

# Modeling interactions between saturated and un-saturated zones by Hydrus-1D in semi-arid regions (plain of Kairouan, Central Tunisia)

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**Abstract** In semi-arid areas like the Kairouan region, salinization has become an increasing concern because of the constant irrigation with saline water and over use of groundwater resources, soils, and aquifers. In this study, a methodology has been developed to evaluate groundwater contamination risk based on the unsaturated zone hydraulic properties. Two soil profiles with different ranges of salinity, one located in the north of the plain and another one in the south of plain (each 30 m deep) and both characterized by direct recharge of the aquifer, were chosen. Simulations were conducted with Hydrus-1D code using measured precipitation data for the period 1998–2003 and calculated evapotranspiration for both chosen profiles. Four combinations of initial conditions of water content and salt concentration were used for the simulation process in order to find the best match between simulated and measured values. The success of the calibration of Hydrus-1D allowed the investigation of some scenarios in order to assess the contamination risk under different natural conditions. The aquifer risk contamination is related to the natural conditions where it increased while facing climate

change and temperature increase and decreased in the presence of a clay layer. Hydrus-1D was a useful tool to predict the groundwater level and quality in the case of a direct recharge and in the absence of any information related to the soil layers except for the texture.

**Keywords** Salinization · Unsaturation zone · Solute transport · Hydrus-1D · Semi-arid region · Kairouan

## Introduction

In arid and semi-arid regions, soil and aquifer salinization is increasingly a concern in irrigated regions, wherein such condition is characterized by high summer temperatures and scarce rainfall. Salinization due to irrigation water is a process whereby soluble salts from the irrigation water accumulate in soil due to inadequate leaching, high water tables, and/or high evaporation rates (Keren 2000). As a result, high contamination risk of the groundwater is present.

Indeed, salinity and sodicity are the principal water quality concerns in irrigated areas of arid and semi-arid climate using poor water quality for irrigation (Cruesi 1970; Gallali 1980; Bahri 1982). Irrigation water quality has a significant role in crop production and has a deep impact on physical and chemical soil properties. In arid and semi-arid regions, agriculture is mainly limited by the availability of suitable irrigation water, and groundwater is the main source of irrigation.

However, even with sufficient water, its use is often not suitable, leading to soil salinization as a

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consequence of inappropriate irrigation and drainage techniques (Luedeling et al. 2005). In order to compensate the increasing water demand, use of poor water quality groundwater for irrigation in arid and semiarid regions has become inevitable.

Surface and groundwater resources are used to fulfill the needs of the rapidly growing human population, and the depletion of these sources is considered as one of the greatest threat to maintaining freshwater supplies. This has been a crucial factor to agricultural production in many arid and semi-arid regions (Bouwer 2000).

In the region of the plain of Kairouan, Central Tunisia, salinization of soils and aquifers is a widespread phenomenon. In such a case, groundwater quality degradation is based on the saline water migration as well as pollutants from the surface to the groundwater through the vadose zone, defined as the unsaturated zone located in-between ground surface and groundwater table.

Hazardous wastes, fertilizers, or pesticides are some of the unwanted substances that might come from the ground surface that are removed by the vadose zone which act as a filter for the aquifers. Biological degradation, transformation of sorption, and contaminants could be stimulated by the high contents of organic matters and clay. We can conclude that the hydrogeological properties of this zone are of great concern for the groundwater pollution (Selker et al. 1999; Stephens 1996).

In order to create models for water and solute transport in the unsaturated zone by providing accurate results regarding water and solute solution profiles, some simplifications and assumptions should be made due to the heterogeneity and complexity of soil nature (Selker et al. 1999). The unsaturated zone processes significantly control water and solute migration into aquifers.

Therefore, the study and modeling of water flow and solute transport in the unsaturated zone is becoming an issue of major concern, generally, in terms of water resources planning and management, and specifically in terms of water quality management and groundwater contamination (Rumynin 2011).

During the last decades, several models have been developed to face this issue of evaluating water flow and solute transfer in the vadose zone.

These models can generally be distinguished as numerical and analytical models for predicting water and solute movement between the groundwater table and the soil surface, such as Hydrus 1D model allowing the simulation of water and solute movement. The two most

commonly used equations which are solved numerically using finite difference or finite element methods are as follows: first, the Richards equation which is the most used equation for variably saturated flow, and second, the Fickian-based convection–dispersion equation commonly used for solute transport (Arampatzis et al. 2001; Šimůnek et al. 1998). These two equations also require an iterative implicit technique (Damodhara et al. 2006).

Water, heat, and solute transport could be simulated either in one, two, or three-dimensional variably saturated porous media based on the finite two element method and this could be done through the Hydrus-1D computer code.

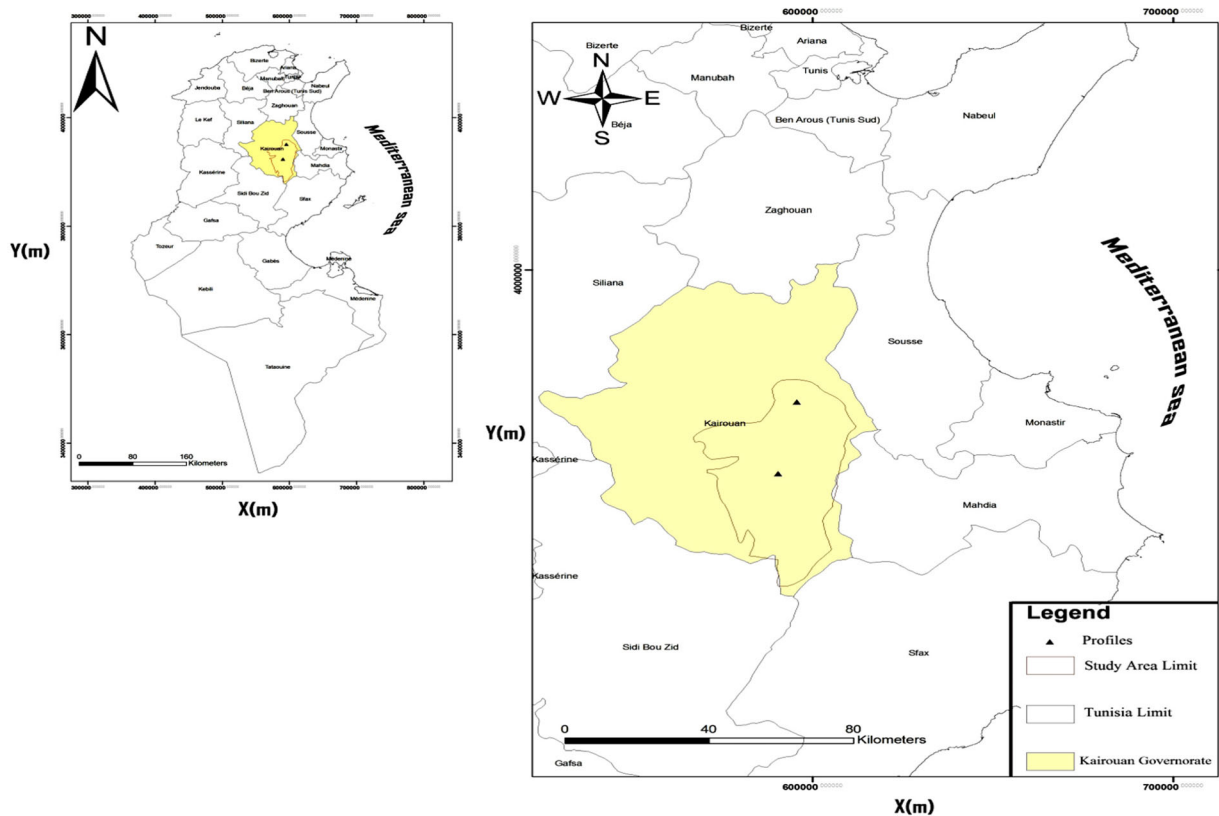
The Richards's equation for variably saturated water flow and advection–dispersion type equations for heat and solute transport are solved deterministically (Šimůnek et al. 1998).

The main objective of this paper is to assess groundwater contamination risk using Hydrus-1D model to simulate the interaction between the unsaturated (vadose zone) and the saturated zone (aquifer) by studying water content and salt concentration variation of two chosen soil profiles in a semi-arid region (Kairouan—Central Tunisia), both characterized by direct recharge of the aquifer and with two different ranges of salinity.

## Materials and methods

### Study area

The plain of Kairouan is located in the southeast of the Kairouan governorate (Fig. 1), covering an area of 100 km long (north–south) and 40 km wide (east–west). It is characterized by a low altitude basin of less than 100 m surrounded by a range of hills to the east and a range of mountains to the west. The study area is supplied by two major rivers and uses sebkhas as a natural outlet that receives surface waters and as a drainage tool of flood waters surrounding the city of Kairouan. This region is known for its climate aridity. The average annual rainfall is 300 mm according to the General Department of Water Resources (GDWR). As for the evapotranspiration, it is approximately about 1600 mm/year. The annual average temperature is 17 °C, and the lowest and highest temperatures are about 11 °C in January and 30 °C in August. According to Hachicha et al. (2013), half of the plain soils is affected by salts. It is mainly characterized by saline and salty soils where



**Fig. 1** Geographic location of the study area and the two profiles

isohumic, halomorphic, and poorly developed soils are distinguished (Belkhdja 1970). Two profiles in agricultural lands in the north and the south of the plain and both characterized by a direct recharge to the aquifer were selected to be subject for this study. The L Tetra profile, located in the south of the plain, is characterized by a sandy loam texture along its depth (30 m). The dry residue of this profile ranges between 2 and 3 g/L. Whereas, the M17 BIS profile located in the North of the plain is a heterogeneous profile characterized by a sandy loam texture (0–25 m), and after this level, the texture becomes essentially sandy (25–30 m) with a dry residue that ranges between 0 and 3 g/L.

