Simulation of Water and Salts Dynamics in Bouhajla (Central Tunisia): Exceptional Rainfall Effect

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Abstract: Arid and semi-arid regions face the risk of soils and aquifers salinization. Rainy events are rare which is characteristic of these regions. They play a significant role in the leaching of salts from topsoil to deeper layers, which increases the risk of aquifers salinization. For this reason, a plot was selected in the semi-arid region of Bou Hajla (Central Tunisia). The simulation of water and salts dynamics was carried out by Hydrus-1D. Model calibration was realised on a flood irrigation experiment during 10 days and in a depth of 4 m. The hydrodynamic parameters were determined by inverse modelling. Model validation was performed successfully during 577 days. The simulation of water and salts dynamics has allowed the analysis of two scenarios: (*i*) the effect of a very rainy event (> 50mm/day) on the dynamics of salts. This type of event allows leaching of the accumulated salts in the topsoil which promotes their burial in the depth; (*ii*) the long-term evolution of the saline profile in 20 years showed the cyclical nature of salts leaching in the topsoil, the permanent accumulation of salts in the depth of around 2 m, and a continuous leaching in the deeper layers (around 4 m), which may increase groundwater contamination risk.

Keywords: aquifer; Central Tunisia; Hydrus-1D; rainfall; salinization; soil

The degradation of soil and groundwater quality is a consequence of brackish water use in irrigation. The impact of this practice is more pronounced in arid and semi-arid regions where irrigation is an important factor of agricultural intensification. In these regions, dry climate creates a high evaporative demand, resulting in the need of large quantities of water for crop irrigation. The soil water balance generates an extra supply of water associated with considerable amounts of salts. The water quantities added over time lead to a cumulative deposit of salts in the topsoil. According to Barica (1972) and Mhiri *et al*. (1998), the topsoil salinization occurs in the short-term, and that of the aquifer through progressive salts transfer from topsoil and subsoil in the long term. In semi-arid areas, exceptional rainfall events with a high intensity play an important role in the dynamics of water and salts in the soil. In a study lasting for 20 years in the arid Basin Makhtesh Ramon, Nativ and Mazor (1986) recorded eight exceptional rain events. Their intensities varied between 50 and 100 mm. The isotopic and chemical characterisation obtained from these exceptional rains showed that they are essential components in the input parameters of hydrological systems in terms of water and salts. Furthermore, these kinds of rainfall events contribute to salts leaching from the upper soil layers and are responsible for their transfer to the subsoil. Tanton *et al*. (1995) demonstrated the effectiveness of salt leaching in clay soil monoliths by rainfall of varying intensities of 2 to 100 mm. Armstrong *et al.* (1996) performed salts leaching experiments in field conditions in a clay-loam soil and observed that salts can be transferred over 1.2 m in depth under the effect of cumulative rainfall during the winter. The simulation of water movement and solute transport is useful for analysing the rain effect on the variation of salts and water dynamics and to predict its effects on soil and groundwater. Armstrong *et al.* (1998) established an empirical model for simulating the leaching of salts in clay soils. The model developed takes into account the soil grain-size distribution, as well as the duration and frequency of the rainfall applied. On the other hand, mechanist models are based on the numerical resolution of the Richards equation for the variably saturated flow in porous media and advection-dispersion equation for solute transport, such as Hydrus-1D (Simunek *et al.* 2005). This model was used by many authors for the simulation of water movement in soil (Suleiman 2008) and solute transport in the unsaturated zone, including heavy metals (Jacques *et al.* 2008), nitrogen (Crevoisier *et al.* 2008) and herbicides (Suárez *et al.* 2007). Hydrus-1D could be an interesting tool to study salts dynamics in the semiarid region of Bouhajla (Central Tunisia), characterised by a strong pressure on the groundwater resources and soil and by shallow groundwater unsuitable for irrigation with a TDS of 6 g/l (Hachicha *et al.* 2005; Kanzari *et al.* 2011). The objectives of this paper are: (*i*) calibration and validation of Hydrus-1D in-field condition, (*ii*) exceptional rainfall events characterisation and the study of their effects through scenarios, (*iii*) long-term simulation of the salt dynamics.

