The effect of time-variable soil hydraulic properties in soil water simulations

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Abstract

Modeling soil water dynamics requires an accurate description of soil hydraulic properties, i.e. the retention and hydraulic conductivity functions. Generally, these functions are assumed to be unchanged over time in most simulation studies. However, there is extensive empirical evidence that soil hydraulic properties are subject to temporal changes. In this paper, we implemented temporal changes in the soil hydraulic properties in a Richards' equation simulation of soil water dynamics. Based on repeated measurement data of the top soil water retention curve, we compared the impact of using constant vs. temporally changing hydraulic functions on water flow simulation for different tillage methods. We observed distinct differences in the soil water content between the simulations for all tillage methods. The results show the remarkable effect of time-variable retention parameters on the soil water dynamics for tilled and non-tilled top soils.

Key Words

Soil hydraulic properties, temporal variability, soil tillage, pore-size distribution

Introduction

For many applied questions in the fields of crop production and agronomy, soil water dynamics are of fundamental importance. Modeling can be a valuable tool to optimize its management (Roger-Estrade *et al.* 2009). However, such soil water modeling requires an accurate description of soil hydraulic properties, i.e. the soil water retention characteristics (WRC) and hydraulic conductivity functions. Generally, these constitutive functions are assumed to be unchanged over time in most simulation studies (Mubarak *et al.* 2009). However, there is extensive empirical evidence that soil hydraulic properties are subject to temporal changes particularly in the near-saturated range where soil structure essentially influences water flow characteristics (Alletto and Coquet 2009; Daraghmeh *et al.* 2008; Or *et al.* 2000). The structure of soil top layers is subject to changes during time, caused by wetting and drying, solution composition, agricultural operations, and biological activity. Soil tillage is used to improve soil structural properties by changing the soil pore-size distribution (PSD). Since these modifications are quite unstable over time, the PSD decreases after tillage (Leij *et al.* 2002; Or *et al.* 2000). This effect should be largest for conventional tillage (CT), where the soil is ploughed after harvest every year.

Many functions for expressing the WRC have been published (e.g. Brooks and Corey 1964; Van Genuchten 1978). They are compatible with models that describe the relative hydraulic conductivity of soils (e.g. Burdine 1953; Mualem 1976). However, most of these models are empirical curve-fitting equations and do not base on physical fundamentals (Kosugi 1994). In contrast, the soil retention model of Kosugi (1994) bases directly on the lognormal distribution of the soil pore-size distribution (PSD) as described by the Laplace-Young equation (Leij *et al.* 2002). Recent publications point out that the demand for a new model approach accounts for the temporal variability of the WRC (Alletto and Coquet 2009; Mubarak *et al.* 2009). In this study, we set up a water flow model that accounts for time variable retention characteristics in the uppermost soil layer. The effect of temporal variability of the WRC on soil water dynamics, as expressed by the volumetric water content, was tested and evaluated for different tillage systems.

Governing equations

Water flow in unsaturated or partly saturated soils can be described with the Richards' equation (Richards 1931):

$$C\frac{\partial h}{\partial t}=\frac{\partial}{\partial z}\left(K\frac{\partial h}{\partial z}-K\right) \qquad (1)$$

where *h* is the soil water pressure head or water potential (dimension L), *t* the time (T), *z* the soil depth (L), *K* is the hydraulic conductivity (L/T) and *C* is the soil water capacity (/L). *C* is defined by the slope of the WRC ($d\theta/dh$), where θ is the volumetric water content of the soil (L^3/L^3). In the present study, the WRC in the upper soil is described by Kosugi's lognormal retention model (Kosugi 1994):

$$\theta(h)=\begin{cases}\left(\frac{1}{2}\mathrm{erfc}\left[\frac{\ln(h/\psi)}{\sqrt{2}\sigma}\right]+\theta_r\right)(\theta_s-\theta_r) & (h<0)\\ \theta_s & (h\geq 0)\end{cases} \tag{2}$$

where ψ (L) and σ are parameters that change the shape of the retention curve, θ_r is the residual volumetric water content and θ_s is the water content at saturation. Applying Mualem's model, the unsaturated or relative hydraulic conductivity K_r is defined as follows (Kosugi 1994):

$$K_r(\theta)=\begin{cases}K_s\sqrt{S_e}\cdot\left(\frac{1}{2}\right)^2\left[\mathrm{erfc}\left(\frac{\ln(h/\psi)}{\sqrt{2}\sigma}+\frac{\sigma}{\sqrt{2}}\right)\right]^2 & (h<0)\\ K_s & (h\geq 0)\end{cases} \tag{3}$$

