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Comparison of Root-Water-Uptake Models

K.Y. Li, R. De Jong and J.B. Boisvert*

ABSTRACT

Soil water simulation models require a description of root water uptake. In this study, four root-water-uptake models, including the linear model and the exponential model of SWAP, and the uptake models from EPIC and CERES, were incorporated in the SWAP soil water simulation model, and they were compared under the same assumed conditions. Under normal root growing conditions, e.g. when 30 % of the total water use comes from the top 10% of the root zone if water is readily available, the exponential and the EPIC model behaved similarly in terms of total root water uptake and its distribution across the soil profile. The linear model slightly overestimated total water uptake, as compared with the two previous models. The water uptake estimated with the CERES model (the root density of 0 – 5 cm depth ranged from 2.0 to 7.0 cm cm^{-3}) was similar to those of the other models, but it increased with higher root densities. Selection of a root-water-uptake model will depend partly on the availability of root distribution data.

INTRODUCTION

The water transpired by plants is captured from the soil by the plant roots. As reviewed by Homaee (1999), numerous mathematical root-water-uptake models, which all differ in concept, in complexity, and in the volume of input data and parameters needed, have been developed. Many of these models may often show a general agreement with the mean measured soil water content of the root zone. However, this does not necessarily imply that they are satisfactory in predicting soil water content profiles and that they perform in the same way, because each model is incorporated into a larger, more complex, soil-water simulation model that differs from one to the next in its way of dealing with the other components of the water balance and the imposed upper and lower boundary conditions. To compare the performance of different root-water-uptake models, it is necessary to incorporate them within the same soil-water simulation model (Alaerts et al., 1985).

Although there are many different root-water-uptake models described in the literature (see e.g. Clothier and Green, 1997), we selected ones, which represented *both* the macroscopic approach (where the entire root system as a whole is considered) *and* the microscopic approach (where water flux to a single root is considered). The four selected models were incorporated into the physically based SWAP (Van Dam et al., 1997) soil-water simulation model and then compared and evaluated under the exact same initial and boundary conditions.

METHODOLOGY

Description of the SWAP model

The **S**oil-**W**ater-**A**tmosphere-**P**lant (SWAP) simulation model (Van Dam et al., 1997) is a transient, one-dimensional model that uses soil physical properties, crop characteristics, and weather data to estimate, on a daily basis, the components of the soil water balance and the distribution of water within the profile. The model is based on Richards' equation expressed as:

$$\frac{\partial h}{\partial t} = \frac{1}{C(h)}\frac{\partial}{\partial z}\left[K(h)\left(\frac{\partial h}{\partial z}+1\right)\right] - \frac{S(h)}{C(h)} \qquad (1)$$

Where h is the soil water pressure head (L), t is time (T), C(h) = dθ/dh is the differential water capacity (L^{-1}), with θ being the volumetric water content (L^{3} L^{-3}), K(h) is the hydraulic conductivity-pressure head relationship (L T^{-1}) and z (L) is the vertical coordinate. The sink term S(h) (L^{3} L^{-3} T^{-1}), which describes water uptake by plant roots, is defined as (Feddes et al., 1978):

$$S(h) = \alpha(h) S_{\max} \qquad (2)$$

Description of the root-water-uptake models

The macroscopic linear root-water-uptake model (Prasad, 1988; Hayhoe and De Jong, 1988) has been expressed as:

$$S_{\max} = \frac{2PT}{Z_r}\left(1 - \frac{Z}{Z_r}\right) \qquad (3)$$

where PT is daily potential transpiration rate (L T^{-1}), Z is soil depth (L), and Z$_r$ is the rooting depth (L).

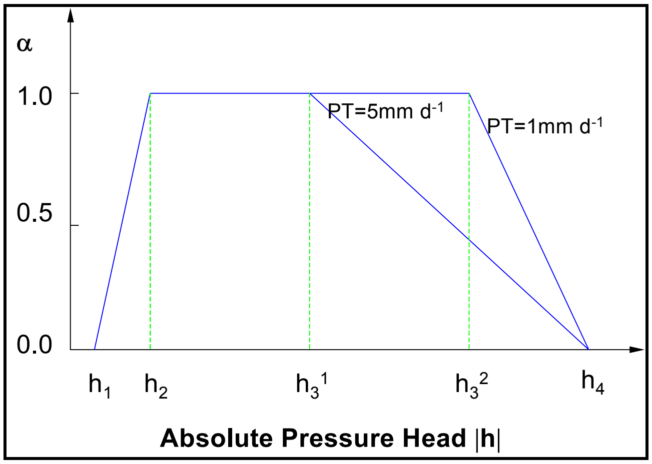

Figure 1. On-field distribution for various critical shear and rill erodibility combinations.

