Advances in Water Resources 88 (2016) 86–96

Contents lists available at ScienceDirect

Advances in Water Resources

journal homepage: www.elsevier.com/locate/advwatres

Mesoscopic aspects of root water uptake modeling – Hydraulic resistances and root geometry interpretations in plant transpiration analysis

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ARTICLE INFO

Article history:
Received 8 July 2015
Revised 13 October 2015
Accepted 5 December 2015
Available online 11 December 2015

Keywords:
Root water uptake
Soil water flow model
Hydraulic resistance
Critical root xylem water potential
Sap flow
Transpiration

ABSTRACT

In the context of soil water flow modeling, root water uptake is often evaluated based on water potential difference between the soil and the plant (the water potential gradient approach). Root water uptake rate is modulated by hydraulic resistance of both the root itself, and the soil in the root vicinity. The soil hydraulic resistance is a function of actual soil water content and can be assessed assuming radial axisymmetric water flow toward a single root (at the mesoscopic scale). In the present study, three approximate solutions of mesoscopic root water uptake – finite difference approximation, steady-state solution, and steady-rate solution – are examined regarding their ability to capture the pressure head variations in the root vicinity. Insignificance of their differences when implemented in the macroscopic soil water flow model is demonstrated using the critical root water uptake concept. Subsequently, macroscopic simulations of coupled soil water flow and root water uptake are presented for a forest site under temperate humid climate. Predicted soil water pressure heads and actual transpiration rates are compared with observed data. Scenario simulations illustrate uncertainties associated with estimates of root geometrical and hydraulic properties. Regarding the actual transpiration prediction, the correct characterization of active root system geometry and hydraulic properties seems far more important than the choice of a particular mesoscopic model.

1. Introduction

Approximate mesoscopic models of root water uptake (RWU) based on the water potential gradient (WPG) approach have been used to parameterize the water transfer at the soil—root interface for decades. These models are attractive for their mechanistic simplicity and a relative ease of implementation into a modular structure of more complex models representing the soil—plant—atmosphere continuum.

Van den Honert [45] was among the first who applied electrical resistance analog, inspired by Ohm's law, to describe transpiration stream of water in plants. In this analog, the gradient of water potential forces water to flow across a series of resistances representing different compartments of the soil—plant—atmosphere system. Since then, the WPG approach to RWU modeling has been applied by many researchers in both the mesoscopic and the macroscopic scales, i.e., as a single-root model or a root system model [19]. A thorough analysis of WPG approaches, based on approximate steady-state or steady-rate radial flow assumptions, was presented e.g. by Gardner [15], Cowan [6] and Jakobsen [22]. More recently, theoretical comparisons of the commonly used WPG approaches were presented e.g. by Feddes and Raats [14] and Raats [35]. Javaux et al. [24] utilized the WPG approach in a three-dimensional model of root water uptake to derive an effective one-dimensional RWU model at the plant scale. De Willigen et al. [9,10] compared four RWU models of different complexity by means of virtual experiments. A process-based transpiration reduction function involving maximum root water uptake rate as a function of soil water status, soil hydraulic properties, root length density, and root radius was presented by de Jong van Lier et al. [8]. Their approach to RWU modeling was tested against soil water content data observed at an irrigated field under tropical conditions. The effect of local root hydraulic properties on soil water availability was quantitatively evaluated by Couvreur et al. [5] using a hypothetical summer drought scenario. So far, a relatively low number of studies compared predictions, obtained with different root water uptake models, to observed field data (under specific soil, plant and atmospheric conditions).

In our previous study [50], several features of the WPG approach to RWU modeling such as root-mediated soil water redistribution, compensation for local water scarcity, and nightly transpiration were examined using data from a temperate humid climate forest site. The predictions based on the WPG approach were

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http://dx.doi.org/10.1016/j.advwatres.2015.12.006
0309-1708/

compared to those obtained with the semi-empirical approach of Feddes et al. [13].

The present study is concerned with mesoscopic aspects of RWU modeling, including selection of a mesoscopic RWU approximation, definition of the active root system geometry, as well as estimation of the root hydraulic properties. The analysis is carried out in two steps: (i) First, we compare the selected approximate root water uptake models with the more exact numerical solution of the Richards equation at the mesoscopic scale. The aim of this step is to test the RWU models' capability of reproducing spatiotemporal variations of soil water pressure in the vicinity of roots, which determines the accuracy of the models when used to project the bulk-soil water pressure onto the root-surface water pressure in macroscopic simulations of soil water flow and transpiration. The mesoscopic analysis is complemented with a comparison of the critical root water uptake rates calculated for the critical root-xylem water potential by each RWU model. (ii) Subsequently, we examine the RWU model functioning when implemented in the macroscopic model of soil water flow. The objective is to assess the sensitivity of the actual transpiration rates predicted by macroscopic simulations to changes in the RWU model parameters. Specifically, consequences of choosing various interpretations of active root geometry, various magnitudes of effective root radial hydraulic resistances, and various critical root-xylem water potentials are inspected. The results of the macroscopic simulations are compared with measured xylem sap flow rates in trunks of spruce trees and soil water pressures in the root zone.

