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Development of hydro-pedotransfer functions to predict capillary rise and actual evapotranspiration for grassland sites

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SUMMARY

New hydro-pedotransfer functions (HPTF) for flat grasslands are presented to estimate both annual capillary rise from the groundwater into the root zone and actual evapotranspiration on a regional scale. Based on easily available site information, soil water components such as percolation rate and therefore groundwater recharge can also be evaluated. This information may be obtained without detailed knowledge of soil hydraulic properties and daily weather data. Rather, the only data needed is soil texture class, groundwater depth, summer rainfall and potential evapotranspiration (ET_0) according to the FAO guideline. The basic idea is to evaluate the increase of actual evapotranspiration (=gain, G) caused by capillary rise from groundwater compared to identical site conditions, but without groundwater influence. This gain (G) represents an effective parameter to express both the soil and climate dependent effective capillary rise for a given grassland site. To develop hydro-pedotransfer functions expressing gain, we first used the numerical simulation program SWAP in order to calculate water balances for a broad spectrum of soils, groundwater depths, and climate conditions. Secondly we analyzed this data statistically in order to obtain simple equations for predicting G without using a numerical model. The new hydro-pedotransfer functions were developed and tested for different climate regions in Germany.

1. Introduction

Reliable quantitative data on water balance for groundwater influenced sites is needed in the field of landscape ecology and for the evaluation of ecosystem functions. Agencies involved in water management and water supply as well as agronomists could also benefit from this data. While measurements are extremely cumbersome, the execution of any comprehensive simulation model requires knowledge of a large number of input data. In contrast, hydro-pedotransfer functions (HPTF) are an alternative way to predict water balance components by using easily available site information. In this way, a methodological bridge between the fields of soil physics and groundwater hydrology can be achieved (Lin, 2003). Wang et al. (2009) have been using a flow model whose soil hydraulic parameters were obtained from pedotransfer functions. In contrast, here we used a numerical model with known soil hydraulic parameters and developed a new hydro-pedotransfer function to reproduce the simulation results. By applying hydro-pedotransfer functions, only information on soil texture class, groundwater depth, and climate is needed.

The study presented here does not aim to predict the groundwater recharge of an entire watershed. To do this, a grid has to be created and for each cell detailed data is needed (Bogena et al., 2005). This paper focuses on developing tools, which can be easily applied to each raster element of such a grid.

Recently, a set of hydro-pedotransfer functions was proposed to predict the annual percolation rate on a regional scale by using easily available soil data (Wessolek et al., 2008). However, this contribution basically uses a simplified approach to calculate the capillary rise from the groundwater into the root zone, which was embedded in a soil water balance model. In this study, we now want to improve the calculation in order to obtain predictive equations to describe site-specific capillary rise that enhance actual evapotranspiration. For our purposes the term "capillary rise" symbolizes an idealized flow pattern where drainage and capillary rise are imagined to be separated flow conditions in the soil. However, in reality the soil water flux at the bottom boundary of the capillary zone periodically changes. One reason is the fluctuating groundwater table during the seasons caused by lateral flow. Another is the instability of hydraulic gradients in the soil profile during the growing period leading to both upwards and downwards soil water fluxes. For these reasons we decided to express the effective capillary rise as gain of actual evapotranspiration in order to make sure that capillary rise is not only dependent on soil

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Nomenclature

c_i	fitting parameters, Eqs. (10)–(13)
D	atmospheric water demand, cm/a, Eqs. (8)–(10), (12), and (13)
D_{root}	rooting depth, cm, Eq. (2)
E_{act}	actual evapotranspiration, cm/a, Eqs. (1), (7), and (14)–(16)
E_o	grass reference evapotranspiration, cm, Eq. (17)
E_{pot}	potential evapotranspiration, cm/a, Eqs. (10), (12), (14), (16), and (17)
E_{ref}	actual evapotranspiration without groundwater influence, cm/a, Eq. (7)
FC	index: field capacity, Eq. (2)
G	gain of actual evapotranspiration attributed to groundwater influence, cm/a, Eqs. (7)–(10), (13), and (14)
g_i	fitting parameters, Eq. (14)
h	soil water pressure head, cm, Eqs. (3) and (4),
K	hydraulic conductivity, cm/d, Eqs. (4) and (5)
m	$m = 1 - 1/n$, Eq. (5)
P	precipitation, cm/a, Eqs. (1), (10), (12), and (14)–(16)
p_1, p_2	parameters of Eq. (6), Eq. (6)
PWP	index: permanent wilting point, Eq. (2)
q	flow rate, cm/d, Eq. (4)
Q_c	capillary rise, cm/a, Eq. (1)
Q_{dr}	drainage rate, cm/a, Eq. (1)
Q_{dr}	rooting depth, cm, Eq. (2)
q_{max}	steady-state maximum flow rate for given soil, flow distance and boundary conditions, cm/d, Eqs. (6), (11), and (13)
Q_p	annual percolation rate, cm/a, Eq. (1)
Q_{surf}	surface runoff, cm/a, Eq. (1)
R	average groundwater recharge, cm/a, Eq. (15) and (16)
S	potential groundwater-induced water supply, cm/a, Eqs. (8), (9), and (11)
W_a	maximum amount of plant available soil water, cm, Eqs. (2), (10), (12), and (14)
z	vertical coordinate, upward positive, cm, Eqs. (4) and (6)
ΔW	soil water storage change, cm, Eq. (1)
λ_i	fitting parameters, Eqs. (9)
θ	water content, cm^3/cm^3, Eq. (2)
$\theta_s, \theta_r, \alpha, n$	parameters of the van Genuchten model, Eq. (3)