MATERIAL AND METHODS

Experimental site, soil and irrigation water

The region of Bouhajla is located about 30 km southeast of the Kairouan city in central Tunisia. This region is characterised by an arid climate and temperate winters. Rainfall is highly variable with an annual average of around 250 mm. The evapotranspiration is about 1600 mm/year. The experimental plot (35°15'47.58''N; 10°4'17.16''E) was selected about 9 km south of the village of Bou Hajla, having surface soils of sandy loam texture (0–0.6 m), and a higher clay concentration to a depth of 2 m (Table 1.). Beyond this level, the texture is loamy sand to loam. Irrigation water comes from a surface well of about 20 m depth, with a pumping rate of approximately 3 l/s, and the water quality corresponding to a TDS of 6.5 g/l, an ECi 7 dS/m and a SAR of about 7.5.

Field experiments

An experiment of flood irrigation was conducted on the experimental plot during 10 days, from July 22, 2008 to July 31, 2008. Water (420 l) was applied on an area of 3 m^2, which was enclosed by a wooden frame. This corresponded to an irrigation dose of 140 mm. The soil profiles were collected to a depth of up to 4 m to calibrate Hydrus-1D, one before irrigation and another one after 10 days. The monitoring of the soil moisture was carried out by gravimetric method and soil salinity by the method of diluted extract of the soil (soil/water = 1/5) with three replications at each 30 cm

Table 1. Soil particle size analysis in the plot (USDA System)

Depth (m)	Clay (%)	Loam (%)	Sand (%)	Texture
0.0–0.6	11.5	4.5	81.5	sandy loam
0.6–1.1	15.5	6.5	77.5	sandy loam
1.1–1.8	13.0	6.0	70.5	sandy loam
2.0–2.5	4.0	8.0	81.0	loamy sand
2.5–3.0	10.0	14.0	76.0	sandy loam
3.0–3.5	11.0	14.0	56.0	sandy loam
3.5–3.7	10.0	19.0	55.0	sandy loam
3.7–4.0	17.0	22.7	47.5	loam

of the soil. The relationship established by Hachicha *et al.* (2005) was used to convert EC(1/5) into electrical conductivity of the saturated paste extract: ECe = 7.4 × EC(1/5). Three profiles were collected on the following dates: December 26, 2006, February 20, 2007, May 08, 2007, and July 22, 2008, to validate Hydrus-1D. The monitoring of the soil moisture and soil salinity was the same as in the flood irrigation experiment. An automatic weather station from Campbell Company had been installed in Bou Hajla since April 2004. ET_0 software (Raes 2007) was used to estimate daily evapotranspiration (ET_0) from the collected data.

Hydrus-1D input data

Hydrus-1D (Simunek *et al.* 2005) simulates one-dimensional water flow and solute transport in incompressible, porous, variably saturated media, in a steady or a transient regime, for a known metric system and various time steps. Van Genuchten hydrodynamic parameters θ_r (residual water content) and θ_s (saturated water content) were determined from the particle size distribution and bulk density of the soil with the Rosetta model (Schaap *et al.* 2001) implemented in Hydrus-1D. The pedotransfer functions obtained were adjusted to the values of volumetric water content and electrical conductivity measured in the field by inverse modelling. It was used for the determination of van Genuchten shape parameters α, *n* and the saturated hydraulic conductivity (K_s). One parameter at a time was optimised for each layer and the remaining parameters were kept fixed. This was repeated for each parameter. For the solute transport parameters, the dispersions coefficients (Disp) were taken from the literature (Vanderborght & Vereecken 2007) for each type of texture and the value 0.05 cm^2/h (Beven 1993) was assigned to the molecular diffusion coefficient (Dw). The adsorption coefficients (K_d) of salts in the well water were determined by batch experiment for different layers. The upper conditions of the soil profile corresponded to the atmospheric BC, with a surface layer where the rainfall and evaporation calculated from the climate data had been specified, and the lower limit was free drainage. For the solute transport, the boundary conditions were the type of Concentration Flux BC. The values of the coefficient of dispersion of each soil material and the absorption coefficients were specified. The modelling result was evaluated by two methods: graphically and statistically. In the graphical approach, the measured and simulated volumetric water contents and soil salinity were plotted as a function of the soil depth. The statistical approach involved the calculation of the normalised root mean square error (RMSE).

