Temporal Variations of Soil Hydraulic Properties and its Effect on Soil Water Simulations

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Abstract

Simulating water dynamics in the soil compartment close below the surface is challenging since this part of the soil profile inhibits large temporal dynamics as a response to climate and crop growth. For accurate simulations the soil hydraulic properties have to be properly known. These properties may be subject to temporal changes as a response to both tillage and natural impact factors. The impact of different tillage techniques – conventional (CT), reduced (RT), and no-tillage (NT) – on the soil hydraulic properties and their temporal dynamics were observed by repeated experiments using tension infiltrometers. The experimental data was analyzed in terms of the near-saturated hydraulic conductivity, inversely estimated parameters of the van Genuchten/Mualem (VGM) model, and the water-conducting porosity. In a second step, the inversely estimated VGM parameters were incorporated into a soil water simulation. By using temporally variable versus constant sets of VGM parameters, the impact on soil water balance components was tested. Simulated water dynamics were compared to observed data in terms of the soil water content and water storage in the near-surface soil profile (0-30 cm). The results show that the near-saturated hydraulic conductivity was in the order CT > RT > NT, with larger treatment-induced differences where water flow is dominated by mesopores. The VGM model parameter $\alpha_{VG}$ was in the order CT < RT < NT, with high temporal variations under CT and RT, whereas the parameter $n$ was hardly affected. The results give indirect evidence that NT leads to greater connectivity and smaller tortuosity of macropores, possibly due to biological activity and a better established soil structure. Simulations with temporally constant hydraulic parameters led to underestimations of soil water dynamics in winter and early spring and overestimations during late spring and summer. The use of temporally variable hydraulic parameters significantly improved simulation performance for all treatments, resulting in average relative errors below 13%. Since simulation results agreed with observed water dynamics in two seasons, the applicability of inversely estimated hydraulic properties for soil water simulations was demonstrated. Our results also showed that simulations addressing applied questions in agricultural water management can be improved by time-variable hydraulic parameters.

1. 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). Such soil water modeling requires an accurate description of soil hydraulic properties, i.e. the soil water retention function $\theta(h)$ and the hydraulic conductivity function $K(h)$. Generally, these constitutive 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 particularly in the near-saturated range where soil structure essentially influences water flow characteristics (Daraghmeh et al., 2008; Or et al., 2000). The structure of soil top layers is especially subject to changes over time, caused by wetting/drying cycles, biological activity, and agricultural operations (Leij et al., 2002; Mubarak et al., 2009). Soil tillage and management affect the hydraulic properties with consequences for the storage and movement of water, nutrients and
pollutants, and for plant growth (Strudley et al., 2008; Xu and Mermoud, 2003). The temporal variability of hydraulic properties can even exceed differences induced by crops, tillage, or land use (Alletto and Coquet, 2009; Bodner et al., 2008; Bormann and Klaassen, 2008; Hu et al., 2009; Zhou et al., 2008).

Compared to deeper soil layers, soil moisture close to the surface (0-30 cm) is subject to rapid changes as response to rainfall, infiltration, evaporation, and root water-uptake. Despite its importance for the supply of water and nutrients for crops, simulation of this highly dynamic soil compartment is difficult and requires adequate sets of hydraulic parameters (Šimůnek et al., 2003). For modeling nutrient or contaminant transport and for the assessment of different tillage methods, soil water simulations should be introduced that account for time-variable hydraulic properties (Mubarak et al., 2009; Or et al., 2000). However, few studies have addressed this task. For instance, Or et al. (2000) introduced a model that describes temporal changes of the soil retention properties after tillage based on the pore-size distribution. Recently, Schwärzel et al. (2011) used the model to describe landuse-induced changes of the retention properties, but the model has not been applied to a more complex time series of measured hydraulic parameters.

