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Research Article
Comparison of Hydrus-1D to Thermal Dispersion Model for Water-heat Transport in a Semi-arid Region of Tunisia

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Abstract

Background and Objectives: In most studies of simulating water and solute transport in the unsaturated soils, soil temperature is considered constant and the temperature of the water that infiltrates the soil is neglected. In main objective of this study was to examine the comparison between a classical soil physics model (Hydrus-1D) and a thermal dispersion model was done, which takes into account the temperature of the water in soil, is carried out in a semi-arid region of Tunisia. **Materials and Methods:** Monitoring of soil water content and soil temperature was conducted during a typical agricultural season. Two models were used; a thermal dispersion model and the Hydrus-1D model for the simulation of the variation of the water content and the temperature in the topsoil at 30 cm in depth. **Results:** The simulated values were close to the measured one. Thus, the modeling results are quite satisfactory for both models. However, the thermo-dispersive model has shown better results since it takes into account the temperature of the water infiltrating in the soil. **Conclusion:** Both models can be powerful tools for water management in field conditions.

Key words: Hydrus-1D, soil water content, soil temperature, water infiltrating, unsaturated soils, typical agricultural season

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Data Availability: All relevant data are within the paper and its supporting information files.

INTRODUCTION

In Tunisia, like the other arid and semi-arid countries, food security and the agricultural potentialities depend on the climate, the soil and the water resources. The rainfalls are highly irregular and violent, happening mainly in autumn and winter with duration of 2-3 months[1]. After, long periods of drought can occur. The crops are often in water stress. The use of irrigation is a necessity. However, limited water resources and poor quality require optimal water management in the soil. Modeling soil water dynamics provides insight into the mechanisms involved as well as when the model is able to reproduce field observations to improve soil water management and to study strategies through scenarios[2-4].

A lot of models currently exist. The most reliable are those based on a deterministic mechanistic approach[5]. The simulation of water dynamics is performed by solving Richard's equation. Most of the models and conducted researches that have studied the water management in arid and semi-arid regions do not take into account the phenomenon of thermal dispersion. Indeed, the differences between the air temperature and the soil temperature are important which favors the phenomenon of the thermal dispersion[6]. Among the most studied models is the Hydrus-1D model[7] which allows the coupled simulation of water and heat transport in unsaturated soils. Another thermal dispersion model was developed by Kanzari and Mariem[8] that allows the modeling of the transport of water, solutes and heat in unsaturated porous media taking into account the temperature of the irrigation water that infiltrates the soil.

The main objective of this manuscript was to study coupled water-heat transport in a soil belonging to a semi-arid region in Tunisia by comparing the Hydrus-1D model and the thermal dispersion model. The thermal dispersion model never been used in field conditions to test its ability to reproduce water flow and heat transport in unsaturated soil. The comparison with an already known model like Hydrus-1D would give the needed feedback for its weaknesses and strengths.

MATERIALS AND METHODS

Soil of the study: The selected soil belongs to the city of Ariana (36°50'40.791"N, 10°11'13.795"E) in Tunisia. The Ariana region has a semi-arid Mediterranean climate, with mild, wet winters and dry and hot summers, the average annual temperature is 18.7°C with minimal of 6°C during the winter and maximum temperatures exceeding 45°C in the summer. Rainfall annual average is 450 mm. The topsoil (0-30 cm) was considered in this study. This layer was silty loam. The hydraulic properties of soil were mentioned in Table 1. Monitoring soil water content and soil temperature was performed using a BIOS probe during 87 days (Fig. 1) from March 16-June 06, 2018.

Fig. 1: Studied soil with the BIOS probe

Table 1: Soil hydraulic properties

Layer	θ_r (cm³ cm⁻³)	θ_s (cm³ cm⁻³)	α (cm⁻¹)	n (-)	K_s (cm day⁻¹)
0-30	0.0547	0.4320	0.0298	1.8898	30.670

Numerical models

Hydrus-1D: Hydrus-1D model allowed the resolution of the main equations of transport in the unsaturated porous media such as soils. It can be used in various and complex conditions with its mesh for geometry and the resolution of Richard equation in a multidirectional form by the method of the finite elements. It combines also, other transport phenomena, such as solutes and heat. Several models of hydraulic and hydrothermal properties for water flow and heat transfer are in the simulation code.