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*K.Y. Li and R. De Jong, Eastern Cereal and Oilseed Research Center, CEF, Ottawa, ON, Canada K1A 0C6; J.B. Boisvert, Soils and Crops R. & D. Centre, 2560 Hochelaga Blvd, Ste-Foy, PQ, Canada G1V 2J3.*Corresponding author: dejongr@em.agr.ca

The exponential root water-uptake model (Li et al., 1999) can be described by:

$$S_{\max} = \frac{G_{Z_i - Z_{i+1}} PT}{\left| Z_i - Z_{i+1} \right|} \tag{4}$$

where $\alpha(h)$ is a dimensionless function of pressure head (Fig. 1) and $S_{\max}$ (L^3 L^{-3} T^{-1}) is the maximum possible root-water extraction when soil water is not limiting Where $G_{Zi - Zi+1}$ is the fraction of the total root length between depths Z_i and Z_{i+1}, estimated from an exponential root distribution function (Dwyer et al., 1988):

$$G_{Z_i - Z_{i+1}} = \frac{ln\left[\dfrac{1+exp\left(-bZ_i\right)}{1+exp\left(-bZ_{i+1}\right)}\right]+0.5\left[exp\left(-bZ_i\right)-exp\left(-bZ_{i+1}\right)\right]}{ln\left[\dfrac{2}{1+exp\left(-bZ_r\right)}\right]+0.5\left[1-exp\left(-bZ_r\right)\right]} \tag{5}$$

Where b (L^{-1}) is an empirical root distribution parameter.

Maximum water uptake in the EPIC (Williams, 1995) model is expressed as:

$$S_{\max} = \frac{u_{pl}}{\left| Z_l - Z_{l-1} \right|} \tag{6}$$

Where u_{pl} (L T^{-1}) is the potential water use rate, defined as:

$$\begin{aligned} u_{pl} &= \frac{PT}{1.0 - \exp(-\Lambda)} \\ &\left[\begin{array}{l} 1.0 - \exp\left(-\Lambda\left(\dfrac{Z_l}{Z_r}\right)\right) \\ -(1.0 - UC)\left(1.0 - \exp\left(-\Lambda\left(\dfrac{Z_{l-1}}{Z_r}\right)\right)\right) \end{array} \right] \\ &- UC \sum_{k=1}^{l-1} u_k \end{aligned} \tag{7}$$

Where u_k is the actual water use rate for all layers above layer i (L T^{-1}); Λ is a dimensionless water use distribution parameter and UC, which varies between 0 and 1.0, is a dimensionless water deficit compensation factor.

The microscopic CERES (Ritchie, 1985) root-water-uptake model uses the "law of the limiting" approach, in which the larger of the soil or the root resistance determines the flow rate of water into roots. Based on the assumptions described by Ritchie (1985), the soil limited water-uptake rate is expressed as:

$$q_r = \frac{2.64 \cdot 10^{-3} \exp(62(\theta - \theta_l))}{6.68 - \ln(RD)} \tag{8}$$

where q_r is the water-uptake rate (L^3 L^{-1} T^{-1}); θ is the soil water content (L^3 L^{-3}), θ_l is the lower limit soil water content (L^3 L^{-3}) and RD is the root length density (L L^{-3}). If the soil limited water uptake exceeds the maximum plant limited flow rate (defined as 0.03 cm^3 cm^{-1} d^{-1}), then the water-uptake rate is set equal to the maximum plant limited flow rate. If the total possible water uptake exceeds the potential transpiration (i.e. the maximum weather limited water-uptake), the possible water-uptake rate calculated for each layer is reduced proportionally so that the total water uptake equals the potential transpiration. Unlike the previous macroscopic uptake models, q_r in Eq. 8 is a soil-limited rate instead of a maximum rate and hence the corresponding sink term in Eq. 2 is defined by:

$$S = RDq_r \tag{9}$$

Simulation runs

The simulations were performed for simplified initial and boundary conditions because the aim of the paper was not to validate the selected models, but to compare them. Soil hydraulic properties of a Manotick sandy loam (Table 1) (De Jong, 1993) were used. The homogeneous soil profile, with a rooting depth of 100 cm, was subdivided into 5 cm grid intervals. The initial soil water content was 0.41 cm^3 cm^{-3} (h=-100cm). Simulations were made for 60 days using time steps, which varied with changing water contents. Precipitation and soil evaporation were set to zero, and the potential transpiration was held constant at 0.4 cm d^{-1}. The simulation was run with three bottom boundary conditions: zero flux, free drainage, and a constant water table at 200 cm depth. The concept of water deficit compensation, as used in the EPIC water-uptake model, was also incorporated into the linear (I) and exponential (II) models. Thus, simulations with and without considering water deficit compensation were made. The b value in the exponential model and Λ in the EPIC model were set to 0.041 cm^{-1} and 3.429, respectively, which allowed the top 10% of the root zone to contribute 30% of the total water uptake if soil water is readily available. In the CERES model, the root length density of the surface layer (0-5 cm, expressed as RD_s) was set to 2.0, 4.5, and 7.0 cm cm^{-3}, representing values for, respectively, soybeans, corn and wheat (De Willigen and Van Noordwijk, 1987) near maturity. Rooting densities in the subsurface layers were calculated according to the modified exponential root distribution function with b=0.041 cm^{-1} (Dwyer et al., 1988).

RESULTS AND DISCUSSION

General analysis of the four root-water-uptake models

The maximum water uptake rate estimated with the linear model decreased linearly from 0.008 d^{-1} at the surface (PT=0.4 cm d^{-1}) to zero at the bottom of the root zone (Fig. 2). Apart from the meteorologically determined potential transpiration, only the rooting depth of the crop controlled the water uptake-depth pattern. On the other hand, the maximum water uptake distribution estimated with the exponential model (Fig. 3) or the EPIC model (Fig. 4) varied considerably with different b and Λ values. As either b or Λ increased, $S_{\max}$ increased in the upper layers and decreased in the lower layers.

Selection of proper b and Λ values depends on crop characteristics and soil properties. For example, crops which have a fairly uniform root distribution throughout the entire rooting depth (like wheat) should be assigned relatively low b and Λ values (e.g. b=0.02 and Λ=2.0), as compared to crops whose root mass is largely concentrated near the

Table 1. Van Genuchten's (1980) soil hydraulic parameters used in the simulation run.[†]

θ_r ($cm^3.cm^{-3}$)	θ_s ($cm^3.cm^{-3}$)	K_{sat} ($cm.d^{-1}$)	α (cm^{-1})	n
0.1802	0.4500	0.3600	0.0063	1.5613

[†] θ_r is residual soil water content; θ_s is saturated soil water content; K_{sat} is saturated hydraulic conductivity; α and n are empirical parameters.

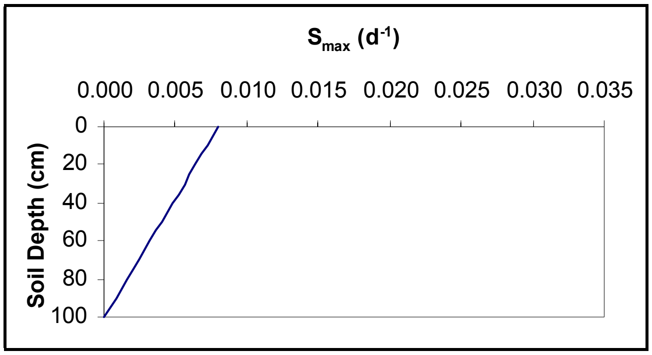

Figure 2. Erosion distribution for field 1 (fallow) with 30 Lpm inflow rate and Keff =10 mm h^{-1}.