**Geology and hydrogeology**

According to Castany (1968), Besbes (1975; 1976), Chaieb (1988), and Mansour (1995, 1997), the aquifer system of the plain of Kairouan is considered as the most important reservoir of central Tunisia (about 3000 km<sup>2</sup>), housing several aquifers stacked on each other and communicating more often with each other.

The plain of Kairouan is considered as a basin filled with detrital sediments corresponding to the Plio-quaternary formation (Fig. 2). However, according to the last recognitions on the East of Djebel Bateun, some sandstone formations attributed to the Miocene were discovered. The heterogeneous filling is formed by sand, clay, and gravel with all the different intercalations (sandy clay, clay sand ...). The endorheic basin of the Zeroud river is supplied from the surface mainly by floods of the Zeroud river and the Merguellil river, and secondarily by their tributaries and the piedmonts of the border landforms (localized type of recharge) (Besbes 1975, 1976; Mansour 1995, 1997). According to the work of Ben Ammar (2007), the plain is occupied by permeable detrital formations with a few discontinuous clay lenses that don't form impermeable shields in its western and central parts. Thus, the plain of Kairouan is formed by a free water table. Beyond that, in the eastern part and to the North East of Kairouan, the fine texture becomes dominant and the terrains correspond to semi-permeable formations separated by a continuous clay layer laterally.

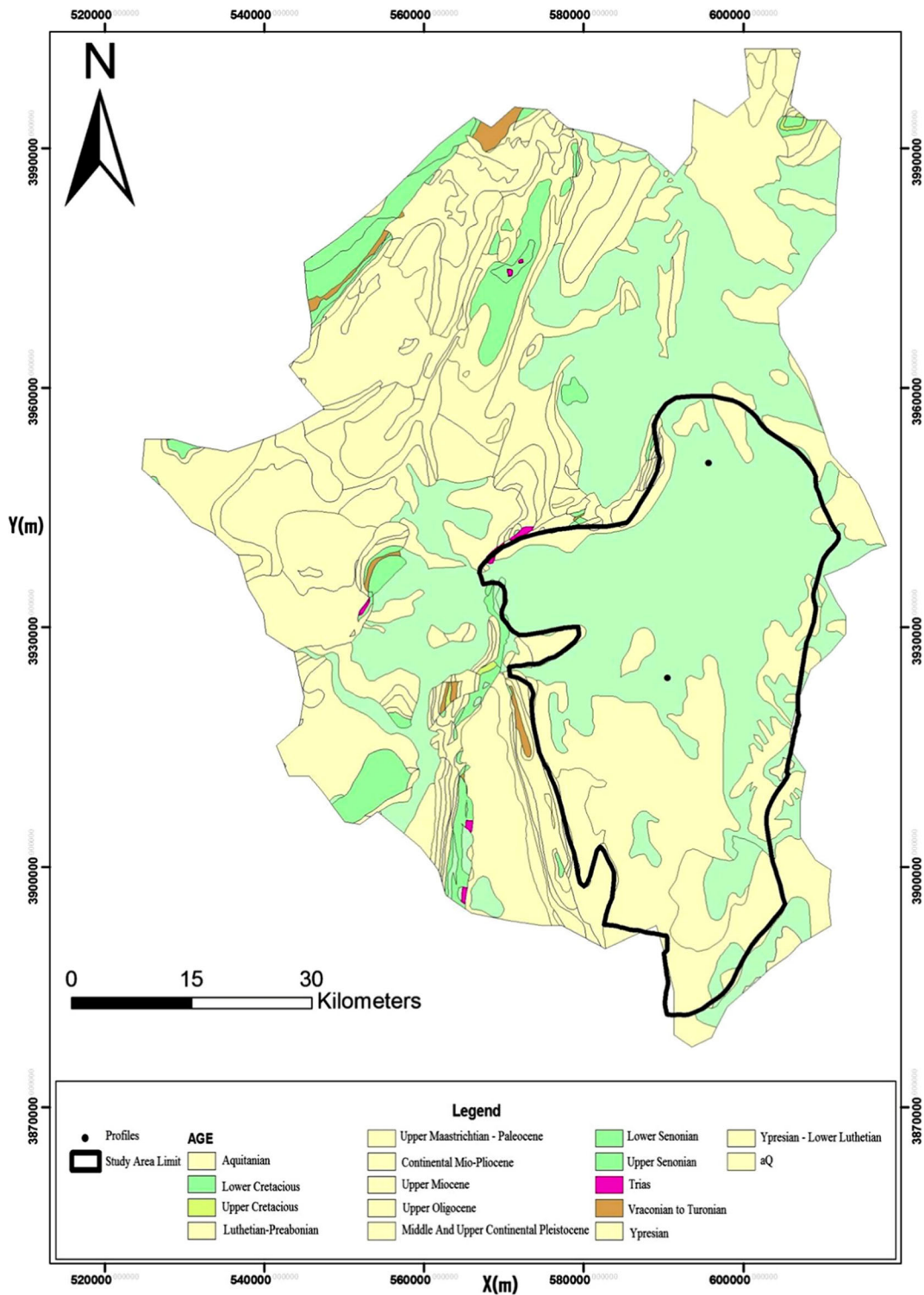


Fig. 2 Geological map of the study area

The groundwater of the Kairouan Plain must therefore be considered as a free aquifer over the whole

upstream and middle part, dividing towards the east between a confined and a phreatic aquifer separated by

an impermeable clay formation. The confined part is located to the north and east of Kairouan (Castany 1968; Besbes 1972). The Fig. 3 illustrates the hydraulic head state of the plain of Kairouan in March 2000.

The total flow of groundwater takes place on the western side towards Sebkhât El Kalbia on the Northeast side. This Sebkhâ is the natural outlet for

groundwater. The piezometric map also shows the effect of the Zeroud and Merguellil rivers on the aquifer recharge. In the upstream and central parts, the divergence of the underground flows from the rivers streams witnesses a significant contribution of their floods to the water supply. The tight form of the isopiezies and the strong hydraulic gradient (11 ‰) observed between

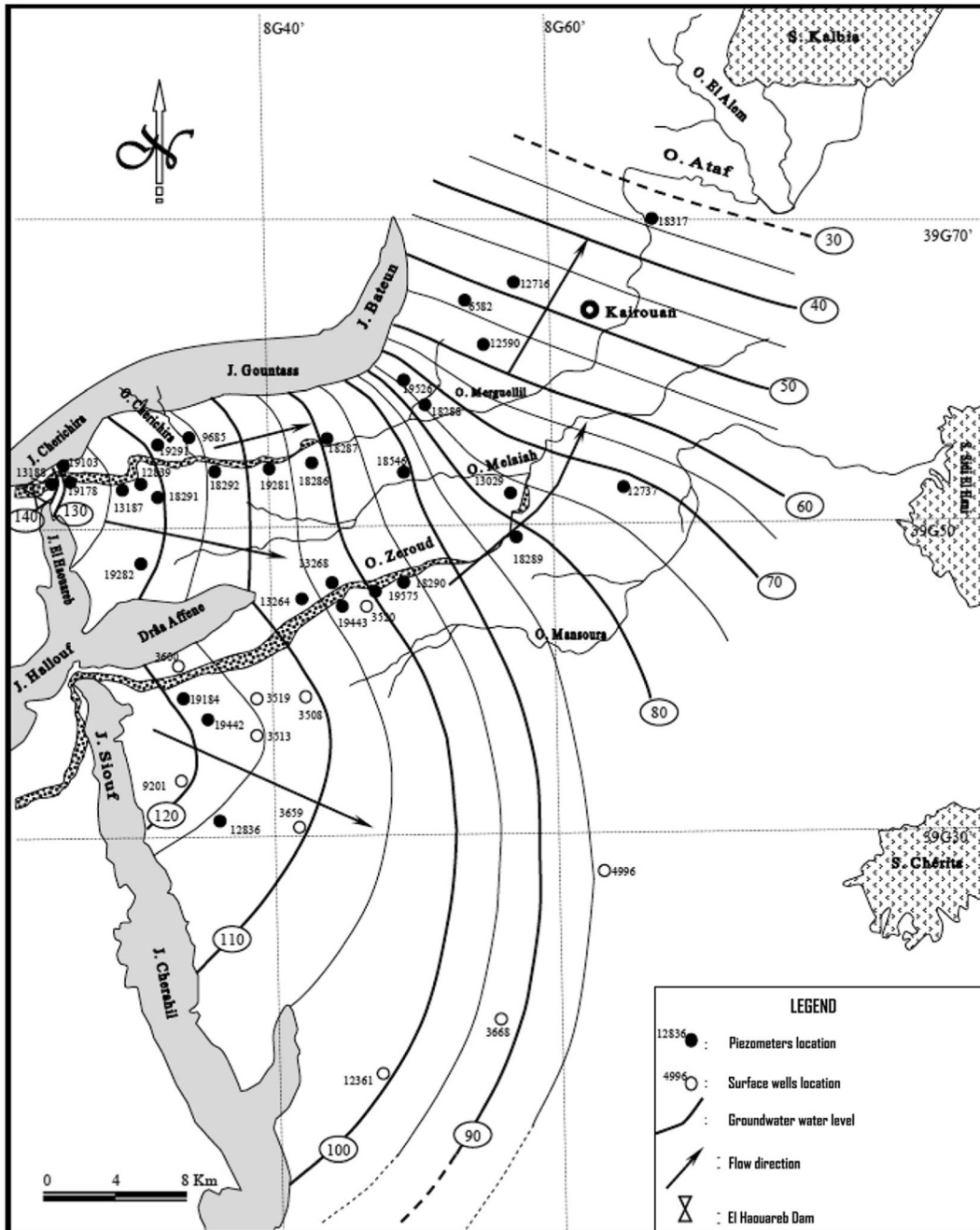


Fig. 3 Piezometric map of the plain of Kairouan in March 2000 (Ben Ammar 2007)



Djebel Cherichira and El Haouareb are due to the hydraulic threshold of Djebel El Haouareb, where the discharge water from the Ain El Beidha basin flows into the Kairouan plain. The recharge of the Kairouan plain from the underground stream of Ain El Beidhais estimated at 3.6 Mm<sup>3</sup>/year (Besbes, 1975).

