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Estimation of Root-zone Salinity Using SaltMod in the Irrigated Area of Kalaât El Andalous (Tunisia)

N. Ferjani[1*], M. Morri[2], and I. Daghari [2]

ABSTRACT

In Tunisia, Kalâat El Andalous irrigated district is one of the most affected areas by salinization. The objective of this study was to predict the root zone salinity (over 10 years) in this area using the SaltMod simulation model for subsurface drainage system. SaltMod is based on water balance, salt balance model, and seasonal agronomic aspects. In the pilot area, irrigated vegetables crops such as tomato (*Lycopersicum esculentum*), melon (*Cucumis mela*) and squash (*Cucurbuta maxima*) occupy the field during summer and rainfed wheat during winter. The model predicted more or less similar values of electrical conductivity in the root zone. Highest value of electrical conductivity reached during the irrigation season was 7.7 dS m^{-1}. Following the fall rains, there was a decrease of the soil salinity when the average minimum value of electrical conductivity was 3.1 dS m^{-1}. The simulation also showed that decreasing the depth of the drain did not change significantly the root zone salinity. The depth of the drain could be reduced to 1.6 m without any damage to crops. There was a slight reduction in drainage flow when the depth of the drain changed from 1.8 m to 1.2 m. Decrease of the drain depth decreased water table level. There was no variation in root zone salinities due to change in drain spacing. The predicted drainage flows were related to the occurrence of irrigation and rainfall. In this study, calibration of SaltMod for water-salt balance parameters proved the validity of the model for the local conditions.

Keywords: Drain discharge, Irrigation, Salinity, Subsurface drainage, Water table.

INTRODUCTION

High soil salinity is a serious problem often encountered in the arid and semi-arid regions of the world where there is insufficient rainfall to leach accumulated salts from the crop root zone, especially in irrigated areas. Other factors contributing to the problem are high evaporative demand and shallow ground water, which cause accumulation of salts at the soil surface. Since soil salinity imposes a stress on the crop, it results in decreased yields, and in some cases, complete crop failure (Reina-Sanchez *et al*., 2005; Campos *et al*., 2006; Kafi, 2009; Dadkhah, 2011). Soil salinization results from accumulation of water soluble salts in the soil surface and sub-surface, mainly consisting of chloride, carbonates, and sulfates of sodium, calcium, and magnesium. There are various factors that cause salinization including natural or inherent and human-induced factors and these are generally categorized into primary and secondary salinization respectively (Shrestha, 2006). Primary salinization results from natural weathering of parent material (i.e. rock and minerals) and is influenced by factors related to climatic, topographic, hydrologic, geologic, and soil condition. Secondary salinization develops from mobilization of the stored salts in the soil profile and/or groundwater due to human activities (Greiner, 1997) and practices including cultivation of marginal lands, inappropriate

[1] Department of Life Sciences, Faculty of Sciences of Bizerte, University of Carthage, 7021 Zarzouna Bizerte, Tunisia.
[*] Corresponding author; e-mail adress: noura_ferjani@yahoo.fr
[2] Resources Management and Conservation Research Unit, National Agronomic Institute of Tunisia (INAT), University of Carthage, Tunisia.

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irrigation practices, deforestation, and mining activities.

In order to control and monitor the process of salinization for the purpose of reclaiming degraded land and preventing further deterioration, information on spatial distribution of salinity, its trends of expansion, and severity levels is essential (Matternicht, 2001). A number of computer models have been developed that are useful in making predictions of soil salinity accumulation. According to Minacapilli *et al*. (2008), the assessment of the actual irrigation water demand in Sicily (Italy) by the spatially distributed agro-hydrological model SIMODIS (Simulation and Management of On-Demand Irrigation Systems), showed that, under the agro-climatic conditions typical for the Mediterranean region, SIMODIS may be a valuable tool in managing irrigation to increase water productivity. Most of the computer models available for water and solute transport in the soil, e.g. SWTRE (Belmans, *et al*., 1983); Drainmod (Skaggs, 1981); Hydrus (Šimůnek *et al*., 2005) are based on Richard's differential equation for the movement of water in unsaturated soil in combination with a differential salinity dispersion equation. The models require input of soil characteristics like the relation between unsaturated soil moisture content, water tension, hydraulic conductivity and dispersivity. These relations vary to a great extent from place to place and are not easy to measure. The models use short time steps and need at least a daily data base of hydrologic phenomena. There is a need for a computer program that is easier to operate and that requires a simpler data structure. Therefore, the SaltMod program was designed, keeping in mind relative simplicity of operation, to promote its use by field technicians, engineers, and project planners. It requires input data that are generally available, or can be estimated with reasonable accuracy, or can be measured with relative ease. In the present study, the interest is in predicting and detecting salinization during its early stages of development. Hence, long term (decadal) prediction of root zone salinity of vulnerable areas using a simplified modeling approach is the basis of this study. The predictions are more reliably made on seasonal (long term) than on a daily (short term) basis. That is, even if the accuracy of the prediction is not very high, it may be useful when the trend of the prediction is clear. Therefore, SaltMod model is used in the present study to predict long term variation and development process of soil salinity.

The SaltMod program was developed to predict the long-term effects of varying water management options on desalinization or salt accumulation in the soil of irrigated agricultural lands. The water management options include irrigation, drainage, and the reuse of surface drainage water or subsurface drainage water from pipe drains, ditches or wells for the irrigation. In addition, predictions are made on the depth to water table, the salt concentration of the groundwater and of the drain or well water. In Tunisia, Kalâat El Andalous irrigated district is one of the most affected area by salinization due to shallow groundwater level. The objective of the present study was to predict the root zone salinity using the SaltMod simulation model. In addition, investigations were made to study the impact of varying drain spacing and drain depth on root zone salinity and water table depth and drain discharge.

MATERIALS AND METHODS

Site Description

The irrigated area of Kalâat El Andalous (latitude: 36° 37´ and 37°2´ N; longitude: 10°5´ and 10° 10´ E) is located on the end part of the Medjerda watershed (Figure 1), with an average annual potential evapotranspiration (ETP) of 1,400 mm and an average annual rainfall of 490 mm. In Figure 2, the exact coordinates of five fundamental boundary points of the irrigated area of Kalaât El Andalous are shown.

