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Modified conceptual model for compensated root water uptake – A simulation study

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SUMMARY

Modeling root water uptake within the macroscopic approach is usually done by introducing a sink term in the Richards equation. This sink term represents potential water uptake reduced by a so-called stress reduction factor accounting for stress due to high suctions, oxygen deficit or salinity. Since stress in some parts of the soil can be compensated by enhanced water uptake in less stressed parts, several compensation models have been suggested. One of them is the empirical model of Jarvis, which is often applied due to its mathematical elegance and simplicity. However, it has been discussed that under certain conditions and assumptions this model might predict too high transpiration rates, which are not in agreement with the assumed stress reduction function. The aim of this paper is (i) to analyze these inconsistencies and (ii) to introduce a simple constraint for transpiration in a way as if the complete water would be taken form the location with highest uptake rate in the uncompensated case. Transpiration from 50 cm deep soils with hydraulic functions representing different textures, ranging from a clay loam to a coarse sand, was simulated with the original and the modified model using HYDRUS-1D. Root distribution was assumed to be uniform or linearly decreasing with depth. In case of the fine textured soils and uniform root density, the original model predicted transpiration equal to potential transpiration even when the complete root domain was already heavily stressed if the maximum enhancement factor for uptake was 2. These results are not in agreement with the original meaning of the stress reduction function. The modification eliminates the inconsistencies by limiting transpiration to a maximum value based on the highest uncompensated uptake rate in the root zone. It does neither increase the mathematical complexity nor require any additional parameters.

1. Introduction

Water dynamics in the soil–plant atmosphere system plays a major role for many topics in environmental and agricultural sciences such as groundwater recharge and plant yield. Moreover, solute and energy transport are closely linked to water dynamics (Zurmühl and Durner, 1996; Schonsky et al., 2014). Therefore, errors in prediction of water dynamics might not only lead to errors in the predicted water budged terms but also to errors in predicted solute and energy partitioning in the different system components.

In the frame of continuum theory, water transport is usually modeled with the Richards equation (e.g. with the HYDRUS (Simunek et al., 2013) or SWAT (van Dam et al., 1997) software packages). Root water uptake (RWU) is then described as a sink term in the Richards equation. Several approaches for modeling RWU have been suggested, differing in spatial dimensionality and complexity of the sink term description (Javaux et al., 2013).

The more complex descriptions of the sink term (e.g. Javaux et al., 2008) are more representative for real system behavior but they require numerous input parameters, which are often not known. Moreover, spatial highly resolved three dimensional simulation models have high computational demand. Therefore, de Jong van Lier et al. (2008) or Couvreur et al. (2012) presented simplifications of such models, which are still physically based.

Yet, for practical purposes, other more simple models are still often used. The most simple models are the single or multi layer water budged models using simple balance equations instead of the Richards equation for water movement (e.g. Leimer et al., 2014). The frequently used effective models for root water uptake combined with the Richards equation as described in e.g. Feddes et al. (1978) or Simunek and Hopmans (2009) are also very simple. Due to their popularity, these models are addressed in this contribution and are shortly outline below.

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The effective description of RWU as function of soil depth and time within this approach is usually done in three steps (Simunek and Hopmans, 2009): First, potential RWU is calculated for each spatial coordinate by multiplying potential transpiration with a normalized root-distribution function. Second, potential RWU is reduced by introducing a stress response function (e.g. Feddes et al., 1978), which accounts for reduction of water availability due stress caused by soil water potential, salt concentration or oxygen deficit. Third, several researchers found evidence that plants can compensate stress in some parts of the root zone by taking up more water from less stressed parts (Hasegawa and Yoshida, 1982; Leib et al., 2006), which has also to be accounted for.

Different approaches for modeling compensated RWU have been suggested. The frequently used empirical approach from Jarvis (1989) calculates the ratio of uncompensated RWU to potential RWU, which is termed stress index, ω. If ω is greater than a critical stress index ω_c, full compensation is assumed, meaning that reduced uptake in some parts of the profile is completely compensated in other parts so that actual transpiration is equal to potential transpiration. If ω is below the critical stress index, transpiration is partly compensated. Due to its mathematical simplicity, this approach is frequently used in vadose zone modeling (Simunek and Hopmans, 2009) and also implemented in the HYDRUS-1D software package (Simunek et al., 2013). Slightly different empirical approaches have been applied by Li et al. (2001), Guswa (2005) and Kuhlmann et al. (2012). In contrast, Adiku et al. (2000) hypothesized that plants take up water in a way that a minimum of energy is required. They formulated RWU as a minimization problem, where total energy requirement for water uptake at a certain time step has to be minimized.