According to the work history interested in the hydrogeology of the plain of Kairouan, the average intakes for the phreatic water table of the plain of Kairouan are estimated to be 25.2 Mm<sup>3</sup> while the exploitation (47.4 Mm<sup>3</sup>) is far beyond it. The plain of Kairouan is one of the most important agricultural areas in Tunisia (over 12.000 shallow wells and boreholes). The number of boreholes is continuously increasing especially after the revolution (January 2011); illegal boreholes are more present. This growth of withdrawals from the aquifer was the cause of overexploitation. The overexploitation of aquifers is noticeable through a general fall of the groundwater level, from 0.25 to 1 m per year for the past two decades and an average annual drawdown of approximately 0.30 m during the period 1995–2007. Withdrawals destined for irrigation reach almost 80%. Irrigating farmers receive water either in irrigation areas served by collective boreholes or by individual wells. These lasts are the biggest overall withdrawers and still barely known. Outside of collective irrigated areas, where water is paid to the manager, farmers pay only their own investment costs and pumping, which makes it difficult to establish water pricing in order to manage request. In order to try to stem the overexploitation, the authorities have stepped initially on the offer through the dam management that store runoff from rivers supplying the system, and secondly the demand by creating a “save area” meant to coerce the construction of new intakes since 1991. But in fact, the water table of Kairouan remains an open access collective resource: there restrictive regulations are not respected and the wells continue to proliferate particularly after the revolution (January 2011). The regulatory tool is even more difficult to implement than the water policy which is provided by the responsible institution of regional development.

#### Hydrus 1D model simulation

##### *Presentation of Hydrus 1D*

Hydrus-1D is a model used for simulating water, heat, and solute movement in one-dimensional variably

saturated porous media. It is based on the numerically solved Richards equation and the advection–dispersion equations respectively for water flow and solute transport. In order to consider the variations of the soil properties, the flow equation underwent different modifications, such as a sink term to account for water uptake by plant roots, and dual-porosity type flow or dual-permeability type flow to account for non-equilibrium flow. The program can deal with different water flow and solute transport boundary conditions (Šimůnek et al. 1998).

In order to complete water movement modeling, Hydrus-1D solves a modified version of the Richards equation. By removing the term that reflects the water root uptake, the mathematical expression is as follows:

$$\frac{\partial \theta}{\partial t} = \frac{\partial}{\partial z} \left[ K \left( \frac{\partial h}{\partial z} + 1 \right) \right] \quad (1)$$

where  $h$  is the water pressure head [L],  $\theta$  is the volumetric water content [L<sup>3</sup> L<sup>-3</sup>],  $K$  is the unsaturated hydraulic conductivity [LT<sup>-1</sup>],  $t$  is the time, and  $z$  is the spatial coordinate.

Hydrus-1D uses Mualem and van Genuchten (1980) equations to set the water retention curve  $\theta(h)$ , which relates the volumetric water content in pressure potential to the hydraulic conductivity curve  $K(h)$ , depending on its state of saturation measured by  $h$ . The equation of van Genuchten (1980) for the retention curve is:

$$\theta(h) = \begin{cases} \theta_r + \frac{\theta_s - \theta_r}{1 + |\alpha h^n|^m} & h < 0 \\ \theta_s & h \geq 0 \end{cases} \text{ where } m = 1 - \frac{1}{n} > 1 \quad (2)$$

where  $\theta_r$  is the residual water content [L<sup>3</sup> L<sup>-3</sup>],  $\theta_s$  is the saturated water content [L<sup>3</sup> L<sup>-3</sup>],  $h$  is the water pressure head [L],  $\alpha$  [L<sup>-1</sup>], and  $n$  [-] are shape parameters.

The MVG equation (Mualem and Van Genuchten 1980) to describe the hydraulic conductivity curve is as follows:

$$K(h) = \begin{cases} K_s r S_e^{1/2} \left[ 1 - \left( 1 - S_e^{1/m} \right)^m \right]^2 h & \\ K_s & h \geq 0 \end{cases} \quad (3)$$

where  $m = 1 - \frac{1}{n} > 1$  et  $S_e = \frac{\theta - \theta_r}{\theta_s - \theta_r}$ ,  $K_s$  is the saturated hydraulic conductivity [LT<sup>-1</sup>],  $S_e$  is the effective saturation [-], and  $r$  is the pore connectivity parameter [-], equal to 0.5 (Mualem 1976).

**Table 1** Initial conditions of water content and solute concentration

$C$ ( $g\ l^{-1}$ )	First combination				Second combination				Third combination			Fourth combination				
	0.5				1				2			3				
$\theta$ ( $cm^3\ cm^{-3}$ )	0.1	0.2	0.3	0.4	0.1	0.2	0.3	0.4	0.1	0.2	0.3	0.4	0.1	0.2	0.3	0.4

$C$  ( $g\ l^{-1}$ ): value of salt concentrations

$\theta$  ( $cm^3\ cm^{-3}$ ): value of water contents

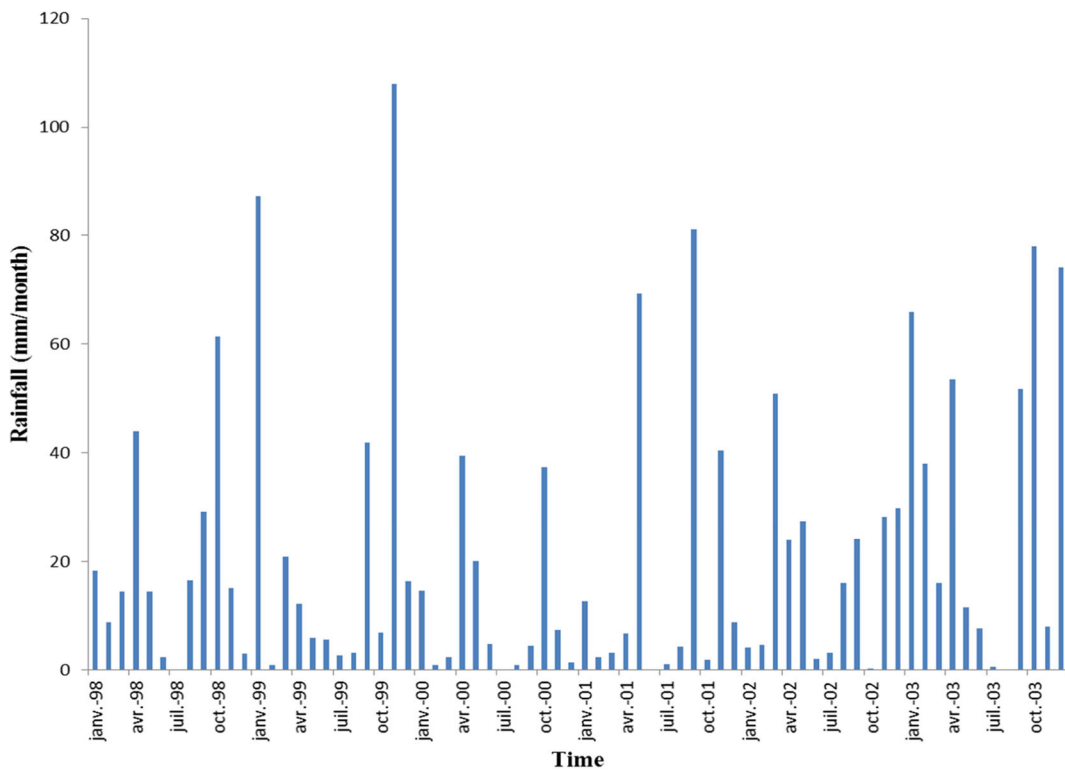
The partial differential equations governing equilibrium one-dimensional solute transport under transient flow in variably saturated medium is defined in Hydrus-1D as:

$$\frac{\partial \rho \cdot S}{\partial t} + \frac{\partial \theta \cdot C}{\partial t} = \frac{\partial}{\partial z} \left\{ \theta \cdot D \cdot \frac{\partial C}{\partial z} \right\} - q \frac{\partial C}{\partial z} \tag{4}$$

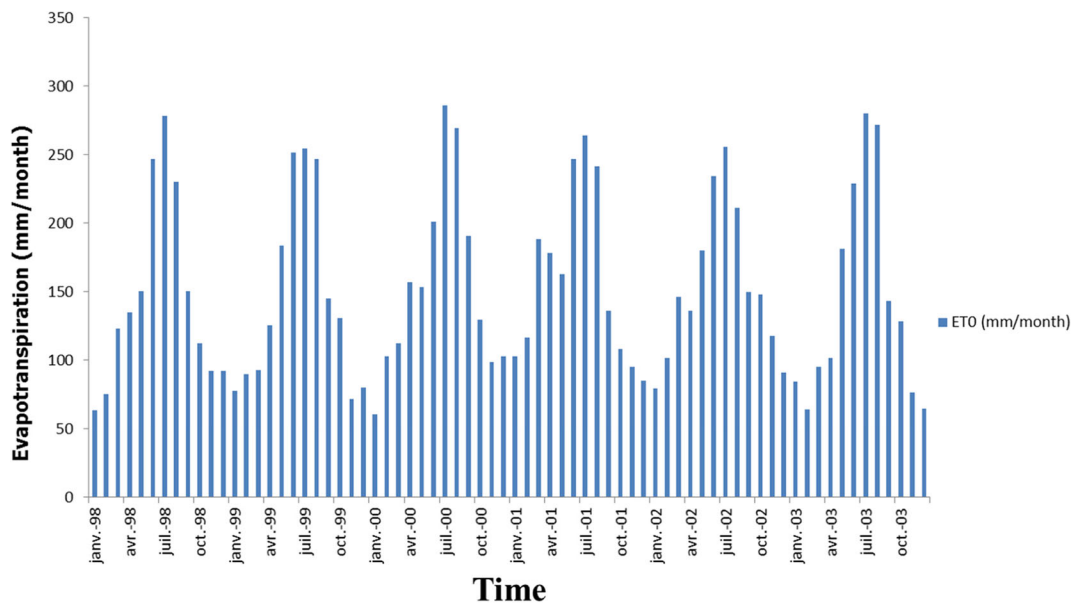
where  $z$  is the spatial coordinate,  $C$  and  $S$  are solute concentrations in the liquid [ $ML^{-3}$ ] and solid [ $MM^{-1}$ ] phases, respectively,  $q$  is the volumetric flux density [ $LT^{-1}$ ],  $D$  is the dispersion coefficient [ $L^2\ T^{-1}$ ], and  $\rho$  is the bulk soil density [ $ML^{-3}$ ] (Mualem and Van Genuchten, 1980).