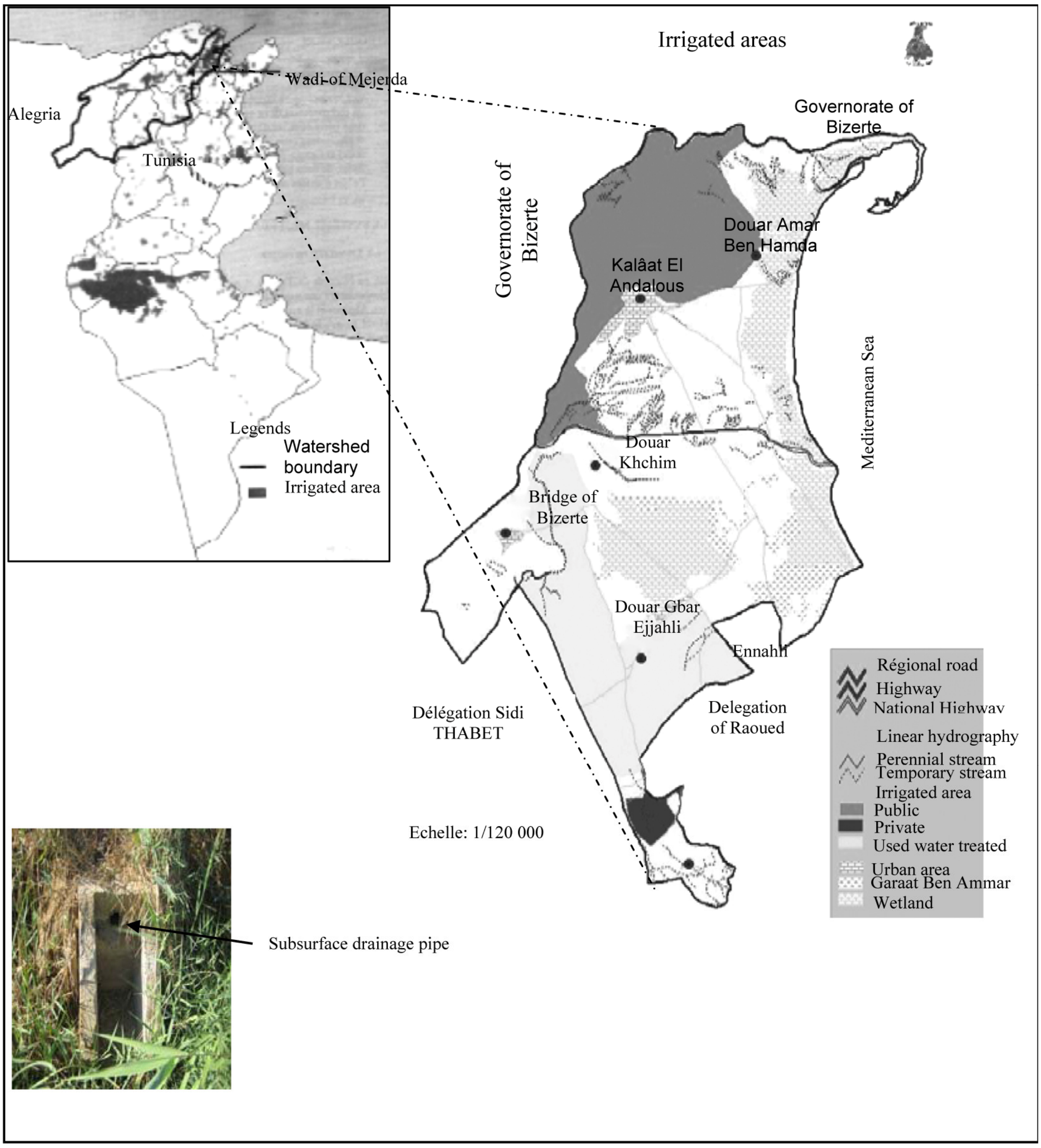

Figure 1. Irrigated area of Kalâat El Andalous.

Irrigation area of Kalâat El Andalous was launched in 1992 on a flood area. It covers an area of 2,905 ha and the effectively irrigated area changes from season to season: the maximum observed in the summer was about 1,000 ha (Cell Territorial of Vulgarization CTV, Kalaât El Andalous, 2008). The irrigated area was divided into plots of 5 ha supplied by a flow rate of 3 l s^{-1} and fed by one hydrant. In the irrigated area of Kalaât El Andalous, 50% of the plots have an area lower than 5 ha and the cover crop is nearly the same for every plot of 5 ha. In fact, the principal crops grown in the study area are cereals, forages and vegetables crops (CTV, Kalaât El Andalous, 2008). All the irrigated area was equipped with a pressurized irrigation network and a subsurface drainage system with a length of 180 m and a depth of 1.8 m, spaced at intervals of 40 m. The irrigation water was taken from

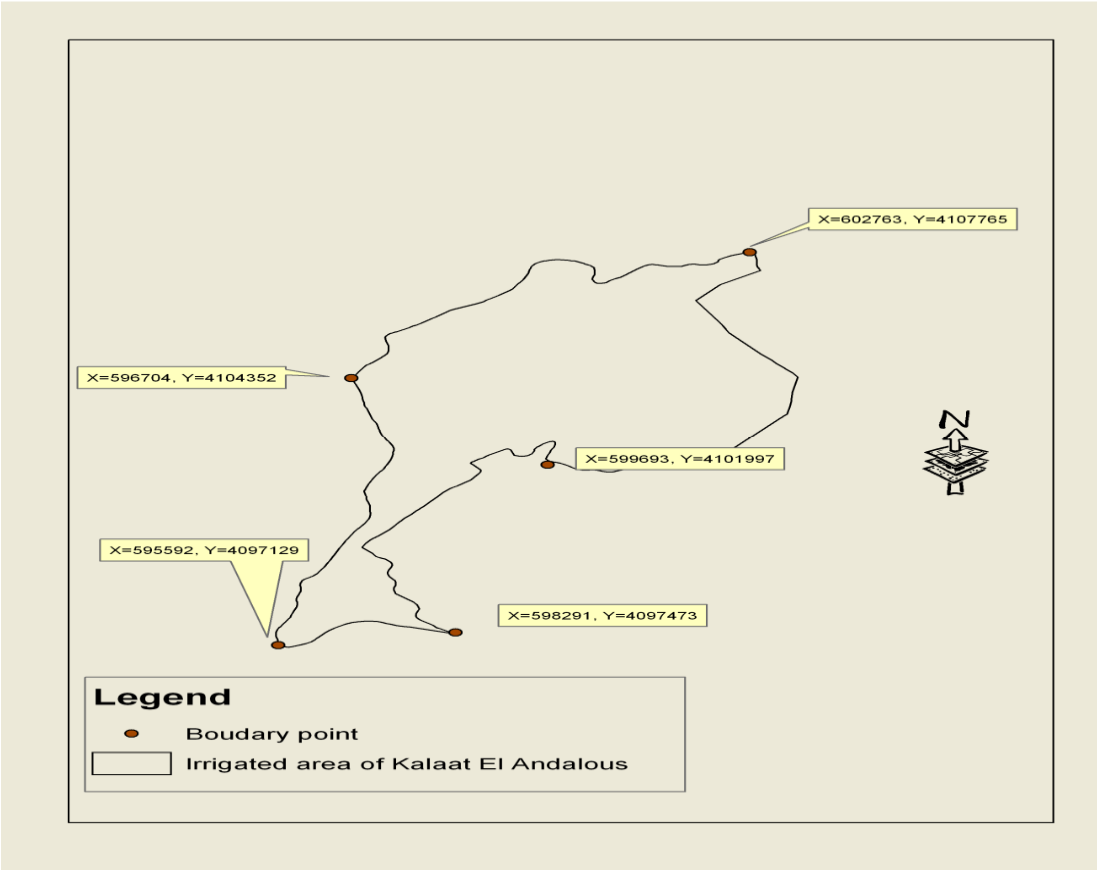

Figure 2. Exact coordinate of five fundamental boundary points of the irrigated area of Kalaât El Andalous.

the Mejreda River. Irrigation water salinity ranged between 3.1 and 2.5 g l^{-1} in winter and between 2.3 and 2.4 g l^{-1} in summer. The drainage outlet was below sea level, and the drainage water was discharged to the Mediterranean Sea through a pumping station (SP4).

