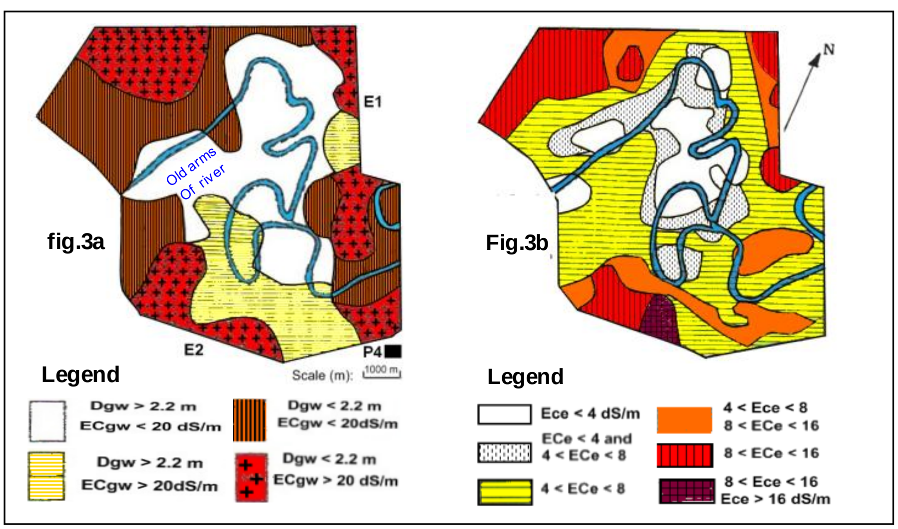


Figure 3. **a)** Spatial variability of groundwater table properties (depth, *Dgw;* salinity, *ECgw*) and **b)** soil salinity (*ECe*) in 0-0.75 m and 0.75-1.25 m soil layer (Bach Hamba, 1992).

Variability of soil salinity and groundwater properties

Figure 3 presents the spatial groundwater properties (*Dgw*, *ECgw*) and the overlay map of *ECe* at 0-0.75 and 0.75-1.25 m soil depths observed in 1989. The spatial similitude observed between groundwater properties (Fig. 3a) and soil salinity (Fig. 3b) shows that groundwater is the main soil salinization risk. The lowest soil salinity corresponds to a relatively coarser soil texture and to deeper groundwater table (*Dgw* > 2.2 m , *ECgw* < 10 dS m^{-1}). In the south of this unit, the *ECgw* reaches 59.6 dS m^{-1} and corresponds to maritime intrusion.

Salt balance

Fifteen years (1992-2006) of irrigation and 17 years (1989-2006) of drainage in Kalâat Landalous decreased the average soil *ECe* from about 7 dS m^{-1} to 3.5 dS m^{-1} and groundwater EC from about 18 to 7 dS m^{-1}. The amount of total dissolved salts exported by the drainage system (P4, Fig. 1) was $945 \cdot 10^3$ ton and the salt balance (Eqn. 2) was negative, about - $685 \cdot 10^3$ ton. According to Bouksila *et al.* (2010b), during the same period, the stored soil salt variation ($\Delta Mss = Mss_{2006} - Mss_{1989}$) in the vadose zone (0-1.80 m, above the sub-drainage pipe) was negative, equal to about $-145 \cdot 10^3$ ton (≈ -50 $ton \cdot ha^{-1}$) which represented 16 and 21% of *Sdw* and salt balance, respectively. These results (ΔMss << SB) clearly showed that soil salinity variation cannot be estimated indirectly from salt balance (SB, Eqn. 2*)* under shallow and saline groundwater. Therefore, the hypothesis of Bouksila (1992) and Bach Hamba (1992) could be rejected.

Spatial variation of soil properties at transect scale

In 1989, at 0-0.70 soil depth, the *ECe* varied from 1 to 13 dS m^{-1}, *ESP* from 7 to 40%, the bulk density from 1.13 to 1.73, and the clay particle size from 5 to 63% (for details, see Bouksila, 1992). The spatial variability of ECe is partly explained by the unfavorable physical properties; the fine particle size and high bulk density (Fig. 4).