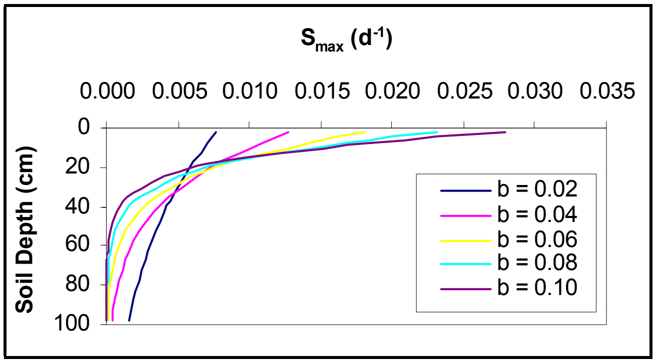

Figure 3. Erosion distribution for field 1 (fallow) with 40 Lpm inflow rate and Keff = 10 mm h^{-1}.

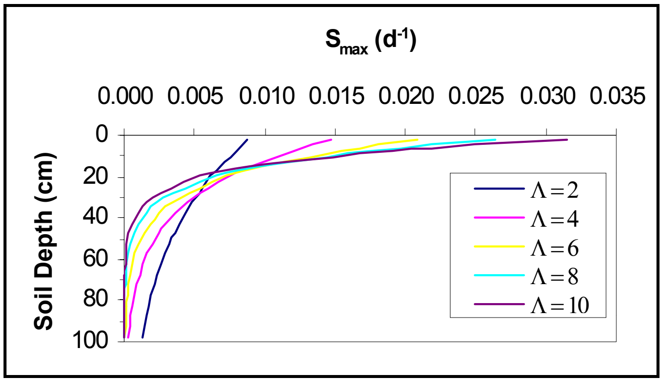

Figure 4. Estimated maximum water uptake (S_{max}) with the EPIC model with various Λ values (PT = 0.4 cm d^{-1}, UC = 0).

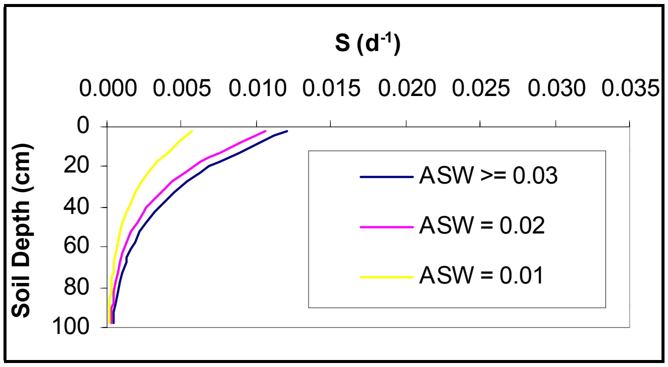

Fig. 5. Estimated water uptake (S) with the CERES model under various soil water conditions (PT = 0.4 cm d^{-1}; the root-length density in the 0 – 5 cm depth (RD_s) was set to 4.5 cm and root distribution follows an exponential function with b=0.041 cm^{-1}).

Table 2. The fraction of the maximum water uptake per soil layer as calculated with the linear, the exponential and the EPIC root-water-uptake model (Values of b and Λ were fixed such that the top 10 % of the root zone supplied 20, 30, 40 and 50 % of the water).

Parameter	Linear	Expon.	EPIC	Expon.	EPIC	Expon.	EPIC	Expon.	EPIC
b[†]		0.045		0.082		0.118		0.160	
b[‡]		0.023		0.041		0.059		0.080	
Λ			1.843		3.429		5.066		6.922
Soil Layer[§]									
1	0.190	0.200	0.200	0.300	0.300	0.400	0.400	0.500	0.500
2	0.170	0.168	0.166	0.218	0.213	0.250	0.241	0.261	0.250
3	0.150	0.141	0.138	0.156	0.151	0.151	0.145	0.128	0.125
4	0.130	0.117	0.115	0.110	0.107	0.088	0.088	0.060	0.063
5	0.110	0.097	0.096	0.076	0.076	0.051	0.053	0.028	0.031
6	0.090	0.080	0.080	0.053	0.054	0.029	0.032	0.013	0.016
7	0.070	0.066	0.066	0.036	0.038	0.016	0.019	0.006	0.008
8	0.050	0.054	0.055	0.024	0.027	0.009	0.012	0.003	0.004
9	0.030	0.044	0.046	0.016	0.019	0.005	0.007	0.001	0.002
10	0.010	0.035	0.038	0.011	0.014	0.003	0.004	0.001	0.001

[†] Refers to a rooting depth of 50 cm; [‡] Refers to a rooting depth of 100 cm; [§] Each soil layer constitutes 10% of the rooting depth.