In this study, the percentage of the soil particles was determined by Robinson's pipette method (Piper, 1964). The soils had a fine texture, ranging from silty-clay to clayey-silt. According to our measurements in the study area, most soils had electrical conductivity values above 2 dS m^{-1}, and may reached values up to 8-10 dS m^{-1} near the south-east sebkha. The hydraulic conductivity varied between 0.2 and 3.6 cm h^{-1}. Soil pH ranged from 7.3 to 8.9. The average bulk density of the soil was about 1.5 g cm^{-3}. Shallow water tables of about 1.4 m depth were present in the lower parts of the district, with very high salinity values that made them unsuitable for irrigation or other municipal and industrial uses.

Properties of SaltMod

In order to estimate the root zone salinity, the SaltMod simulation model was used. The hydro-salinity model "SALTMOD" developed by Oosterbaan and Pedrose de Lima (1989), computes the salt and water balance for the root zone, transition zone, and aquifer zone. It is a computer-based model for simulating the salinity of soil and drainage waters, water table depth, and drain discharge in irrigated agricultural lands under different hydrological and geo-hydrological conditions, varying water management options, and several crop rotation schedules.

The model was developed to make long-term predictions of the impact of water management programs (including drainage) on the level of the water table, and on the salt content of the soil, ground water, and drainage effluent. It can also assess the impact of re-used drainage water. It includes area frequency distributions of salinity. SaltMod can also simulate farmers' agricultural and water-management responses to changes in water table depth and soil salinity, which, in turn, can influence the salt and water balance (Oosterbaan, 1998). The program uses input data that are generally available, or can be estimated with reasonable accuracy, or can be measured with relative ease.

The SaltMod model is based on three components systems: water balance (hydrological model), salt balance model, and seasonal agronomic aspects. Therefore, the model would require input data that is related to agricultural aspects, hydrological data, and soils characteristics. The computation method SaltMod is based on seasonal water balances of agricultural lands. Four seasons in one year can be distinguished, e.g. dry, wet, cold, hot, and irrigation or fallow seasons. The number of seasons (Ns) can be chosen between a minimum of one and a maximum of four. The larger the number of seasons becomes, the larger is the number of input data required. The duration of each season (Ts) is given in number of months ($0< Ts< 12$). The method uses seasonal water balance components as input data. These are related to the surface hydrology (like rainfall, evaporation, irrigation, use of drain and well water for irrigation, runoff), and the aquifer hydrology (like upward seepage, natural drainage, pumping from wells).

The input data on irrigation, evaporation, and surface runoff are to be specified per season for three kinds of agricultural practices, which can be chosen at the discretion of the user: A (irrigated land with crops of group A), B (irrigated land with crops of group B) and U (non-irrigated land with rainfed crops or fallow land). The groups, expressed in fractions of the total area, may consist of combinations of crops or just of a single kind of crop. Creative combinations of area fractions, rotation indexes, irrigation quantities and annual input changes can accommodate many types of agricultural practices. Variation of the area fractions and/or the rotational schedule gives the opportunity to simulate the impact of different agricultural practices on the water and salt balance. SaltMod accepts four different reservoirs, three of which are in the soil profile: an upper (shallow) soil reservoir or root zone, an intermediate soil reservoir or transition zone and a deep reservoir or aquifer.

The upper soil reservoir is defined by the soil depth from which water can evaporate or be taken up by plant roots. It can be equal to the root zone. The root zone can be saturated, unsaturated, or partly saturated, depending on the water balance. All water movements in this zone are vertical, either upward or downward, depending on the water balance. The transition zone can also be saturated, unsaturated, or partly saturated. All flows in this zone are vertical, except the flow to subsurface drains. If a horizontal subsurface drainage system is present, this must be placed in the transition zone, which is then divided into two parts: an upper transition zone (above drain level) and a lower transition zone (below drain level). If one wishes to distinguish an upper and lower part of the transition zone in the absence of a subsurface drainage system, one may specify in the input data a drainage system with zero intensity. The aquifer has mainly horizontal flow. Pumped wells, if present, receive their water from the aquifer only.

In order to use SaltMod some factors should be determined first. Determination of the data required could be done by entering different values for leaching efficiency (Flr), and natural drainage (Gn) into SaltMod until values that match the actual measured soil salinity and water table depths are obtained. Some of the data used as input parameters in SaltMod were estimated or determined with in situ, laboratory, while the others were calculated by the model. The input parameters used in the model calibration are shown in Tables 4 and 5.

For each crop potential evapo-transpiration was estimated following the FAO methodology (Allen *et al*., 1998). The amounts and the salinity of irrigation water were measured in situ. The precipitation was determined in the meteorological station located near the study area and rainfall salinity was taken from the analysis of rain water samples for the year 2008. Percolation losses from the irrigation canal system (5%) and storage efficiency of rain water in the root zone of the un-irrigated land (80%) were estimated.

In this study, the root zone depth was measured. In order to measure this parameter, three plants of each crop were selected and the depth of roots was manually measured monthly by a ruler during different stages of development. The maximum root zone depth was about 0.5 m, under vegetables crops (tomato, melon and squash), and 0.6 m under wheat. As the SaltMod model implies the requirement of one single input as the parameter of root zone depth, in this study, the root zone depth (0.6 m) was based on the rooting depth of the wheat, since it had the deepest root. Depth of the transition zone (0.7 m) and aquifer (6 m) were estimated. Total porosity of root zone (0.43 m), transition zone (0.46 m), and the aquifer (0.5 m) were estimated (Payette and Rochefort, 2001). Measured parameters included salt concentration of the water in the transition zone, root zone, and in the aquifer when saturated. Also, salt concentration of the ground water, the irrigation water, and the rain water as well as the depth of the water table was measured.

Measurements

This study was carried out from Jun 2008 to May 2010 in a farm plot of 2.38 ha (170×140 m) equipped with three subsurface drainage pipes D1, D2, and D3 and by drip irrigation system. There were two cropping seasons per year i.e. winter (December to May) and summer (June to September) with a fallow season in between (October to November). In the field, summer irrigated crops were tomato (*Lycopersicum esculentum*) (1 ha), melon (*Cucumis mela*) (1 ha) and squash (*Cucurbuta maxima*) (0, 38 ha) and rain fed wheat occupied the field during winter season. Table 1 shows the irrigation system characteristics.

