

Modelling water uptake by various root systems in a clay loam soil under a high transpiration demand

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Abstract. Hydrological models are increasingly becoming important tools in agricultural water management. In this study, the effect of root length distribution on water uptake in a clay loam soil, a key process in agricultural hydrological models, is numerically investigated under a high transpiration demand. Four different root distributions (uniform, linear and exponential) are employed in the simulations. Results shown that roots distributed more evenly in the soil profile have an overall greater capacity and a smaller ability at later stages of transpiration of extracting water from the soil. Soil water 10 cm below the rooting depth has a very limited impact on crop transpiration.

1. Introduction

With the advances in soil, plant and computer sciences, great efforts have been directed to develop agricultural hydrological models for studying crop-water relations, and as a result, numerous models have been proposed with various degree of complexity [1]. It is now becoming a common practice to use such models for managing water use in a more scientific way in crop production [1].

Soil-crop is a complicated system, and involves a number of key processes governing water dynamics. One of them is root water uptake, which has a great effect on crop transpiration and is difficult to predict due to uncertainty of root length distribution. There is a large body of literature reporting experimental findings on root growth of various crops [2-4], and the root length distribution in the soil profile is mainly described in three forms: linear, polynomial and exponential [5-8]. Attempts have also been made to distribute roots more uniformly in soil to capture water and nutrients more effectively [9]. It is, therefore, of great interest to study the effects of root length distribution on water uptake to enhance model performance.

In this study, a numerical investigation is carried out to quantify the effects of 4 different root length distributions on water uptake in a clay loam soil under a high transpiration demand. The results obtained could potentially be used for precise management of agricultural water resources.

2. The model and parameter values in simulations

2.1. Governing equation for water dynamics in the soil-crop system

The equation controlling water dynamics in the soil-crop system can be expressed as follows:



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

Where θ is the volumetric soil water content, h is the soil pressure head, z is the coordinate, t is the time, K is the soil hydraulic conductivity, β is the reduction coefficient of root water uptake, T is the potential crop transpiration rate. L is the function of root length distribution, which is described in this study as:

$$L(z) = \begin{cases} 1 & \text{Uniform distribution} \\ 1-z/L_0 & \text{Linear distribution} \\ e^{-az/L_0} & \text{Exponential distribution} \end{cases} \quad (2)$$

Where L_0 is the rooting depth, a is the shape parameter for root length distribution.

The used soil hydraulic functions are given by van Genuchten (V-G) [11] and the determination of β can be seen elsewhere [10].

2.2. Parameter values and initial conditions

The simulated domain is 100 cm depth, and is divided into 100 layers equally during the simulations. The V-G hydraulic properties of the clay loam are shown in table 1. The potential crop transpiration rate is 0.5 cm/d. The simulation period is 30 d. Four different root length distributions are assumed: uniform, linear, and exponential with $a = 1$ and 3, respectively. The rooting depth is 30 cm. The initial soil water content is set to be at the field capacity, i.e. at $h = -330$ cm.

Table 1. The V-G soil hydraulic parameters used in the simulations

θ_s (cm ³ /cm ³)	θ_r (cm ³ /cm ³)	α (1/cm)	n (-)	K_s (cm/d)
0.410	0.095	0.019	1.31	6.24

3. Results and analysis

3.1. Simulated root water uptake

Figure 1 shows the cumulative simulated root water uptake under 4 root distributions with the potential transpiration rate of 0.5 cm/d. During the first 3 days, the potential daily transpiration is generally met despite different root length distributions. Root uptake gradually reduces afterwards with different paces, depending on the distribution. The cumulative root water uptake ranges from 2.5 cm to 3.5 cm on the 10th day, in the order of exponential ($a = 3$), linear, exponential ($a = 1$) and uniform distribution. However, the gap is reduced to 0.5 cm at the end of simulation with the cumulative water uptake being about 4.0 cm for the uniform and exponential ($a = 1$) distributions, and some 3.5 cm for the other distributions, implying that roots distributed more evenly in the soil profile have an overall greater capacity and a smaller ability at the later stages of simulations of water uptake. It is in the middle period of simulations that the capacity of root water uptake is significantly different with the highest for uniform root distribution, and the lowest for exponential ($a = 3$) distribution. Overall the root water uptake ability is close to each other for the uniform and exponential ($a = 1$) distributions, while the exponential ($a = 3$) and linear distributions have approximately the same capacity of extracting soil water.

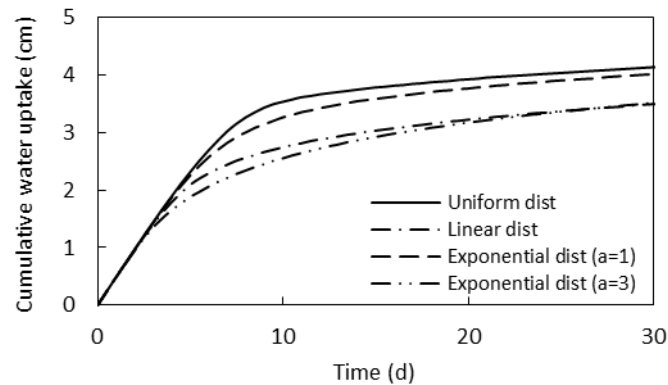


Figure 1. Cumulative simulated water uptake under various root length distributions

3.2. Simulated water content in various soil layers

The variation of water content in different soil layers is also simulated (see Figure 2). It is clear that in the top two soil layers water content all converges to $0.16 \text{ cm}^3/\text{cm}^3$ after 10 days for the 0 -10 cm layer and 20 days for the 10 - 20 cm layer, a value close to the permanent wilting point. This suggests that no water uptake by roots is possible for all different root length distributions at the later stages of simulations. It takes 10 days for uniformly distributed roots to be unable to extract water from the soil due to soil drying in the top layer, while in the case of exponential ($a = 3$) distribution it is only 5 days. This can be explained by the fact that the most and least roots distribute in the top soil layer in the cases of exponential ($a = 3$) and uniform distributions, respectively.