The model used Van Genuchten[9] equations to set the water retention curve θ(h), which relates the volumetric water content in pressure potential to the hydraulic conductivity curve K(h):

$$\theta(h) = \begin{cases} \theta_r + \dfrac{\theta_s - \theta_r}{1+|\alpha h^n|^m} & h<0 \\ \theta_s & h \geq 0 \end{cases} \qquad (1)$$

Where:

$$m = 1-\frac{1}{n} \qquad n>1$$

where, θ_r is the residual water content [L^{-3} L^{-3}], θ_s is the saturated water content [L^{-3} L^{-3}], h is the water pressure head [L], α [L^{-1}] and n [-] are shape parameters.

For describing the hydraulic conductivity, the used equation of Mualem[10] and Van Genuchten[9] is:

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

Where:

$$m = 1 - \frac{1}{n} \quad n > 1 \quad \text{and} \quad S_e = \frac{\theta - \theta_r}{\theta_s - \theta_r}$$

Ks is the saturated hydraulic conductivity [L T^{-1}], se was the effective saturation [-] and r is the pore connectivity parameter[10] [-], equal to 0.5.

In order to take into account the soil temperature in the simulation of water flow, a factor named ζ (h, T) was introduced in Eq. 2. The new expression of the soil hydraulic conductivity is given in Eq. 3:

$$K_{LT}(h) = K_{LT}\zeta(h, T) \quad (3)$$

$$\zeta(h,\ T) = hG_{wT}\frac{1}{\gamma_0}\frac{d\gamma}{dT} \quad (4)$$

where, G_{wt} [-] is a gain factor, equal to 8 according to Nimmo and Miller[6] for a silt loam soil, γ_0 is the surface tension at 25°C [MT^{-2}] (= 71.89 g s^{-2}), γ the surface tension is given by Eq. 5:

$$\gamma = 7.56\text{-}0.1425T\text{-}2.38.10^{-4}T^2 \quad (5)$$

The thermal conductivity of porous medium in the absence of water flow [MLT^{-3} K^{-1}] (e.g., Wm^{-1} K^{-1}) can be given as:

$$\lambda_0(\theta) = b_1 + b_2\theta + b_3\sqrt{\theta} \quad (6)$$

where, b_1, b_2 and b_3 (Wm^{-1} K^{-1}) are, respectively, 1.47 10^{14}, -1.55 10^{15} and 3.16 10^{15} Nimmo and Miller[6].

Thermal dispersion model: The model was developed by Kanzari and Mariem[8]. It was a mathematical model that describes solute transport through the unsaturated soil with the combination of three key processes: Water flow, heat transfer and solute transport. Resolution of such one-dimensional problem was performed using a numerical approach based on the finite difference method with an implicit scheme. The detailed equations of this model can be found in the previous study[8]. The model used the same equations from before and the same input parameters as Hydrus-1D except for the temperature of the rainfall which it must be specified.

Simulation input parameters: The studied soil profile is comparable to a 30 cm deep column. The soil was considered a homogeneous and isotropic. The used mesh size was 1 cm. The construction of the mesh includes 31 regular nodes. The simulation period was set from March 16-June 10, 2018. The initial water content was set at 0.02 cm^3 cm^{-3} for the date of March 16, 2018. The upper conditions of the soil profile correspond to atmospheric BC, with a surface layer where rainfall and evaporation from the National Institute of Meteorology data base had been specified and the lower limit was free drainage.

RESULTS

Soil water content: The variation of the water content of the soil during the simulation period showed that it increased during the months of March and April following the significant amounts of rainfall, occurring in the week between March 20 and March 26, 2018 (Fig. 2).

