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NUMERICAL MODEL FOR THE SIMULATION OF SOIL WATER FLOW: EVAPORATION ANALYSIS

MODELO NUMÉRICO PARA LA SIMULACIÓN DEL FLUJO DE AGUA EN EL SUELO: ANÁLISIS DE LA EVAPORACIÓN

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Abstract:

In previous publications, routine for direct integration of infiltration equation (Richards Equation) under trickle irrigation boundary conditions was presented. The model is able to simulate irrigation features as evolution of the superficial water pond, flow redistribution, overpressure around the emitter and root flow absorption, among others. It was proved that, model behaves robust and efficiently. Recently, the numerical model was improved in order to reproduce water evapotranspiration flow according to several known model schemes such as the evaporation empirical formula of del Vigo *et al.* that was inferred from experiment data taken in the province of Imbabura (Republic of Ecuador). This article presents some results provided for this numerical routine (moisture profiles and infiltration patterns) focusing in the aspects involved to evapotranspiration. The results presented in this paper were obtained with several evaporation schemes that were implemented in the routine what are tested in this article. It is conclude that, moisture pattern description are highly affected by evaporation conditions; therefore, evaporation is an important factor to consider when analyzing soil water flow dynamics in irrigation systems.

Key words: Geocomputation, Drip Irrigation, Evapotranspiration, Agriculture, Water Resources

Resumen:

En publicaciones anteriores se presentó un modelo para la integración de la ecuación de la filtración en medios porosos (Ecuación de Richards) bajo condiciones de riego por goteo. Se demostró la capacidad del modelo para simular de forma eficiente y robusta características del riego como son: la evolución del agua acumulada en la superficie (o charco), la redistribución del flujo, la sobrepresión alrededor del emisor y la absorción del flujo de agua a través de la raíz de la planta, entre otros aspectos. Recientemente, el modelo numérico ha sido mejorado dotándole de capacidad para reproducir la pérdida de flujo de agua en el sistema por evapotranspiración a través de varios modelos matemáticos de referencia (o ecuaciones empíricas). Uno de estos modelos para la evaporación es la fórmula empírica de del Vigo *et al.* que fue inferida a partir de datos experimentales tomados en un laboratorio de la provincia de Imbabura (en la República del Ecuador). Este artículo presenta algunos resultados obtenidos con el citado programa, atendiendo especialmente a los aspectos relacionados con la evapotranspiración. Se muestran y evalúan algunos resultados que se han obtenido con el programa a través de los distintos modelos de evaporación que se han implementado en el mismo. Se concluye que, los patrones de humedad y descripción del flujo están fuertemente influenciados por las condiciones de evaporación y, por lo tanto, este es un factor importante a tener en cuenta al analizar la dinámica del flujo de agua en el suelo en los sistemas de riego.

Palabras clave: Geocomputación, Riego por Goteo, Evapotranspiración, Agricultura, Recursos Hídricos

1. Introducction

Evapotranspiration is the most important factor in energy and water balance ground interchange. Studies have concluded (Brutsaert 1982; Ritchie *et al.* 2009) that evaporation involves, at least, the half of the solar incoming energy and two thirds parts of the water precipitation.

In a previous paper (del Vigo *et al*. 2023a) a numerical model for the simulation of soil water flow under root flow absorption conditions was presented. It was observed that, simulations performed under root flow absorption conditions fitted better in front of experiments than the previous numerical model (del Vigo *et al*. 2020) what did not consider this irrigation feature. However, evaporation is a phenomenon that also substantially affects infiltration patterns, soil water flow, and therefore, water available for crops. Then, it is of great interest to implement this environmental feature to existing numerical models in order to improve its prediction capacity and progress in trickle irrigation projects. This is the main goal of the present study.

