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Root zone salinity modeling within Kalaat El Andalous irrigated district (Tunisia) using SaltMod model

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Abstract—SaltMod simulations indicate a slight change of root zone salinity remaining between 3 and 6 dS/m and do not causes risks to forage and cereal crops. However, such salinity is causing a yield decrease of 10 to 20% for tomato crop. During the next 10 years, groundwater water table depth will range between 1.33 and 1.76 m. and remains lower than that of the root zone (0.6 m). Therefore, groundwater table will not pose problems as long as we keep the same management conditions during this period. Moreover, the simulation of drainage system depth variation impacts on root zone salinity indicates that a decrease of drainage lines depth does not affect root zone salinity which remains constant (4.94 dS/m and 3.68 dS/m respectively during the first season and the second season). Regarding groundwater table depth, it is noted that there is a variation for each drainage lines depth variation and groundwater level is ranging from 1.26 to 0.26 m and 1.76 to 0.76 m during the first season and the second season respectively. Thus, optimum drainage lines depth corresponds to that for which salinity and groundwater level have acceptable values not threatening crops and generating minimum drainage flow. Referring to model simulations, we notice that the most appropriate drainage lines depths under these management conditions range between 1.4 and 1.8 m. Therefore, drainage lines depth can be reduced to 1.6 m without any damage of crops and yields. Simulations have also showed that root zone salinity has a tendency to increase due to an increase of irrigation water salinity and irrigation water volume on one hand and to a decrease of rainfall amount on the other hand. Moreover, it has been found that root zone salinity showed a tendency to decrease due to a decrease of irrigation water volume, a decrease of irrigation water salinity and an increasing amount of rain.

Keywords— Irrigation; SaltMod; Soil salinity; Drainage; Kalaat El Andalous

I. INTRODUCTION

In arid and semi-arid areas, water resources of good quality are becoming increasingly scarce and in gradual decrease hence their priority assigning to urban areas water supply. Therefore, to meet the irrigation water needs, the use of salty waters becomes inevitable with the risk of salts accumulation in the root zone and consequential damages of crop production and soil fertility ([8], [7]). Therefore, such saline irrigation water constitutes a potential resource to be used in within areas of scarce water resources and those where access to fresh water is sometimes limited [5], but also in areas affected by shallow groundwater where the main objective is to fold the depth of groundwater ([1], [13], [14]). Although the exact affected area is not known, it is estimated that about 25% of irrigated land worldwide is damaged by salt ([12], [6]). Reference [15] points out that serious problems related to salt occur within the boundaries of at least 75 countries. In New South Wales (NSW) in Australia alone, salinization generated by irrigation is affected about 15% of irrigated land. Thus, reference [16] had estimated that about 10 million hectares of irrigated land are abandoned each year because of water logging and salinization. According to some estimations, the losses of agricultural production in the world which are related to irrigated land salinization is around 11 billion dollars and still increasing [2]. In Tunisia, salinity problems are notably due to the presence of saline surface water table and soils affected by salt cover about 1.5 million hectares which represent about 10% of Tunisian territory surface and 25% of the total area of arable land [3]. Hence, viable and permanent sustainability of an agricultural system, especially with use of saline irrigation water, requires the implementation of an appropriate management practices to control salinity, not only within irrigated land, but also in irrigation projects and geo-hydrological systems. Thus, overuse and misuse of irrigation water in agriculture causes undesirable onsite effects as well as offsite effects [17]. Prediction of soil salinity evolution constitutes a determining factor in judging the effectiveness of the installed irrigation scheme and represents a crucial element in irrigated land management. However, to achieve a sustainability of an irrigation system, it is appropriate to monitor soil salinity all over the time. In this context, modeling constitutes a quick and less expensive tool capable to fulfill this task by its contribution in agriculture water management and soil salinization prediction. Some existing models are designed for a specific irrigation system, a specific process like water and solute movement, infiltration, leaching, roots plant water uptake or for a specific combination of these factors. In this study we were interested to the irrigated district of Kalaat El Andalous for which modeling of salinity in the root zone was carried out using SaltMod model aiming to control of soil salinization when irrigation water of poor quality is used.