$$\mathrm{RMSE} = \sqrt{\frac{\sum_{i=1}^{n}(p_i - m_i)^2}{n}} \times \frac{1}{\overline{m}} \qquad (1)$$

where:

p_i – predicted values

m_i – measured values

$\overline{m}$ – average value of the observed data

n – number of observations

RESULTS

Hydrus-1D calibration and validation

The simulation of the flood irrigation experiment was conducted with an hourly time step. The soil profiles were modelled down to a depth of 4 m considering 13 layers corresponding to the soil samples, which were collected at each 30 cm. The initial conditions were the volumetric soil moisture for the water flow and soil electrical conductivity for the salts transfer (Table 2). During the experiment, no rain had occurred. As for ET_0, it was estimated for each day of the simulation. The values varied between 6 mm/day and 7.4 mm/day. During calibration, the shape parameter alpha was rounded to 0.03 for the first eight layers of the soil, and, the dispersion coefficients were adjusted from the literature values recommended for each soil texture. Tables 3 and 4 contain the values of the hydrodynamic and solute transport parameters used in modelling the water and salts dynamics in the short term. The measured and predicted profiles for the last day of the experiment are presented in Figure 1. Showing a good agreement between the simulated and measured profiles. RMSE values were calculated for the water and salt profiles and were 0.0323 and 0.0152, respectively. These values are close to 0, which attests to the calibration success of Hydrus-1D in simulating the water movement and salts transfer in the short term in field condition.

Hydrus-1D validation was done for 577 days, for the profiles collected between December 26, 2006

Table 2. Initial profiles of water content and soil electrical conductivity

Layer (cm)	July 22, 2008		December 26, 2006	
	θ_v (cm^3/cm^3)	ECe (dS/m)	θ_v (cm^3/cm^3)	ECe (dS/m)
0–30	0.0808	5.40	11.88	6.47
30–60	0.0968	4.38	13.98	5.46
60–90	0.0775	3.89	12.62	4.04
90–120	0.0903	3.50	13.22	3.87
120–150	0.115	4.83	16.15	5.21
150–180	0.2111	8.70	22.73	9.84
180–210	0.2285	19.60	30.45	21.44
210–240	0.2700	19.10	29.60	20.93
240–270	0.2490	13.90	19.56	15.30
270–300	0.2418	12.85	20.48	13.11
300–330	0.1620	6.71	4.66	4.71
330–360	0.1290	4.61	3.58	2.61
360–400	0.1362	12.89	20.56	15.89

θ_v – volumetric water content; ECe – soil electrical conductivity of the saturation paste extract

and July 22, 2008. The print times were on the 57^{th}, 134^{th}, and 577^{th} days corresponding to the date collection on February 20, 2007, May 08, 2007, and July 27, 2008, respectively. The initial profiles of the volumetric water content and electrical conductivity of the soil are those of the December 26^{th}, 2006. The same input parameters were used as in the flood irrigation experiment, except the upper boundary conditions where the values of reference evapotranspiration ET_0 estimated from

Table 3. Hydrodynamic parameters of Hydrus-1D

Layer (cm)	θ_r (cm^3/cm^3)	θ_s (cm^3/cm^3)	α (cm^{-1})	n (–)	K_s (cm/day)
0–30	0.055	0.3720	0.0300	1.8898	129.67
30–60	0.055	0.3732	0.0300	1.7062	84.59
60–90	0.054	0.3727	0.0300	1.5870	62.98
90–120	0.054	0.3729	0.0300	1.6895	85.07
120–150	0.055	0.3732	0.0300	1.4608	39.84
150–180	0.055	0.3725	0.0300	1.5638	57.80
180–210	0.055	0.3732	0.0300	1.4608	39.84
210–240	0.055	0.3732	0.0300	1.4608	39.84
240–270	0.045	0.3816	0.0363	1.5087	59.69
270–300	0.045	0.3816	0.0363	1.5087	59.69
300–330	0.047	0.3795	0.0346	1.4708	52.78
330–360	0.027	0.4020	0.0418	1.4594	86.09
360–400	0.055	0.3858	0.0250	1.3761	22.94

θ_r – residual water content; θ_s – saturated water content; α, n – van Genuchten shape parameters; K_s – saturated hydraulic conductivity

Table 4. Solute transport parameter of Hydrus-1D

Layer (cm)	Disp (cm)	K_d (cm^3/g)
0–30	17.5	0.10
30–60	17.5	1.00
60–90	5.5	0.10
90–120	5.5	0.10
120–150	5.5	0.10
150–180	5.5	0.10
180–210	40.0	0.20
210–240	40.0	0.20
240–270	40.0	0.30
270–300	17.5	0.10
300–330	17.5	0.05
330–360	40.0	0.05
360–400	40.0	0.05

Disp – dispersion coefficient; K_d – adsorption coefficient

climatic data collected, rainfall (Figure 2), and, the initial conditions corresponding to the profiles measured on December 26, 2006 (Table 2). An exceptional rainfall event of 50 mm/day was recorded on the 74th day of simulation (Figure 2, March 9, 2007).