Physical based evaporation models as Philip and de Vries (1957) or Ritchie (1972), consider the equations coupling for the energy and mass transfer balance between the soil and atmosphere interface. These equations which has been implemented in numerical models such HYDRUS (Šimůnek *et al.* 2006) may be very sensitive to initial conditions and soil characteristics. For this reason, some authors have asserted that empirical expressions may provide more precise evaporation results in simulations that physically derived formulations (Dekic *et al.* 1995; Merlin *et al.* 2016) when environmental information is known with accuracy. Furthermore, evaporation empirical models are easier and more flexible to implement in the numerical routines, because they can be introduced in the integration process as a flow sink boundary condition. This feature also makes the empirical models more efficient in terms of computational effort than physical based evaporation models. Nevertheless, validity of empirical evaporation equations is normally restricted to the area, climatic conditions and/or soil characteristics, what they were obtained for.

An explicit finite differences routine for the simulation of three dimensional water flow from trickle irrigation was developed, validated and presented in previous studies (del Vigo *et al.* 2019; del Vigo 2020). Recently, the model was improved (del Vigo *et al.* 2023a) in order to describe the root flow absorption. In this article, an evolution of this model for the simulation of soil water flow assuming evapotranspiration conditions is presented. The routine was developed to model the evapotranspiration phenomenon via the next empirical and semi-empirical schemes: Jensen and Haise (1963), Stephens (1965), Hargreaves and Samani (1985), Abtew (1996), the FAO revised Penman and Monteith model (Smith *et al.* 1998), Irmak *et al.* (2003) and del Vigo *et al.* (2023b). This last empirical equation has been recently inferred from experimental data obtained in the Imbabura province (Republic of Ecuador). Some simulations with these evapotranspiration schemes and physical conclusions are presented in this work. It was observed that this new version of the model improves the predictability of soil water dynamics in scenarios where evaporation plays a significant role.

2. Material and Methods

2.1. Simulation Scheme

A finite differences explicit scheme was developed to approximate Richards equation using a cylindrical system of coordinates (r, z) according to the trickle irrigation symmetry. Isotropic and homogeneous porous media is assumed (Eq. 1):

$$k\frac{1}{r}\frac{\partial h}{\partial r} + \frac{\partial}{\partial r}\left[k\frac{\partial h}{\partial r}\right] + \frac{\partial}{\partial z}\left[k\frac{\partial h}{\partial z}\right] + \frac{\partial k}{\partial z} = \frac{\partial \theta}{\partial t} \qquad (1)$$

Where h [m] represents the matric potential, k [m/s] the hydraulic conductivity, θ [dimensionless] is the water content and time t [s]. The approximation in terms of the potential matric field is given by Figure 1 (Eq. 2):

$$\begin{aligned} h_{t+\Delta t} = h &+ \frac{\Delta t \Delta h}{2\Delta\theta}\left[\frac{k(h_2 - h_4)}{r \cdot \Delta r}\right. \\ &+ \frac{(k+k_2)(h_2-h)+(k+k_4)(h_4-h)}{(\Delta r)^2} \\ &\left. + \frac{(k+k_1)(h_1-h)+(k+k_3)(h_3-h)}{(\Delta z)^2} + \frac{k_1-k_3}{\Delta z}\right] \end{aligned} \qquad (2)$$

Such as, the unknown $h_{t+\Delta t}$, is solved at each point of the grid with a constant spatial resolution $(\Delta r, \Delta z)$ and an adaptive time step Δt. As discussed in the bibliography (del Vigo *et al.* 2020; del Vigo 2020) next restriction for time resolution is assumed in order to ensure the numerical stability (Eq. 3):

$$\Delta t < \frac{\theta_s \cdot \Delta z^2}{8000 k_s} \qquad (3)$$

Where θ_s [dimensionless] represents the soil saturated water content, k_s [m/s] is the saturated hydraulic conductivity, and $\Delta r = \Delta z$ is normally used. The code was widely validated in front of analytical solutions, other numerical models and experiments for several boundary conditions that may change with time. The model has been successfully tested to study irrigations features such as, the evolution of puddle on surface, overpressure around the emitter, infiltration-redistribution water patterns and root flow absorption, among others.

More details about the model structure, boundary conditions, validation results, and the MATLAB source code may be found at the bibliography (del Vigo 2020).