Initial and boundary conditions

Initial conditions were set with 16 different combinations (Table 1) in the model with different soil water contents and salt concentrations taken based on the data history collected from the General Department of Water Resources (GDWR) (Mualem 1976). Based on the observed values of groundwater salinity, each range of soil salinity corresponds to four water content initial conditions. The minimum value of water content taken was ( $\theta = 0.1\ cm^3\ cm^{-3}$ ) and the maximum value of water content is the one of a saturation state was ( $\theta = 0.4\ cm^3.cm^{-3}$ ). At the soil surface, an atmospheric boundary condition was



**Fig. 4** Variations of rainfall during the period 1998–2003



**Fig. 5** Evapotranspiration results measured by the ET<sub>0</sub> calculator over the study period (1998–2003)

**Table 2** Input parameters of both studied profiles

Parameters	Values		
	L tetra profile	M17 BIS profile	
<b>Geometry information</b>			
Depth	30 m	30 m	
Number of layers	1	2	
<b>Time information</b>			
Simulation time	2191 days		
<b>Hydraulic properties</b>			
Layers (meters)	0–30	0–25	25–30
$\theta_r$ (cm <sup>3</sup> cm <sup>-3</sup> )	0.65	0.065	0.045
$\theta_s$ (cm <sup>3</sup> cm <sup>-3</sup> )	0.41	0.41	0.43
$\alpha$ (cm <sup>-1</sup> )	7.5	7.5	14.5
$n(-)$	1.89	1.89	2.68
$K_s$ (cm j <sup>-1</sup> )	1.061	1.061	7.128
$L$	0.5	0.5	0.5
<b>Boundary conditions</b>			
<b>Water flow</b>			
Upper boundary condition	Atmospheric BC with surface layer		
Lower boundary condition	Deep drainage		
<b>Solute transfer</b>			
Upper boundary condition	Concentration flux BC		
Lower boundary condition	Concentration flux BC		
<b>Solute transfer properties</b>			
Layer (meters)	0–30	0–25	25–30
Dispersion coefficient [L]	17	25	5
Kd[M <sup>-1</sup> L <sup>3</sup> ]	0	0	0

specified that required the daily data of precipitation and evapotranspiration (ET<sub>0</sub>). Daily values of the ET<sub>0</sub> were calculated using the climate data via Penman–Monteith method.

Deep drainage was utilized as the lower BC, for which the release rate  $q(n)$  at the base of the soil profile at node  $n$  is characterized as an element of the position of the groundwater table (Hopmans and Stricker 1989).

$$q(n) = q(h) = -A_{qh} \exp(B_{qh} | h - \text{GWL0L} |) \quad (5)$$

where  $q(h)$  [cm day<sup>-1</sup>] is the discharge rate,  $h$  [cm] is the pressure head at the bottom of the soil profile,  $A_{qh}$  [cm day<sup>-1</sup>] and  $B_{qh}$  [cm<sup>-1</sup>] are empirical parameters and GWL0L [cm] is the reference groundwater depth. In our case, vertical drainage across the lower boundary of the soil profile is approximated by a flux, which depends on the position of the groundwater level (Hopmans and Stricker 1989).

As for solute transport, concentration flux BC was used as both the upper and the lower boundary conditions.

### Climate data

Climate data were collected for the study period (6 years) at a daily step from the meteorological station starting from January 1st, 1998, to December 21st, 2003. Monthly variations of rainfall data during the study



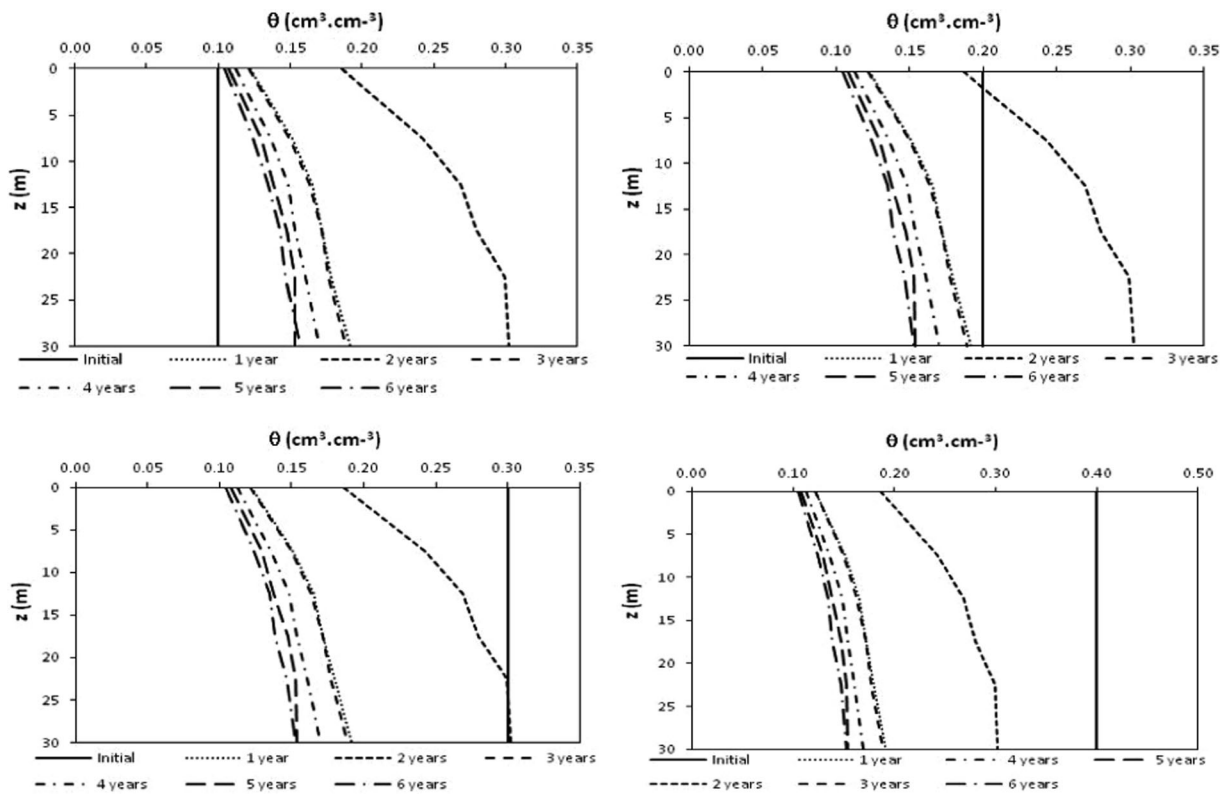


Fig. 6 Water content variation for L tetra profile  $C = 0.5 \text{ g.l}^{-1}$ ,  $C = 1 \text{ g.l}^{-1}$ ,  $C = 2 \text{ g.l}^{-1}$ , and  $C = 3 \text{ g.l}^{-1}$