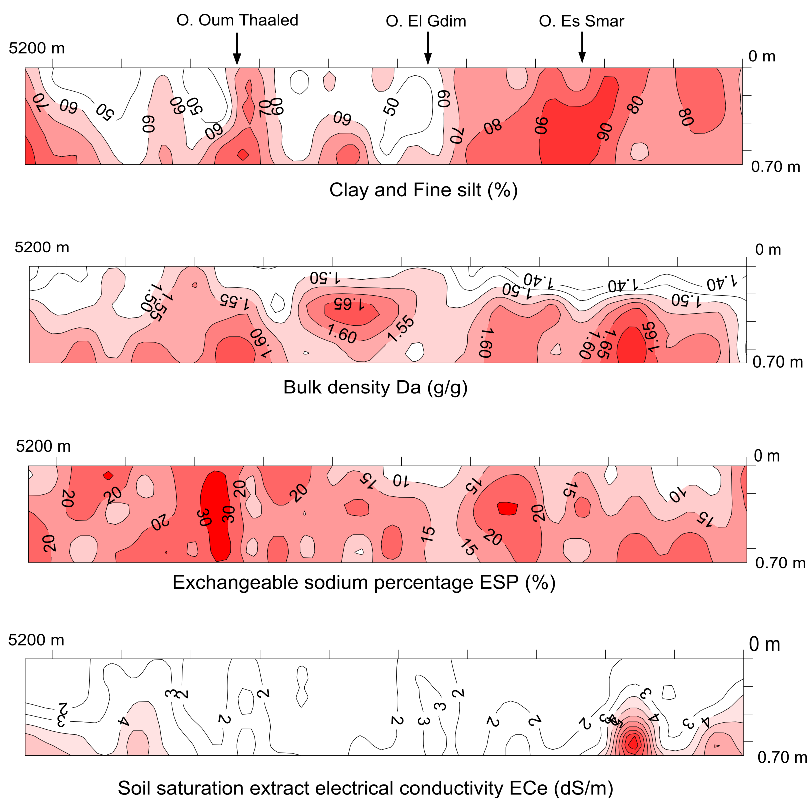


Figure 4. Impact of the old arms of Medjerda River (O. Oum Thaaled, O. El Gdir and O. Es Smar) on spatial variation of soil salinity, exchangeable sodium percentage and bulk density at 0-0.75 m soil depth at the transect T1.

The natural drainage constituted by the old arms of Medjerda seemed to have a large impact on soil solute and less on soil sodicity process. The high *ESP* (average of 18%) and the smectite clay (about 70% montmorillonite) generated poor soil structure, poor circulation of air and water, soil swelling, shrinkage when drying, high adhesion to the tools working the ground. The average *Ks* was 3.46, 1.59, and 1.36 cm h^{-1} when Müntz, Porchet and Reynolds *et al.* (1985) methods were used, respectively. Because the importance of lateral flow observed especially during the *KsM* measurement, it not recommended using Müntz method when soils are dry. Also, in dry soil, it could be better to use *KsR*, which takes better in to account the impact of unsaturated soil on the *Ks* than Porchet method.

Soil salinity variation at profile scale

Generally, capillary rise is larger in a medium-textured (loamy-sandy) soil than in a fine-textured (clay or loam clay) and sandy soil (Servant, 1975). In Kalâat Landalous, several soil profiles present a coarse soil particle size horizon positioned between two fine-textural horizons. The maximum observed *ECe* was for these stratified layers, situated at soil depth less than 1 m. This observation suggests that soil textural stratification could be one cause of soil salinization.

3.4 Soil salinization risk units (SRU)

Based on the results of soil and groundwater properties observed during 1989, three areas with different levels of risk salinization were identified (Fig. 5, for details, see Bouksila, 1992):

1- Low risk of salinization unit (about 400 ha) located around the old arms of the river: relatively coarser texture; *Dgw* > 1.4 m in winter and *Dgw* > 2.2 m in summer, *ECgw* < 15 dS m^{-1}, 10 < *ESP* < 15 and *ECe* < 4 dS m^{-1}. The fine texture at surface soil was a risk factor of salinization.