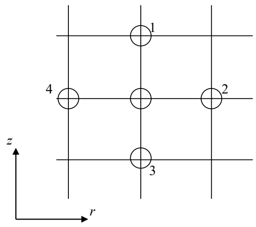

Figure 1: Discretization scheme.

2.2. Simulation Scheme

The root flow absorption sink is modelled according to the next expresión (Eq. 4):

$$q_a = q_{max} e^{-\frac{t}{\tau}} \qquad (4)$$

That represents the absorbed flow rate [s^{-1}] at each point of the root plant, as a function of time (t) from the beginning of the irrigation. The parameter q_{max} [s^{-1}] is the maximum root absorbed flow rate, at the beginning of the irrigation $(t = 0)$, which is the moment when the water plant necessity and root capillary suction are maximum. The time-parameter τ [s] represents, in accordance to an electrical capacitor system, the time interval required for the absorbed flow rate to decrease to 37% of its maximum value (q_{max}). This formula is equivalent to the transient charge process of a capacitor in a DC circuit (Resistor-Capacitor circuit). Therefore, the model considers that absorbed flow rate is maximum at the beginning of the process (as plant water necessity), and it decreases with time following an exponential decay. When time tends to infinite, the absorbed flow rate tends to zero since the root absorption potential became equal to the matric soil matrix potential.

As a macroscopic approach absorption model, the root absorbed rate (q_a) is extracted over all the grid points that belongs to the root plant domain at each time integration step. Accordingly to the system symmetry, a cylindrical root-shape is supposed, with radius R_r [m] and depth Z_r [m]. These root parameters are system inputs that may be obtained by root plant direct observation.

Integrating the Eq. (4), yields the next expression for the root plant absorbed water content (Eq. 5):

$$q_a = \frac{d\theta_a}{dt} \Rightarrow \theta_a(t) = \theta_{max}\left(1 - e^{-\frac{t}{\tau}}\right) \quad (5)$$

Where the next relation is also obtained for the maximum absorved water content $\theta_{max} = \tau q_{max}$ [dimensionless].

The exponential decay described by Eq (4) describes the system tendency to an energy balance when time tends to infinity. This conceptualization is analogous to the circuit intensity in a charge process of an electric capacitor system. The root uptake ends when the root absorption potential became equal to the matric soil potential following a first order differential equation. This mathematical structure is equivalent to the Neuman and Feddes modelling schemes, as was discussed in the bibliography (del Vigo *et al*. 2023a).

2.3. Evapotranspiration routine

The evapotranspiration effect is modelled via an extraction flow term that is introduced as a boundary condition on the system surface according to the empirical and semi-empirical models that are collected at Table 1.

The routine assumes that 75% of the evaporation flux is extracted from the surface boundary grid points, while the remaining 25% is taken from the grid points immediately below, *i.e.,* the second row of the grid. Thus, evaporation water is assumed to be extracted from a superficial layer of thickness Δz, which corresponds to the spatial grid resolution in the vertical direction in the simulations performed.

Apart from the evapotranspiration schemes given in Table 1, any other evaporation empirical equation may be easily implemented in this routine if were needed.

The model presented in the last row of this table (Colimba and del Vigo model) was inferred using experimental data obtained in a laboratory located at the province of Imbabura, in the Republic of Ecuador (del Vigo *et al*. 2023b).

3. Results and discussion

Some simulations results are presented in this article to display the characteristics and funtionallity of the evapotranspiration routine. The soil used in these simulations is described in the Tables 2 and 3 (the site of Natabuela, province of Imbabura, Republic of Ecuador):

The irrigation time used for the simulations presented in this paper was $t_{irr} = 5min$ at a constant flow rate of $q = 2.1L/h$, in all cases. Other data used in the simulations presented are collected in Table 4.

Table 1: Empirical and semi-empirical models implemented in the numerical routine. Reference evapotranspiration ETo [mm/day]. The rest of the parameters are: daily average temperature T_m [ºC], solar irradiation R_s [mm/day], maximum daily temperature T_{max} [ºC], minimum daily temperature T_{min} [ºC], average wind speed v_m [m/s], slope of vapor pressure curve Δ [kPa/ºC] and psychronometric constant γ [kPa/ºC].