Daily climatic data were collected by a Campbel meteorological station located near the site and reference evapotranspiration (ET_o) was calculated with the FAO Penman-Monteith method (Allen *et al*., 1998). Crop evapotranspiration (ET_c) was calculated as:

$$ET_c = ET_0 K_c \quad (1)$$

Where, K_c is crop coefficient taken from local information or the literature (Allen *et al*., 1998). The temporal distribution of precipitation and ET_0 during the study period is given in Figure 3. During the irrigation season (May-September), rainfall was negligible.

In the field, measurements included irrigation water volume and salinity, pipe drainage discharge and salinity, water table level depth and salinity, and soil water content and salinity. The water supplied volumes V (m^3) were determined as follows:

$$V = NQT10^3 \quad (2)$$

Where, N is the number of emitters per hectare, Q the average emitter discharge (l/h), and T irrigation duration. The discharge of emitters was measured weekly. The duration of irrigation was estimated according to farmers' practice and it varied between 3 and 3.5 hours day^{-1} for squash, 1.5-4 hours day^{-1} for tomato, and 1-3 hours day^{-1} for melon. The applied water during the irrigation season ranged from 4 to 16 mm day^{-1} for tomato, 3 to 9 mm day^{-1} for melon, and 4 to 5.5 mm day^{-1} for squash. The Amounts of irrigation water diverted to crops and the *ETc* values are shown in Table 2.

In order to estimate crops yields, three plants of tomato, melon, and squash were harvested. In fact, average fruit number per plant and average fruit weight were determined and the total fruit yield was estimated at the end of the harvesting season. Wheat yield was determined according to farmers' practice. Measured yields of the different crops are presented in Table 2. The crop yield recorded in this area is less than the national value. As an example, for tomato, which is the main crop, yield recorded in this study area is low and it is about only 50 tons/ha, whereas the national average tomato yield is more than 80 tons ha^{-1}. According to Reina-Sanchez *et al*. [16], tomato fruit is the most sensitive organ to

Table 1. Irrigation system characteristics during irrigation season (May 2008- September 2008).

Crops	Field size (ha)	Row spacing (m)	Emitter spacing (m)	Average emitter discharge (l/h)
Tomato	1	1.5	0.4	2.1
Melon	1	1.5	0.8	1.5
Squash	0.38	1.5	0.8	1.9

Table 2. Amounts of irrigation water diverted to crops and mass of salts added by irrigation water.

Crops	ET_c (mm)	Water amounts diverted (mm)	Mass of salts added by irrigation water (tons ha^{-1})	Average calculated yield (tons ha^{-1})	Tunisian national average yield (tons ha^{-1})
Tomato	449	1030	24	50	80
Melon	332	503	12	43	60
Squash	285	299	7	60	70
Wheat	-	-	-	1.6	2

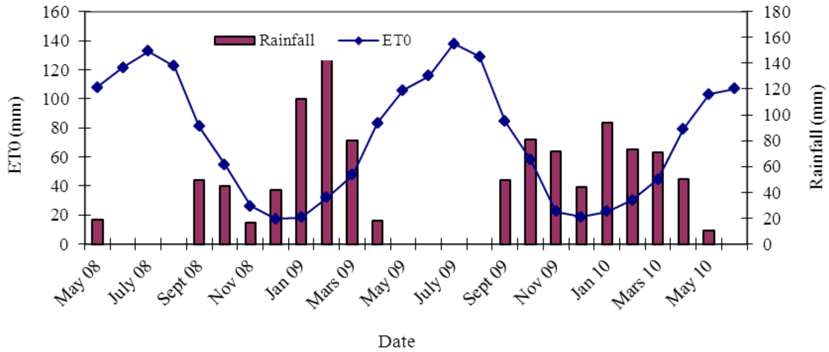

Figure 3. The temporal distribution of precipitation and reference evapotranspiration (ET0) during the study period.

salinity, and it shows significant yield reduction under irrigation with saline water having *EC* of 2.5-7.3 dS m^{-1}. Ayers [15] reported that the use of irrigation water with *EC* of 1.7, 2.3, 3.4 and 5 dS m^{-1} reduces tomato yield by 0, 10, 25 and 50 %, respectively.

The salt tolerance of a crop can best be described by plotting its relative yield as a continuous function of soil salinity. For most crops, this response function follows a sigmoidal relationship (Tanji and Neeltje, 2002). Considering that the US Salinity Laboratory norms and criteria for water use in irrigation (Richards et *al*., 1954) are not suited for the Tunisian context, research in saline water use in agriculture has been conducted in many experimental stations of this country under field condition (CRUESI, 1970). Yield functions are obtained for many crops (tomato, pepper, ryegrass, sorghum, alfalfa, artichoke) for the Lower Mejerda Valley. For tomato, results showed that the maximum soil salinity that does not reduce yield was 1.9 dS m^{-1}, but when electrical conductivity of the soil saturated paste extract (ECe) increased from 1.9 to 2.7 dS m^{-1}, a 10% decrease in yield was observed. Results showed also that yield of tomato was reduced by 50% when *ECe* reached 5.6 dS m^{-1} (CRUESI, 1970). Tolerances for crops cultivated in our field study are given in Table 3 (FAO, 1985). Tomato seems to be the most sensitive crop to salinity.

The water table levels were measured monthly using a piezometer installed in the plot. Also,

Table 3. Crop tolerance and yield potential of selected crops as influenced by irrigation water salinity (ECw) or soil salinity (ECe) (FAO, 1985).

Crops	Yield potential									
	100%		90%		75%		50%		0%	
	ECe (dS m^{-1})	ECw (dS m^{-1})	ECe (dS m^{-1})	ECw (dS m^{-1})	ECe (dS m^{-1})	ECw (dS m^{-1})	Ece (dS m^{-1})	Ecw (dS m^{-1})	Ece (dS m^{-1})	Ecw (dS m^{-1})
Tomato	2.5	1.7	3.5	2.3	5.0	3.4	7.6	5.0	13	8.4
Melon	4.7	3.1	5.8	3.8	7.4	4.9	10	6.7	15	10
Squash	4.7	3.1	5.8	3.8	7.4	4.9	10	6.7	15	10
Wheat	6.0	4.0	7.4	4.9	9.5	6.3	13	8.7	20	13

samples were monthly taken to measure the *EC* of the groundwater. To assess the amount of salts removed from the study area, drain discharge was measured monthly at the outlet of the subsurface drainage pipes D_1, D_2 and D_3. Furthermore, soil sampling was carried out to monitor soil salinity under irrigated crops (tomato, melon and squash), under rainfed crops (wheat), and bare soil. Sampling was done on three spots at 0-30 cm, 30-60 cm and 60-90 cm every two weeks during the irrigation season and about once a month for the other periods. Soil, irrigation water, drainage water, and groundwater samples were analysed to determine *EC*.

The computation method of SaltMod is based on seasonal water and salt-balance of agricultural lands, which can be expressed by the general water-balance equation as:

$$\textit{Incoming water} = \textit{Outgoing water} \pm \delta \quad (3)$$

Where, δ is the change in water stored. Some of the data used as input parameters in SaltMod were estimated or determined with in situ, laboratory, while the others were calculated by the model.