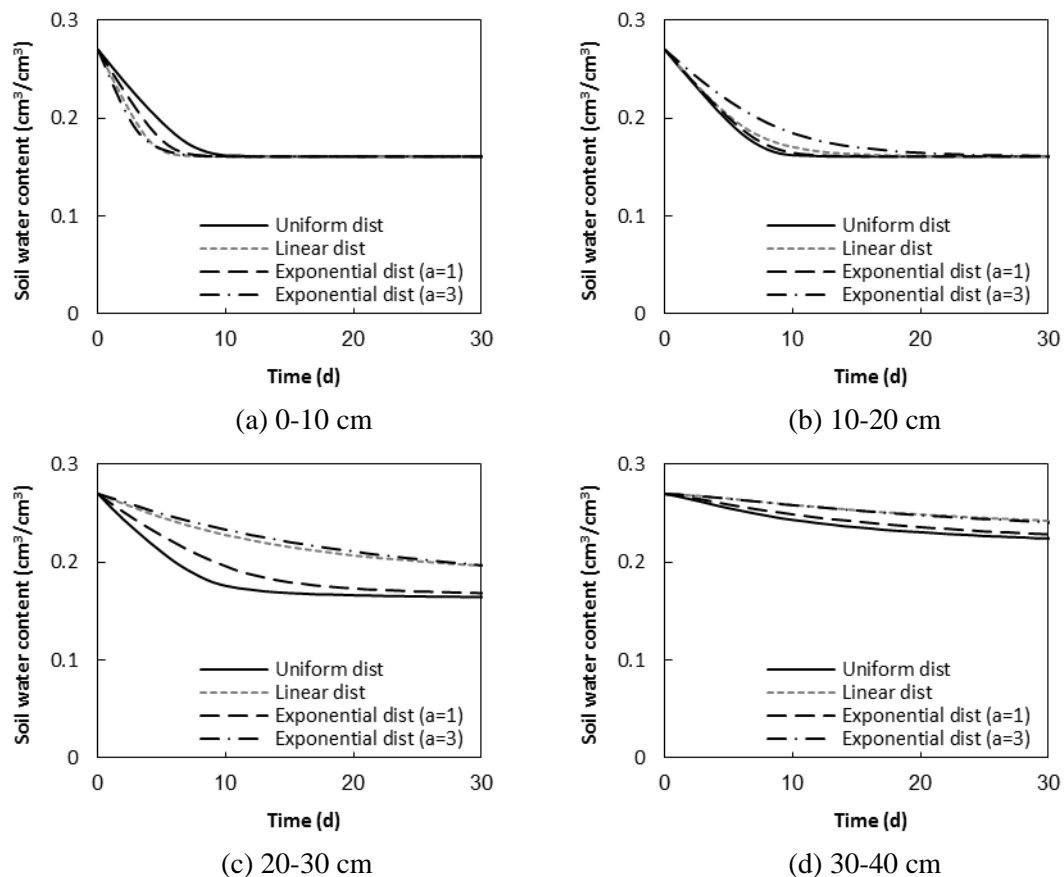


Figure 2. Simulated water content in different soil layers under various root length distributions

Soil water content decreases during the whole simulation period for the cases of exponential ($a = 3$) and uniform distributions, while it tends to be stable towards the late stages of simulations for the other two cases in the 20 -30 cm soil layer. At the end of the simulation soil water content drops to $0.17 \text{ cm}^3/\text{cm}^3$ for the cases of exponential ($a = 3$) and uniform distributions and $0.20 \text{ cm}^3/\text{cm}^3$ for the others. The variation of soil water content in the 30-40 cm layer follows a similar pattern, with the value of soil water content ranges from 0.23 to $0.24 \text{ cm}^3/\text{cm}^3$ at the end of simulation. In the 40-50 cm soil layer (data not shown), soil water content decreases slightly from $0.27 \text{ cm}^3/\text{cm}^3$ to $0.26 \text{ cm}^3/\text{cm}^3$ in an approximately linear manner for all the cases. The amount of water uptake from this layer only accounts for about 2.5% for the cases of uniform and exponential ($a = 3$) distributions and 2.9% for the other two cases, respectively. Overall it can also observed from Figures 1 and 2 that the simulated results for the case of uniform distribution are close to those from the case of exponential ($a = 3$) distribution, while the roots behaviour similarly in other two cases.

4. Conclusions

Some preliminary conclusions could be drawn based on the results presented the above.

Roots distributed uniformly or exponentially with the shape parameter a being 1 are more capable of extracting water from the soil, compared with those distributed linearly or exponentially with $a = 3$.

The simulated results are similar for the cases of uniform and exponential ($a = 1$) distributions, and for the cases of linear and exponential ($a = 3$) distributions, respectively.

Soil water 10 cm below the rooting depth makes ignorable contributions to root water uptake regardless of root length distribution.

Acknowledgments

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