Empirical Formula	*Evapotranspiration (ETo)*
Jensen and Haise (1963)	$ETo = R_s(0.0252T_m + 0.078)$
Stephens (1965)	$ETo = R_s(0.0158T_m + 0.09)$
Hargreaves and Samani (1985)	$ETo = R_s \cdot 0.0023 \cdot (T_{max} - T_{min})^{1/2} \cdot (T_m + 17.8)$
Abtew (1996)	$ETo = 0.01786 \cdot R_s \cdot T_{max}$
FAO-56 (1998)	$ETo = \frac{0.408 \cdot \Delta \cdot R_s + 900 \cdot \gamma \cdot v_m/(T_m + 273)}{\Delta + \gamma(1 + 0.34v_m)}$
Irmak (2003)	$ETo = -0.611 + 0.149 \cdot (2.451) \cdot R_s + 0.079 \cdot \frac{T_{max} - T_{min}}{2}$
del Vigo and Colimba (2023)	$ETo = 0.258 \cdot T_m + 0.111 \cdot R_s - 4.307$

Table 2: Physical soil parameters. Experimental data. Site of Natabuela (Imbabura Province, Republic of Ecuador).

Parameters	*Clay (%)*	*Silt (%)*	*Sand (%)*	*Density (g/cm³)*	Θ_{33kPa}	$\Theta_{1500kPa}$
Sandy-loam	9	34	57	1.22	0.3538	0.1455

Table 3: Van Genuchten-Mualem coefficients. Data estimated by ROSETTA software using the information given at Table 2. Site of Natabuela (Imbabura Province, Republic of Ecuador).

Parameters	Θ_r	Θ_s	*α (cm-1)*	*n*	k_s
Sandy-loam	0.0515	0.4518	0.0044	1.5427	0.03453

Table 4: Other simulation parameters. Environmental data, boundary conditions and numerical resolution.

Parameters	T_m (ºC)	T_{max} (ºC)	T_{min} (ºC)	R_s (mm/day)	P (kPa)	v_m (m/s)	θ_{max}	τ (min)	R_r (cm)	Z_r (cm)	$N_r = N_z$	$dr = dz$ (cm)
Data	20	28	10	4	75.54	1	0.01	20	10	10	40	1

Figure 2 presents results obtained by the model in a bare soil (no-root conditions) using the evapotranspiration schemes collected at Table 1. Notice that, under no evaporation conditions (black continue line) moisture content under the dripper is maximum at any depth. Penman and Monteith (FAO-56 1998) and del Vigo-Colimba (2023) empirical schemes are also marked using a continue line representation in this picture.