The water and saline profiles measured and simulated for the three print times are shown in Figure 3. The predicated profiles were close to those measured for each output date. The calculated values of the water content RMSE were, 0.027, 0.021, and 0.026, and those of the soil electrical conductivity RMSE were, 0.033, 0.033, and 0.014, respectively, for each output date. The values are close to 0, which indicates the reliability of the model for the reproduction of the water movement and salts transfer in field conditions.

Effect of 50 mm/day rainfall

An exceptional rainfall of 50 mm/day occurred on March 9, 2007. To study its effect on the profile saline variation, it was removed from the upper-boundary conditions and the other input parameters were the same as those in Table 3. The results of this simulation show:

– A significant decrease of the water storage (about 35 mm) from that one registered with the rain;
– An almost complete absence of salt leaching and its accumulation in the surface layer (Figure 4). The rain events, which came afterwards, could only move the salinity peaks slightly to the depth.

This result demonstrates the effect of this type of rainfall (over 50 mm/day) on the soil salinity

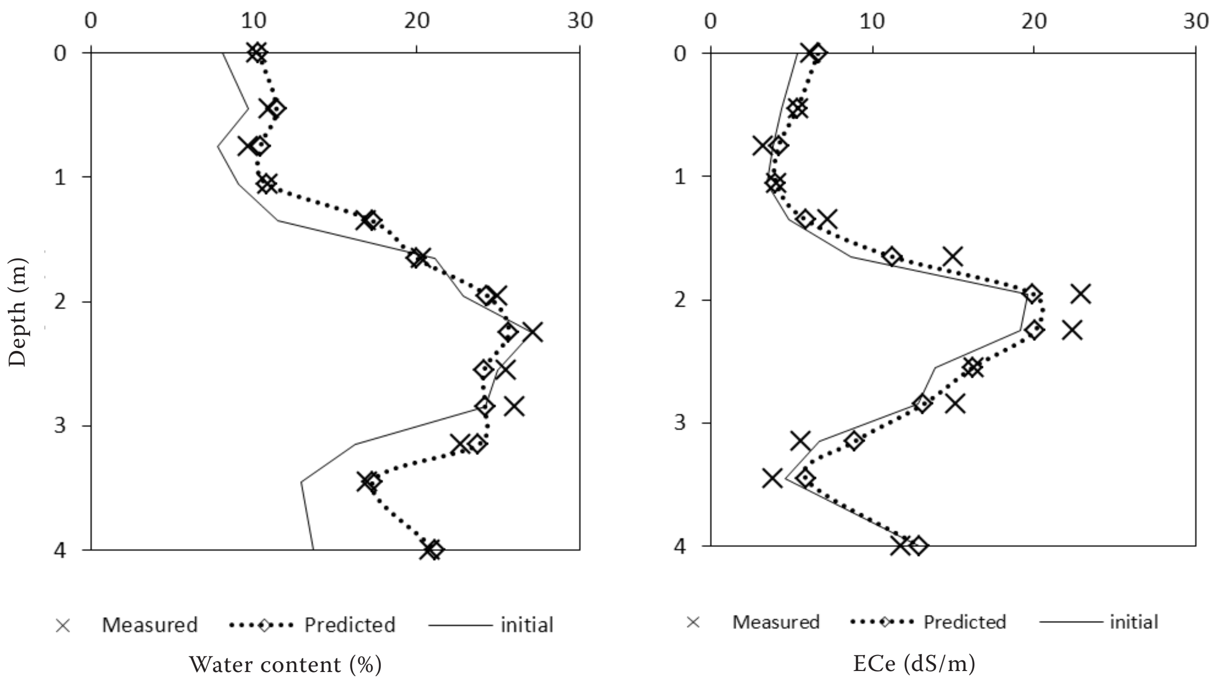

Figure 1. Measured and predicted profiles of 10th day of flood irrigation experiment