To capture temporal variations in the soil hydraulic properties, suitable measurement methods have to be applied. As most of the temporal changes are expected to occur in the structural pores, due to changes in different groups of macro- and mesopores, field methods are preferable to laboratory methods (Angulo-Jaramillo et al., 2000; Hu et al., 2009; Yoon et al., 2007). To determine the near-saturated hydraulic properties of agricultural soils directly in the field, tension infiltrometry has become a commonly used method (Angulo-Jaramillo et al., 1997; Messing and Jarvis, 1993; Reynolds et al., 1995). Before now, hardly any study assessed the applicability of inversely estimated parameters in soil water simulations.

The main hypothesis underlying the presented study was that soil water simulations can be improved by accounting for temporal changes of near-surface soil hydraulic properties. Thus, the objectives of this study were 1) to capture temporal changes of soil hydraulic properties by repeated tension infiltrometer measurements, 2) to implement time-variable soil hydraulic properties in a soil water simulation. This study also aims to assess the feasibility of inversely estimated hydraulic parameters in soil water simulations. We acknowledge that this proceedings paper has been subject to previous publications (Schwen et al., 2011ab).

2. Materials and Methods

2.1. Experimental Site

Measurements were obtained on an arable field near Raasdorf, Lower Austria (48°41′N 16°35′E). Climatic data have been recorded at the site since 1998 (Figure 1). The reference evapotranspiration \( ET_0 \) was calculated using the Penman-Monteith equation. The site has a mean annual precipitation \( R \) of 546 mm, a mean temperature of 9.8 °C, a mean relative humidity of 75%, and an annual reference evapotranspiration \( ET_0 \) of 912 mm. A field trial was established in 1997 to assess the following soil cultivation techniques: 1) Conventional tillage (CT) with moldboard ploughing and seedbed preparation using a harrow prior crop seeding; 2) Reduced tillage (RT) with a chisel plough to 10 cm for seedbed preparation; and 3) No-tillage (NT) using direct seeding technique.
The soil can be classified as Chernozem in the WRB (IUSS, 2007). The humous A-horizon (0-30 cm) is followed by an AC-horizon (30-60 cm) over the mature silty sediments (C-horizon, >60 cm). Due to particle size analysis (Table 1), the texture throughout the profile can be classified as silt loam according to the FAO classification (FAO, 1990). The organic carbon content was 24 g kg\(^{-1}\) in the topsoil. In the two seasons analyzed for this study (2008/09 and 2009/10) the site was cropped with winter wheat (Triticum aestivum L.) in mid October and harvested in mid July of the following year (Figure 1).

Soil water content in the field was continuously measured over two consecutive seasons using capacitance moisture sensors (C-Probe, Adcon Telemetry GmbH, Austria). For each treatment, three replicate probes were installed in depths of 10, 20, 40, 60, and 90 cm. The measurement interval was 15 min, and data was averaged to daily values. The probes were installed after seeding in November and removed from the field prior to harvest in July in both analyzed seasons. The water storage in the soil profile to a depth of 0.30 m was derived from the water content measurement.

![Figure 1. Soil water regime, climatic conditions, and times of measurements: Volumetric water content \(\theta\), measured in 10 cm depth for the different tillage treatments (mean of three replicate sensors), air temperature \(T\) (grey line); rainfall \(R\) (peaks), and times of infiltration measurements (diamonds), soil tillage (triangle), and crop growing period. The grey areas indicate frost periods.](image)

2.2. **Sampling and Infiltration Measurements**

Infiltration measurements were made nine times, starting immediately before crop seeding in October 2008 and continuing until shortly before harvest in July 2010, using three tension infiltrometers (Soil Measurement Systems Inc., Tucson, AZ) of the design described by Ankeny et al. (1988). The supply pressure heads were \(-10, -4, -1,\) and 0 cm: the first two were maintained for approximately 50-60 min, and the last two for about 10-20 min. Preliminary tests found these durations to be sufficient to achieve steady-state infiltration. For each treatment, three replicate infiltration measurements were carried out. Before each infiltration measurement, soil samples were
taken with steel cores near the measurement location to obtain the initial water content \( \theta_i \). Immediately after each measurement, another core sample was collected directly below the infiltration disc to quantify the final water content \( \theta_f \), bulk density \( \rho_b \), and total porosity \( \phi \). We used Wooding’s solution (1968) as described by Reynolds and Elrick (1991) and Ankeny et al. (1991) to determine \( K(h) \) from the infiltration measurements. More details can be found in Schwen et al. (2011).