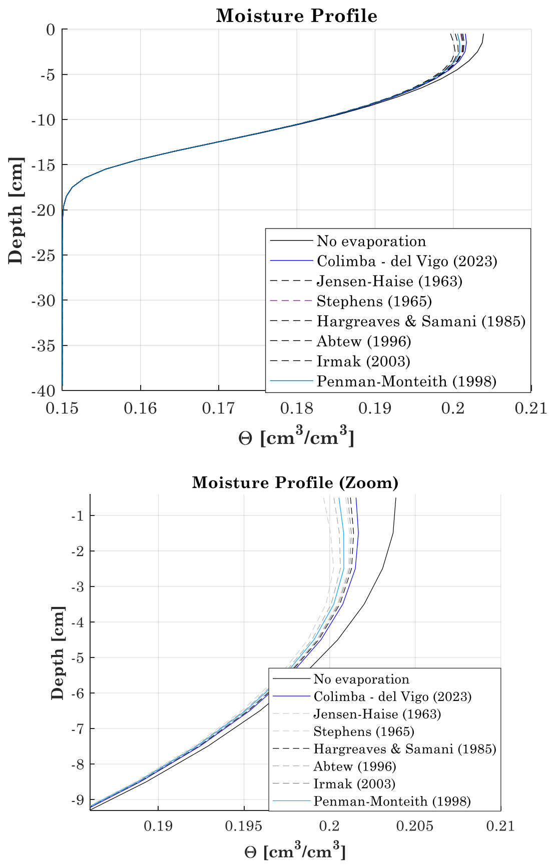

Figure 2: Moisture profile under the dripper at 120 minutes after irrigation starts. Bare soil. Comparison among models given in Table 1. Time of irrigation t_{irr} = 5min, using an applied flow rate of q = 2.1L/h. Environmental data: T_m = 20ºC, R_s = 4mm/day, T_{max} = 28ºC, T_{min} = 10ºC, h = 2445m and v_m = 1m/s.

It might be notice that, evaporation conditions affects mainly to the water content near the surface. As seen in Figure 2, the moisture content profile is similar for all the curves (including no evaporation) under 8 cm depth. Moreover, it is seen that, under this conditions, the model of Colimba and del Vigo predicts the lower evaporated water rate among the models. Besides, though the appreciable differences among these curves, water content variations on the surface are not much significant among these models. For instance, according to Figure 2 the maximum surface water content deviation between these models (corresponding to the differences between Jensen and Haise and del Vigo and Colimba models) is only around 0.9%. On the contrary, the differences observed in surface water content between evaporation and no-evaporation conditions are significant ($\Delta\theta \cong 0.004$), especially taking into account that the experimental uncertainty of typical soil hygrometers is around $\Delta\theta \cong 0.001$.

Figure 3 presents differences in the moisture content profile prediction under the dripper for several irradiation rates according to del Vigo and Colimba model evaporation scheme, at 120 minutes after the irrigation starts ($t_{irr} = 5min$). It is observed that, as solar irradiation increases, the surface moisture content decreases. The differences in the surface water content between the no-evaporation conditions and the rest of the curves that considers the evaporation effect, range from 1.2% to 2.3% depending on solar irradiation data. This corresponds to a difference in terms of water content in the range $\Delta\theta \cong (0.001, 0.003)$.

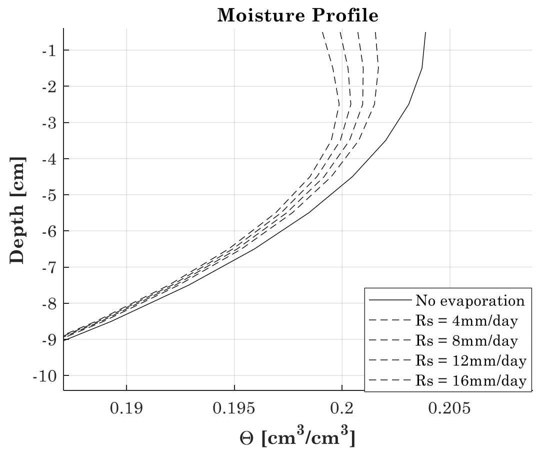

Figure 3: Moisture profile under the dripper at 120 minutes after irrigation starts. Bare soil. No evaporation conditions (continue line) in front of evaporation conditions (dash lines) for different solar irradiation rates: R_s = 4,8,12,16mm/day. Constant daily average temperature T_m = 20ºC. Evaporation model of del Vigo and Colimba (2023).

On the contrary, Figure 4 represents various moisture content profile results obtained for different daily average temperature data, according to the del Vigo and Colimba (2023) evaporation scheme. It is clearly observed that this is a more affecting factor to the surface water content, giving arise deviations from no-evaporation condition in a range from 1.2% to 3.1% (up to $\Delta\theta \cong 0.006$ in terms of water content). It might be notice that, coefficient associated with daily average temperature is higher in this evaporation scheme (Tab. 1) that the coefficient related to the solar irradiation: 0.258 > 0.111.

Figure 5 represents moisture content isolines (infiltration patterns) for the bare soil described in Table 2. Results over the plane of symmetry r-Z are given in this picture. The evaporation scheme of del Vigo and Colimba (2023) is also used in this simulation. Figure 5 shows the infiltration patterns obtained under no-evaporation conditions (continue lines) in front of patterns yielded using the mentioned evaporation scheme. The effect of evaporation is evident, with an increasing loss of moisture content over time near the surface, due to the evaporation process.