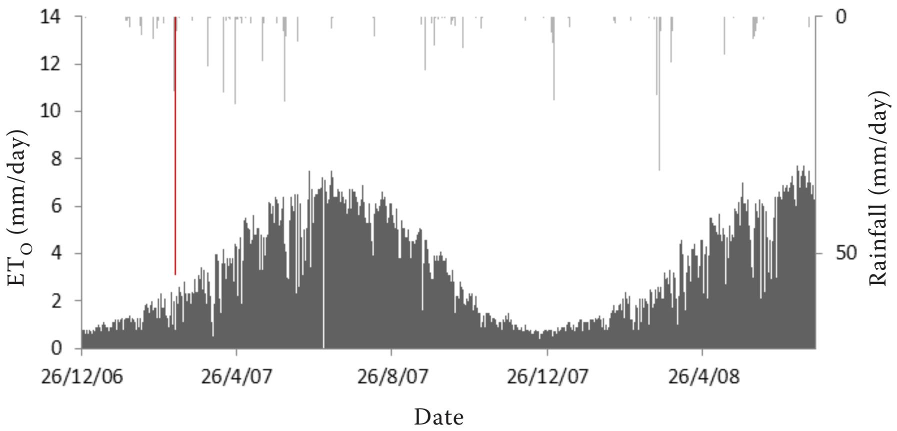

Figure 2. Values of precipitation and reference evaporation used for model validation (577 days: 26dec06 /22July 08)

