Transient Flow Experiments for the Determination of the Soil Hydraulic Properties – An Evaluation of Different Experimental Boundary Conditions

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Summary

We investigated three methods of transient flow experiments (*Onestep*, *Multistep*, *Smooth*) with regard to their suitability for the determination of hydraulic properties of large undisturbed soil samples. The methods differ in the way how a pressure gradient is applied which induces the flow of water out of or back into the soil core. The instantaneous application of one large pressure step is called *Onestep,* the application of several smaller increments is called *Multistep*, and the smooth continuous change of the pressure gradient is called *Smooth*. The three methods were compared with regard to the uniqueness, identifiability and stability of the estimated parameters of the hydraulic functions. The functions used were able to represent unimodal or bimodal pore systems, with or without hysteresis.

The results for a sandy forest soil show that the *Onestep* method yields nonunique solutions. Further, since the method does not represent conditions that occur in nature, it appears not suitable for estimating the soil hydraulic parameters. In contrast, the *Multistep* and *Smooth* methods lead to a unique parameter identification. Both methods yield the same soil water retention curves $\theta(\psi)$ for the respective soil core. However, the parameter for the saturated hydraulic conductivity, K_{sat}, is insensitive to the optimization of the outflow data of the *Smooth* flow experiments. The optimized K_{sat} values are in some cases one order of magnitude smaller than those obtained by the *Multistep* method. This in turn yields different $K(\theta)$ relationships for the two methods. A further result is that the use of hydraulic functions which can represent bimodal pore systems gives in most cases a better match between simulated and measured data. The hysteretic properties of the analyzed soils could not be adequately described by the Kool and Parker (1987) hysteresis model.

With the present level of information it can be concluded that the *Multistep* and *Smooth* method are equally suitable in the estimation of the soil hydraulic functions of soil cores.

1. Introduction

Numerical simulation models are an important tool for the estimation of the transport of water and solutes in soils. When applying such models on natural soils, the critical bottleneck lies in the knowledge of the appropriate of the parameters. For the simulation of water flow, the water retention curve and the unsaturated hydraulic conductivity must be known. The determination of the hydraulic functions takes place most oftenly in the laboratory on little soil samples, because the conventional field methods require a great deal of instruments and time. Conventional laboratory methods are the pressure or tension method for determining the retention curve, and the the constant head or falling head method for the saturated hydraulic conductivity. The unsaturated conductivity is in most cases not measured, but estimated from the retention curve with the van Genuchten/Mualem model. These estimations are extremely problematic for natural soils with structured pore systems (Durner, 1994).

The standard methods, listed above, are unsatisfying for a variety of reasons:

- The requirement of hydraulic equilibrium restricts the methods to very small sample sizes and leads to very long measurement times.
- The small soil samples are in most cases below the size of the representative elementary volume (REV) of a soil (Measuring on the wrong scale).
- Hysteresis of the retention curve is generally neglected.
- Measurement of the retention characteristics and the conductivity are often inconsistent, because the determinations are done with different samples.

From the critiques above it follows that all hydraulic parameters should be determined simultaneously *in situ* or on soil samples as big as possible. This requires the use of nonequilibrium methods.

A qualified tool for the identification of the hydraulic properties under nonequilibrium conditions is the inverse simulation. By this method, transient flow experiments are simulated. During the simulation, the parameters of a model for the hydraulic functions are modified systematically, until the best agreement between the measurement and simulation is found. The most frequently used transient flow method in the past was the so called „*Onestep*“-method, where the water pressure at the lower boundary of a soil core is changed in one step, generally from saturation to some unsaturated value, and the cumulative outflow from the soil core and the pressure head in the core are measured and used for the simulation. However, the quick change of the boundary condition does not represent natural conditions and further leads presumably to nonequilibrium in the soil sample. Also it was reported that the method yields nonunique solutions. The historic reasons for favoring the *Onestep* method lie in its simple experimental setup and in the possibility to apply simplified identification procedures for the hydraulic functions. However, by principle the inverse simulation allows any change of the boundary conditions (van Dam et al. 1992). As an alternative for the *Onestep* method, a *Multistep* method may be applied, where the pressure at the boundary is changed in small steps. As a borderline case of the *Multistep* method, a continuous change of the pressure may be applied. In the following sections, this method is called the „*Smooth*“ method.