Table 3. The threshold value of soil water content (cm^3 cm^{-3}) under which the sink term (S) will decrease from the maximum value.

PT	Root Density ($cm\ cm^{-3}$)		
($cm\ d^{-1}$)	2.0	4.5	7.0
0.1	0.03	<0.01	<0.01
0.4	0.05	0.03	0.03
0.8	0.06	0.05	0.04

surface (like soybeans). Similarly, soils with properties, which restrict root development in the lower layers (e.g. a plow pan), should have higher b and Λ values. The b and Λ values can be estimated from Eqs. 5 and 7 using the numerical secant method (Phillips and Cornelius, 1986) if the fraction of the root length (for the exponential model) and the fraction of the maximum water uptake (for the EPIC model) in the surface layer are given. Using this methodology, and assuming that UC=0, we then fitted the following regression equations (R^2>0.99) through the data:

$$b = \frac{24.6637 G_{10}^{1.5901}}{Z_r}, or, b = \frac{13.8802 G_{20}^{1.9047}}{Z_r} \qquad (10)$$

$$\Lambda = 22.1768 F_{10}^{1.6445}, or, \Lambda = 16.1274 F_{20}^{2.7024} \qquad (11)$$

where G_{10} and G_{20} are the fractions of root length in the top 10 % and 20% of the root zone, Z_r is the rooting depth (cm) and F_{10} and F_{20} are the fractions of water uptake from the top 10 % and 20% of the root zone. Eqs. (10) and (11) can be used if limited measurements or estimates of G and F are available.

For a given fraction of maximum water uptake in the top 10% of the root zone, the exponential model and the EPIC model performed similarly in estimating water uptake (Table 2). The water uptake pattern of the linear model was fairly similar to that of the exponential and the EPIC model when b and Λ were set to values which allowed the top 10% of the root zone to supply 20% of the water to the crop (Table 2), i.e. characteristic of relatively good root development throughout the entire rooted zone. With poor root growth (e.g. presence of a plow pan, poor soil aeration, etc) the linear model may give less realistic results because it assigns a relatively high proportion of water uptake to deep layers. The CERES water uptake model directly estimates the actual water uptake, which is different from the other three models. Fig. 5 shows that the water uptake rate reaches the maximum value (the total water uptake per day equals to the potential transpiration rate of 0.4 cm d^{-1}) when the available soil water content ($\theta - \theta_l$ = ASW) is over 0.03, but decreases with decreasing available soil water contents. Threshold values of ($\theta - \theta_l$) under which the CERES sink term will decrease from its maximum values as shown in Table 3, is determined by weather and root characteristics: the larger the value of the root density or the smaller the value of the potential transpiration rate, the smaller the threshold value.

Comparison of the root-water-uptake models

The SWAP model was run with the aforementioned imposed lower boundary conditions, and we found that the relative differences in water uptake among them were not appreciably affected by the lower boundary conditions. Hence, only the simulated results for zero-flux condition are presented.

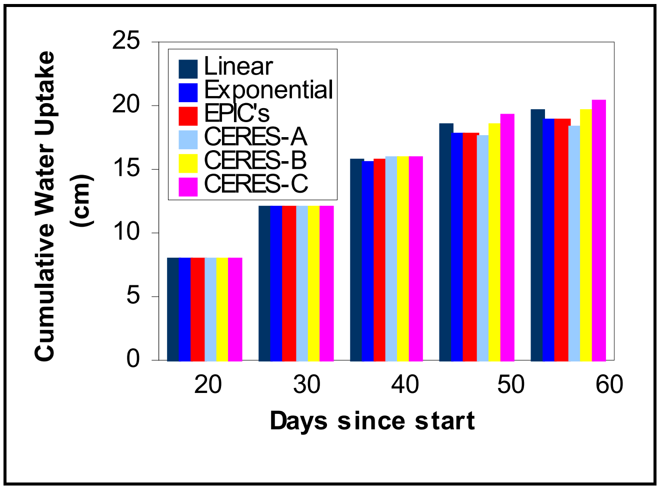

Figure 6. Simulated cumulative water uptake (PT = 0.4 cm d^{-1}, b = 0.041 cm^{-1}, Λ =3.429, UC = 0, RD_s for CERES-A, -B and –C was respectively 2.0, 4.5 and 7.0 cm cm^{-3}).