II. MATERIALS AND METHODS

2.1. Study area description and data acquisition

The irrigated district of Kalaat El Andalous belongs to the Mejerda watershed and is located at 35 km north of Tunis in the North-East of Tunisia. Kalaat El Andalous irrigated district covers an area of about 3000 ha. Mejerda River constitutes the main water resource in the study area with a salinity reaching 3.1 g/l in winter and 2.4 g/l in summer. The whole irrigated area is equipped with a pressurized irrigation (drip and sprinkler irrigation) and a subsurface drainage network containing buried pipes drains. Soils are deep and characterized by a fine texture ranging from silty-clay to clayey-silt [4] and practiced crops are mainly cereals, fodder crops and vegetables. Referring to nearest weather station (1997-2011), average annual rainfall is 512.5 mm/year ranging from 275.0 mm (2001) to 857.5 mm (2003). Average monthly rainfall ranged between 1.3 mm and 91.0 mm respectively in August and December. Evapotranspiration (ET0) remains relatively low during winter season (December: 68.8 mm/month) and becomes increasingly important during summer months (August: 165.2 mm/month). During full irrigation period (March-September), evapotranspiration amount ranged from 9.5 to 11.6 million m^3 (average value of 10.1 million m^3) and throughout remaining period (October-February), evapotranspiration amount ranged from 6.8 to 7.2 million m^3 (average value of 7 million m^3). During (1997-2011) period, the average of annual irrigation water volume is about 8.8 million m^3 and average monthly irrigation water volume fluctuated between 0.1 and 1.8 million m^3 respectively during December (wettest month) and August (hottest month). During (1997-2011) period, average irrigation water salinity ranged between 1.7 to 2.7 g/l. Irrigation water is therefore considered of poor quality whose utilization must be coupled to an adequate drainage and adequate leaching. During (1997-2011) period, annual average drainage water volume is approximately 6.6 million m^3 and average monthly volume of drained water recorded during this period fluctuated between 0.8 and 0.9 million m^3. Throughout full irrigation period (March-September) monthly drained water volume fluctuated between 0.3 and 0.7 million m^3 derived mainly from irrigation water inflows.

2.2. SaltMod Model description

In order to predict the root zone salinity we have used SaltMod model. SaltMod model has been developed as a generic model that can be used for a variety of irrigation systems, soil types, soil stratifications, crops and trees, water application strategies, different nitrogen applications and different water qualities. The early version of the model was developed under the EU funded project

SALTMED and has been successfully tested against field experimental data from Egypt and Syria [14]. SaltMod was developed in the International Institute for Land Reclamatation and Improvement (ILRI) Wageningen) by Oosterbaan R.J. and Isabel Pedroso de Lima (Figure 1).

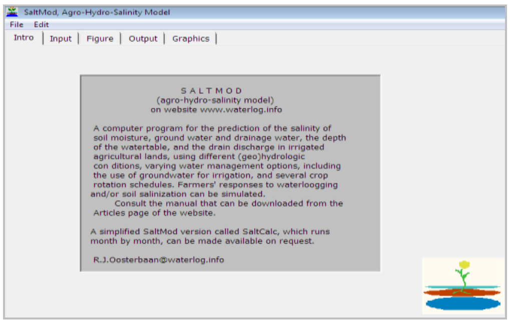

Figure 1: SaltMod model presentation (Version 2002)

This model is used in order to simulate soil salinity, drainage water salinity and water table depth within irrigated lands under different hydrologic and geo-hydrologic conditions [11]. SaltMod model has been tested in some countries like Egypt, Inde, Portugal, Thaïlande and Turquey and Tunisia [10]. SaltMod model was used successfully for root zone salinity prediction at long term scale within the Nil delta. It was also applied in order to measure hydromorphy in Tungahadra zone, in Inde, and to analyze salty water equilibrium. In fact, this model permits the evaluation of subsurface drainage system installation effects on root zane salinity within irrigated lands and on water table depth [9]. SaltMod needs simple inputs data which are generally available or can be estimated or measured easily. This model takes also into account farmers' responses to hydromporphy, water scarcity, soil salinity and ground water pumping under different geo-hydrologic conditions [11]. SaltMod model contains three submodels: Hydrologic submodel (water balance), Salinity submodel (salts balance) and Agronomic submodel (seasonal agronomic aspects). The hydrologic submodel is divided into four reservoirs: surface reservoir, superficial reservoir or root zone, intermediate reservoir or transition zone and deep reservoir or aquifer (Figure 2).