Calibration of SaltMod

After collection of the necessary input-data, they were then converted into the input-format as required by the model. The input-data for each year was given as average values over three seasons i.e. irrigated season, un-irrigated season, and fallow season of each year, given separately to simulate the results for the next year. The model was applied to calibrate for local conditions of the irrigated area of Kalaât El Andalous, under existing irrigation and cropping practices, to simulate seasonal water table changes, root-zone salinity, quantity, and quality of tile drainage flow. The match of the data was obtained by optimizing and varying the leaching-efficiencies and the natural drainage to the aquifer, establishing the validity of the model. The simulated results were analyzed and compared with field-data collected.

Some factors could not be measured, notably the leaching efficiency of the root zone (Flr) and transition zone (Flx), and the natural drainage (Gn) of groundwater through the aquifer. All these factors should be determined prior to applying the SaltMod model. This can be done by trials with SaltMod using different values of root zone and transition zone leaching efficiency, and the natural drainage, choosing those values that produce soil salinities and water table depths that correspond with the values actually measured (Oosterbaan, 1998, 2000). Field observations on water table and soil salinity of the three seasons of the two years 2008-09 and 2009-10 were used for calibrating the model and, subsequently, the projections were made starting from the year 2009 till 2019. The input parameters used in the model calibration are shown in Tables 4 and 5.

Determination of Leaching Efficiency

Leaching efficiency of the root (Flr) or transition zone (Flx) is defined as the ratio of the salt concentration of the water percolating from the root or transition zone to the average concentration of the soil water at saturation. This definition was taken from Description of Principles, User Manual, and Examples of Application On website: www.waterlog.info/saltmod.htm A range of arbitrary values were given for the leaching efficiency of the root zone (Flr) and transition zone (Flx); the corresponding root zone salinity results of the program were compared with the values actually measured. The arbitrary *Flr* values were taken as 0.2, 0.4, 0.6, 0.8, and 1.0, salinity levels of the root zone were obtained, and the data are shown in Figure 4. *Flr*= 0.8 was the best matching value to the observed values and was used in all calculations.

Determination of the Natural Subsurface Drainage

In SaltMod, natural subsurface drainage (Gn= G0-Gi) is defined as the quantity of horizontally outgoing ground water (G0, m^3/season per m^2 total area) minus the quantity of horizontally incoming ground water (Gi) in season. This value was determined by setting the natural drainage values (Gi) at zero, arbitrarily changing the outgoing ground water values, and finding

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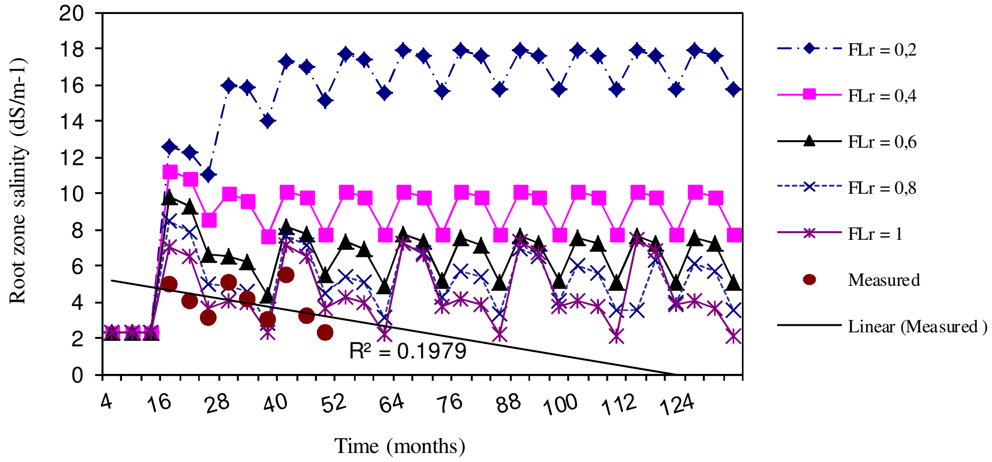

Figure 4. Calibration of root zone salinity and leaching efficiency in the test area.

Table 4. Season-wise input parameter for use in SALTMOD and origin of data (Measured (M) and Estimated (E)).

SI.N°.	Parameters	Origin of data	Season 1	Season 2	Season 3
1	Duration		1st Jun to 30th Sept	1st Oct to 30 Nov	1st Dec to 31 May
2	Crop grown		Tomato, melon and squash	Fallow	Rainfed wheat
3	Water sources		Irrigation water	Rainfall	Rainfall
4	Fraction of area occupied irrigated crop other than rice		1		
5	Fraction of area occupied irrigated rice crop				
6	Fallow			1	
7	Rainfall (m)		0.03	0.02	0.15
8	Water used for irrigation in crops other than rice (m)	M	1		
9	Potential evapo transpiration of other than rice crops (m)	E	0.254		
10	Potential evapo transpiration form un irrigated area(m)	E		0.02	0.063
11	Percolation losses from the irrigation canal system (m)	E	0.05		
12	Storage efficiency of rain and irrigation water in the root zone	E	0.9		
13	Storage efficiency of rain water in the root zone of the un-irrigated land	E		0.8	0.8
14	Incoming surface runoff into the un-irrigated land (m)			0	0
15	Outgoing ground water flow through the aquifer (m)		0	0	0

Table 5. Other input parameters used in SALTMOD and origin of data (Measured (M) and Estimated (E)).

S.No	Parameter	Origin of data	Value
1	Depth of root zone (m)	M	0.6
2	Depth of transition zone (m)	E	0.7
3	Depth of aquifer (m)	E	6
4	Total porosity of root zone	E	0.43
5	Total porosity of transition zone	E	0.46
6	Total porosity of aquifer	E	0.5
7	Effective porosity of root zone	E	0.02
8	Effective porosity of transition zone	E	0.02
9	Effective porosity of the aquifer	E	0.07
10	Initial salt concentation of the water in the transition zone when saturated (dS m^{-1})	M	4
11	Initial salt concentration of the soil moisture in the root zone when saturated (dS m^{-1})	M	2.8
12	Initial salt concentation of the water in the aquifer when saturated (dS m^{-1})	M	5.5
13	Initial salt concentration of the ground water in the upper part of the transition zone (dS m^{-1})	M	3.9
14	Initial salt concentration of the ground water in the lower part of the transition zone (dS m^{-1})	M	6.2
15	Salt concentration of the irrigation water (dS m^{-1})	M	3
16	Salt concentration of the rain water (dS m^{-1})	M	0
17	Initial depth of the water table (m)	M	1.33
18	Critical depth of the water table for capillary rise (m)	E	1

the corresponding values for water table depth (Dw) and drain discharge (Gd). Since the third season (6 months) was longer than the second season (2 months) and the first season (4 months), the arbitrary G01, G02 and G03 values, i.e. the Go values for the 1st, the 2nd and the third season respectively, are in pairs: (0.00, 0.00, 0.00), and (0.02, 0.01, 0.04), (0.05, 0.02, 0.07) and (0.07, 0.04, 0.1), and (0.09, 0.06, 0.13). As inflow Gi values were taken to be equal to zero, G0 values for three seasons together gave Gn values (Table 3).