One soil profile per treatment was excavated and sampled with soil cores in depths of 5 cm, 40 cm, and 70 cm with three replicates during July 2009. The hydraulic properties of the subsoil layers were determined using pressure plate extractors (Soil Moisture Inc., USA) at \( h = 0.2, 0.5, 1.0, 2.0 \) and \( 3.0 \) bar. The RETC code (van Genuchten et al., 1991) was used to fit the parameters of the van Genuchten/Mualem model (referred to as VGM, van Genuchten, 1980; Table 1).

Table 1. Physical soil properties and hydraulic parameters at the experimental site. Texture (content of sand, silt and clay), bulk density \( \rho_b \), saturated water content \( \theta_s \), saturated hydraulic conductivity \( K_s \), and the VGM model parameters \( \alpha_{VG} \) and \( n \) are listed.

<table>
<thead>
<tr>
<th>Depth cm</th>
<th>Tillage</th>
<th>Sand (kg kg(^{-1}))</th>
<th>Silt</th>
<th>Clay</th>
<th>( \rho_b ) (g cm(^{-3}))</th>
<th>( \theta_i ) (m(^{-3}))</th>
<th>( K_s ) (m d(^{-1}))</th>
<th>( \alpha_{VG} ) m(^{-1})</th>
<th>( n )</th>
</tr>
</thead>
<tbody>
<tr>
<td>0-30</td>
<td>CT</td>
<td>0.27</td>
<td>0.54</td>
<td>0.20</td>
<td>1.38</td>
<td>0.48</td>
<td></td>
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<tr>
<td>30-60</td>
<td>CT</td>
<td>0.35</td>
<td>0.47</td>
<td>0.18</td>
<td>1.27</td>
<td>0.52</td>
<td>0.40</td>
<td>6.77</td>
<td>1.168</td>
</tr>
<tr>
<td>60-90</td>
<td>CT</td>
<td>0.31</td>
<td>0.57</td>
<td>0.12</td>
<td>1.36</td>
<td>0.49</td>
<td>0.31</td>
<td>1.15</td>
<td>1.571</td>
</tr>
<tr>
<td>0-30</td>
<td>RT</td>
<td>0.27</td>
<td>0.54</td>
<td>0.20</td>
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<td>30-60</td>
<td>RT</td>
<td>0.35</td>
<td>0.47</td>
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<td>5.57</td>
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<tr>
<td>60-90</td>
<td>RT</td>
<td>0.31</td>
<td>0.57</td>
<td>0.12</td>
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<td>0.31</td>
<td>1.55</td>
<td>1.452</td>
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<tr>
<td>0-30</td>
<td>NT</td>
<td>0.27</td>
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<td>0.20</td>
<td>1.42</td>
<td>0.47</td>
<td></td>
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<tr>
<td>30-60</td>
<td>NT</td>
<td>0.35</td>
<td>0.47</td>
<td>0.18</td>
<td>1.27</td>
<td>0.52</td>
<td>0.30</td>
<td>12.34</td>
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<tr>
<td>60-90</td>
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<td>0.31</td>
<td>1.40</td>
<td>1.575</td>
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2.3. Inverse Estimation of Soil Hydraulic Parameters