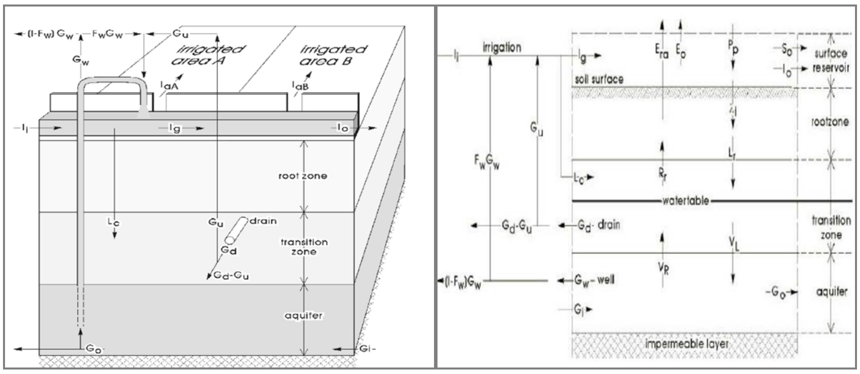

Figure 2: Concept of the four reservoirs with inputs/outputs hydrologic terms

Water balance can be calculated using hydrologic component which is linked to hydrologic surface and aquifer. Others terms such as deep infiltration, capillarity rise, subsurface drainage are considered as outputs data. All terms of the balance are expressed in term of seasonal volume per surface unit and water table depth is supposed the same for the whole study area. For each reservoir, water balance can be calculated separately and the water volume generated by the first reservoir constitutes the input for the second reservoir and the same for the third and the fourth reservoirs.
In fact, the three reservoirs can be with different depths and storage coefficients. Salts balances are governed by mass conservation principle and are based on water balances and are calculated separately for the different reservoirs thus, for different crop rotation types. All concentrations are

expressed in term of electrical conductivity EC (dS/m). Calculation method is based on seasonal inputs and outputs data. The number of seasons (Ns) ranges between 1 and 4 and the duration of each season (ts) is expressed in term of number of months (0≤ts≤12). Inputs data related to irrigation, evaporation and runoff should be specified per season for three agronomic practices types; A: irrigated lands (crops of group A); B: irrigated lands (crops of group B); U: non irrigated lands (rainfed crops or bare soil). Groups of land, expressed as fractions, can constitute a combination of crops or simply one type of crops.

III. RESULTS AND DISCUSSION

3.1. Modeling of root zone salinity using SaltMod model: Case study and required data

In order to predict root zone salinity evolution under tomato crop, a modeling test was conducted using the SALTMOD model. The application of SaltMod model is based on experimental data recorded during the campaign (2010/2011) within a private plot belonging to the irrigated district of Kalaat El Andalous whose characteristics are as follows:

- Plot size: 2.3 ha
- Irrigation water: Water of Mejerda River
- Drainage: Three buried drain lines D1, D2, D3
- Irrigation Season: May to September 2011

The main database for SALTMOD is summarized in Table 1. The significance of each of these data is available in the SALTMOD model guide which is downloadable free from the internet.

Table 1: SaltMod model inputs

Variable	Designation	Unit	Value
Area	Plot surface	Ha	2.3
Ns	Seasons number	-	2
Kd	Existence of groundwater drainage	0 : no 1 : yes	1
Kf	Farmers response simulation	0 : no 1 : yes	0
Ny	Duration of simulation period (year)	-	10
Ky	Continuous simulation	0 : no 1 : yes	0
Ts1	Month number of season 1		5
Ts2	Month number of season 2		7
A1	Percentage of irrigated area with comparison to total area A during season 1	0≤ A1≤ 1	1
RcA1	Existence of riz crop during season 1	0 : no 1 : yes	0
LcA1(*)	Water losses from canal distribution	m^3/season/m^2 of total area	0.05
I_0A1	Water flow through bypass canal during season 1	m^3/season/m^2 of total area	0
I_aA1	Irrigation water volume applied during season1	m^3/season/m^2 of total area	1
E_PA1	Evapotranspiration from irrigated area during season 1	m^3/season/m^2 of total area	0.254
PP 1	Rainfall amount during season 1	m^3/season/m^2 of total area	0.02
PP2	Rainfall amount during season 2	m^3/season/m^2 of total area	0.174
EpU_2	Evapotranspiration from rainfed area during season 2	m^3/season/m^2 of total area	0.083
FsA1(*)	Storage efficiency of rainfall and irrigation waters within root zone in irrigated area during season 1	0≤FsA1≤ 1	0.9
FsU1	Storage efficiency of rainfall and irrigation waters within root zone in rainfed area during season 1	0≤FsU1≤ 1	0
FsU2(*)	Storage efficiency of rainfall and irrigation waters within root zone in rainfed area during season 2	0≤FsU2≤ 1	0.8

