Hydro-pedotransfer functions for predicting the effective annual capillary rise

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Abstract
New hydro-pedotransfer functions for grassland are presented to calculate both annual capillary rise from the groundwater into the root zone and actual evapotranspiration for regional water balances. The functions i.e. the procedure has two advantages. Firstly, only easily available site information is necessary for the calculation, such as the soil texture class, groundwater depth, summer rainfall and potential evapotranspiration (ET_{pot}) according the FAO guideline. Secondly, we follow the principle idea to define the gain (G) of actual evapotranspiration (ET_{act}) caused by capillary rise from groundwater as an effective parameter to express both, the soil and climate dependent effective capillary rise for a given site. In order to define a reference, we used the actual evapotranspiration of a site without groundwater influence but with same soil hydraulic properties and climate conditions. In order to predict *G* without using the numerical model, a new hydro-pedotransfer concept was developed and tested for several regions in Germany, Europe.

Key words
Capillary rise, actual evapotranspiration, hydro-pedotransfer functions, regional scale

Introduction
Recently, a set of hydro-pedotransfer functions was proposed to predict the annual percolation rate on a regional scale using easily available soil data (Wessolek et al. 2008). However, the above mentioned functions use a very simple approach to calculate the capillary rise from the groundwater into the root zone. Our aim was to improve the calculation in order to get an expression for a site specific capillary rise that enhances at least the actual evapotranspiration. We should keep in mind that the term “capillary rise” symbolizes an idealized flow pattern where drainage and capillary rise are imagined to be separated flow conditions in soil. In reality the flux at the bottom boundary changes magnitude and direction frequently due to actual conditions in the soil profile. For this reason we decided to express the effective capillary rise as a gain of actual evapotranspiration in order to make sure that capillary rise is not only dependent on soil hydraulic properties but also on climate and plant conditions such as rooting depth.

Methods
Firstly we used the numerical simulation model “SWAP” (Kroes et al. 1999) to simulate soil water dynamics for a broad spectrum of boundary conditions: in total we calculated water flow for four typical soil classes through 30 years using different values of groundwater depth. This was done for three different meteorological observation stations in Germany, one station with little rainfall and high potential evapotranspiration, the second one with average rainfall and average potential evapotranspiration, and the third one with high rainfall and low potential evapotranspiration. In total we obtained 1710 values of annual evapotranspiration. For each of the soil texture classes and observation stations one simulation was run without influence of groundwater. We compared this reference condition with simulation runs for various groundwater depths conditions. The latter indicate the increase in actual evapotranspiration. The increment was termed “gain” (G) and was attributed to so-called “effective capillary rise”.
Secondly, to predict gain without using the numerical model, functions were established to estimate gain from easily accessible data in two steps, (1) expressing the maximum capillary rise rate for a given soil and groundwater depth, and in step (2) we followed a suggestion after Visser (1968) to derive a gain (*G*= effective capillary rise rate) based on water supply (*S*), and water demand (*D*).

Results
In the first step the groundwater influence is denoted by steady-state flow rates, which only depend on soil hydraulic properties and the distance between groundwater table and the bottom of the root zone (*z*). These steady-state flow rates could be calculated using an arbitrary threshold of soil water potential. The selected value of ψ= -3200 hPa ensures obtaining a standard flow rate close to the maximum flow rate that would

occur at the threshold ψ= -∞. Using this threshold, the steady-state flow was evaluated numerically (Bohne, 2003) for various data points of $q(z_{max})$. In order to facilitate the results, the empirical function (1) was introduced to express $q_{max}(z)$.

$$q(z) = p_1 z^{p_2} \tag{1}$$

The parameters p_1 and p_2 could be easily gained for various soil texture classes (Table 1). Fig. 1 shows exemplarily how z controls the maximum flux rates at ψ= -3200 hPa for a sandy and a loamy soil (Lts).

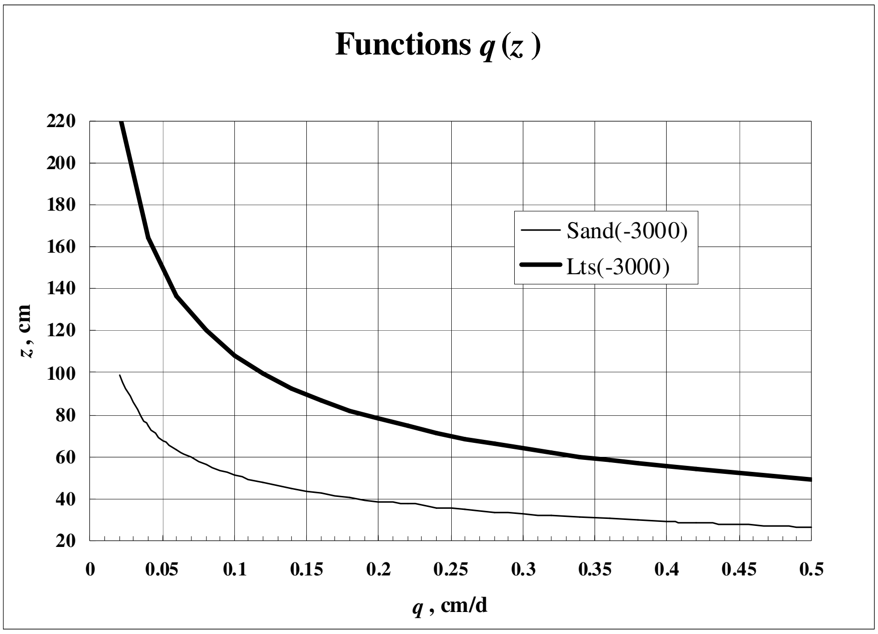

Figure 1. $q(z)$ functions for two soils, parameters of $p1$ and $p2$ are listed in Table 1.