According to Leij *et al.* (2002), the PSD can be obtained with a similar equation:

$$f(r)=\frac{(\theta_s-\theta_r)}{\sqrt{2\pi}\sigma r}\exp-\left(\frac{\ln(r/r_m)}{\sqrt{2}\sigma}\right)^2 \tag{4}$$

where f (/L) is the frequency of a certain pore radius r (L). r_m (L: µm) is the median pore radius that can be calculated from ψ (hPa) by $r_m = 1490/\psi\ \exp(\sigma^2)$ (Leij *et al.* 2002).

Methods

Field measurements were obtained on an arable field near the village of Raasdorf, Lower Austria, 20 km east of the city of Vienna. At this agricultural investigation site, the effects of different tillage methods, in specific conventional tillage (CT), reduced tillage (RT), and no-tillage (NT), were observed by our working group. For the different tillage systems the near-saturated hydraulic properties of the uppermost soil layer (0–15 cm) have been determined by infiltration measurements with tension-disc infiltrometers (Soil Measurement Systems, USA; diameter of the disc: 20 cm). Three replicate measurements were conducted for every type of tillage several times between August 2008 and July 2009 (Table 1). The adjusted hydraulic pressure heads were −10 cm, –4 cm, −1 cm, and 0 cm. Additional data points of the retention curve (0.2 – 3.0 bar) were determined by steel core samples. The software HYDRUS 2D/3D (Šimůnek *et al.* 2006) was used to fit the retention model of Kosugi (1994) inversely to the infiltration measurements. The resulting parameters were used to calculate the PSD for every time of measurement. The lower soil horizons were sampled with steel cores (volume: 200 cm^3) in depths of 40 cm and 70 cm in July 2009. The WRCs of the subsoil layers were determined in the laboratory with a low pressure plate extractor (Soil Moisture Inc., USA) at pressure heads of 0.2, 0.5, 1.0, 2.0 and 3.0 bar. The program RETC was used to fit the parameter of the Van Genuchten retention model (1978) to the observed data. For calibration of the model, data of the soil volumetric water content measured directly in the field were available over the modelled time.

Numerical model

Model geometry

The Richards' equation was solved numerically using COMSOL Multiphysics (COMSOL AB) with MATLAB (The MathWorks Inc., USA). The 2D model geometry was defined by a rectangle soil column with a width of 1.00 m and a depth of 1.20 m. According to the observed soil horizons in the field, the geometry was divided into three layers: the upper soil from 0 to 0.15 m (A-horizon, WRC determined by infiltration measurements), the lower part of the A-horizon between 0.15 m and 0.50 m, and the subsoil from 0.50 m to 1.20 m (C-horizon). The soil hydraulic properties of the lower layers were defined by the Van Genuchten retention model. Since the time-dependent effect of tillage was expected to be negligible, we set the hydraulic properties to be constant in the lower soil horizons.

Initial and boundary conditions

The model geometry was laterally confined by no-flux boundaries. The lower boundary was defined by a free drainage condition. On the basis of measured precipitation data, we used the empirical method of Allen *et al.* (1998) to calculate the potential evaporation and transpiration. The precipitation and the evaporation, the latter reduced by a pressure-head dependent reduction function, were applied to the model as upper boundary condition. Transpiration was implemented in a sink term using a growth function and a reduction function according to Feddes *et al.* (2001).

Initially, the hydraulic pressure head h_0 was set to −0.5 m for the whole model geometry. To account for the WRC changing with time in the upper soil layer, adequate functions were fitted to the measured values for the Kosugi retention model parameters ψ and σ, the saturated hydraulic conductivity K_s,, and the soil water content at saturation θ_s (Table 1). For the simulations with constant hydraulic properties, median values for these parameters were used.