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Dr	Root zone depth	M	0.6
Ptr	Root zone total porosity	m/m	0.43
Dx(*)	Depth of tansition zone	M	0.7
Ptx	Transition zone total porosity	m/m	0.46
Dq	Groundwater thikness	M	6
Ptq	Aquifer total porosity	m/m	0.5
Per (*)	Drainage porosity of the root zone	m/m	0.02
Flr	Leaching efficiency coefficient within root zone	$0 \leq Flr \leq 1$	0.8
Pex(*)	Drainage porosity of transition zone	m/m	0.02
Flx	Leaching efficiency coefficient of transition zone	$0 \leq Flx \leq 1$	0.8
Peq	Drainage porosity of the aquifer	m/m	0.07
Flq	Leaching factor of the aquifer	$0 \leq Flq \leq 1$	1
Cx0	Initial salts concentration of water within transition zone	ds/m	4
Cq0	Initial salts concentration within the aquifer	ds/m	5.5
Cic	Initial salts concentration of irrigation water	ds/m	3
Cp	Rainfall water salinity concentration	ds/m	0
Ca0	Initial salts concentration of soil (root zone)	ds/m	2.8
Dw0	Initial groundwater depth	M	1.33
Dc	Critical groundwaetr depth (capilarity rise)	M	1
Dd	Drainage lines depth	M	1.8
Cxa0	Initial salts concentration of groundwater within zone located above transition zone	ds/m	3.9
Cxb0	Initial salts concentration of groundwater within zone located below transition zone	ds/m	6.2

3.2. SaltMod model calibration

Some parameters which are difficult to measure, in particular the leaching efficiency coefficient of the root area and the transition area and the natural drainage of groundwater must be determined before the application of SALTMOD model. This can be done by simulation tests using different leaching efficiency coefficient and natural drainage values. These different tests yield different salinities and different groundwater depths; the suitable value is the one that generates the closest values to those measured [11].

3.2.1. Leaching efficiency coefficient

Determination of the leaching efficiency coefficient with SALTMOD within the root zone and the transition zone is possible through an arbitrary simulation involving different efficiency coefficient values (0.2; 0.4; 0.6; 0.8 and 1.0). Indeed, each simulated coefficient value generates different root zone salinities that should be compared with those measured within the study area and the accurate leaching factor is the one that generates salinity values which are close to measured salinity values (Figure 3).

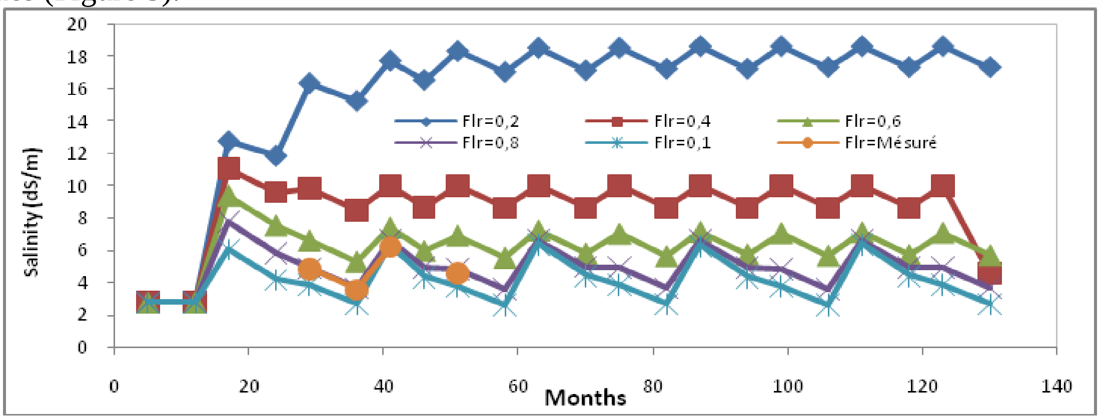

Figure 3: Calibration curve of leaching efficiency coefficient

Referring to Figure 3, we can conclude the following conclusions:

- Curve corresponding to Frl = 0.8 indicates the salinity values closest to those observed
- Observed discrepancy may be due to measurement errors and / or imperfection of the model
- Curves have a shaped stair form explaining the succession of a salinization and desalination phenomena.