The inverse analysis of tension infiltrometer data required a numerical solution of the modified Richards’ equation. The initial and boundary conditions were defined as proposed by Šimůnek et al. (1998). To describe the unsaturated soil hydraulic properties, we used the van Genuchten/Mualem model (van Genuchten, 1980). We formulated the objective function (OF) that is minimized during parameter estimation by combining the cumulative infiltration data, the \( K(h) \) values calculated by Wooding’s analysis, and \( \theta_i \). OF minimization was accomplished using the Levenberg-Marquardt nonlinear minimization method (Marquardt, 1963), as provided by the program HYDRUS 2D/3D (Šimůnek et al., 2006). For a numerical solution, a quasi-3D (axisymmetric) model geometry was chosen, as described by Šimůnek et al. (1998). Initial values for the parameters were derived from the soil’s texture using the Rosetta pedotransfer package (Schaap et al., 2001; input parameters: soil texture and \( \rho_b \)). To reduce the amount of unknown variables, for all parameter estimations \( l \) was set constant at 0.5 (Ramos et al., 2006), and \( \theta_i \) was fixed at 0.065 m\(^{-3}\), as predicted by Rosetta (Lazarovitch et al., 2007). \( K_s \) was set to the value obtained by Wooding’s analysis (Lazarovitch et al., 2007; Schwen et al., 2011ab; Yoon et al., 2007). The remaining parameters \( \theta_s \), \( \alpha_{VG} \), and \( n \) were inversely estimated.
Representative mean parameters for each cultivation treatment were derived using the scaling approach. Following the approach of Schwärzel et al. (2011) and Vereecken et al. (2007), a conventional scaling procedure was applied in which scaling factors were estimated by minimizing the residual sum of square differences between the data and the scaled $K(h)$ and $\theta(h)$ reference curves.

### 2.4. Simulation with Time-variable Hydraulic Parameters

Soil water dynamics were simulated with a daily temporal discretization for the wheat growing seasons (Oct. 2008 – July 2009 and Oct. 2009 – July 2010; Figure 1). The vertical 1D Richards’ equation was solved numerically using the Earth Science Module within Comsol Multiphysics (Comsol AB). According to the observed soil horizons for the different tillage treatments, the geometry was divided into three layers: the surface soil (A-horizon) was between 0 and 0.15 m for RT and NT, and 0 - 0.30 m for CT, the AC-horizon down to 0.60 m, and the subsoil (C-horizon) from 0.60 m to 1.00 m.

Potential evaporation $E_{pot}$ and transpiration $T_{pot}$ were derived using the FAO 56 dual crop coefficient method (Allen et al., 1998). We used tabulated values for the crop coefficient $K_c$ ($K_{c\ ini} = 0.4$, $K_{c\ mid} = 1.15$, $K_{c\ end} = 0.25$, Allen et al., 1998) and observed crop development stages. We acknowledge that we did not calculate $E_{pot}$ and $T_{pot}$ as treatment-specific but assumed them to be the same for the different tillage treatments. $R$ and $E_{pot}$, the latter reduced by a $h$-dependent reduction function, were applied as the upper boundary condition (Bodner et al., 2007). $T_{pot}$ was implemented via a sink term using a growth function, a linear decreasing root distribution function (Prasad, 1988), and a $h$-dependent reduction function according to Feddes et al. (2001) and Wu et al. (1999). The lower boundary was defined by a unit gradient condition.

Simulations were made with constant and time variable VGM parameters ($\alpha_{VG}$, $K_s$, and $\theta_s$) of the upper soil layer for all tillage methods. The measured parameter values were connected using cubic splines to allow a continuous description. Since the temporal variability was expected to be negligible in the lower soil horizons, the hydraulic parameters were set constant (Table 1). To get a comparison between observed and predicted values, $O_i$ and $P_i$, the average relative error (ARE) was calculated as follows (Popova and Pereira, 2011):

$$ ARE = \frac{1}{N} \sum_{i=1}^{N} \left( \frac{|O_i - P_i|}{O_i} \right) $$

(1)

Here, $N$ is the number of observations. For further comparison between $O_i$ and $P_i$, regressions of the form $P_i = \text{slope} \times O_i + \text{intercept}$ were performed (Moret et al., 2007) and the determination coefficient $R^2$ was calculated. Root mean square errors (RMSE) were also calculated by (Ji et al., 2009; Popova and Pereira, 2011):

$$ RMSE = \left[ \frac{1}{N} \sum_{i=1}^{N} (P_i - O_i)^2 \right]^{1/2} $$

(2)
To account for the spatial variability of the observed values, $O_i$ used in the differences was defined as mean ($O_i$) ± standard deviation.

