Root water uptake modelling

November 2013, Jos van Dam
Root water uptake simulation

Root water uptake relevant for:
- Evapotranspiration
- Vegetation growth
- Soil moisture and oxygen conditions
- Groundwater recharge

In this presentation:
- Macroscopic concept
- Microscopic concept
- Current research issues

source: Taiz L., Zeiger E., 2010)
Continuum of hydraulic potentials in soil-plant-atmosphere system

Total leaf transpiration equal to total root water uptake

1 MPa = 100 m pressure head
Common macroscopic reduction function

Soil is considered as a continuum of solids, roots, water and air

$h_3$ depends on transpiration rate $T$

$T_{\text{low}}$ and $T_{\text{high}}$

Too dry

Too wet

Critical pressure heads $h_1$ – $h_4$ are plant specific

Soil water pressure head

Uptake reduction factor
Limitations macroscopic concept

• the limiting pressure head $h_3$ depends on the actual plant – soil – weather combination: therefore calibration is required

• relation between pressure head and reduction factor in the dry range might be strongly non-linear

• it is not clear how water and salt stress interact

• compensation of root water uptake is not included

Can we learn from microscopic root water uptake models?
Radial flow to single roots

Darcy: \[ q = -k \frac{\partial h}{\partial r} \]

near root surface:

- flow area becomes small \( \rightarrow \) large flux density \( q \)
- lower pressure head \( h \) \( \rightarrow \) small conductivity \( k \)

Therefore near root surface
very large gradients \( \frac{\partial h}{\partial r} \)

analytical solutions only with gross simplifications
Matric flux potential

Darcy:

\[ q = -k \frac{\partial h}{\partial r} \]

Define matric flux potential:

\[ M = \int_{h_w}^{h} k(h) \, dh \quad \Rightarrow \quad \frac{\partial M}{\partial r} = k(h) \, dh \]

In stead of considering very low values of hydraulic conductivity and very large differences of soil water pressure head, with the matric flux potential we only consider their product!

Linear relation between \( q \) and \( M \):

\[ q = -k(h) \frac{\partial h}{\partial r} = -\frac{\partial M}{\partial r} \]

With the matric flux potential we are able to derive robust analytical solutions for radial root water uptake.
General root water extraction equation

Derived general extraction equation:

\[ S_z = \frac{4 \left( M_{a,z} - M_{0,z} \right)}{r_{0,z}^2 - a_z^2 r_{m,z}^2 + 2 \left( r_{0,z}^2 + r_{m,z}^2 \right) \ln \frac{a_z r_{m,z}}{r_{0,z}}} \]

Required input data are limited and physically defined:
- potential transpiration rate
- plant wilting point
- root length density profile
- root radius
- soil hydraulic functions \((h - \theta - k \text{ relations})\)

In a numerical model, soil hydraulic functions, root density and water content may vary with depth.
## Improvement microscopic concept

<table>
<thead>
<tr>
<th>Macroscopic concept</th>
<th>Microscopic concept</th>
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</thead>
<tbody>
<tr>
<td>Critical pressure heads require calibration</td>
<td>Input data can be measured directly</td>
</tr>
<tr>
<td>Linear reduction in dry range adopted</td>
<td>Reduction in dry range follows from hydraulic potentials</td>
</tr>
<tr>
<td>Not clear how water and salt stress affect each other</td>
<td>Osmotic head due to salinity can be added to hydraulic potentials</td>
</tr>
<tr>
<td>No compensation of root water uptake</td>
<td>Compensation of root water uptake occurs automatically</td>
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</tbody>
</table>
Include flow in plant

Assumed boundary condition: wilting point at soil surface

In case of low root density wilting point probably cannot be reached

Improvement: calculate root water extraction, taking into account root radial resistance, stem axial resistance and leaf water potential
Most soil physical models stop at root surface. Instead of pressure head at root surface, boundary condition becomes leaf water potential. Include radial flow in roots and axial flow in xylem tubes.
Modeling Water Potentials and Flows in the Soil–Plant System Comparing Hydraulic Resistances and Transpiration Reduction Functions

Transpiration reduction functions are often used in hydrological modeling to estimate actual transpiration as a function of soil water status. Empirical reduction functions are most frequently used due to the higher data needs and computational requirements of mechanistic models. Empirical models, however, lack a description of physical mechanisms and their parameters require extensive calibration. We derive a process-based reduction function predicting system potentials, resistances, and water flows. An analytical solution for a special case of Brooks and Corey soils is presented. A numerical version of the reduction function for van Genuchten soils was implemented in the Soil–Water–Atmosphere–Plant (SWAP) hydrological model, allowing predictions for layered soil profiles and root length density variations over depth. The analytical and numerical versions of the model allow an increasingly quantitative insight into the mechanism of root water uptake, such as the existence of a maximum root water uptake rate as a function of soil water status, soil hydraulic properties, root length density, and root radius, in addition to the fact that sensitivity of simulated root water uptake to the radial root conductivity and axial conductance decrease when root length density increases. The approach can be used for the estimation of threshold values for empirical reduction functions.

Abbreviations: CWSI, Crop Water Stress Index; FRF, Feddes et al. (1978) reduction function; JRF, de Jong van Lier et al (2008) reduction function; PRF, proposed reduction function; RMSE, root mean square error; SWAP, Soil–Water–Atmosphere–Plant model.
Example: Uptake rate as function of leaf pressure head

Soil pressure head = -5 m

- Uptake rate (d⁻¹)
- Leaf pressure head (m)
- Pressure heads (m)

S_{max}

Root surface pressure head
Xylem pressure head
Leaf pressure head

WAGENINGEN UR
For quality of life
Simulated versus measured transpiration

Growth of common bean, Brasil
Next steps

• Verification with lysimeter and field measurements
• Derive empirical parameters of macroscopic models
• Include horizontal root density variation
• Include dynamic root density development
WaterWijzer Landbouw

Op dit moment in Nederland 3 methoden voor schade door te nat of te droog:
- HELP tabellen
- TCGB tabellen
- Agricom

Actualisatie schadefuncties nodig:
- Veel impliciete kennis opgenomen
- Resultaten niet reproduceerbaar
- Alleen langjarige gemiddelde schades
- Gebaseerd op verouderde weer- en gewasgegevens
- Geen zoutstress opgenomen

Einddoel project WaterWijzer (STOWA, 2013):
‘Een uniform en breed gedragen systeem voor het bepalen van klimaatrobuuste relaties tussen waterhuishoudkundige condities en gewasopbrengsten’
In opdracht van STOWA, samenwerking tussen:
- Alterra (penvoerder)
- KWR Watercycle
- Wageningen Universiteit
- Bakelse Stroom

Eerste fase (gereed):
- SWAP-WOFOST operationeel om klimaatrobuuste verdampingsreducties voor droogte, natheid en zout te simuleren

Tweede fase (oktober 2013 – maart 2015):
- Toetsing koppeling SWAP – WOFOST voor de gewassen gras, aardappel en snijmaïs voor berekening opbrengstreducties
- Afleiden metarelaties, gebaseerd op SWAP-WOFOST, voor diverse bodemtypen, meerdere klimaatscenarios en voor de gewassen gras, aardappel en snijmaïs
- Actualiseren kennis over indirecte schade (structuur, opkomst, oogst)
- Koppeling SWAP-WOFOST aan BBPR (BedrijfsBegrotingsProgramma Rundvee)