2- Average risk unit (500 ha) located around the first unit: fine texture, low soil saturated hydraulic conductivity (*Ks* <1 cm h^{-1}), 1.0 < *Dgw* (m) <2.0, 10< *ECgw* (dS m^{-1}) <20, *ESP* > 15 and 4< *ECe* (dS m^{-1}) < 8. In the east, the low slope of the natural land and the main drain collector (E1) often generated an increase in water logging risk, especially in the winter season. In the East, first the groundwater depth and then the soil texture were the factors of soil salinization risk. For the rest of the unit, first soil texture and then the groundwater constitute the main risks of soil degradation.

3- High risk (500 ha) situated close to the main drainage collector (E1 and E2): The soil has fine texture with the presence of textural stratification. The *Ks* <0 .5 cm h^{-1}, 15 dS m^{-1} < *ECgw* <30 dS m^{-1}, 1 m< *Dgw* <2 m, 15 dS m^{-1} < *ECgw* < 60 dS m^{-1}, *ESP* > 15 and *ECe* > 8 dS m^{-1}. The texture and then the groundwater are factors of soil salinization risk.

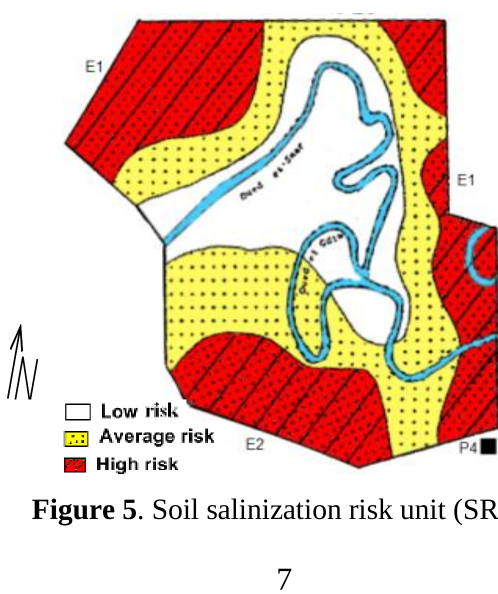


Figure 5. Soil salinization risk unit (SRU).

This mapping of SRU can be used by both land planners and farmers to make appropriate decisions related to crop production, soil and water management, and agronomical strategy (as plant tolerance to salinity, and crop rotation). The drainage network is the main factor in the success of reclamation of initially salt affected soil. In the north-west, the installation of an additional subsurface drain at 20 m spacing instead of the present 40 m could improve the drainage efficiency and consequently reduce the risk of soil salinization. Also, deep tillage could reduce the risk of formation of perched groundwater and the accumulation of salts in the shallow stratified textural profiles. However, the SRU needs to be updated for sustainable land planning and water management. Taking into account the measurements taken in 2005-2006, this map is being updated for better water and soil management.

3.5 Conclusion

In semiarid Tunisia, 50% of the total irrigated areas are considered highly sensitive to salinization and 56% are affected by waterlogging. To keep track of changes in salinity and anticipate further soil degradation, the multi-scale analysis of soil properties the monitoring of soil salinity is consequently essential so that proper and timely decisions can be made.

The present study had an objective to provide farmers and rural development offices with a tool and methodology for better prediction, monitoring of soil salinity, and agronomical strategy. The experiment was conducted in semiarid Kalâat Landalous irrigated district (North Tunisia) in 1989 and 2005 at different scales (2900, 1400 ha, transect 5200 m long and soil profile).

Seventeen years of reclamation of initial salty soil led to the reduction of the average soil salinity from7 dS m^{-1} to 3.5 dS m^{-1} and to the dilution of the groundwater from 18 to7 dS m^{-1}. The amount of total dissolved salts exported by the drainage system was $945 \cdot 10^3$ ton and the salt balance (input–output) was negative, about $– 685 \cdot 10^3$ ton.

Based on the findings related to the multiscale assessment of soil salinity and groundwater properties at various soil depths (0 - 2 m), soil salinization factors were identified and a soil salinization risk map (SRU) was elaborated. The depth and salinity of the shallow groundwater constituted the main risk of soil salinization. This map can be used by both land planners and farmers to make appropriate decisions related to crop production, and soil and water management. However, the SRU needs to be frequently updated for sustainable land planning and water management.

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