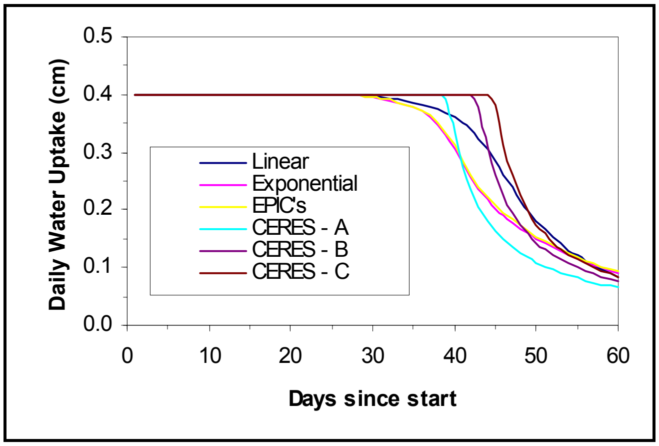

Figure 7. Simulated daily water uptake (PT = 0.4 cm d-1, b = 0.041, Λ =3.429, UC = 0, RDs for CERES-A, -B and –C was respectively 2.0, 4.5 and 7.0 cm cm-3).

After the first 30 days of simulation (no water deficit compensation) the cumulative water uptake from all four models was the same (Fig. 6). After 60 days, at the end of the simulation, the cumulative water uptake for the linear, the exponential, and the EPIC model was, respectively, 19.7, 18.8, and 18.9 cm, i.e. within 5 % of each other. Water uptake with the CERES model increased with increasing root densities: for CERES-A (RD_s=2.0 cm cm^{-3}), CERES-B (RD_s=4.5 cm cm^{-3}) and CERES-C (RD_s=7.0 cm cm^{-3}) the cumulative root water uptake was 18.4, 19.4, and 20.3 cm, respectively. Depending on the value of the root density, water uptake simulated with the CERES model would be either higher or lower than those of the other three models, with a maximum difference of 8%.

In terms of daily water uptake rate, one can recognize two stages: constant and falling rate stages (Fig. 7). In the constant rate stage, in which the soil water condition is optimal, the roots absorbed the water at the maximum rate, i.e. at the potential transpiration rate. In the falling rate stage, the water uptake rate dropped rapidly due to a soil water deficit. The decreasing rate varied from one model to the next, except that the exponential and the EPIC model behaved very similarly. The critical date on which the uptake rate began to fall was different for the CERES model as compared to the other three models. The critical date for CERES-A, CERES-B, and CERES-C was day 39, 43, and 45, respectively; but for other three models it was approximately day 30. It was apparent that, for the CERES model, the critical date was dependent on the root density: a higher root length density would make the constant rate stage last longer. This implied that water stress might more easily occur in crops with low rooting densities.

The profile soil water content, as expected, decreased at a constant rate before the critical date, and then at a lower rate (Fig. 8). The threshold soil water content corresponding to the critical date was 29.0 cm for the linear, exponential and the EPIC model, and 25.4, 23.8 and 23.0 cm for CERES – A, CERES - B and CERES – C, respectively. Obviously, the simulated threshold soil water content with the CERES model was significantly lower than the one with the other models, which indicates that the water stress occurs less easily in the simulation with the CERES model (when $RD_s > 2.0$ cm cm^{-3}) than with the other three models. For the CERES model, the threshold soil water content decreased with increasing RD_s. This once again implies that the indication of water stress by the CERES model depends on the root density: the higher the root length density, the less likely that water stress will happen.

As similar results were obtained for the water uptake models with considering water deficiency compensation, only the EPIC simulation results are shown in Fig. 9. The simulation with water deficiency compensation did not make any appreciable difference from the one without compensation prior to day 40. However, thereafter the water uptake increased in the lower layers as compared to the simulation without compensation. The water uptake rate was not very sensitive to a compensation factor UC greater than 0.1. This can be explained by the fact that in a physically based model like SWAP, the water deficiencies in relatively dry layers can be partly compensated for by water flow from wetter layers. On the other hand, in the budget-based models, like EPIC, water flow between layers is neglected when the soil water content is below field capacity. This may cause an incorrect indication of water stress in the upper layers, so water deficiency compensation in such models is imperative. The increase in total water uptake resulting from 'with compensation' was approximately 10% (e.g. for the EPIC model on day 60, the cumulative total water uptake with UC = 0 (no compensation) and UC = 0.1 was respectively 18.9 and 20.9 cm). The soil water content on day 60 in the bottom layer (70 – 100 cm) was reduced from 0.24 to 0.20 cm^3 cm^{-3} when UC was increased from 0 to 0.1.

