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Sequential estimation of hydraulic parameters in layered soil using limited data

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ABSTRACT

Field-scale estimation of soil hydraulic parameters is important for describing water movement in vadose zones. The importance of soil water measurements has been acknowledged with increasing soil water measurements becoming available; thus, the estimation of hydraulic parameters from observed soil water would be quite useful for hydrological modeling. This study estimated the hydraulic parameters of Brooks–Corey and Mualem model using the monitored soil water changes at two depths together with the rainfall intensity at two soil plots in a tropical rain forest in Indonesia. A one-dimensional multi-scale parameterization method was used for the analysis, beginning with homogeneous parameterization and identifying the depth of discontinuity using refinement indicators, thus increasing the number of zones. A method for sequential parameterization was developed in each step of zoning. The measured and simulated volumetric water contents with the optimized parameters showed good agreement for one plot (standard error is 0.0419) with 2-zone parameterization, and the effects of the initial parameters derived from different pedo-transfer functions on the optimized hydraulic functions were small, confirming the robustness of this method. However, at another field site, agreement between measured and simulated water contents was not very good (standard error is 0.0854), because the effect of the soil water repellency might have influenced the results, and the effects of the initial parameters were large. The algorithm proposed in this study systematically determines the hydraulic parameter set that describes field-scale water flow.

1. Introduction

Soil water is an essential variable for understanding hydrological processes in vadose (unsaturated) zones and is important for various agricultural management practices, i.e., irrigation control, especially in arid and semi-arid regions in which water is a precious resource. Soil water is also important for climate modeling and numerical weather prediction. Recently, the importance of soil water monitoring has increased because of the need for climate change research. The Global Climate Observing System (GCOS) specified soil water as one of the Essential Climate Variables (ECVs) required to implement a comprehensive observation system to support scientific research on climate change (GCOS, 2010). Soil water is estimated using different methods, including in situ methods, satellite data, and hydrological models. Each method exhibits pros and cons, and hence, the integration of different techniques may decrease the drawbacks of a single given method (Brocca et al., 2011). The most reliable source of data is in situ measurements, and consequently, the need for direct soil water data is increasing.

To model vadose zone hydrology, it is important to characterize the hydraulic parameters that describe water movement in the vadose zones, i.e., parameters in soil water retention function and unsaturated hydraulic conductivity functions. It would be useful to obtain a reliable estimate of soil hydraulic parameters from soil water measurements which are becoming more easily available due to this increasing demand. However, inverse estimation of soil hydraulic parameters from field observed soil water content is difficult. Vereecken et al. (2008) compiled a review on soil water measurement in vadose-zone hydrology. After reviewing the extensive literature on the estimation of hydraulic properties in laboratory column experiments, this group noted that only a limited number of studies use field-scale soil water data to inversely estimate the soil hydraulic properties. The authors argued that field studies remain limited because inverse estimation requires additional information, i.e., measured matric potential, soil structural information, homogeneous soil assumptions, measured values of hydraulic properties, well-defined flow conditions with gravity-dominated flow, and known bottom boundary conditions. With these restrictions, only a few field studies were used to estimate soil hydraulic parameters from soil water data under naturally occurring boundary conditions. Jacques et al. (2002) recorded the time series of water content, pressure head, and solute concentration under experimental field conditions and found that the observed data could be described by Richards' equation for water flow

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and the non-equilibrium convection–dispersion equation for solute transport with a layered soil profile. The authors were successful to inversely estimate the hydraulic parameters within the range of earlier determined parameters. Ritter et al. (2003) estimated hydraulic parameters from the measured time series of soil water content at three different depths, with the amount of irrigation measured by rain gauges and the reference evapo-transpiration estimated with weather data measured by an on-site weather station. The authors showed that inverse optimization is a promising parameter estimation procedure; however, it requires a well-posed inverse problem. In addition, considerable deviation was observed between the directly determined and inversely estimated soil water retention curves because soil water flow at the field scale is poorly represented by the soil retention curves directly measured at the core scale. Therefore, even if directly measured soil hydraulic parameters are available, it is better to obtain optimized hydraulic parameters from field observed data, which better represents the field scale water flow.

To optimize the hydraulic parameters of heterogeneous soil structure, Hayek et al. (2008) developed an algorithm for adaptive multi-scale parameterization. Usually, for optimization of heterogeneous soil hydraulic parameters, the structure of heterogeneity must be predetermined, and the depths of the discontinuity of the hydraulic parameters are specified. In the adaptive multi-scale parameterization method (Hayek et al., 2008), parameterization begins with the homogeneous soil structure, and detects the best depth for a new discontinuity by comparing the refinement indicator which shows the decrease of the objective function by increasing the number of zones, and the number of zones for parameterization increases stepwise. Hayek et al. (2008) conducted numerical experiments with noisy data and missing data and showed the efficiency and robustness of their algorithm. Sequential estimation of hydraulic parameters can stabilize the identification of parameters and avoid local minima of the objective function compared to a single-level strategy (Berre et al., 2009).

In this study, we estimated the soil hydraulic parameters of tropical forest soils from the monitored data on soil water contents and rainfall intensity. The soil water contents at two depths on 75 successive days with many rainfall events were used for the estimation. The one-dimensional multi-scale parameterization method developed by Hayek et al. (2008) was used for analysis of the heterogeneous soil structure to verify that it can be used with real field data. The objective of this study was to establish a method for estimating the soil hydraulic parameters that describe soil water behavior based on a limited field study dataset of soil water contents and rainfall.