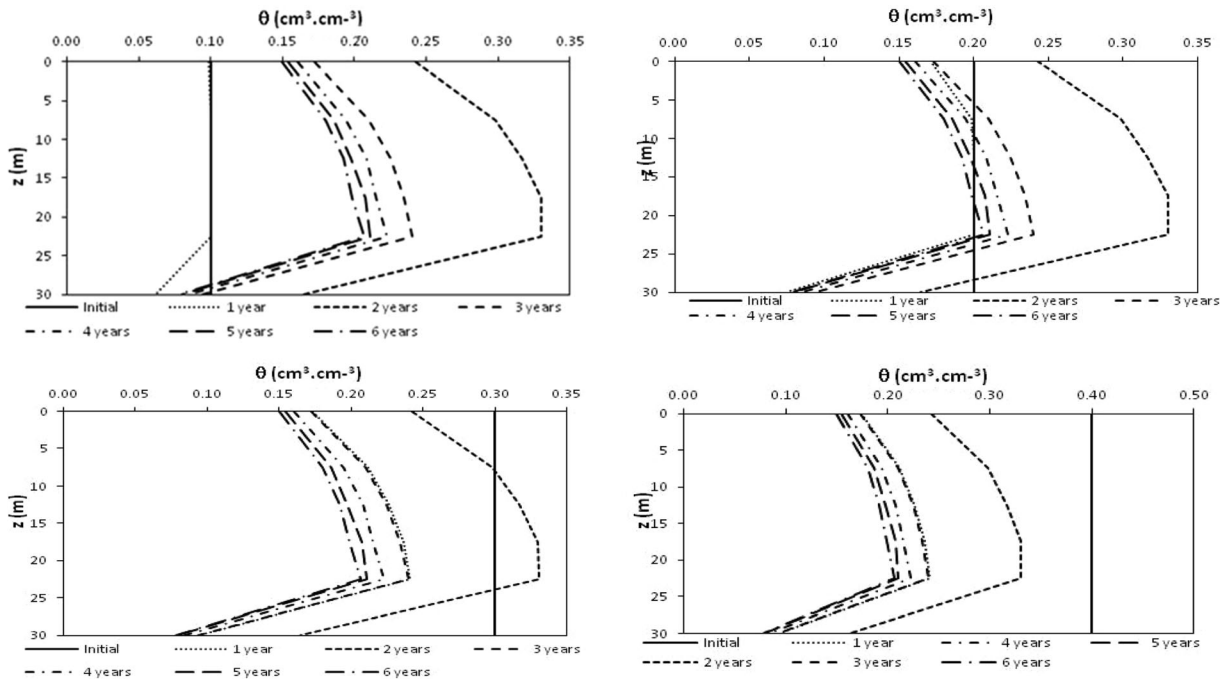
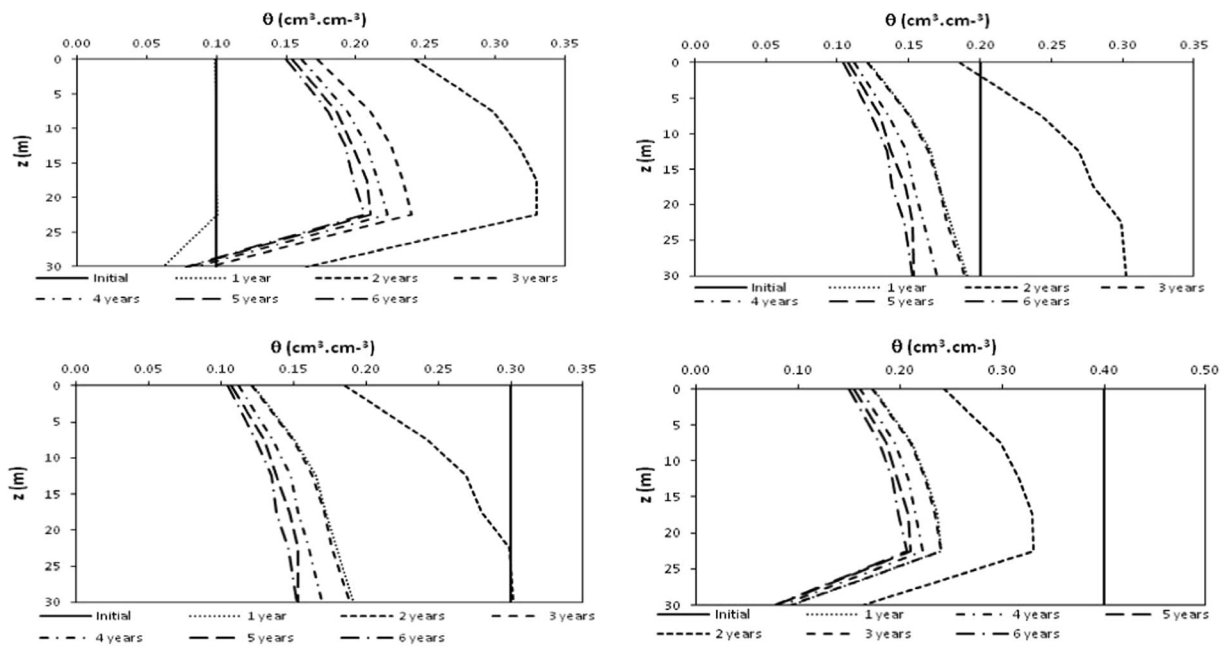


Fig. 7 Water content variation for M17BIS profile  $C = 0.5 \text{ g.l}^{-1}$ ,  $C = 1 \text{ g.l}^{-1}$ , and  $C = 2 \text{ g.l}^{-1}$

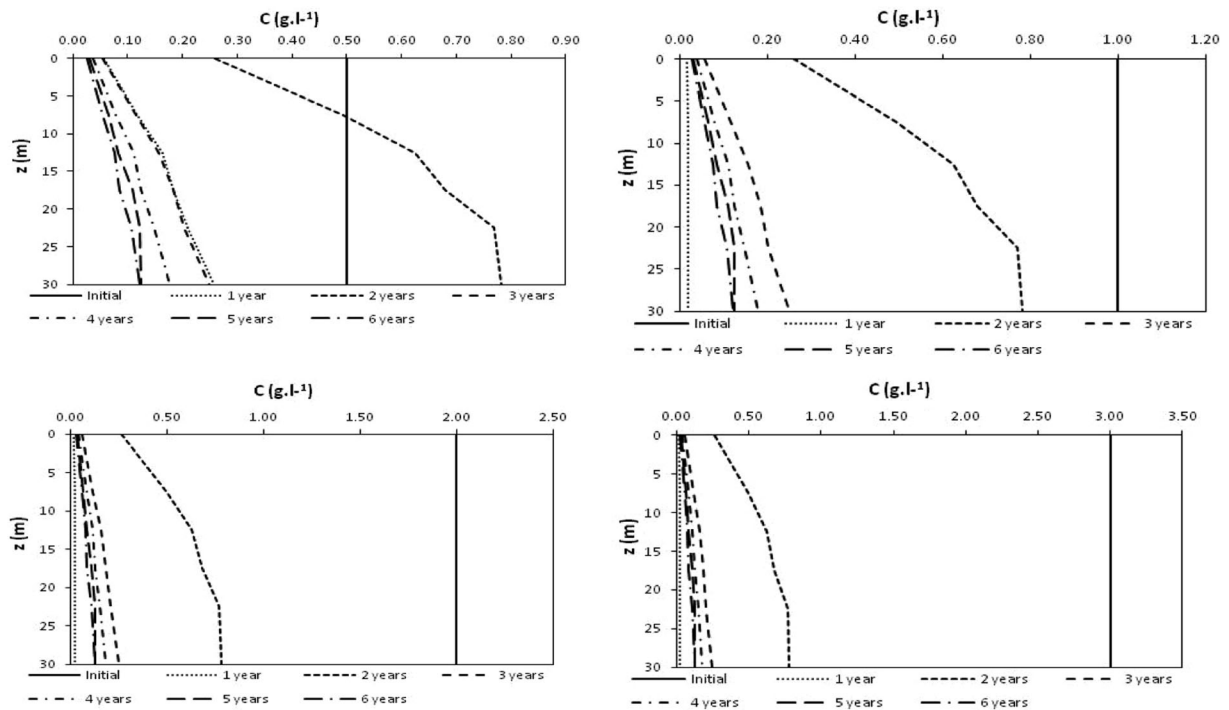


**Fig. 8** Water content variation for M17BIS profile  $C = 3 \text{ g.l}^{-1}$

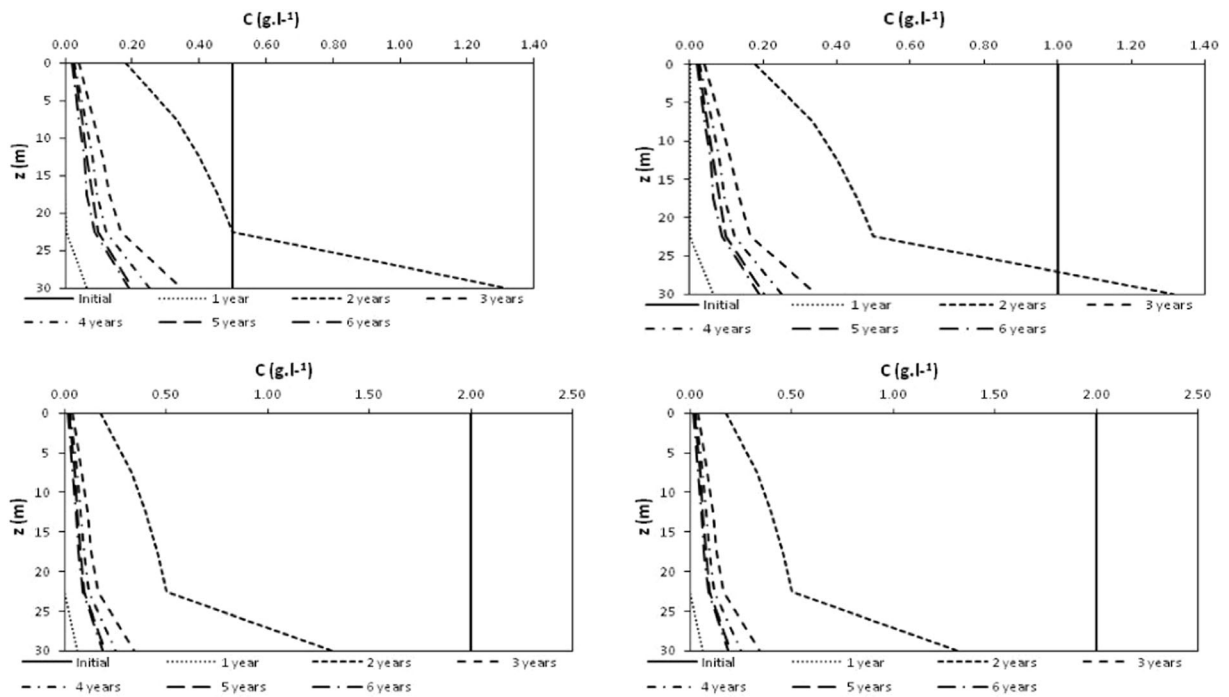
period are presented in Fig. 4. As for evaporation, the Penman–Monteith equation (Allen et al. 1998) was used for calculating evapotranspiration ( $ET_0$ ) from available climatic data presented in Fig. 5.