Table 1. Parameters p_1 and p_2 of the empirical equation $q = p_1 z^{p_2}$ (cm/d).

Soil class	p_1	p_2	Soil class	p_1	p_2
Ss	1.5244E+03	-2.4467	**Uu**	9.6900E+03	-2.0996
Sl2	1.8344E+03	-2.3827	**Uls**	2.7659E+03	-1.9182
Sl3	5.8747E+03	-2.5284	**Us**	1.9477E+03	-1.8381
Sl4	5.1832E+02	-1.7925	**Ut2**	3.8354E+03	-1.9891
Slu	5.6573E+02	-1.7205	**Ut3**	3.7122E+03	-1.9858
St2	3.9707E+02	-1.4971	**Ut4**	3.0780E+03	-2.0077
St3	2.2651E+02	-1.8035	**Tt**	6.2126E+01	-1.8051
Su3	8.5042E+02	-1.7423	**Tl**	9.9199E+01	-1.8691
Su4	1.2992E+03	-1.7361	**Tu2**	9.8138E+01	-1.8643
Ls2	1.4856E+03	-1.5862	**Ts2**	2.2292E+02	-1.9629
Ls3	9.7394E+02	-1.7943	**Ts3**	8.5734E+02	-2.1027
Ls4	7.2012E+02	-1.7661	**Ts4**	2.0702E+02	-1.5199
Lt2	7.6150E+02	-1.7619	**fS**	3.0197E+03	-2.4811
Lt3	3.8861E+02	-1.6707	**mS**	1.5653E+03	-2.4537
Lts	2.2340E+03	-2.1450	**gS**	1.6850E+04	-3.4299
Lu	1.1664E+03	-1.8089			

As mentioned above, we intended to predict the increase of actual evapotranspiration (=gain, G) caused by capillary rise from the groundwater table using easily accessible soil and climate data. The gain is limited either by the water demand D or by the soil water supply S. Following a suggestion after Visser (1968) this condition leads to the equation:

$$(D-G)(S-G)=0 \tag{2}$$

Rearranging yields a quadratic equation with the solution

$$G=\frac{D+S}{\lambda_1}+\lambda_2\left[(D+S)^2-4DS\right]^{\lambda_3} \tag{3}$$

Where the λ_i are empirical fitting parameters and listed in Table 2.

Table 2. Parameters of Eqs.3, 4, 6 and 7.

Parameter	Value
λ_1	3.04093
λ_2	-0.22966
λ_3	0.52642
c_1	0.31273
c_2	0.46787
c_3	23.1155
c_4	0.94361
g_1	-0.601
g_2	0.02374
g_3	0.03529
g_4	0.07083
g_5	0.38338

Another empirical equation (4) was introduced to expressing the water demand and supply in terms of known data:

$$D=c_1+ET_{pot,summer}-P_{summer}-c_2\,W_a \tag{4}$$

Where $ET_{pot,summer}$ denotes the grass reference evapotranspiration during summer, P_{summer} the precipitation in summer (April 1st – September 30th) and W_a is known as the amount of plant available soil water with

$$W_a=RD*(FC-PWP) \tag{5}$$

RD rooting depth
FC field capacity, taken here as $\theta_{(-63\ hPa)}$
PWP permanent wilting point, taken here as $\theta_{(-15800\ hPa)}$

c_2 provides the means to partition W_a so that only water that is easily available for evapotranspiration, it is include in calculation of *D*. The capability of soil to supply water is expressed by

$$S=c_3\,q_{max}^{\;c4} \tag{6}$$

Where q_{max} is the appropriate function value $q_{max}=q(GW-RD)$ of Eq.(1) for the texture class chosen and GW represents the depth to groundwater. After fitting the unknown parameters, the increase *G* of the actual evapotranspiration was calculated by Eqs. 3, 4, and 6. Based on 1710 comparisons, the root mean squared

difference (*RMSD*) between G_{model} as calculated by the numerical simulation model and $G_{predicted}$ as calculated by Eq. (3) was $RMSD$ =18.03 mm with a correlation coefficient of R =0.9025.
Actual evapotranspiration during summer depends on both potential evapotranspiration and on the amount of water available for evapotranspiration. The amount of available water consists of precipitation during summer P_{summer}, the effect of groundwater and part of soil water storage at the start of summer.

Using the estimated Gain G, also the actual evapotranspiration during summer can be estimated by

$$ET_{act,summer} = ET_{pot,summer}(g_1 + g_2 P_{summer} + g_3 G + g_4 W_a)^{g5} \quad (7)$$

Eq. 7 estimates the actual evapotranspiration during summer with an accuracy of $RMSD$=23.73 mm (R=0.8884). The ratio ET_{act}/ET_{pot} has shown to be a good coefficient to assess water supply to crops.

Conclusions

The new hydro-pedotransfer functions for predicting the annual effective capillary rise and actual evapotranspiration lead to results which are in very good agreement with results of numerical simulation models. The method is applicable on a regional scale when easily available weather data and soil texture class are known. Since the equations are statistically based, they should not be used unverified in areas exhibiting climatic and soil conditions different from Central Europe.

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Review Comments

The derivation of eqn (3) from eqn (2) is not correct. This means that estimates of G based on eqn (3) will not satisfy eqn (2). The empirical relationships that have been developed may still be useful but the authors will need to modify the manuscript to reflect the fact that these are not based on eqn (2).