Results from the simulation showed that when the annual natural drainage was set at 0.0 m^3/ m^2 of total area per season for the three seasons, drain discharge (Gd) was 0. 15 and 0.0511 and 0.785 m for the first and the second and the third season, respectively. These discharge values are much higher than those observed in the study area. Drain discharge (Gd) was simulated by the model as 0.0514 and 0.0166 and 0.711 m when the annual natural drainage was assumed to be 0.21 m. The simulated values were close to the discharge values measured during the summer and winter seasons.

RESULTS AND DISCUSSION

Once the model has got verification-reliability for an area, it could then be applied with confidence for further use and application, to make predictions and for various alternative water-management scenarios.

The main objective was to determine how salinization would change over long term basis in the study area, given the present land use practices continue. In order to achieve the objective, SaltMod was used to model temporal changes of salinization over one decade (10 years) periods. The root zone (≤ 60 cm depth) salinity and the level of groundwater table and drain discharge were the main variables of interest predicted by SaltMod. However, there are other parameters that are predicted by the model but are not of concern in the present study. For the prediction period, it was assumed that there would be no significant yearly deviations of the input parameters, such as rainfall, irrigation, evapotranspiration, cropping-pattern, etc., from the observed data given as average input to the model.

Prediction of Root Zone Salinity

Prediction of salinities for a 10-year period is shown in Figure 5. Generally, the model predicts more or less similar values of the root zone salinity (Cr4) provided that the current land use practices are maintained. According to model prediction, the highest *EC* value of 7.7 dS m^{-1} would be reached during the irrigation season in the first year. During the first season, due to irrigation, salt accumulation is more than in the second season. Following the rainfall, particularly during the winter season, there would be a decrease in the soil salinity when the average minimum value of *EC* would reach 3.1 dS m^{-1} in the second year. In fact, rainwater leaches down the salts from the top layer and contribute to the desalination of the soil profile. By the end of 10 years, the predicted root zone salinity would be 6.21, 5.84, and 3.67 dS m^{-1} during the first, the second, and the third season, respectively. If one compares the actual values (two-years) with the simulated values, more or less similar trend is observed during the three seasons. Observed values of soil salinity during

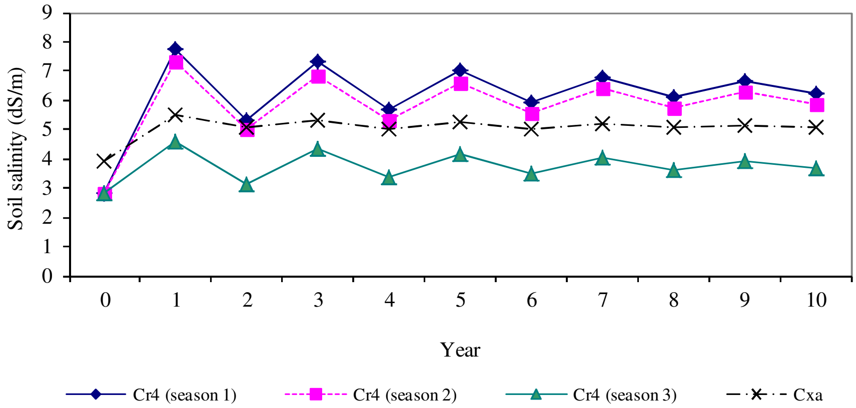

Figure 5. Predicted root zone salinity and soil salinity above drain level (Cxa).

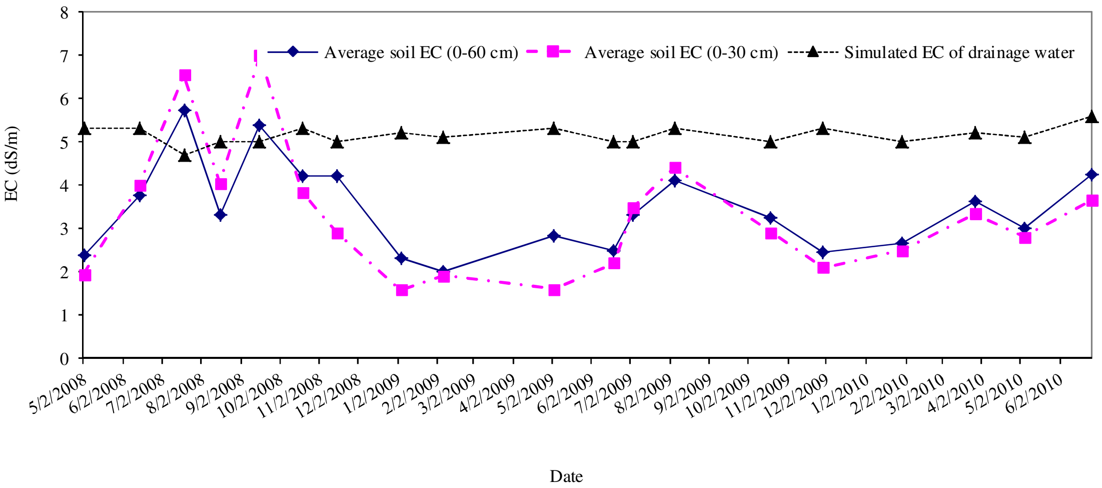

Figure 6. Average soil profile electrical conductivity observed during the study period (May 2008-June 2010) and simulated electrical conductivity of drainage water.

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the study period are shown in Figure 6.

The soil salinity above drain level (Cxa) increased from 3.9 dS m^{-1} to around 5.5 dS m^{-1} during the first year, as salts from the top layers leached down, thus increasing the salinity above drain level. Thereafter, the Cxa value is practically constant and is maintained at the same level (5 dS m^{-1}). The level of root zone salinity predicted by SaltMod was confirmed from field tests and can reduce crops yield. According to Reina-Sanchez *et al.* (2005), tomato fruit is the most sensitive organ to the salinity, and it shows significant yield reduction under irrigation with water having EC equal to 2.5-7.3 dS m^{-1}.

Prediction of Water Table Depth

The model also predicts the seasonal changes of the water table depth. The simulated water table depths in three seasons over the 10 years are given in Figure 7. The simulation shows a variation in water table level between 1.21 and 1.77 m. The water table depth exhibits seasonal variation, being influenced by recharge from rainfall and irrigation. The model tends to maintain almost the same depths for each season throughout the simulation period. By comparing the actual values (two years) with the simulated values, we found that simulated values of water table depths remained higher than measured values (Figure 8). The depth of the water table is always less than the depth of the root zone (0.6 m) and the critical water table depth, therefore, the level of the water table should have no adverse effect on crop if the conditions remain the same for the 10-year period.