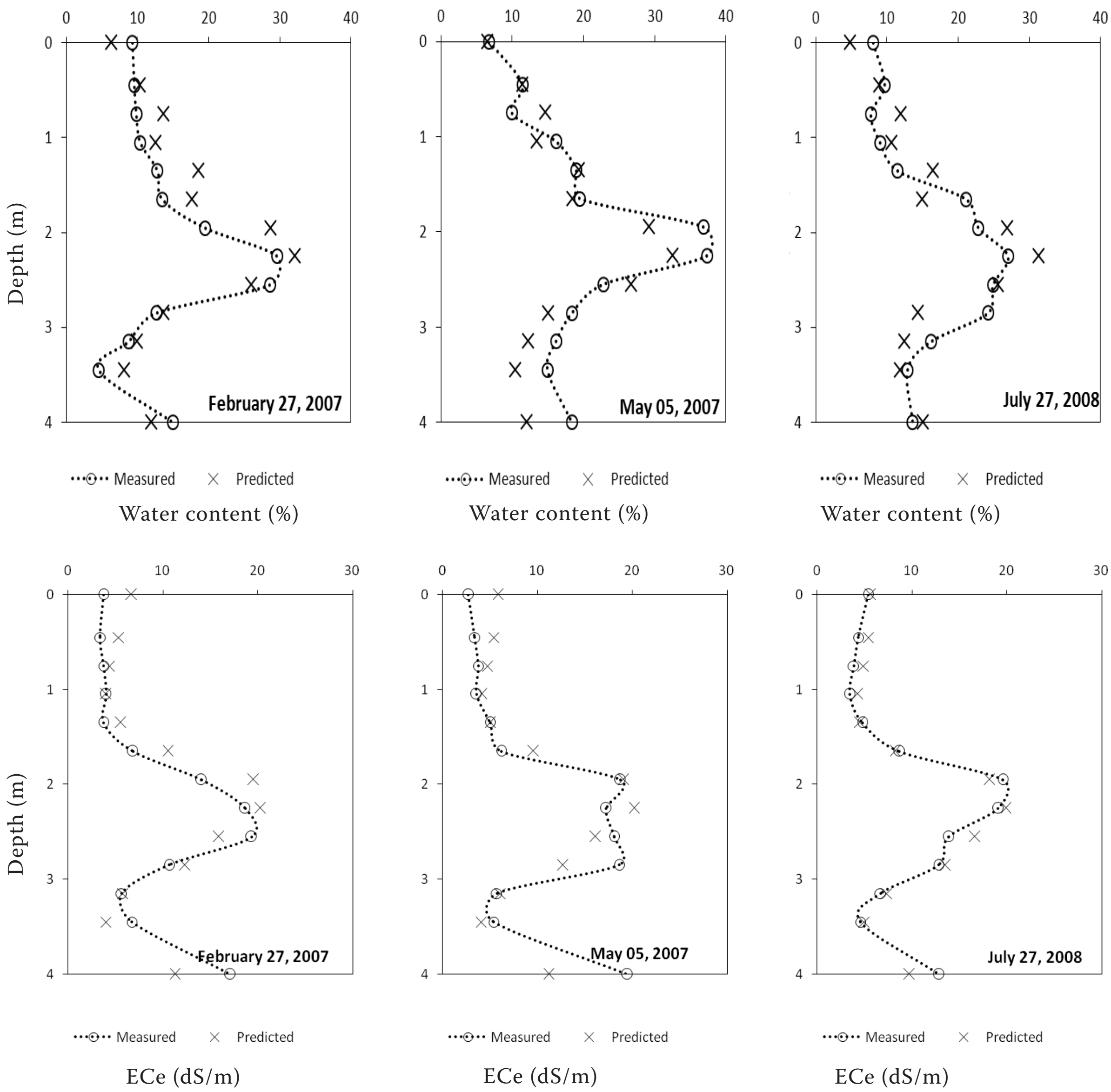

Figure 3. Measured and predicted profiles for each output time

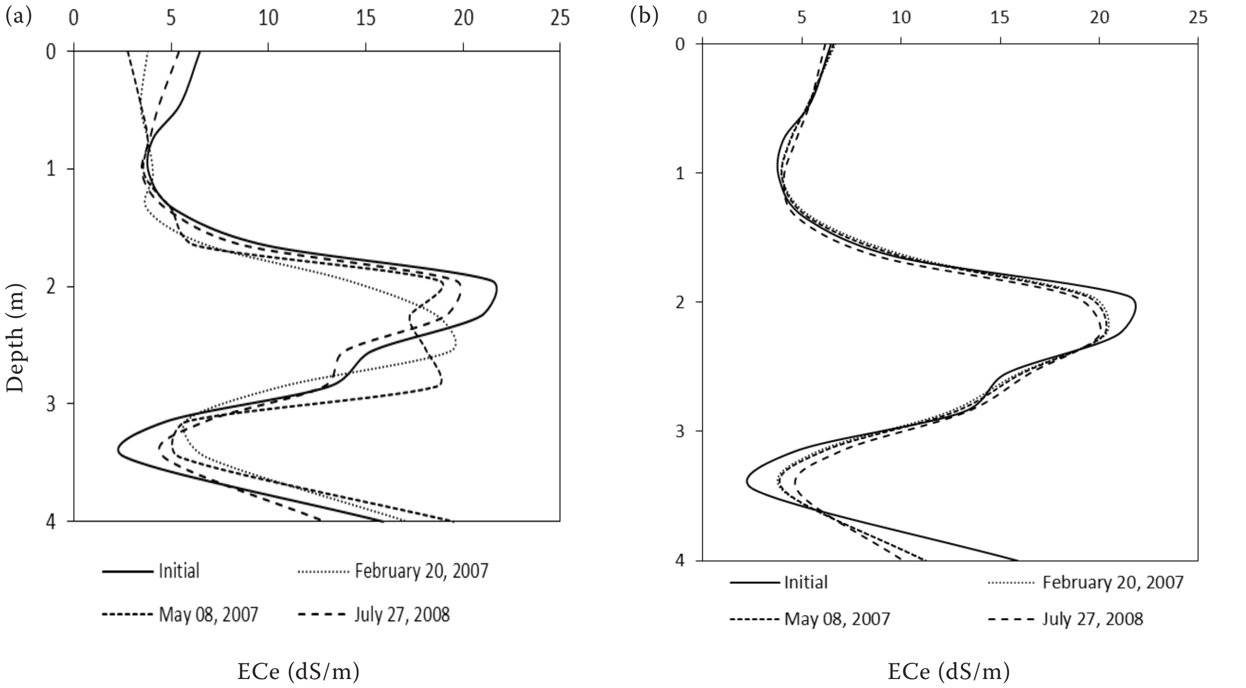

Figure 4. Effect of exceptional rain (50 mm/day) on salts dynamics; (a) with 50 mm/day, (b) without 50 mm/day

in the region of Bou Hajla. Indeed, it causes the leaching of significant amounts of salts that were previously accumulated in the top soil during irrigation with saline water, and their transfer to the depth.