The aim of this work was to examine the three different variants of the out/inflow methods, namely the *Onestep, Multistep,* and *Smooth* method, with regard their suitability to the determination of the hydraulic properties.

2. Methods

2.1 Sensitivity analysis

Zurmühl (1994) examined, from a theoretical point of view, the *Onestep, Multistep* and *Smooth* methods with regard to the identifiability of the hydraulic parameters. On the base of numerical simulations he performed sensitivity analyses of the hydraulic parameters for a sandy and a clay soil. The van Genuchten/Mualem model was used for the hydraulic functions. The water of a saturated soil core was extracted by putting down the pressure head at the boundary from $\psi_{bound} = +15\ cm$ to $\psi_{bound} = -60\ cm$. This was done in three different ways: in one step („*Onestep*“), in 11 steps within 20 hours („*Multistep*“), and in a linear pressure decrease within 20 hours („*Smooth*“).

Apart from the trivial result that residual water content θ_r and saturated water content θ_s may not be optimized simultaneously, the numerical analyses gave the following findings:

- Only the *Multistep* method yields absolutely independent parameters and seems to be most appropriate to determine parameters by inverse modeling.

- The *Smooth* method is as well suitable for the estimation of the retention curve parameters, but the saturated conductivity parameter is highly correlated with θ_s.
- For *Onestep,* the retention curve parameters α and *n* show in the early passage of the outflow a high correlation, in the later passage this is found for α and θ_s. This method appears therefore less suitable.

2.2 Experiments

For the experimental comparison of the methods, a sandy soil from a forest near Forchheim, Bavaria, was selected. Undisturbed soil samples with a volume of 1000 cm^3 (diameter: 9.4 cm, height: 14.5) had been taken in two parallels from a Bv horizon and were placed in a computer-controlled testing system (Scheibke and Durner, 1991). With this equipment, the boundary conditions are controlled and the cumulative outflow and inflow as well as the matric potential in the soil is measured continuously with time and with high accuracy. A detailed description of the soil and the experimental system is given by Zurmühl (1994). For both samples, the three methods were applied consecutively, with each run being once repeated. The order of the methods was *Multistep, Smooth* and *Onestep.*

Each measured run of outflow and inflow data was used together with the measured tensions in the object function for the inverse simulation of the experiments. The program NOLIPEST 2.0 (Zurmühl 1994) was used for the parameter optimization. This model is able to optimize the parameters of uni- and bimodal hysteretic hydraulic functions. The model of Kool and Parker (1987) served as hysteresis model.