So, the real leaching efficiency coefficient is about 0.8 and all subsequent calculations will be based on this value.

3.2.2. Natural drainage determination

In SaltMod model, underground natural drainage (Gn = G0-Gi) is defined as the difference between the amount of outgoing water horizontally from the soil (G0) and the amount of incoming water (Gi) horizontally during the season. This value was determined by fixing the Gi value to zero and then changing arbitrarily G0 value. Simulation with different values gives depth values (Dw) and various drainage rate (Gd). The most probable value of the natural flow is the one that generates Dw and Gd values that are close to measured values. The G01 and G02 arbitrary values correspond to the amount of outgoing water during seasons 1 and 2, which are respectively (0.00; 0.00); (0.04; 0.03); (0.08; 0.06); (0.12; 0.09) and (0.16; 0.12). G02 is greater than G01 since the season 2 comprises seven months while season 1 corresponding to the irrigated season extends only over 5 months. As the water input value Gi = 0, so Gn is the sum of G02 G01 values (Table 2).

Table 2: Simulation results in order to determine natural drainage (Gn, m/year)

Annual G0	Season 1		Season 2	
	Dw	Gd	Dw	Gd
0	1.24	0.12	1.74	0.79
0.07	1.26	0.07	1.76	0.76
0.14	1.28	0.03	1.78	0.73
0.21	1.32	0	1.79	0.7
0.28	1.35	0	2.67	0.63

Results indicate that actual groundwater depth ranges from 1.3 to 1.2 m and from 1.5 m to 2 m respectively during seasons 1 and 2.

3.3. Root zone salinity and Groundwater depth prediction using SaltMod model

3.2.1. Salinity prediction

SaltMod allows predicting the salinity in the root zone for long periods. In our case, we chose to do simulation for a period of 10 years (Figure 4):

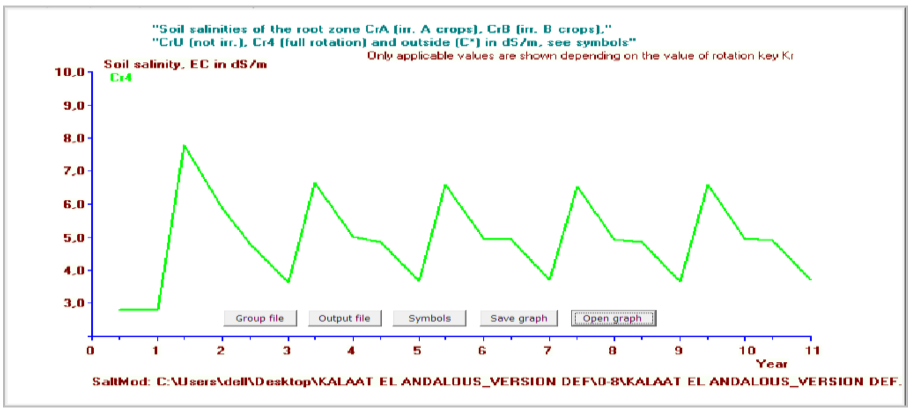

Figure 4: Salinity prediction using SaltMod model (10 years)

For the next decade, simulation results indicate a slight change of root zone salinity which remains always between 3 and 6 dS/m. This grid of salinity is moderately acceptable and does not cause risks

to forage and cereal crops. However, such salinity is causing a yield decrease ranging from 10 to 20% for tomato crop.
The staircase shape of the curve is very remarkable indicating the succession of salinisation and desalination phenomena. Indeed, SALTMOD simulates changes of salinity (Cxa) above the drain and salt concentration (Cd) of the drainage water (Figure 5).