The accuracy of the implementation of the evapotranspiration was evaluated by a comparative simulation using HYDRUS 2D/3D. The model was calibrated with measured soil water contents. Calculations were made with constant and time variable retention parameters of the upper soil layer for all observed tillage systems.

Table 1. Retention data of the upper soil layer as observed by infiltration measurements for the different tillage methods (CT: conventional tillage, RT: reduced tillage, NT: no-tillage). The date of the infiltration measurement, the day in the simulation, the volumetric water content at saturation θ_s, the residual water content θ_s, the saturated hydraulic conductivity K_s, the parameters of the Kosugi retention model, ψ and σ, and the median pore radius r_m are listed.

tillage	date	day	θ_s ($m^3 m^{-3}$)	θ_r ($m^3 m^{-3}$)	K_s ($m d^{-1}$)	ψ (kPa)	σ (-)	r_m (µm)
CT	2008-08-01	1	0.51	0.11	2.29	5.64	1.79	1.07
	2008-10-23	84	0.51	0.11	2.78	2.12	1.34	11.76
	2008-12-03	125	0.50	0.11	1.56	3.12	1.55	4.38
	2009-04-01	244	0.43	0.11	1.00	4.13	1.68	2.13
	2009-07-21	355	0.48	0.11	2.18	3.64	1.77	1.79
RT	2008-08-01	1	0.53	0.11	1.14	0.93	1.19	39.11
	2008-10-23	84	0.45	0.11	1.56	4.97	1.75	1.40
	2008-12-03	125	0.50	0.11	0.33	2.93	1.61	3.83
	2009-04-01	244	0.41	0.11	0.23	2.80	1.37	8.23
	2009-07-21	355	0.49	0.11	0.68	2.80	1.59	4.27
NT	2008-08-01	1	0.47	0.11	0.61	3.63	1.73	2.09
	2008-10-23	84	0.43	0.11	0.12	3.44	1.54	4.04
	2008-12-03	125	0.46	0.11	0.05	3.76	1.29	7.56
	2009-04-01	244	0.43	0.11	0.10	3.95	1.44	4.77
	2009-07-21	355	0.43	0.11	0.11	3.43	1.04	14.61

Results and discussion

Evolution of the pore-size distribution

The evolution of the PSD determined by the infiltration measurements showed distinct differences between the applied tillage methods. As proposed by Leij *et al.* (2002), the PSD at the CT site shifted towards smaller pore sizes after mouldboard tillage. Here, the change of the PSD is mostly dominated by the agricultural operation. Compared to the other tillage methods, a large total porosity exists, as it is also expressed by the integral of the PSD, θ_s (Table 1). On the other side, the determined PSDs for RT and NT show a smaller shift during time and a smaller total porosity. Moreover, the shift of the PSD is slightly towards larger pores. This effect might be caused by biological activities, such as earthworm burrows and plant root development (D'Haene *et al.* 2008).

Water dynamics with constant vs. time-variable hydraulic properties

The results show distinct differences between the simulations for all methods of tillage. In autumn and winter 2009, we observed the most obvious differences in the soil water content, whereas in the later part of the simulation, these differences decreased. We trace this back to high volumetric water contents in late autumn and winter in the upper soil, provided by a low evapotranspiration. This result is in agreement with the findings of Daraghmeh *et al.* (2008). The results of the CT simulations show the effect of ploughing in mid-October impressively, as the retention potential decreases shortly after it. Noticeable differences for the other tillage methods occur mainly at high precipitation events and may be traced back to an underestimation of biological induced macropore-flow in the simulations with constant soil retention properties.

Conclusion and perspective

As classical simulations of the soil water dynamics do not account for time-variable soil retention properties, we implemented a model approach that enables the flexible definition of these important control quantities. The implementation of the Kosugi retention model allowed the definition of the soil retention properties strongly connected to the PSD of the soil. However, until now we used only empirical fitted functions for the time-variable retention parameters. Recently, we began work on the adaptation of a suitable PSD-evolution model, as proposed by Or *et al.* (2000).

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