2. Materials and methods

2.1. Site description and soil properties

Seki et al. (2010) measured soil hydraulic properties in a *Dipterocarpaceae* forest in Bukit Bangkirai on Borneo Island in Indonesia. Bukit Bangkirai is located close to the equator (1°1.5′S), and has a tropical rainforest climate with a high average annual temperature of 28 °C and a heavy annual rainfall of 2500 mm. In this study, we focused on two plots, the K plot (K1 pit) and the HD plot with relatively flat soil surface, where continuous measurements were conducted.

In the K plot, root mats were observed in the 3-cm soil surface layer, below which lay a brown sandy clay loam layer. *Dipterocarpaceae* plants near the pit grew most of their root at the soil surface, where the root mats were observed. The clay content gradually increased to a depth of 60 cm. Based on the International Union of Soil Science classification, the soil texture was sandy clay loam to a depth of 40 cm, sandy clay within the 40–50 cm, and light clay within the 50–60 cm depths.

Two distinct soil layers were found in the HD plot: an upper quartz sand layer and a lower sandy loam layer. The upper sand layer was white in color and the lower sandy loam layer was brown in color, and therefore, the border between the two layers could be visually distinguished. The visible depth of the border fluctuated between 20 cm and 30 cm.

The soil water retention curves (SWRC) were measured by the hanging water column and pressure plate methods using two undisturbed samples of 5 cm diameter and 2.5 cm height from each plot sampled at the end of August 2006 (Fig. S1). The curves were fitted with the Brooks and Corey equation (Brooks and Corey, 1964) using SWRC fit software (Seki, 2007):

$$\begin{cases} S_e = \dfrac{\theta - \theta_r}{\theta_s - \theta_r} = (-\alpha h)^{-n} & \text{if } h < -1/\alpha \\ S_e = 1 & \text{if } h \geq -1/\alpha \end{cases} \tag{1}$$

where h is the soil water pressure head [L], θ is the volumetric water content $[L^3/L^3]$, θ_s is the saturated water content $[L^3/L^3]$, θ_r is the residual water content $[L^3/L^3]$, S_e is the effective saturation (also known as the normalized water content) $[L^3/L^3]$, and α $[L^{-1}]$ and n [−] are parameters that determine the shape of the water retention curve, where 1/α is the air entry value (AEV). All the fitted curves were in good agreement ($R^2 > 0.98$) with the measured curves.

The saturated hydraulic conductivity K_s [L/T] was measured by the falling-head and constant-head methods using undisturbed soil cores of 5 cm diameter and 5 cm height. Three replicates were measured for every 5 cm from 5 cm to 50 cm depth, producing highly variable results. In the K plot, the average value was 1.77×10^{-3} cm/s, ranging from 1.18×10^{-4} cm/s to 1.10×10^{-2} cm/s. In the HD plot, the average value was 1.31×10^{-2} cm/s in the sand layer (upper layer) and 9.65×10^{-4} cm/s in the sandy loam layer (lower layer).

The soil water content was monitored with frequency domain reflectometry probes (ECH_2O sensors EC-10, Decagon Devices Inc.) at two locations in the K plot (10 cm, 20 cm) and the HD plot (20 cm, 30 cm) both not very close to the tree trumps from the end of September 2005 to the end of August 2006. Amount of rainfall was also measured in the HD plot; however, the data are available only until 20 December 2005 due to a fault in rainfall gauge.

2.2. Numerical simulation

2.2.1. Description of the forward problem

The one-dimensional vertical model in the unsaturated water flow equation is expressed as Richards' equation (Richards, 1931) as follows:

$$\frac{\partial \theta}{\partial t} - \frac{\partial}{\partial z}\left[K(h)\left(\frac{\partial h}{\partial z} - 1\right)\right] = 0 \tag{2}$$

where K is the hydraulic conductivity [L/T], z is the soil depth (taken as positive downwards) [L], and t is the time [T]. Based on the initial and boundary conditions (as described later), Richards' equation was solved using the Galerkin finite element method with an implicit scheme for time discretization. The discretized Richards' equation was resolved with a Fortran code using the Newton linearization method associated with the primary variable switching method (Lehmann and Ackerer, 1997; Hayek et al., 2008).

To solve Richards' equation, the water retention function θ(h) and the hydraulic conductivity function K(h) must be defined. We used the hydraulic model of the Brooks and Corey Mualem-type equation (BC model). The hydraulic conductivity function of the BC model is derived by substituting the water retention function of the BC model (Eq. (1)) into Mualem's function (Mualem, 1976), which produces the following equation:

$$K = K_S S_e^{\frac{2}{n} + \lambda + 2} \tag{3}$$

where λ [−] is the pore-connectivity parameter, which was estimated by Mualem (1976) as an average value of approximately 0.5 for many soils. Many researchers use the van Genuchten–Mualem type equation (VG model) (van Genuchten, 1980) to describe hydraulic properties; however, in this study, the BC model was selected because it has a distinct AEV shape. In the VG model, the shape of K(h) near saturation is quite steep,