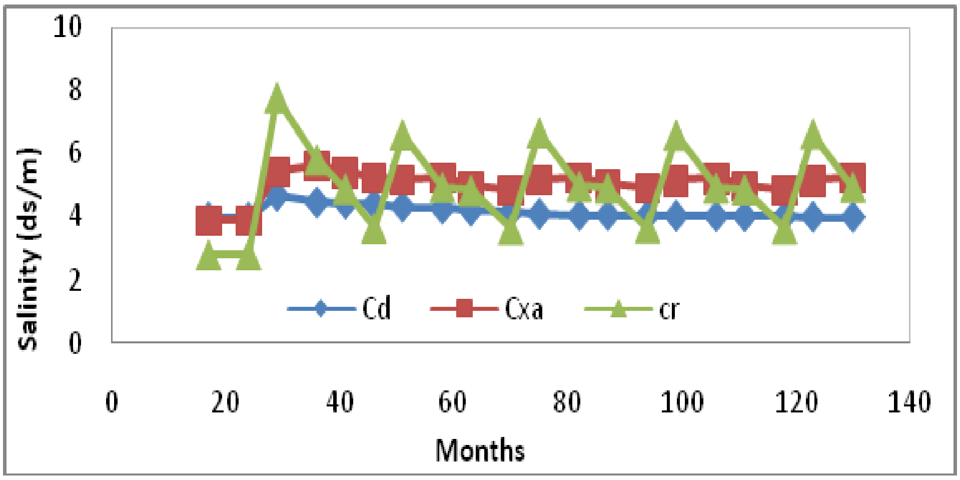

Figure 5: Prediction of root zone salinity (Cr), superior transition zone salinity (Cxa) and drainage water salinity (Cd) at the end of season

Referring to Figure 5, we see that salinity (Cxa) shows a slight increase during the first year resulting from salts provided by the leaching of the root zone. Thereafter, a decrease is observed. On the other hand, drainage water salinity remains almost unchanged at around 4 dS/m.

3.2.2. Groundwater depth prediction

The simulation for a period of 10 years indicates a variation of groundwater water table depth ranging from 1.33 to 1.76 m. However, we note that the depth of the water table remains lower than that of the root zone (0.6 m). Therefore, groundwater table will not pose problems as long as we keep the same management conditions during the next 10 years (Figure 6).

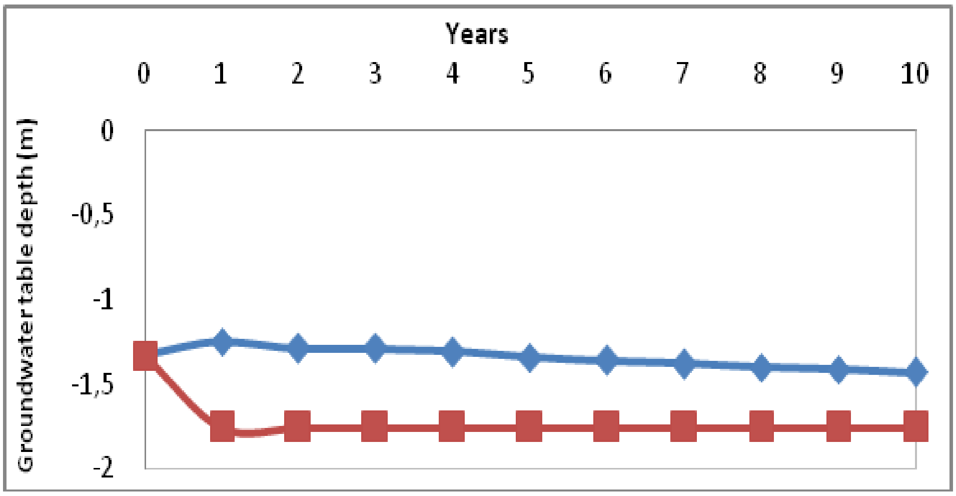

Figure 6: Groundwater table depth prediction during season 1(◆) and season 2 (■)

3.3. Determination of Optimum drainage network depth

Over time, irrigated soils salinity is variable. This variation is function of irrigation water amount and drainage system management efficiency. SALTMOD allows the simulation of drainage system depth variation impacts on groundwater level as well as soil salinity in the root zone. A simulation was performed for different depths ranging from 0.8 to 1.8 m. (depth of current drainage system within the study area).