Soil moisture in the soil reached a saturation state in early (10-20 days) and then gradually decreased. After that, the soil moisture content stabilized at about 20%. The simulation results (Fig. 3) of both models showed that they can reproduce quite well the behavior of soil moisture status, represented by the variation of its water content as a function of time. According to the graphical evaluation, the values of the soil volumetric water contents simulated by the thermal dispersion model were closer than those simulated by Hydrus-1D. Indeed, the model takes into account the temperature of the rainfall, which included it in its calculation of thermal dispersion during the simulation of water flow. On the contrary in the Hydrus-1D model, the phenomenon of thermal dispersion was included as the interaction with the soil solid matrix through the thermal conductivity. These results were confirmed by the statistic evaluation (Fig. 4). The value of the coefficient of the linear correlation between the measured and simulated water contents was greater in the case of the Hydrus-1D model.

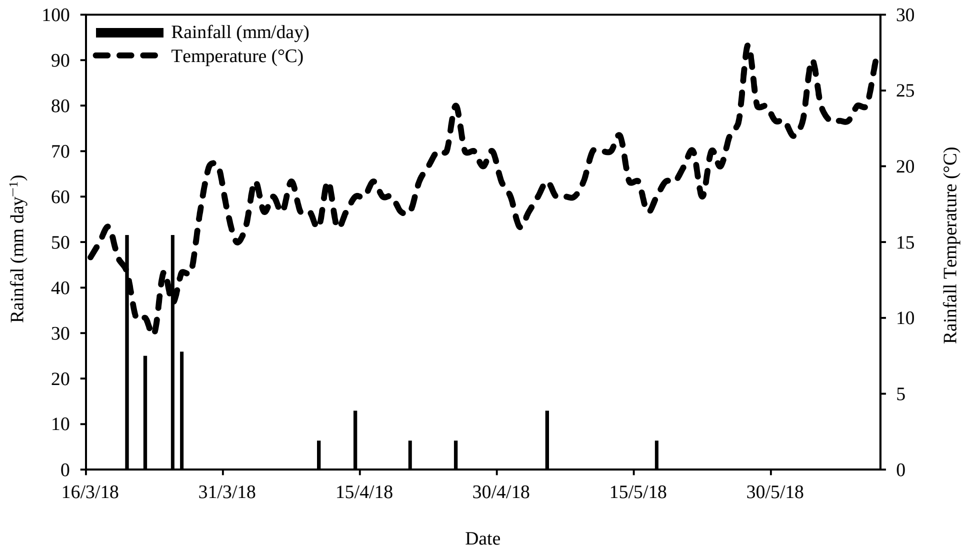

Fig. 2: Variation of the rainfall and the rainfall temperature during the period of study

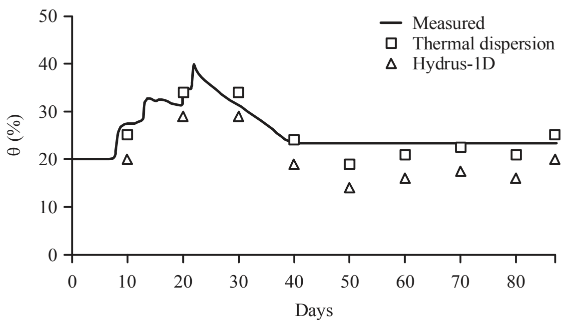

Fig. 3: Evolution of the soil water content and the values of the simulated soil water content of Hydrus-1D and the thermal dispersion model

Soil temperature: The variation of the soil temperature during the studied period showed that the temperature values are between 14°C recorded on March 23, 2018 and 38°C recorded on May 27, 2018. Generally, the evolution of the temperature of the soil followed the same line of variation as that of the temperature of the rainwater (Fig. 5). However, the soil temperature is higher. After the 15th of May, 2018, the soil temperature values exceeded 30°C, which indicated high evaporation. This did not seem to have an effect on the soil moisture regime which had remained constant. The heavy texture of the soil as well as the rainfall may be the cause of the water retention.

In the simulation results, both models underestimate the measured soil temperature. This underestimation was less important for the Thermal dispersion model. The differences between the simulated and measured values were greater in the case of using Hydrus-1D model (Fig. 5). The graphic evaluation was confirmed by the static evaluation where the thermal dispersion model has the largest coefficient R^2 (Fig. 6).