hydraulic properties but also on climate and plant conditions. It should be noted that knowledge of actual evapotranspiration allows for the approximate estimation of the soil water balance and hence, of groundwater recharge.

2. Methods and approach

2.1. Basic principles

Defining the annual percolation rate Q_p in annual values of downward flow Q_{dr} and of capillary rise Q_c as separate terms, the soil water balance equation reads

$$P = E_{act} + Q_p + Q_{surf} + \Delta W \tag{1}$$

with $\quad Q_p = Q_{dr} - Q_c$

where P is precipitation, E_{act} actual evapotranspiration, Q_{surf} surface runoff and ΔW soil water storage change. These terms may be expressed as volume of water per unit surface area valid for a selected time span that is chosen here to be 1 year. Hence, the units are cm/year. As shown in Fig. 1, the soil profile is imagined to consist of a root zone above subsoil containing essentially no roots. The atmosphere influences the system by precipitation and potential evapotranspiration. In this view, capillary rise is seen as the flow of water from the groundwater table up to the lower boundary of the root zone where it is taken up by roots in the root zone, Fig. 1.

The difference ($Q_{dr} - Q_c$) is the effective soil water drainage Q_p i.e. percolation rate contributing to either interflow or groundwater recharge. The term Q_{surf} is of high importance in urban areas but since this study is focusing on flat sites under grassland, it is neglected here. Eq. (1) was set up separately for the growing season (April 1st–September 30rd) and the remainder of the year.

2.2. Soil hydraulic properties as predictors for target variables

The above mentioned terms of soil water balance depend on both soil physical properties and site-specific conditions such as weather data, groundwater depth, slope, root zone thickness, root density distribution, and vegetation properties. To set up site-specific estimation equations, terms describing soil hydraulic properties are calculated beforehand. The maximum amount of plant available soil water W_a, is expressed as:

$$W_a = D_{root}(\theta(h_{FC}) - \theta(h_{PWP})) \tag{2}$$

In this equation D_{root} denotes rooting depth, θ volumetric soil water content as a function of soil water pressure head h and indices FC and PWP indicate field capacity and permanent wilting point. In this study, we selected $h_{FC} = -63$ h Pa and $h_{PWP} = -15{,}800$ h Pa. More detailed discussions on using these expressions are given by Hillel (1980), Renger et al. (2009), and Bohne (2005).

Eq. (2) provides a conventional parameter describing the maximum amount of soil water plant roots are able to withdraw. Under field conditions, however, plant available water consists of the major part of P falling during summer. Q_c and part of W_a that has been built up by winter precipitation, has been temporarily stored and is partially depleted from the root zone during the growing season. $\theta(h)$ values are furthermore expressed by van Genuchten's model (van Genuchten, 1980).

$$\theta(h) = \theta_r + \frac{\theta_s - \theta_r}{[1 + (\alpha|h|)^n]^{1/n}}, \quad h \leqslant 0 \tag{3}$$

θ_s, θ_r, α and n are soil hydraulic parameters. These are essentially fitting parameters. Based on a large number of observations, Renger et al. (2009) provided soil water retention and hydraulic conductivity data, which may be regarded as characteristic for texture classes according to the German soil texture classification (Fig. 2).

Using the RETC4 code (Schaap and Leij, 2000), this data was parametrized successfully with the Mualem/van Genuchten model (Table 1). For a detailed discussion of hydraulic properties of soil classes readers are referred to Renger et al. (2009).

Steady-state flow of water from the groundwater table to the root zone may be described by using Darcy's law as described by Hillel, 1980:

$$z = \int_0^{h_{\min}} \left(\frac{q}{K(h)} + 1\right)^{-1} dh \tag{4}$$