Table 3: Effect of drainage lines depth on root zone salinity, groundwater table depth and natural drainage flow

Drainage lines depth (m)	Season	Cr4 (dS/m)	Dw (m)	Gd (m)
1.8	1	4.94	1.26	0.077
	2	3.68	1.76	0.762
1.6	1	4.94	1.06	0.077
	2	3.68	1.56	0.762
1.4	1	4.94	0.86	0.077
	2	3.68	1.36	0.762
1.2	1	4.94	0.6	0.077
	2	3.68	1.16	0.762
1.0	1	4.94	0.47	0.074
	2	3.68	0.96	0.741
0.8	1	4.94	0.27	0.068
	2	3.68	0.76	0.747

Table 3 indicates that a decrease drainage lines depth, under these conditions, does not affect the salinity in the root zone which remains constant reaching 4.94 dS/m and 3.68 dS/m respectively during the first season and the second season. In addition, there was a slight decrease of drainage rate (Gd) when drainage lines depth ranges from 1.2 m to 0.8 m. Beyond 1.2 m, the flow rate remains unchanged. Regarding groundwater table depth, it is noted that there is a variation for each drainage lines depth variation and groundwater level is ranging from 1.26 to 0.26 m and 1.76 to 0.76 m during the first season and the second season respectively. Thus, optimum drainage lines depth corresponds to that for which salinity and groundwater level have acceptable values not threatening crops and generating minimum drainage flow. However, the critical values of Cr4 vary from 3 to 5 dS/m and the depth Dw must be greater than 0.6 m (the depth of the root zone). Referring to model simulations, we notice that the most appropriate drainage lines depths under these management conditions range between 1.4 and 1.8 m. Therefore, drainage lines depth can be reduced to 1.6 m (that seems most suitable with a groundwater table depth ranging between 1.06 and 1.56 m) without any damage of crops and yields. A depth of 1.8 m seems to be excessive. The advantage of reducing the depth of the drainage lines allows easier installation of the drain with less cost allowing so an irrigation water saving.

3.4. Simulation of farmers responses

3.4.1. Simulation of farmers response: case of leaching efficiency Flr=0.8

In order to struggle against soil salinity increase, farmers manifest several responses such as:

- Reduction of irrigated areas
- Changing crops with other crops that are more resistant to salinity
- Reduction of irrigation water supply when groundwater table level is very close to the surface
- Abandonment of lands that are highly threatened by salinity

Since the risk of salinity on cereal and forage crops is minimal (Salinity between 3 dS/m and 6 dS/m) and the groundwater table depth is safe (acceptable), so the simulation of farmers' responses with SALTMOD in this case would result in no change and its response will be similar to that presented above.

3.4.2. Simulation of farmers response: case of leaching efficiency Flr=0.5

Simulation results, illustrated in Figure 7 and Figure 8, lead to the following conclusions:

- After two years, farmers begin to leave the land because of high salinization.

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- After two years, output data (outputs) on irrigated crops is interrupted and replaced by two series of salinity CrU (salinity in the root zone of non-irrigated crops) and C* (salinity in the root zone within permanent fallow area)
- The salinity in the root zone of rainfed crops varies from 4 dS/m to 9 dS/m while salinity within fallow land could reach 10 dS/m
- Groundwater table level is variable and can reach 1.4 m during season 1 because of irrigation water amount provided by the farmer decreasing.

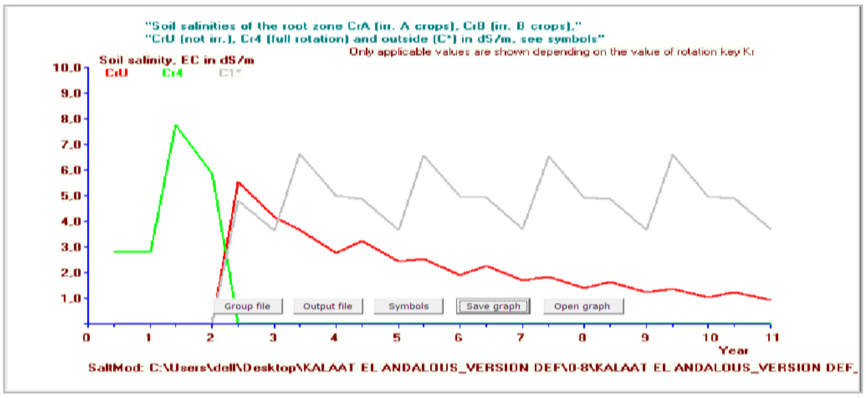

Figure 7: Prediction of root zone salinity (Cr4), root zone salinity of rainfed crops (CrU) and salinity of permanent fallow root zone (C*) for Flr=0.5