CONCLUSIONS

The selection of a root water uptake model partly depends on the availability of root distribution data. The CERES model requires the root length data in each layer, while the exponential and EPIC model respectively require input of b and Λ values, which can be either obtained from measurements or estimated with the equations proposed in this study. No root distribution parameters are needed for the linear model (except rooting depth), but one should be prudent when it is used in a poor rooting environment. With proper inputs, all four models can give fairly similar results; testing them under field conditions, within the SWAP model, to determine whether or not the work involved in

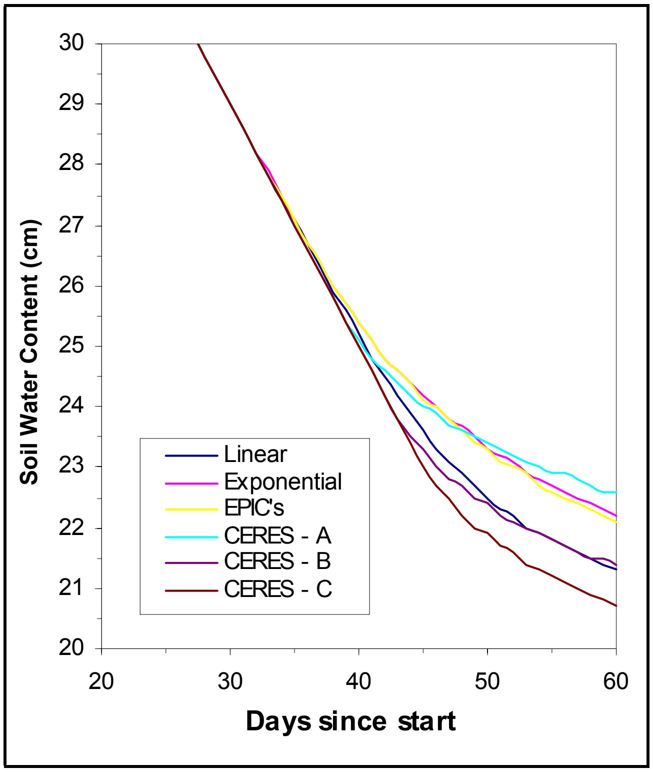

Figure 8. Simulated soil water content of root zone (PT = 0.4 cm d^{-1}, b = 0.041 cm^{-1}, Λ =3.429, UC = 0, RD_s for CERES-A, -B and –C was respectively 2.0, 4.5 and 7.0 cm cm^{-3}).

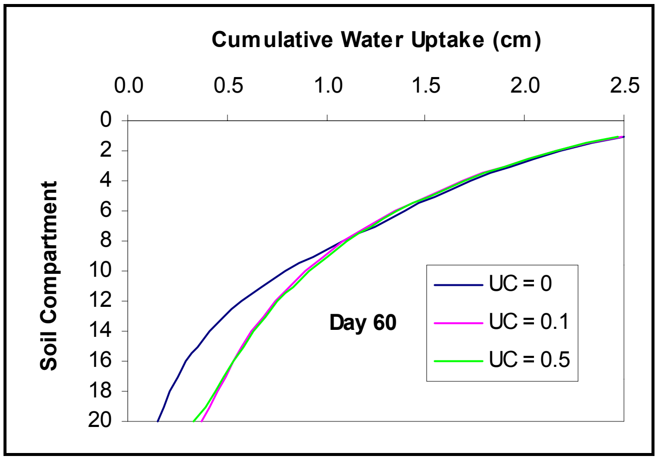

Figure 9. Estimated cumulative water uptake with the EPIC model for the simulations with (UC = 0.1 and 0.5, Λ =3.429) and without the water deficit compensation (UC = 0, Λ =3.429).

obtaining root distributions is justified, remains to be done. Field-testing also might reveal certain model advantages, which were not apparent when using the simplified soil and atmospheric boundary conditions used in this study.

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