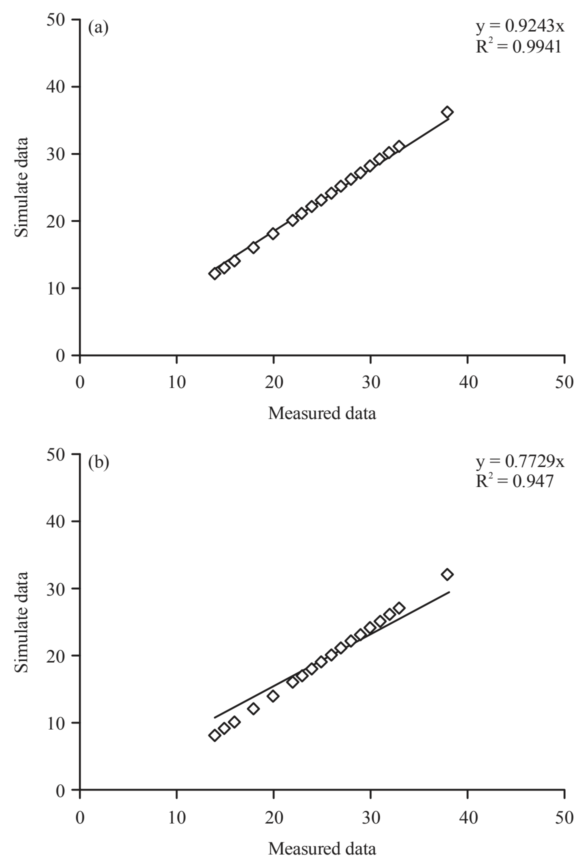

Fig. 4(a-b): Comparison of measured and the simulated values of soil water content, (a) Hydrus-1D and (b) Thermal-dispersion