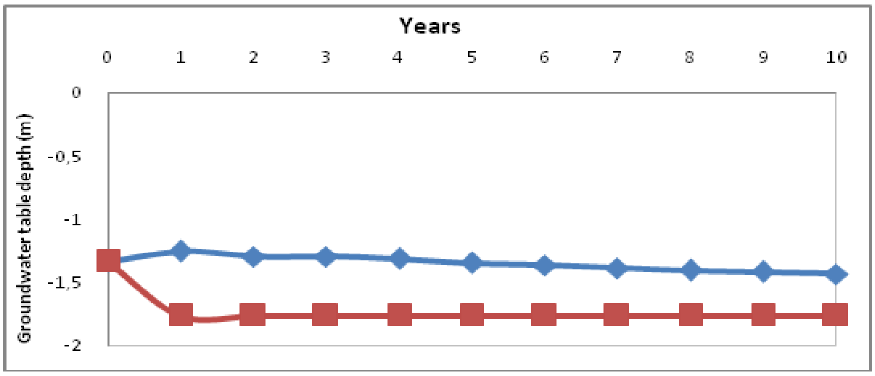

Figure 8: Groundwater table depth prediction for FLr=0.5 during season 1(◆) and season 2 (■)

3.5. Effect of irrigation water salinity, rainfall amount and irrigation water volume variations on root zone salinity: Efficiency coefficient Flr=0.8

In this section, we have tested the effects of irrigation water volume variation, irrigation water salinity variation and a rainfall amount variation on root zone salinity. The variables C0, V0 and P0 are related to the modeling standard state for which we have divided the crop into three seasons S1 (four months irrigated), S2 (2 months fallow) and S3 (6 months rainfed). Tthis rotation is commonly used within the study area. In this simulation, initial root zone salinity is 5.2 dS/m. Simulation results are illustrated in Figure 9.

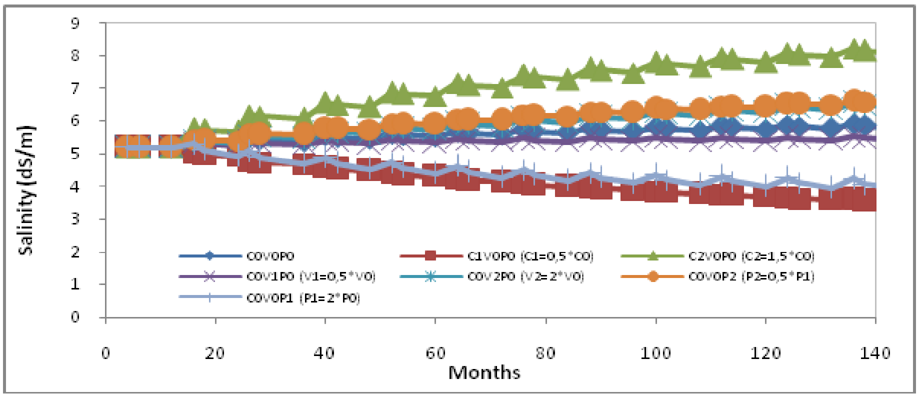

Figure 9: Effect of irrigation water salinity, rainfall amount and irrigation water volume variations on root zone salinity: Efficiency coefficient Flr=0.8

The simulation showed that root zone salinity has a tendency to increase due to an increase of irrigation water salinity and irrigation water volume on one hand and to a decrease of rainfall amount on the other hand. Moreover, it has been found that root zone salinity showed a tendency to decrease due to a decrease of irrigation water volume, a decrease of irrigation water salinity and an increasing amount of rain. Therefore, if poor quality water is used for irrigation, it is necessary to minimize the applied amounts to avoid the risk of salinization while enjoying fall and winter rains.

IV. CONCLUSION

Due to frequent irrigations salts contained in irrigation water can accumulate in soil which reduces water availability to crops and hastens water shortage appearance. Farmers' tendency to over-irrigation constitutes an important source of water losses both in terms of quantity and in terms of energy required for its mobilization. Moreover, excessive irrigation water volumes involve excessive amounts of salts those contribute to soil salinization. In this study, modeling using SaltMod model was done keeping the same conditions for 10 years. But actually it is very difficult to keep the same conditions for a very long time, so results validity remains limited. Thus, model simulation is done on an area very limited, thereafter we cannot generalize such results on the whole study area. On the other hand, drainage system management within this plot is acceptable and it is not the case for all study area plots. Therefore, results of these simulations are limited and cannot be generalized for the entire study area. The use of more sophisticated models such as Hydrus 2-3D will be necessary to generate good results that can be generalized.

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