2. Material and methods

2.1. Root system geometry

Plants take up water through the surface of active roots, a distinct subsystem of the whole root system. The active roots are usually defined as a certain root-size class. For the purpose of the root water uptake modeling, it is commonly represented by a single value of an average active root radius, r_0 (m). The active root surface area can be computed using a simple formula based on the assumption of cylindrical root geometry:

$$\sigma(z) = 2\pi r_0 R(z) \tag{1}$$

where σ is the specific effective root surface (m^{-1}), R is the effective root length density (m^{-2}), and z is the vertical coordinate (m). $R(z)$ and r_0 are often used in root water uptake models as the root geometry parameters.

In reality, σ and R vary in all spatial directions throughout the root zone. However, in most model applications, the variation is restricted to the vertical direction, assuming horizontal invariance of σ and R. The choice of the average active root radius value and its interpretation differ widely among different RWU modeling studies. In the present study, the active root subsystem is associated with the fine roots, i.e. roots with a diameter < 2 mm (e.g. [38]).

Another root system characteristic related to the root length density is the radius from which a single root can extract water, r_1 (m), often referred to as the rhizosphere radius:

$$r_1(z) = \frac{1}{\sqrt{\pi R(z)}} \tag{2}$$

Alternatively, it may be convenient to use a more general characteristic of the length associated with the transport of water from soil to root surface. The effective length (flow path) can be expressed as a fraction of r_1:

$$\lambda(z) = a\, r_1(z) \quad r_0/r_1 < a \le 1 \tag{3}$$

2.2. Water uptake by a single root – mesoscopic RWU models

Water extraction from the inter-root space by a single root can be idealized as transient radial flow toward the root surface described by Darcy–Buckingham law. Using radial coordinate and neglecting gravity, the following applies for a unit root length:

$$Q(r) = -2\pi r K(r) \frac{\partial h}{\partial r} \tag{4}$$

where $Q(r)$ is the water uptake rate per unit root length (m^2 s^{-1}) at a distance of r from the root center, h is the soil water pressure head (m), and K is the soil hydraulic conductivity (m s^{-1}).

Continuity equation for the radial flow can be written as:

$$2\pi r \frac{\partial \theta}{\partial t} = -\frac{\partial Q}{\partial r} \tag{5}$$

where θ is the soil water content (dimensionless) and t is time (s).

Governing partial differential equation (PDE) of radial flow towards root (Richards's equation in radial coordinates) is then obtained by combining the flux and continuity equations (Eqs. (4) and (5)), i.e.:

$$\frac{\partial \theta}{\partial t} = \frac{1}{r}\frac{\partial}{\partial r}\left(rK \frac{\partial h}{\partial r} \right) \tag{6}$$

This PDE can be solved numerically to describe mesoscale water flow and spatiotemporal soil water content changes around individual roots. However, for use in macroscopic scale models, approximate solutions have been sought that would provide direct (computationally simple) link between the root water uptake rate and the soil water pressure drop between the bulk soil and the root surface. Three of these solutions, which we refer to as mesoscopic RWU models, are briefly presented in the following subsections.

2.2.1. Mesoscopic model based on the finite difference approximation (FD model)

Considering Eq. (4) for the root surface ($r = r_0$) and approximating the partial derivative by a simple finite difference formula gives:

$$Q_0 = -2\pi r_0 K(h(\lambda)) \frac{h(\lambda) - h(r_0)}{\lambda - r_0} \tag{7}$$

where Q_0 is the water uptake rate at the root surface (m^2 s^{-1}), and $\lambda - r_0$ is the effective length over which the soil water pressure drop is applied (see also Eq. (3)). An important difference between this model and those described in the following subsections is the direct use of the soil hydraulic conductivity associated with the bulk-soil water pressure head. This feature represents a notable advantage when implementation in a macroscopic model is considered.

2.2.2. Mesoscopic steady-state root water uptake model (SS model)

This approximation is equivalent to the solution of radial steady-state flow to a well introduced by Thiem [44] and applied in the context of RWU analysis by Gardner [15].

Considering quasi-steady-state flow conditions yields the state variables in Eqs. (4)–(6) independent of time. Thus the governing equation for the steady-state model is an ordinary differential equation (SS ODE) which can be written as:

$$Q_0 = -2\pi r K(r) \frac{dh}{dr} \tag{8}$$

The solution of SS ODE is obtained by integrating Eq. (8):

$$h(r) - h(r_0) = -\frac{\ln(r/r_0)}{2\pi \bar{K}} Q_0 \tag{9}$$

where:

$$\bar{K} = \frac{1}{h(r) - h(r_0)} \int_{h(r_0)}^{h(r)} K(h)dh \tag{10}$$