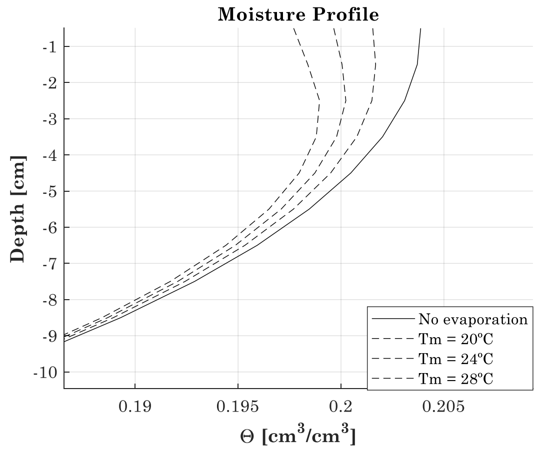

Figure 4: Moisture profile under the dripper at 120 minutes after irrigation starts. Bare soil. No evaporation conditions (continue line) in front of evapotranspiration conditions (dash line) for various daily average temperature: T_m = 20,24,28 ºC. Constant solar radiation at R_s = 4mm/day. Evaporation scheme of del Vigo and Colimba (2023).

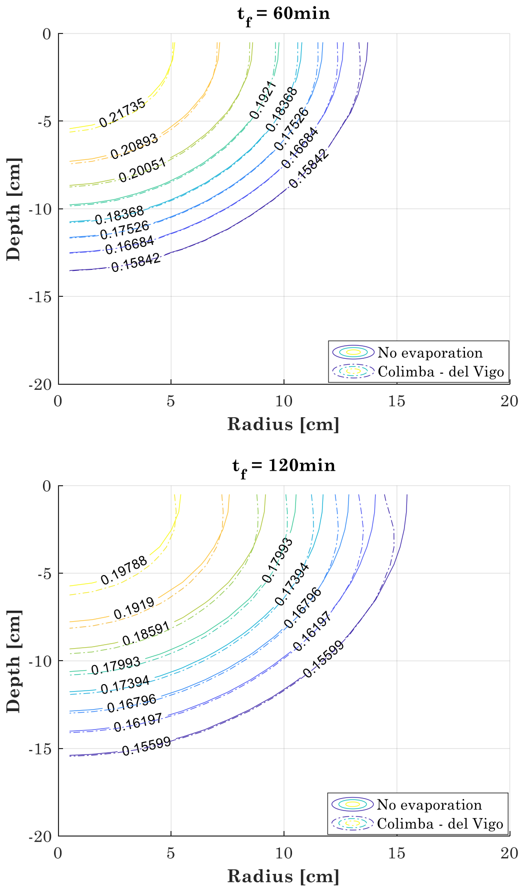

Figure 5: Moisture content patterns at 60 minutes and 120 minutes after irrigation. No evaporation conditions (continue line) in front of evapotranspiration conditions (dash line). Evaporation scheme of del Vigo and Colimba (2023). Time of irrigation t_{irr} = 5min for an applied flow rate of q = 2.1L/h. Environmental data: T_m = 20ºC and R_s = 4mm/day.

Finally, Figure 6 represents the combined effect of root flow absorption with the evaporation water sink. In the first case, (up picture) it is represented the independent effect of evaporation (dash line) against the root flow absorption (dot line). The second case (down picture) represents the combined effect of evaporation and root flow absorption over the system. It is clearly observed that root water sink affects regularly to all the system while the evaporation is mainly significant near the surface. This figure represent moisture patterns at 120 minutes after the irrigation starts. Model of del Vigo and Colimba (2023) for evaporation and del Vigo *et al* (2023) for root flow absorption were used in this simulation.