3. Results and Discussion

3.1. Climatic Conditions and Soil Water Content

For the present study two consecutive wheat growing seasons were analyzed. $R$ between October 15, 2008 and July 13, 2009 was 398 mm, which is in line with the long-term average. Remarkably, there was hardly any rain during April and May 2009 (Figure 1). Between October 15, 2009 and July 12, 2010, the rainfall was 395 mm. Potential evapotranspiration $E_{tpot}$ in the seasons 2008/09 and 2009/10 was 366 and 332 mm, respectively, which can be divided into $E_{pot}$ (117 and 101 mm), and $T_{pot}$ (249 and 231 mm). In the growing seasons 2008/09 and 2009/10 the climatic water balance resulted in a surplus of 32 mm and 63 mm, respectively.

Figure 2. Simulated vs. measured volumetric soil water content $\theta$ in a depth of 10 cm (upper plots) and water storage $S$ in the near-surface soil profile (0-30 cm; lower plots). $\theta$ and $S$ (mean ± standard deviation) were measured using three replicate sensors per treatment in depths of 10, 20, and 40 cm (grey areas). The gaps in winter are due to frost periods (Figure 1). The results of simulations using constant and time-variable hydraulic properties are shown for the tillage treatments CT (a), RT (b), and NT (c).
In response to climatic conditions and crop growth, the soil water content varied over time (Figure 1). With high water contents in winter and early spring and dryer periods between April and June 2009, the first analyzed year shows a broad variety of soil moisture conditions. Since there was sufficient rainfall in spring 2010, the soil moisture in the season 2009/10 was more balanced. During frost periods in winter, the shallow sensors did not give meaningful values so they had to be excluded from further analysis (Figure 1). Only small differences in the near-surface water content occurred between treatments CT and RT, whereas NT resulted in significant higher soil moisture contents. This agrees with findings of Moret et al. (2007) and Moreno et al. (1997).

The variability within a treatment indicated by the replicate probes was considerably high (Figure 2). Since technical problems with the moisture sensors could be ruled out due to careful data processing, this variability might be attributed to the natural spatial variability in the hydraulic properties. As the variability was smallest for CT and slightly larger for RT, it reflects the effect of spatial homogenization of repeated tillage operations. Contrarily, considerable differences among the replicate sensors under NT indicate a high spatial variability, especially in the season 2008/09. Under NT, the variability was much smaller in the season 2009/10 than in 2008/09. This may be explained by the fact that the probes were removed before harvest in July and reinstalled at slightly different positions after seeding in October 2009.

3.2. Temporal Dynamics of Soil Hydraulic Properties

The temporal variability of soil hydraulic properties and its underlying water-conducting porosity at the experimental site has been discussed in detail by Schwen et al. (2011a). In both analyzed seasons, $K_s$ and $\theta_s$ under CT and RT strongly decreased after tillage during winter (Figure 1), which might be due to rainfall-induced pore sealing and settling (Cameira et al., 2003; Mubarak et al., 2009; Xu and Mermoud, 2003). The decrease is followed by a gradual increase in spring and summer, possibly induced by biological activity, root development, and wetting / drying cycles, as proposed by Mubarak et al. (2009). Beside considerable higher $K_s$ values in October 2009 and June 2010, NT showed only small temporal variability and no systematic dynamic. The high $K_s$ values in the non-tilled soil may be due to the existence of preferential flow paths (earthworm burrows), as reported by Moreno et al. (1997).

Regarding the VGM model parameters, $n$ showed only small temporal dynamic for all treatments. However, $\alpha_{vg}$ showed a considerable temporal dynamic. This dynamic was smallest for NT, indicating the relatively greater temporal stability of the hydraulic properties under this treatment (Schwen et al., 2011a). We found no systematic trend that reasonably explains the temporal dynamic of $\alpha_{vg}$ for both analyzed seasons. Possibly, this indicates that temporal dynamics of the VGM parameters are quite complex, even for the tilled treatments (CT, RT). Therefore, we did not apply a pore-size evolution model (e.g., Or et al., 2000), but used cubic splines to continuously describe the hydraulic parameters.