SaltMod is a very useful tool for predicting root zone soil salinity and the amount of drainage water from land equipped with subsurface drainage systems. The model successfully predicts water table depth and drain discharge rates across agricultural areas using various water management practices (Oosterbaan, 2000; Srinivasulu *et al.*, 2004;

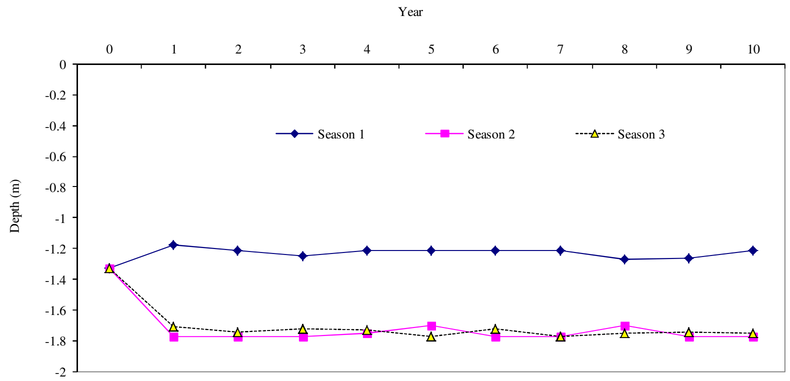

Figure 7. Simulated water table level fluctuation.

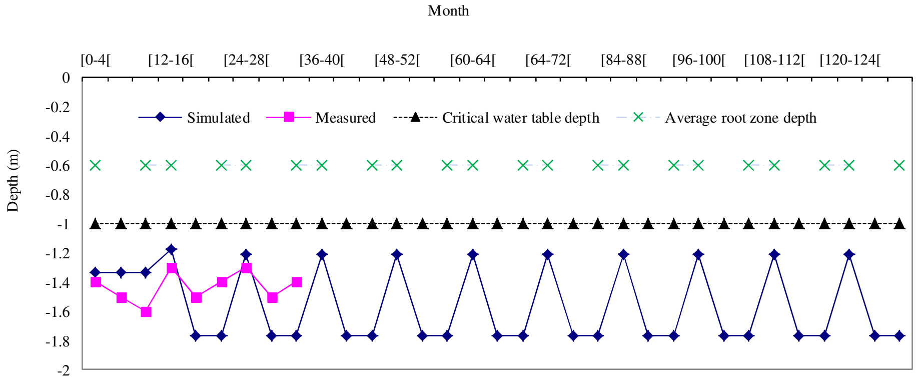

Figure 8. Comparison of actual and predicted water table depth. water.

Bahceci *et al*., 2006; Bahceci and Nacar, 2007). Rao *et al*. (1990) revealed that the time-averaged depth of the water table during the critical season need not be more than 0.8 m below the soil surface to allow for adequate reclamation of saline soils. According to Kitamura *et al*. (2006), secondary salinization (irrigation-induced salinization) of land develops in irrigated areas due to excessive and inefficient water use, where water losses raise the level of the groundwater table and cause waterlogging and land salinization. The SaltMod was applied by Nasir *et al*. (2004) in Faisalabad (Pakistan) to predict the hydro-salinity status of the area for the next 20 seasons. The results showed the watertable depth fluctuations within the lower transition-zone to the aquifer zone in the successive wet and dry seasons, with average rise to 2.24 m (after monsoon) and drop to 2.55 m (before monsoon). No significant rise in the water table depth was predicted for the next 20 seasons in the area.

Prediction of Drainage Water Quality and Flow Rate

The predicted values of drainage water quality in Figure 6 show no significant variation of EC of drainage water, which varies between 4. 7 and 5.7 dS m^{-1}. These values are less than the measured values which varied from 7 to 8.4 dS m^{-1} (Figure 9). The observed drainage flows was related to the occurrence of irrigation and rainfall. In fact, the maximum values were observed during winter season. The predicted values of drainage flow changed seasonally. The minimum values were observed during season 2 and the maximum were observed during season 3 (0.711 m $season^{-1}$).

Effects of Varying Drains Depth

In this scenario, keeping all the other parameters constant, the effect of varying drains depth on root zone salinity, water table level, and drain discharge was studied. The simulation showed that the decrease in the depth of the drain did not change significantly the root zone salinity, which ranged between 5.84 and 6.31 dS m^{-1} during the first season, between 5.55 and 5.87 dS m^{-1} during the second season, and between 3. 28 and 3.82 dS m^{-1} during the third season (Table 6). There was a slight reduction in drainage flow (Gd) when the depth of the drain decreased from 1.8 m to 1.2 m. Table 6 shows also that a decrease of the drain depth decreased the water table level which varied between 0.55 and 1.15 m in the first season, between 1.14 and 1.71 m in the second season, and between 1.1 and 1.71 m in the third season. The optimal drain depth is the depth where the water table depth and salinity have no adverse effect on crop. The critical values of Cr4 vary from 3 to 6.5 dS m^{-1}; the water table depth must be greater than 0.6 m (the depth of the root zone). According to the simulations, the drain depth that is most compatible with these conditions is between 1.4 and 1.8 m, thus, the depth of the drain can be reduced to 1.6 m (which seems the most suitable with a water table level that varied between 0.94 and 1.53 m) without any damage to crops. A water table depth of *Dw*= 1.8 m appears to be excessive and would increase the cost of system installation.

The advantage of reducing the drain

Table 6. Simulated values of annual natural drainage (Gn m $year^{-1}$), seasonal average of water table depth (Dw, m), and quantity of drainage water (Gd, m $season^{-1}$).

Gn annual	Season 1		Season 2		Season 3	
	Dw	Gd	Dw	Gd	Dw	Gd
0	1.15	0.15	1.71	0.0511	1.71	0.785
0.07	1.17	0.11	1.73	0.0419	1.74	0.764
0.14	1.19	0.0807	1.74	0.0327	1.75	0.733
0.21	1.21	0.0514	1.77	0.0166	1.77	0.711
0.28	1.22	0.0171	1.85	0	1.79	0.691
Observed values	1.2	0.02304	1.5	0.00216	1.4	0.0864

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depth allows easy installation of the drain with less cost. Safwat and Ritzema (1990) have shown that the seasonal average drain depth in the Nile delta should not be less than 0.7 m to avoid decline in crop yield. Therefore, a minimum drain depth of *Dd*= 1 m is required to safeguard the crop production. A drain depth of *Dd*= 1.4 m appears to be excessive. Safwat and Ritzema (1990) determined that a seasonal average drain depth of 0.8 m is also sufficient for good crop production. By employing the 0.8 m depth as a drainage criterion, one can avoid the design of an excessively expensive drainage system.

Effect of Varying Drain Spacing on Root Zone Salinity

The drain spacing is represented by the parameter *QH1* in the input file. The higher the *QH1* value, the narrower will be the spacing between the drains . The *QH1* value under the present drain spacing in the pilot area is 0.0095. In order to simulate the effect of drain spacing on root zone salinity, the *QH1* values were varied in the range of 60% (QH1= 0. 0057), 80% (QHl= 0.0076), 120% (QH1= 0.014) of the present value. It was observed that the results of all the simulations do not change the root zone salinity (Figure 10). In fact, the highest values of this parameter were reached during the first year of simulation when average values reached 7.7, 7.3, and 4.6 dS m^{-1} during the first, the second, and the third season, respectively. During the other years of simulation, the root zone salinity deceased and minimum values were observed at the end of the period of simulation.