Long-term simulation and salinisation risk

The long-term simulation was conducted over a period of 20 years. The climatic data of the year 2007 were used without considering the exceptional rain of 50 mm/day as the upper boundary condition. The output dates correspond to 2, 5, 10, and 20 years. The evolution of the saline profile (Figure 5) over the simulation time shows:

– A cyclical salinization / desalinisation in topsoil under the effect of evaporation and rainfall with low intensities;
– A continuous salinity in the deep layers (4 m).

The long-term simulation shows that even in the absence of exceptional rainfall events, the risk of aquifers salinization is important, being caused by the continuous leaching of salts in the deep layers of the soil. On the other hand, the salinization risk in the topsoil is less important because of the low intensity rainfall events, which are responsible for the leaching of salts accumulated in deeper layers.

DISCUSSION

Hydrus-1D was able to simulate the dynamics of water and salts in the semi-arid region of Bouhajla (Central Tunisia), as indicated by the low

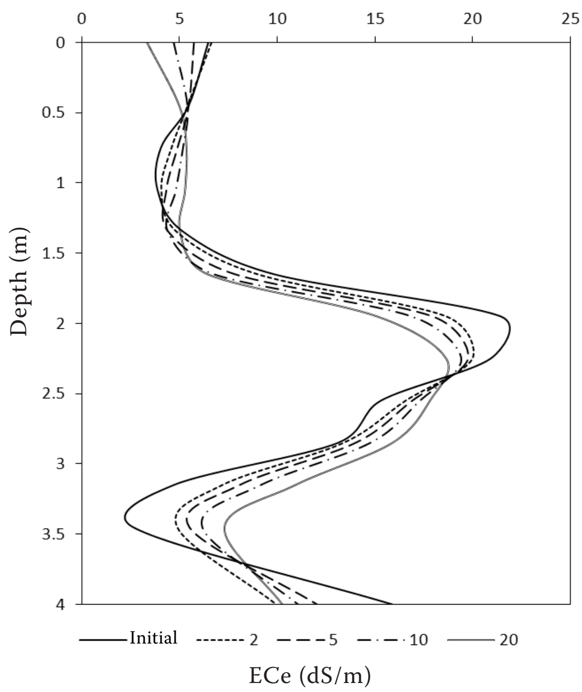

Figure 5. Long-term simulation of saline profile

calculated values of RMSE. The inverse modelling used to optimise the hydrodynamic parameters resulted in a good correlation between the measured and simulated data. However, it was unable to give us precise values of these parameters, due to the heterogeneity and spatial and structural organisation of each soil layer. It is suggested to increase the number of the measurement points in time and in space to understand the variation of the soil moisture and salts content (Köhne *et al*. 2009). In this study, most of the solute transport parameters were taken from the literature. The characterisation of these parameters for Bouhajla soils is essential to simulate the transport processes (Gonçalves *et al*. 2001).

In this paper, we have demonstrated that in the topsoil, salinisation is cyclical, and that salts are leached, even without any exceptional rainfall, which reduces the risk to the crops (Tanton *et al*. 1995; Armstrong *et al*. 1996). Furthermore, deep salts transfer exceeds 4 m in depth, which increases the aquifer salinization risk. It is essential to monitor the groundwater level and aquifer quality to highlight the contamination of groundwater by irrigation with saline water and to assess this risk. Finally, the consideration of different types of irrigation designs as used by the farmers in the region is needed to assess better the magnitude of the phenomenon of secondary salinization, and to find appropriate management strategies (Forkutsa *et al*. 2009). All these recommendations will be considered in future research work and papers.

CONCLUSION

The application of Hydrus-1D for the modelling of the salts dynamics over a period of 577 days has been successfully completed. The effect of torrential rains, characteristic of semi-arid areas, was evaluated. Such natural climatic events are responsible for leaching considerable amounts of salts to the deep layers reducing soil salinization but increasing the risk of the aquifer salinization. The long-term simulation lasting 20 years has shown the cyclical nature of salinization in the topsoil reducing the risk of its contamination, whereas in the deeper layers, the continuous leaching of salts is observed indicating the transfer of large amounts of salts into the depth. Our results cannot be concluding as concerns the salts transfer into the aquifer. The characterisation of the unsaturated zone between 4 m of depth and the aquifer will quantify and model, on a local scale, the transfer of salts into the unsaturated zone – aquifer and accurately assess the risk of groundwater contamination.

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