Although the compensation approach of Jarvis (1989) is often used, it might have a conceptual shortcoming (Skaggs et al., 2006), which is shortly repeated here. If, for example, the suction in the soil profile is uniformly distributed, i.e. the whole root domain is equally stressed, water uptake will be completely compensated if the corresponding reduction is less than the critical stress index. Thus, the water uptake would be greater by the factor $1/\omega$ than the rate specified by the stress response function. This does not mimic compensatory uptake and seems to contradict the original meaning of the stress response function.

Note that other interpretations are possible. Jarvis (1989, 2010) attributed the stress response function to local water uptake reduction due to water stress and the compensation function to the whole plant response to water stress. Then, compensation could mean that the whole plant can maintain potential transpiration even if $\omega \ll 1$, regardless of spatial distribution of α. In the above outlined example the Jarvis model would then not reproduce a compensation, but rather a stronger suction applied by all roots. This implies that the meaning of the stress response function is different from the original meaning when it is combined with the Jarvis (1989) compensation model. However, Albasha et al. (2015) compared measured and modeled RWU patterns using the Jarvis (1989) compensation model and conclude that compensation is independent of the plant stress status and should be interpreted as a response to soil–water status heterogeneity. In the remainder of this paper, the interpretation of Skaggs et al. (2006) of the stress reduction function and compensation is followed when the term "inconsistency" of the original model is addressed. This interpretation keeps the original meaning of the stress function.

The above outlined problems do not exist in the more complex root architecture models, which account for water flow within the plant system (Doussan et al., 2006; Javaux et al., 2008). The recently introduced simple physically based models of de Jong van Lier et al. (2008) or Couvreur et al. (2012, 2014) are applicable for 1-D simulations and therefore promising means to bridge the gap between the complex physical models on the one hand and the simple conceptual models on the other hand. These models define a maximum transpiration based on plant properties and the water stress status, which is determined in the Couvreur et al. (2012) model directly by soil water potential and by the de Jong van Lier et al. (2008) model by matrix flux potential. Maximum transpiration is thus independent of atmospheric conditions and can be higher than the atmospherically determined potential transpiration, therefore actual transpiration is given by the minimum of potential and maximum transpiration in both models. The de Jong van Lier et al. (2008) model implicitly accounts for compensation (Jarvis, 2010), whereas water stress and compensation are decoupled in the Couvreur et al. (2012) model. However, those models account only for stress due to matric or total water potential but not for other stress sources such as oxygen deficit.

For practical purposes, such as agricultural water management, the Jarvis compensation model in combination with simple macroscopic stress response functions, like the Feddes function, is widely used for an effective description of RWU (e.g. Simunek and Hopmans, 2009).

The aim of this paper is therefore (i) to show and discuss the impact of the original Jarvis (1989) compensation model on RWU for different soil textures and (ii) to introduce a simple modification to overcome the above mentioned conceptual shortcoming.

2. Theory

2.1. Water movement in soils

Water flow in variably saturated soils is usually modeled with the Richards equation (e.g. Simunek et al., 2013; van Dam et al., 1997), which is in the one dimensional case given by:

$$\frac{\partial\theta(h)}{\partial t} = \frac{\partial}{\partial z}\left[K(h)\frac{\partial h}{\partial z} - K(h)\right] - S, \tag{1}$$

where θ [–] is the volumetric water content, h [L] the soil suction, t [T] the time, z [L] the depth coordinate defined negatively downward, K [L T^{-1}] the hydraulic conductivity and S [T^{-1}] is a source (when negative) or sink (when positive) term, which accounts in this study solely for root water uptake (RWU). In order to solve Eq. (1), the initial and boundary conditions, the hydraulic functions, i.e. the water retention ($\theta(h)$) and hydraulic conductivity ($K(h)$) functions as well as the spatial and temporal variable sink term S have to be specified. One of the main challenges remains the adequate description of S as a function of root distribution and evaporative demand as well as oxygen, suction and salinity stress.

2.2. Root water uptake – common approach

The description of S as function of time and soil depth is often formulated by a combination of the approaches of Feddes et al. (1978) and Jarvis (1989) (see Simunek and Hopmans, 2009), which are briefly repeated here.

First, the potential uptake S_p [T^{-1}] is calculated, which is determined by the potential transpiration T_p [L T^{-1}] and normalized root distribution b [L^{-1}]:

$$S_p(z,t) = T_p(t)b(z) \tag{2}$$

The potential uptake is then converted into reduced uptake S_u [T^{-1}] by multiplying S_p with a so-called stress reduction factor:

$$S_u(z,t) = \alpha(z,t)S_p(z,t) \tag{3}$$

where the subscript u indicates uncompensated (see below). The stress reduction factor α [–] takes all kinds of stress reduction into account. The stress due to oxygen deficit and suction is often