3.3. Performance of Near-Surface Water Simulations

The present study focuses on the simulation of water movement and storage in the highly dynamic near-surface soil compartment (0-30 cm). Therefore in the following, only the results for the uppermost soil layer are discussed. However, we acknowledge that we found a good agreement
between measured and simulated soil water contents in the deeper soil layers for all simulations. For quality assessment of the simulations, we compared simulated and measured values of $\theta_{10}$ and $S$ using Eq. 9 and 10. Overall, the simulations resulted in soil water dynamics that agreed with the measured range for all treatments (Figure 2). Since the hydraulic parameters that were used in the topsoil were estimated inversely from tension infiltrometer measurements, this demonstrates the general applicability of this method for soil water simulations.

However, the degree of agreement between simulated and measured soil water dynamics differed among the tillage treatments and between simulations with temporally constant and variable hydraulic parameters. We observed that simulations with time-constant sets of hydraulic parameters tend to underestimate $\theta_{10}$ and $S$ in winter and spring (November 2008 – March 2009 and November 2009 – April 2010), whereas they resulted in overestimations during late spring and summer (June and July 2009 and 2010). Contrarily, application of time-variable hydraulic parameters significantly increased the agreement of both $\theta_{10}$ and $S$ for all tillage treatments in both seasons. This was also reported by Xu and Mermoud (2003). Compared to simulations with constant parameters, values of $ARE$ for $\theta_{10}$ and $S$ approximately halved and the $RSME$ for $S$ was reduced by up to 93% (Table 2). $RSME$ values of $\theta_{10}$ for CT, RT, and NT were 0.042, 0.062, and 0.074 m$^3$ m$^{-3}$, respectively (Table 2), and thus in the same range as reported by Moret et al. (2007). As the $ARE$ values for $\theta_{10}$ and $S$ were below 13%, the simulation results were satisfactory (Ji et al., 2009).

Within simulations with time-variable hydraulic parameters, the best agreement was found for CT with $ARE$ and $RSME$ values for $\theta_{10}$ of 0.09 and 0.042 m$^3$ m$^{-3}$, respectively, (Table 2) and a correlation of $R^2 = 0.81$ (Figure 3), followed by NT ($ARE = 0.09$, $R^2 = 0.78$). Simulations for RT resulted in slightly larger differences and showed the weakest correlation ($R^2$ for $\theta_{10} = 0.65$, Figure 3). For all treatments, the agreement was better in the season 2008/09 than in 2009/10.

These results show that the accuracy of simulations of the near-surface soil water dynamics can be substantially improved by applying time-variable hydraulic parameters. The presented approach might help to improve the quality of soil water simulations, not only for the assessment of different tillage methods, but also for other applied questions in agricultural water management.

To capture temporal and management-induced dynamics in the near-surface soil hydraulic properties, adequate and expeditious methods have to be applied. As demonstrated by this study, repeated tension infiltrometer measurements followed by the described data analysis procedure can meet this requirement. However, to derive physically-based descriptions of the complex temporal and management-induced dynamics of soil hydraulic properties, more research is necessary. We suggest that future research should focus on measurements at different temporal scales that might be correlated to underlying changes in the soil’s structure.

Table 2. Performance of the soil water simulation. Sums of relative differences $SRD$ and root mean square differences $RSMD$ are listed for the volumetric water content in 10 cm depth, $\theta_{10}$, and the water storage $S$ in the near-surface soil profile (0-30 cm). Results for simulations with constant and time-variable hydraulic parameters are shown for all tillage treatments.
4. Conclusion

The present study reveals the applicability of repeated tension infiltrometer measurements to capture temporal and tillage-induced changes in soil hydraulic properties. As classical simulations of the soil water use temporally constant hydraulic parameters, we used a Richards’ equation water simulation that enables the flexible definition of these important control quantities. Simulated water content and storage in the near-surface soil compartments under different tillage treatments were compared to measured data. The performance of the simulation could be improved significantly using time-variable hydraulic parameters, regardless the tillage. By giving meaningful results, our simulations demonstrate the applicability of inversely estimated hydraulic parameters for soil water simulations.

Acknowledgement

The content of this proceedings paper has been published previously in Schwen et al. (2011ab).

References