CONCLUSIONS

The present study aimed at long term prediction of root zone salinity changes by means of deterministic modelling using SaltMod. Generally, the model predicts more or less similar value of the root zone salinity (Cr4). In fact, the highest *EC* value of 7.7 dS m^{-1} would be reached during the irrigation season in the first year. Following the rainfall, particularly during the winter season, there would be a decrease in the soil salinity when the average minimum value of electrical conductivity would reach 3.1 dS m^{-1} in the second year. The simulations show that the decrease in the depth of the drain does not change significantly the root zone salinity. The depth of the drain can be reduced to 1.6 m without any damage to crops. A water table depth of *Dw*= 1.8 m appears to

Table 7. Effect of variation of drain depth on root zone salinity (Cr4), water table depth (Dw), and drain discharge (Gd).

Drain depth (m)	Season	Cr4 (dS m^{-1})	Dw (m)	Gd (m $season^{-1}$)
	1	6.31	1.15	0.0514
1.8	2	5.87	1.71	0.0148
	3	3.69	1.71	0.711
	1	6.31	0.945	0.0497
1.6	2	5.87	1.53	0.0057
	3	3.69	1.51	0.722
	1	6.03	0.74	0.0463
1.4	2	5.68	1.34	0
	3	3.82	1.31	0.732
	1	6.21	0.555	0.0429
1.2	2	5.84	1.14	0
	3	3.67	1.11	0.723
	1	5.84	0.356	0.0429
1	2	5.55	0.945	0
	3	3.28	0.983	0.71
	1	6.21	0.155	0.0429
0.8	2	5.84	0.745	0
	3	3.67	0.713	0.71

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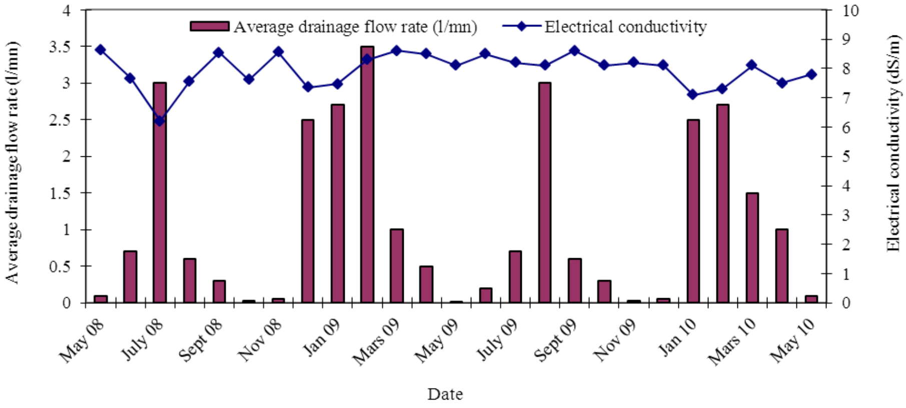

Figure 9. Observed values of drainage flow rate and electrical conductivity of drainage water.

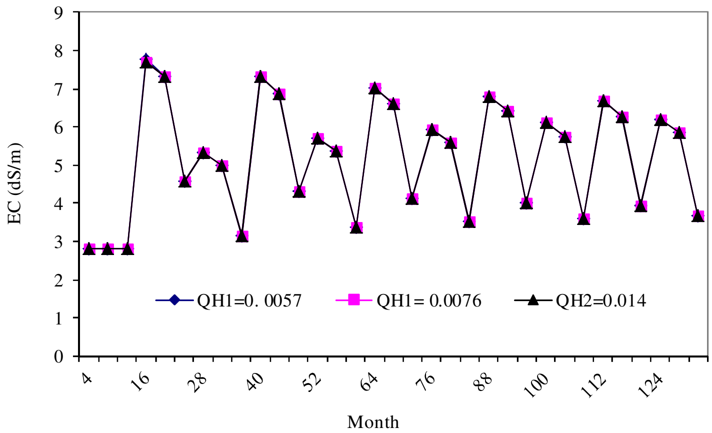

Figure 10. Effect of varying drain spacing on root zone salinity.

be excessive and would increase the cost of system installation. We can see a slight reduction in drainage flow when the depth of the drain decreases from 1.8 to 1.2 m. Furthermore, a decrease of the drain depth decreases the water table level. However, there was no variation in root zone salinities due to change in drain spacing. In this study, calibration of SaltMod for water- salt balance parameters shows the reliable validity of the model for the local conditions and, therefore, it could be applied with confidence for other areas.

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برآورد شوری ریشه گاه با کار بست مدل SaltMod در مناطق آبیاری شده کلات آندولس در تونس

ن. فرجانی، م. موری، و ی. داگاری

چکیده

اراضی آبیاری شده بخش کلات آندولس در تونس ازمناطقی است که شدیدا تحت تاثیر فرایند شور شدن قرار داشته است.هدف پژوهش حاضر این بود که با کاربست مدل شبیه سازی SaltMod شوری ریشه گاه گیاه برای سامانه زهکشی زیر زمینی را در یک دوره ۱۰ ساله پیش بینی نماید.این مدل بر پایه تراز آبی، تراز نمک، و جنبه های اگرونومیکی ساخته شده است. در اراضی منطقه نمونه که محل اجرای مطالعه بود، در تابستان سبزیجاتی شامل گوجه فرنگی(Lycopersicum esculentum)، انواع خربزه(Cucumis mela)، و کدو (Cucurbuta maxima) کاشت می شود و در زمستان زیر کشت گندم دیم است. نتایج مدل مزبور نتایج مشابهی در مورد هدایت الکتریکی ریشه گاه نشان داد. بیشینه مقدار آن برابر ۷/۷ دسی زیمنس بر متر در طی فصل آبیاری بود. پس از بارندگی های پائیزه، شوری خاک کاهش یافت و میانگین کمینه هدایت الکتریکی به۳/۱ دسی زیمنس بر متر رسید. مدل همچنین نشان داد که کاهش عمق زهکش ها شوری خاک ریشه گاه را به طور معنی دار دگرگون نمی کند و می توان عمق زهکش ها را تا ۱/۶ متر کاهش داد بدون آن که صدمه ای به گیاه وارد شود. با کم کردن عمق زهکش ها از ۱/۸ به ۱/۲متر کمی کاهش در مقدار جریان آب در زهکش ها مشاهده شد.کاهش عمق زهکش ها منجر به کاهش سطح ایستابی شد.همچنین، با تغییر فاصله زهکش ها، هیچ گونه تغییری در شوری ریشه گاه پدید نیآمد. مقدار پیش بینی شده جریان زه آب ها با وقوع آبیاری و بارندگی ارتباط داشتند. در این پژوهش، کالیبره کردن مدل SaltMod برای پارامتر های تراز آبی ونمک، روائی پذیری مدل در شرایط محلی را ثابت کرد.

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