Input parameters of Hydrus 1D

The Rosetta model (Schaap et al. 2001) implemented in Hydrus-1D was used to define the soil



**Fig. 9** Salts content variation for L tetra profile  $C = 0.5 \text{ g.l}^{-1}$ ,  $C = 1 \text{ g.l}^{-1}$ ,  $C = 2 \text{ g.l}^{-1}$ , and  $C = 3 \text{ g.l}^{-1}$



**Fig. 10** Salt content variation for M17BIS profile  $C = 0.5 \text{ g.l}^{-1}$

hydraulic parameters which were determined from the particle size distribution and bulk density. The simulation was performed on a total duration of 2191 days with a daily time step (2.67 to 5). In this case, there are six printing times matching the 6 years of the study period.

Initial values of the soil hydraulic parameters are presented in Table 2. The residual water content,  $\theta_r$ , and the saturated water content,  $\theta_s$ , were estimated from the particle size distribution using the Rosetta (Schaap et al. 2001) pedo-transfer functions.

As for solute transport parameters, dispersion coefficients (Disp.) and the adsorption coefficients (Kd) were taken from the literature (Vanderborght and Vereecken 2007) for each type of texture.

**Table 3** Hydraulic parameters of deep drainage boundary condition

Parameters	L tetra profile	M17 BIS profile
$A_{qh}$	-0.3173	0.31727
$B_{qh}$	-0.03463	-0.03436

### Model calibration and validation

The model was evaluated by both graphical and statistical methods. In the graphical approach, the measured and simulated volumetric water contents and soil salinities were plotted as a function of the soil depth at different times. The statistical approach involved the calculation of the root-mean-square error (RMSE):

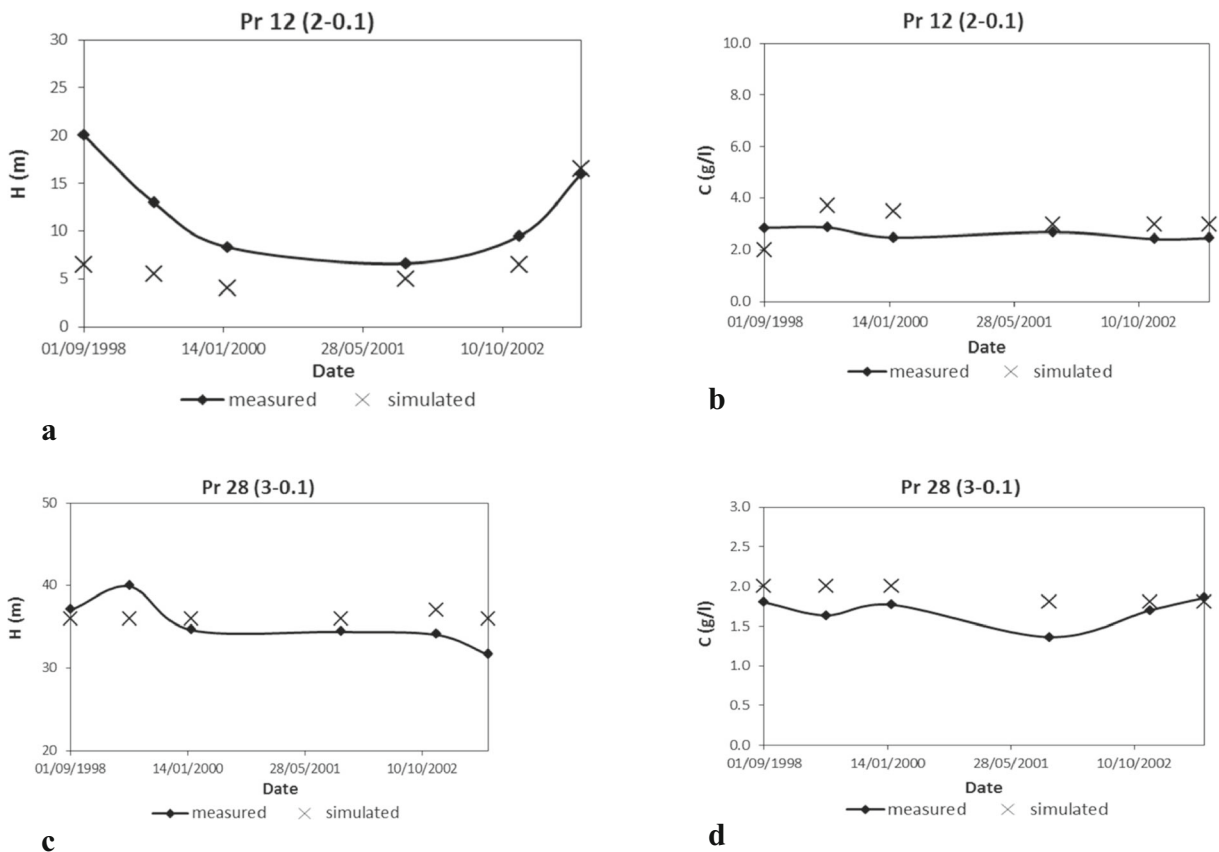
$$RMSE = \sqrt{\frac{\sum_{i=1}^n (p_i - m_i)^2}{n}} \times \frac{1}{\bar{m}} \times 100 \tag{6}$$

where  $p_i$  are the predicted values,  $m_i$  are the measured values,  $\bar{m}$  is the average value of observed data, and  $n$  is the number of observations.

### Results and discussion

#### Characterization of water movement and salt transport dynamics

Depending on the water content initial condition, soil humidity profile (for each output time) varies from a dry state to a saturated state according to the values in the



**Fig. 11** Simulated values versus measured values of water content variation of the L tetra profile Pr 12 and the M17 BIS Pr 28. **a** Simulated values versus measured values of water content variation of the L tetra profile for the 3rd combination. **b** Simulated values versus measured values of salt concentration variation of

the L Tetra profile for the 3rd combination. **c** Simulated values versus measured values of salt concentration variation of the M17 BIS profile for the 4th combination. **d** Simulated values versus measured values of water content variation of the M17 BIS profile for the 4th combination

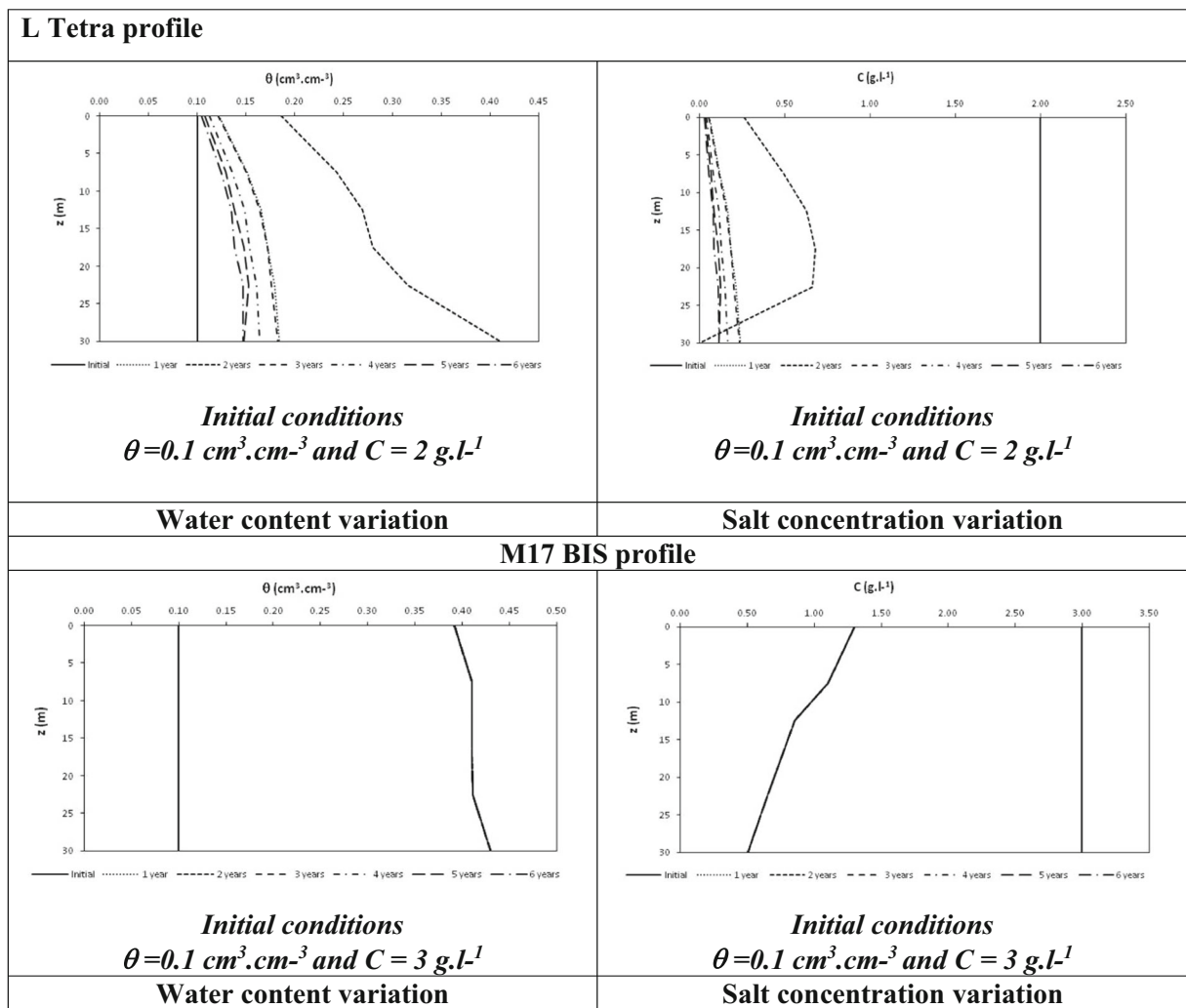
unsaturated zone that can exceed or be lower than the water initial condition. According to the results shown in Figs. 6 and 7, two layers were distinguished:

- From 5 to 20 m: a slight increasing mainly in the 1 and 3 years responses represent a noticed variation in water content profiles.
- From 20 m until the bottom of the profile 30 m: water content values remain constant and varying between  $0.13$  and  $0.18 \text{ cm}^3 \text{ cm}^{-3}$ .