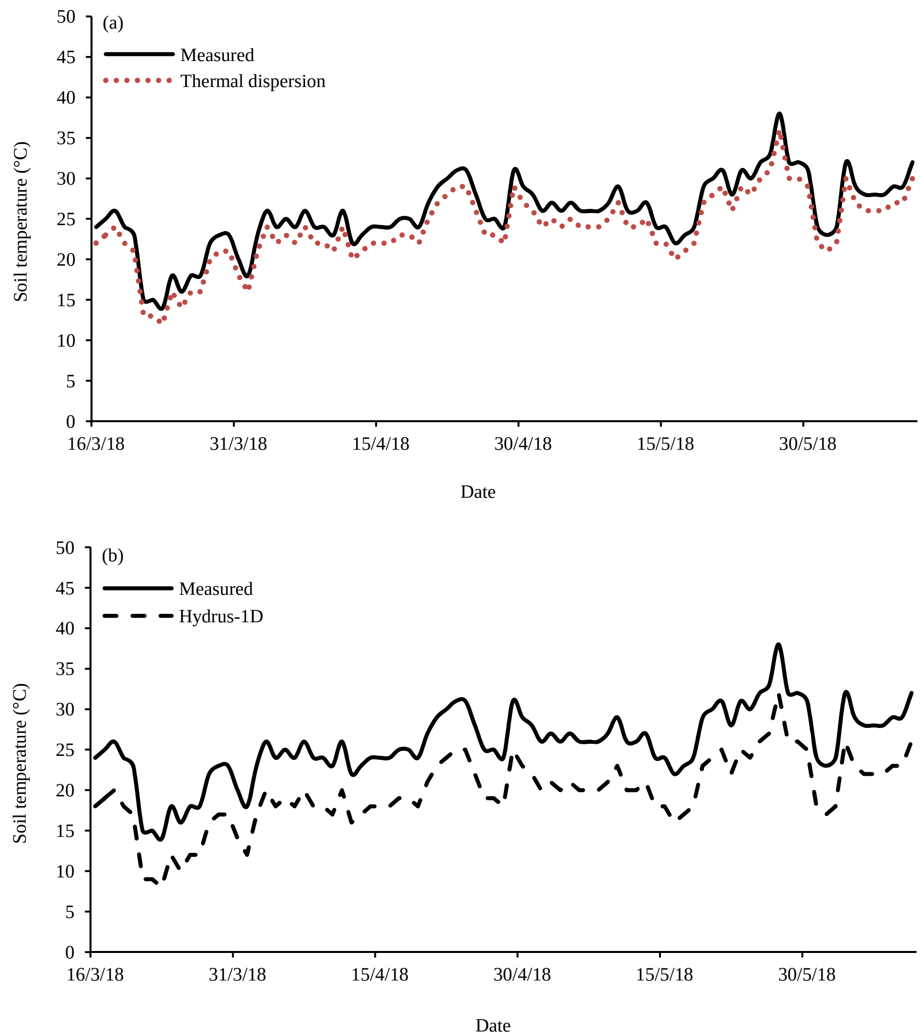

Fig. 5(a-b): Evolution of the soil temperature and the values of the simulated soil water content of Hydrus-1D and the thermal dispersion model

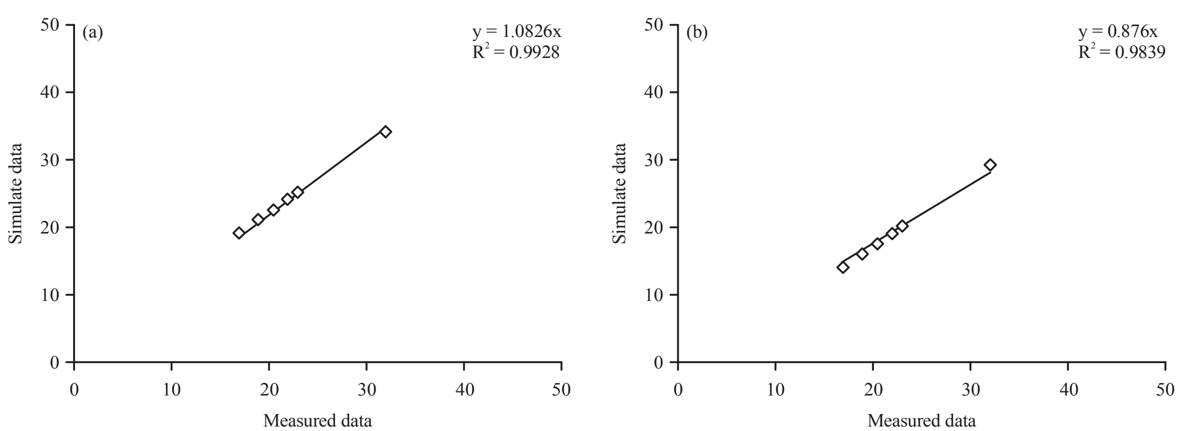

Fig. 6(a-b): Comparison of measured and the simulated values of soil temperature, (a) Hydrus-1D and (b) Thermal-dispersion

DISCUSSION

Temperature is a soil physical property that involved in most transport processes of water and solutes and in the biological (roots) and microbial activities the unsaturated soils. The Hydrus-1D model has been used by many authors for the simulation of soil moisture content and soil temperature[11-14]. Kleissl *et al.*[11] have coupled the model with the equations of the balance to simulate the temperature of soil. Zhang *et al.*[14] applied the model for soil temperature modeling with root water uptake. Other authors have also been interested in coupled water-heat simulation with agronomic models[15-18]. In all the previous researches, modeling approaches did not take into account of the temperature of the water flowing through the soil and therefore of the thermal dispersion of water. In this case and based on current results, simulation results can be improved if the thermal dispersion of water is considered in the transport equations. Despite the fact that Hydrus-1D model and the other models had fairly satisfactory results of modeling soil temperature in field conditions.

CONCLUSION

In this study, coupled water-heat coupled transport modeling was conducted in unsaturated soil belonging to a semi-arid region of Tunisia. The simulated values were quite close to the measured values with an advantage for the Thermal dispersion model compared to the Hydrus-1D model. The good results of both models make it possible to conclude that they are robust tools for studying coupled water-heat transport phenomena in field conditions and for investigating management scenarios.

SIGNIFICANCE STATEMENT

This study highlights the importance of including the water temperature in the process of modeling coupled transport of water-heat in unsaturated soils. This study will help the researcher to uncover the critical areas of heat transport in soils associated with water flow, solute transport and root water uptake that many researchers were not able to explore.

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