3. Results

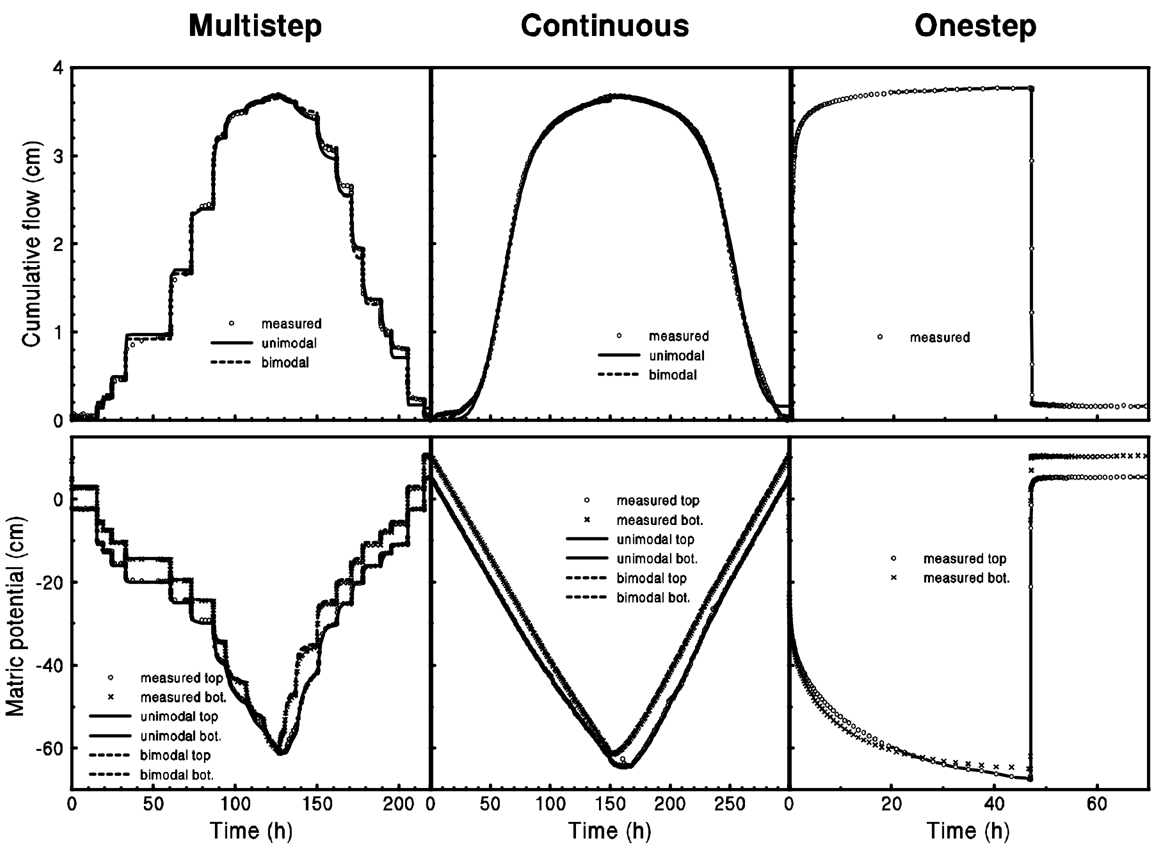

Fig. 1: *Simulated and measured outflow and inflow curves and tensions for the experiment.*

The observed tension curves and out- and inflow curves of the two parallel soil cores were practically identical. Figure 1 (bottom) shows for one of the soil cores the tensions in the soil core as well as the difference of the measured hydraulic potentials. Figure 1 (top) shows the measured and simulated cumulative outflow and inflow curves. The depicted simulated out-/inflow curves have been optimized separately. It can be seen that the outflow and also the inflow is described very good with the van Genuchten/Mualem model, if the hysteretic branches are optimized *separately*. The attempt to describe the inflow and outflow simultaneously with the hysteretic model lead to a much worse match. Obviously, the hysteretic model of Kool and Parker (1987) is inapplicable for the present soil.

By varying the initial values of the parameters it was examined whether the parameter identification led to unique results. While the parameters for *Multistep* and *Smooth* in each case could be uniquely identified, *Onestep* gave different results for different starting values. Thus, within the scope of our experimental design the *Onestep* method is unsuitable. *Multistep* and *Smooth,* on the other hand, gave nearly identical results and are therefore suitable. *Smooth* resulted in narrower confidence intervals for the parameters.

4. Conclusions

The inverse simulation of outflow and inflow experiments on large, undisturbed soil samples is a useful tool for estimating soil hydraulic properties. By using a computer-controlled automated measuring device we can preselect boundary conditions that are optimal for the identification procedure. In- and outflow methods are suitable to identify hydraulic properties with high sensitivity in a intermediate moisture range. The theoretical and experimental comparison of different types of boundary conditions showed that the *Multistep* method is optimal, the *Smooth* method is useful if the saturated hydraulic conductivity is measured separately, whereas the *Onestep* method is insensitive with respect to the determination of the hydraulic properties.

Future research must aim at identifying more accurate models of the soil water hysteresis, at investigating the effects of nonequilibrium water flow which is induced by sudden changes of pressures at the column boundary, and at the optimal combination of different experimental procedures to cover the problematic ranges near saturation and at very dry conditions with highest sensitivity.

5. References

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