The different combinations show that water content values vary between  $0.10$  and  $0.15 \text{ cm}^3 \text{ cm}^{-3}$  for year 1, year 3, year 4, year 5, and year 6 which highlight a continuous dryness of the unsaturated zone compared to the initial conditions. However, for the year 2 response, water content starts from  $0.19 \text{ cm}^3 \text{ cm}^{-3}$  at the surface and tends to increase rapidly until reaching

approximately  $0.22 \text{ cm}^3 \text{ cm}^{-3}$  at 5 m,  $0.27 \text{ cm}^3 \text{ cm}^{-3}$  at 20 m, and finally  $0.30 \text{ cm}^3 \text{ cm}^{-3}$  at the bottom. This exception shows a higher value of water content that exceeds the initial condition, which might be explained by the important amount of water infiltrated after some rainfall events.

For both profiles, the four combinations of initial conditions have the same patterns of variation of soil water content during the simulation period. A distinguished over saturation of the soil after 2 years is also noticed. The soil response towards infiltration (rainfall) and evaporation is observed as well as the effect of the initial condition on the water flow dynamic. Water content initial values over  $0.2 \text{ cm}^3 \text{ cm}^{-3}$  stimulate a constant infiltration to the groundwater. The only exception noticed in these results is shown in the M17 BIS profile due to its heterogeneity. It is characterized by a sandy layer at the bottom were a difference in water content responses



**Fig. 12** Scenario results for rainfall effects of both profiles L tetra and M17 BIS

is noticed compared to the sandy loam layer. In fact, this layer accelerates water infiltration to the aquifer and influence water dynamics in the unsaturated zone.

To resume, the different results show that, at some point, the water content profiles have a certain pattern similarity for the different output years except for the second years, where an increase of soil humidity is distinguished.

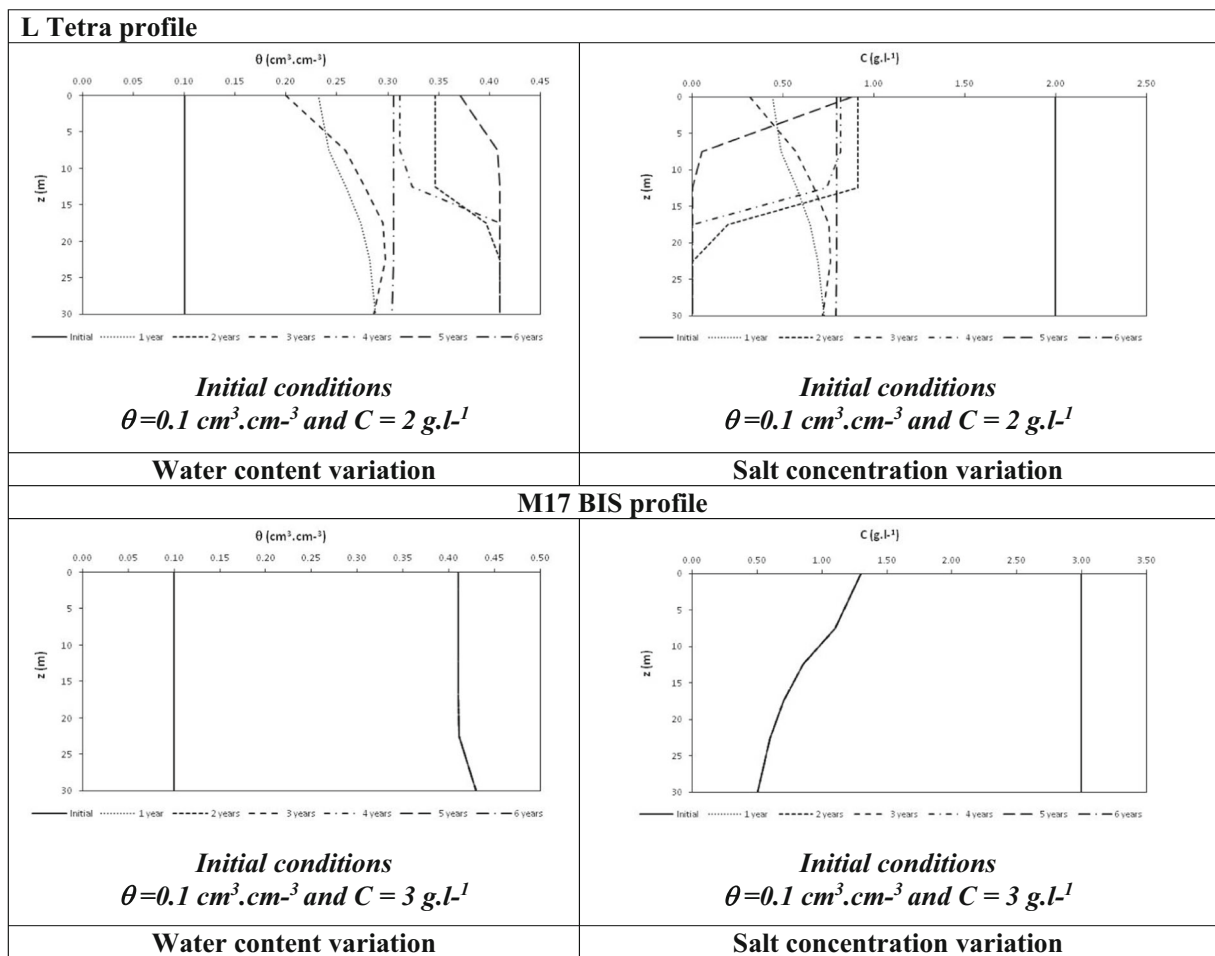
As for solute transport, the salt concentration profiles during the simulation period have the same shape for all the combinations, except the year 2 response where the salt concentration increase. The same range of variation was well observed while discussing the variation of the water content profiles.

According to the initial conditions, the concentration rate reaches a very low value that does not appear at the

surface and it increases moderately to stabilize at around  $0.25 \text{ g l}^{-1}$  at the bottom of the profile (30 m) for year 1 and year 3 responses. However, as for year 4, year 5, and year 6 responses, solute concentrations do not vary significantly. The noticed variation range is in the bottom with an interval of 0.1 and  $0.15 \text{ g l}^{-1}$  at the bottom. For year 2, solute concentration reaches an important value at the soil surface up to  $0.55 \text{ g l}^{-1}$ . According to Figs. 8 and 9, three major layers were distinguished:

- From 0 to 12.5 m, salt concentration in this response increases constantly from  $0.25 \text{ g l}^{-1}$  to get to  $0.64 \text{ g l}^{-1}$ .
- From 12.5 to 22.5 m, the shape of the profile changes but is still increasing until it reaches 22.5 m with a final salt concentration value of  $0.8 \text{ g l}^{-1}$ .





**Fig. 13** Scenario results for climate change effects of both profiles L tetra and M17 BIS

- From 22.5 to 30 m, salt concentration values remain constant with a final value of  $0.8 \text{ g l}^{-1}$ .

The simulated salt content profiles for the different combinations of initial conditions show that there is an increase of soil salinity after 2 years. From the third year, a continuous leaching of salts through the unsaturated zone is noticed. In some cases, as mentioned before, there is a complete leaching with a value of concentration near  $0 \text{ g l}^{-1}$ . These results match with those of the water profiles analysis and highlight the high contamination risk of the groundwater in the case of the L tetra profile. As noticed in the water content variation, the M17 BIS profile brings a difference in the salt concentration responses that are easily seen at the bottom of the profile. In fact, the second layer at the bottom, with sandy texture, accelerates salt leaching into the aquifer that increases the contamination risk (Fig. 10).

#### Modeling of water flow and solute transport

The simulation results of water content and solute concentration were compared to measured values of groundwater level and groundwater salinity taken from the GDWR (2016) for each output time. The relation of Hopmans and Stricker (1989) relates to the movement of the groundwater level and the infiltrated flux. As for the solute transport, the concentration of the soil solution at the lower boundary (30 m) is supposed to be equal to the solute concentration of the aquifer.

Calibration of Hydrus 1D was performed in two steps consisting in the calibration of the groundwater level by adjusting the parameters  $A_{qh}$  and  $B_{qh}$  until having a combination that gives an acceptable match between simulated and measured values as the first

**Table 4** Input parameters of Hydrus 1D module used for clay layer effects study

Parameters	Values						
	L tetra profile			M17 BIS profile			
Geometry information							
Depth	30 m			30 m			
Number of layers	1			2			
Time information							
Simulation time	2191 days						
Hydraulic properties							
Layers (meters)	0–30		0–25		25–30		
$\theta_r$ (cm <sup>3</sup> .cm <sup>-3</sup> )	0.65		0.065		0.045		
$\theta_s$ (cm <sup>3</sup> .cm <sup>-3</sup> )	0.41		0.41		0.43		
$\alpha$ (cm <sup>-1</sup> )	7.5		7.5		14.5		
$n(-)$	1.89		1.89		2.68		
$K_s$ (cm j <sup>-1</sup> )	1.061		1.061		7.128		
L	0.5		0.5		0.5		
Time variable boundary condition	Presence of a clay layer in the middle of the profile						
Solute transfer properties							
Layer (meters)	0–15	15–17	17–30	0–15	15–17	17–25	25–30
Dispersion coefficient[L]	17	3	17	25	5	25	3
Kd[M <sup>-1</sup> L <sup>3</sup> ]	0	0	0	0	0	0	0

step. The second step that was performed after the calibration of the model for the groundwater level consists in the calibration of the solute concentration using different values from the literature (Kanzari et al. 2014) of the linear adsorption coefficient shown in Table 3 until having well matches between the simulated concentrations and the measured groundwater salinity values.