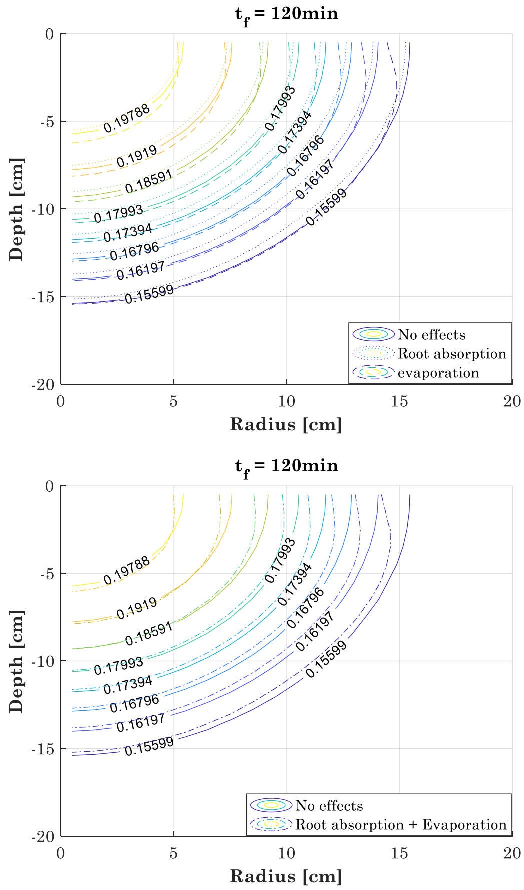

Figure 6: Infiltration patterns 120 minutes after irrigation. Up: bare soil with no-evaporation conditions (continue lines), in front of bare soil with evaporation conditions (dash line) and soil affected by root absorption without evaporation effect (dot lines). Down: no-evaporation conditions for a bare soil (continue lines), in front of results for the combined effect of evapotranspiration and root absorption conditions (dot-dash lines). The scheme of del Vigo and Colimba (2023) for evapotranspiration was used. The root absorption routine (del Vigo *et al*. 2023) was also used in this simulation. The time of irrigation was t_{irr} = 5min at an applied flow rate of q = 2.1L/h. Root absorption parameters and environmental data are given at Table 4.

It was observed, accordingly to this figure that, two hours after the irrigation starts the evaporation volume loose was 9.04% in front of the total water volume applied to the system. On the other hand, the root absorption sink was 10.11% of the total applied volume. Moreover, it is seen that the combined effect of evaporation and root uptake curves at Figure 6 (down) is approximately equal to the superposition of the two independent effects (up).

Nevertheless, this visual property must not be interpreted as the sum of two particular solutions since the governing equations describing these phenomena are nonlinear. Remarks that, when considering both effects at the same time root flow uptake influence over evapotranspiration effect, and viceversa; then, the final result is not exactly the same as the sum of both independent effects.

4. Conclusions

An improved numerical model with capacity to describe soil evapotranspiration water flow is presented in this article.

The experimental analysis performed in previous publications (del Vigo *et al*. 2023) established that daily average temperature and irradiance are the two main factors involved in evapotranspiration process. This is rational from a physical point of view because these two magnitudes affects to evaporation during the entire day. On the contrary, factors such as maximum and minimum daily temperature that are used in other evaporation schemes collected at Table 1 are tipically relevant only during a day interval. In this sense, empirical models that depends on daily average temperature and irradiance, such as Jensen and Haise (1963), Stephens (1965) or del Vigo *et al.* (2023), should be more accurate than others what depends on magnitudes with less influence in evapotranspiration as mentioned before. Obviously, complex models that depends on daily average temperature and irradiance, but also, include extra information as pressure or wind velocity, such Penman and Monteith model are accurate while all the environmental data and parameters are known.

The numerical model presented in this article improve the last version of the code and provide results that are consistent from a physical point of view. The simulation results conclude that soil water content decrease significantly when evaporation conditions are assumed around the surface layer, as expected. Depending on the empirical scheme, it can be found slightly differences for the available water content in this layer (Fig. 2).

It clearly established that moisture content patterns are highly influenced by the effect of evaporation and root uptake as illustrated in Figures 5 and 6. Thus, including this irrigation features in the simulation models is needed to find accurate physical descriptions.

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