The measured values of groundwater level and groundwater salinity versus the simulated values by Hydrus-1D were plotted. According to these lasts, the initial conditions of 0.1 cm<sup>3</sup> cm<sup>-3</sup> and 2 g l<sup>-1</sup> for the L tetra profile and the initial conditions of 0.1 cm<sup>3</sup> cm<sup>-3</sup> and 3 g l<sup>-1</sup> for the M17BIS profile have the best agreement between the measured and the simulated values (Fig. 11a, b). The same results are confirmed by the statistical evaluation. The initial conditions of 0.1 cm<sup>3</sup> cm<sup>-3</sup> and 2 g l<sup>-1</sup> for the L tetra profile (Fig. 11c, d) and the initial conditions of 0.1 cm<sup>3</sup> cm<sup>-3</sup> and 3 g l<sup>-1</sup> for the M17BIS profile have the smallest values of RMSE as shown in Table 5.

The Hydrus-1D model was able to simulate water and salt dynamics. Both graphical and statistical method results in the used approach were able to prove the calibration of the model. The lowest

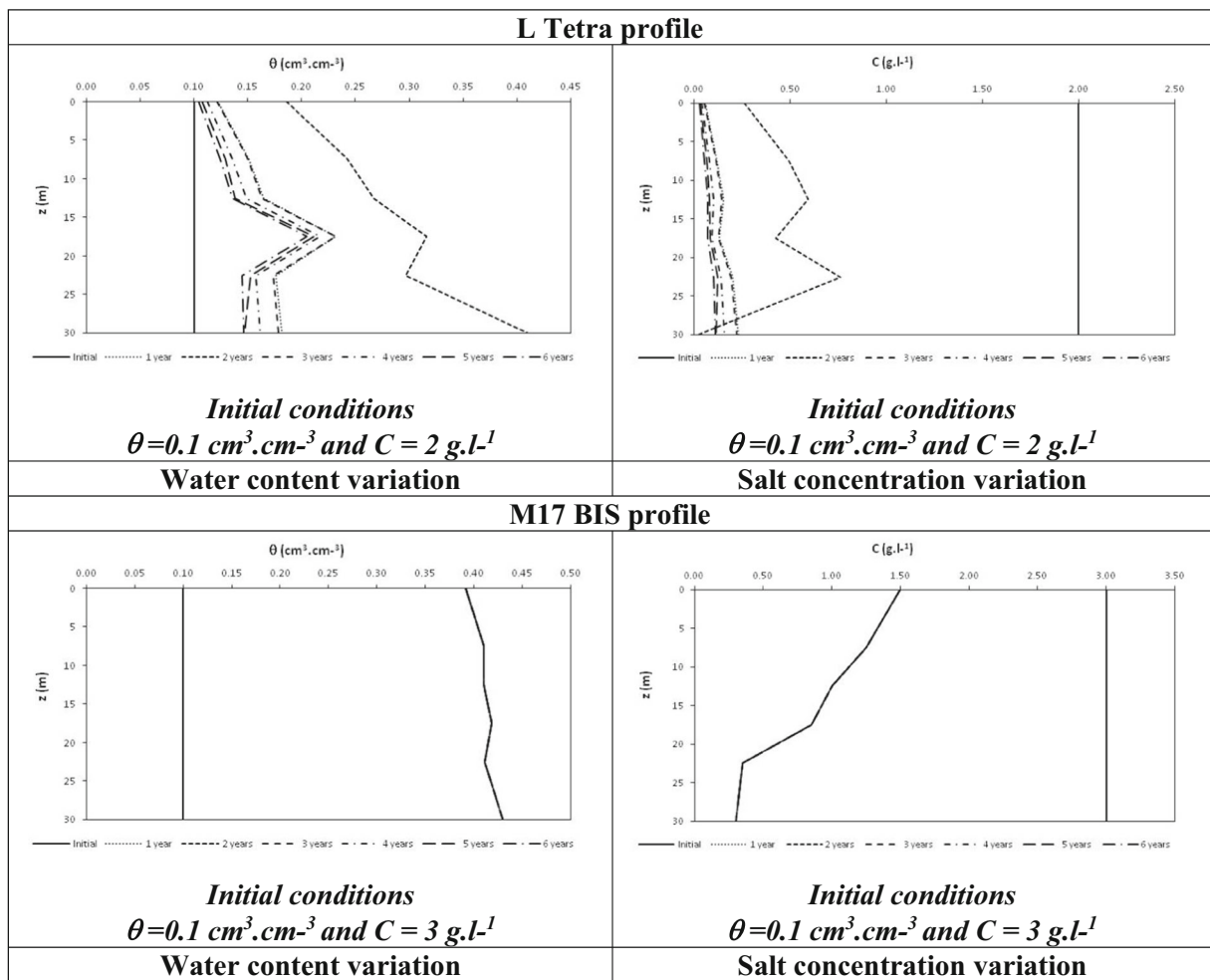
values of the calculated RMSE (statistical method) that were taken as results have met the same results of the figures of the best agreement between simulated and measured values of groundwater level and salinity (graphical method).

#### Scenario simulation

Calibration of the Hydrus-1D allowed the analysis of different scenarios on water and salt dynamics in the study area. Other than the understanding of the different processes of water and solute transfers in the unsaturated zone, modeling allows the prediction of the contamination risk under numerous natural conditions.

##### a) Rainfall effects

In order to understand the impacts of natural conditions, change on hydro-saline dynamics were simulated under an exceptional rainfall with an intensity of 50 mm/day every month of September during the study period, which showed an increase of the soil water content that reaches a near saturated state in the bottom of the profile and a faster salt leaching (Fig. 12). These results prove



**Fig. 14** Scenario results for a clay layer effect of both profiles L tetra and M17 BIS

the role of this type of rainfall in increasing the contamination risk of the aquifer.

#### b) Climate change effect

An increase of the temperature by 2 °C changes the evaporation  $ET_0$  values that were introduced in the upper boundary condition. This scenario resulted in a saturation status for the L tetra profile where the wetting front moves from a lower to a higher value (Fig. 13). This is explained by the fact that the increase of evaporation makes the soil drier and it favors water infiltration (Hillel 1986; Soutter and Musy 1999). Due to the evaporation effect, the salt content increased in the surface layers exactly along the first 15 m. However, a less significant effect on salts that transferred in deeper layers is observed. The M17 BIS profile showed

a stable response through the profile except for the deepest layers that presented a complete water saturation of the soil reaching 45%. For salt concentration, evaporation increase has favored the concentration of salts in surface and its decrease in deeper layers.

#### c) Clay layer effect

Since the clay layer present in the unsaturated soil has a huge role on water and salt dynamics, a clay layer was added in the soil profile at a depth of 15 m with a thickness of 2 m. Thus, Table 4 presents the input parameters of Hydrus 1D module used for clay layer effect study. The hydraulic parameters of this layer and the other input values are shown in Table 4. It resulted in an obvious effect on water content that increased exactly at

**Table 5** Statistical evaluation of the simulation results

	L tetra		M17BIS	
	RMSE	RMSE C	RMSE	RMSE C
0.5–0.1	0.5576	0.7448	0.0812	0.4925
0.5–0.2	0.5428	0.6341	0.0812	0.6513
0.5–0.3	0.6030	1.5106	0.0812	0.5342
0.5–0.4	0.5312	0.6243	0.1847	0.3492
1–0.1	0.5724	0.5141	0.0812	0.6513
1–0.2	0.5599	0.6764	0.0812	0.3492
1–0.3	0.5197	0.7927	0.0812	0.3161
1–0.4	0.6435	0.6708	0.0812	0.4344
2–0.1	0.5825	0.2744	0.0812	0.3502
2–0.2	0.6713	0.2744	0.0812	0.4255
2–0.3	0.5469	0.4077	0.0812	0.0112
2–0.4	0.5469	0.4077	0.0812	1.0804
3–0.1	0.5932	0.4600	0.0812	0.1600
3–0.2	0.5419	0.7804	0.0812	1.0804
3–0.3	0.5496	0.7805	0.0812	2.0569
3–0.4	0.7854	0.7805	0.0812	3.1537

the clay layer level (Fig. 14) with a higher value than the one of the sandy loam, which makes the variation of water content obvious on both profiles (Soutter and Musy 1999). The clay layer has an accelerator role on water infiltration and favors the aquifer recharge. As for salt concentration, the clay layer accumulates salts and has a moderator role, which decreases the risk of aquifer contamination (Table 5).

**Conclusion**

The Kairouan plain comes to face a huge problem of groundwater quality degradation due to salinization caused mainly by the climate aridity. It seems to show a variation depending on the dry residue of the different aquifers, which they would be considered good if it's ranging from 0.5 to 2 g/l and bad if it exceeds those values too much. The Kairouan region was selected to assess salinization risks of the soil as well as the aquifer through two profiles characterized by a direct recharge to the groundwater table in an agricultural land. The assessment of this problem comes with an approach of modeling that needed a range of collected data on the

studied area to simulate their impact as well as the different climatic impacts, which resulted in a huge risk of groundwater quality degradation due to these factors. These results were shown by the high contamination risk of groundwater due to the increase of salinity proven by salt leaching to the aquifer resulted from both studied profiles. The texture of the profile plays a major role in these results since it influences water and solute movements in the vadoze zone, which allows a variation difference while moving from the first profile to the second one. The variation of water content as well as salt concentration varies with the variation of soil texture. The different results have proven the calibration of the modeling approach that allowed scenario studies that showed the different impacts of natural factors on both profiles.

Despite all the made simplifications, Hydrus-1D is a powerful tool to simulate the movement of water and solutes in partially saturated porous media, since it can deal with different water flow and solute transport boundary conditions. The used approach based on the initial condition combinations is useful to predict the groundwater level and quality in the case of a direct recharge and in the absence of any information related to the soil layers except for the texture.

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