Measuring unsaturated hydraulic conductivity (\(K(\psi_m)\)) of the F and H soil organic layers at small matric potential (\(\psi_m\))

B. Wilske and E. A. Johnson

Biogeosciences Institute, University of Calgary, Calgary, Alberta, Canada T2N 1N4
(e-mail: brkwils@yahoo.com). Received 8 March 2011, accepted 11 July 2011.

The fermentation and humus organic layers (F, H) lie between the litter and the mineral soil in cold-climate forests (Miyanishi 2001). The F and H layers, also referred to as duff, are key to the hydrology of these forests, as they redistribute precipitation, have field capacities of up to >500% of water on dry weight basis, and impede evaporation from the underlying mineral soil (e.g., Johnson 1992; Raaflaub and Valeo 2009; Keith et al. 2010).

Price et al. (2008) recently developed a twin suction disc apparatus (TSD) to determine unsaturated hydraulic conductivity (\(K(\psi_m)\)) of large and heteroporous media that are sensitive to compression. The TSD method determines \(K(\psi)\) at defined matric potential (\(\psi_m\)) and measured volumetric water contents (\(\kappa, \text{m}^{-3}\)). The objective of the present study was to test the twin suction disc apparatus (TSD) as a new method to measure \(K(\psi_m)\) of the F and H layer directly. Hence, we determined \(K(\psi_m)\) of the F and H layer using the TSD method over the range of \(\psi_m\) of −0.3 to −3.1 kPa, and compared this \(K(\psi_m)\) curve with results of two previous studies. The study by Raaflaub and Valeo (2009) provided a good comparison because its samples were from the same locations. The other study by Lauren and Mannerkoski (2001) represents an important benchmark with respect to both the compiled data base on soil organic layers, the number of samples processed and their spatial coverage. Lauren and Mannerkoski (2001) presented the \(K(\psi_m)\) curve at \(\psi_m \leq -4\) kPa with temporal changes in \(\psi_m\) calculated from differential tensiometer measurements employed in the instantaneous profile method (Plagge et al. 1990). Raaflaub and Valeo (2009) measured the saturated hydraulic conductivity (\(K_s\)) using the constant head approach (Klute 1986) and employed these values in the equation \(K(\psi_m) = K_s(\psi)\) \(K_s\). Both studies relied on additional data from pressure plate measurements and parameters from fitting measured \(0-\psi_m\) relations to the soil water characteristic curve with results of two previous studies.

Abbreviations: SWCC, soil water characteristic curve; TSD, twin suction disc apparatus
characteristic curve (SWCC) based on the model of van Genuchten (1980).

Methods
F and H layer duff was collected from subalpine forests of Pinus contorta Dougl. and Picea engelmannii Parry ex Engelm. in Kananaskis Country, Alberta, at elevations of 1450–2100 m a.s.l. Sample locations included three spruce and two pine stands, but the pine H layer was only obtained from one of the two stands. Samples included locations under and between trees in equal numbers. Oversized samples of about 20 cm × 20 cm and including the whole duff layer were cut from the forest floor and stored in a freezer. Sub-samples were cut from the undisturbed core to fit the measuring cylinder as separate F and H layers. All loose material was removed from the top of the F layer. F and H layer separation was then determined using von Post’s (1924) humification method.

Raaflaub and Valeo (2009) also sampled from locations in Kananaskis Country. Their K(ψm) curves were recalculated to reflect forests of Pinus contorta and Picea glauca (Moench.) Voss that are comparable with those sampled in the present study (L. Raaflaub and C. Valeo, personal communication). Lauren and Mannerkoski (2001) sampled across Finland and processed five samples from each of 17 stands of Pinus sylvestris L. and 15 stands of Picea abies (L.) Karst.

The investigated layers were defined differently in the two previous studies. Lauren and Mannerkoski (2001) used two parallel sample cores (A, B). K(ψm) was measured from sample A comprising both the F and H layer. The SWCC was determined from two sub-samples of B, which represented the upper and lower layer at a relative depth of 0.25 and 0.75, respectively. Raaflaub and Valeo (2009) sampled the bottom and top 2.7 cm plus a 2.7-cm middle layer equidistant from the upper and lower samples and compared the upper plus middle layer with the lower layer. Despite the different sampling methods, it is reasonable to assume that the F layer and upper layers were equivalent, whereas lower layer samples may not be assumed to represent a distinct H layer.

Unsaturated hydraulic conductivity of the F and H layers was determined using a twin suction disc apparatus (TSD; Price et al. 2008), i.e., a cylinder with a suction disc, which was connected to a water reservoir at each end. Following an equilibration phase for the matric potential (ψm) and the volumetric water content (i.e., no head difference), a constant head difference was applied at different ψm [see Price et al. (2008) for a diagram explaining the setup and the method]. K(ψm) was calculated in meters per day (m d⁻¹) according to Darcy’s law:

\[ K(\psi_m) = \frac{Q}{A \times h/l} \]

where \( Q \) is discharge (m³ d⁻¹) measured as the outflow passing the upper disc, \( A \) is the surface area (m²), \( h \) is the suction pressure applied by a negative water head (kPa), and \( l \) is the depth of the sample (m).

The TSD method related K(ψm) to matric potential (ψm) because saturated samples were allowed to drain. The samples were further equilibrated to the start-up suction pressure of −0.31 kPa. The osmotic potential was negligible with the TSD because ions, such as
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Table 1. Unsaturated hydraulic conductivity of pine (p) and spruce (s) F and H layer

<table>
<thead>
<tr>
<th>( \Psi_m )</th>
<th>( K(pF) ) Mean( ^a )</th>
<th>Var</th>
<th>( K(pH) ) Mean</th>
<th>Var</th>
</tr>
</thead>
<tbody>
<tr>
<td>(-0.3)</td>
<td>9.213 ( 4.9E-00 )</td>
<td>7.4185 ( 2.6E+01 )</td>
<td></td>
<td></td>
</tr>
<tr>
<td>(-0.7)</td>
<td>12.685 ( 3.0E-01 )</td>
<td>7.753 ( 6.8E-01 )</td>
<td></td>
<td></td>
</tr>
<tr>
<td>(-1.1)</td>
<td>10.152 ( b ) ( 2.3E-02 )</td>
<td>6.200 ( 4.5E-02 )</td>
<td></td>
<td></td>
</tr>
<tr>
<td>(-1.5)</td>
<td>9.005 ( c ) ( 1.9E-03 )</td>
<td>6.061 ( 4.5E-03 )</td>
<td></td>
<td></td>
</tr>
<tr>
<td>(-1.9)</td>
<td>11.016 ( b ) ( 1.8E-04 )</td>
<td>5.002 ( 6.7E-04 )</td>
<td></td>
<td></td>
</tr>
<tr>
<td>(-2.3)</td>
<td>9.005 ( c ) ( 3.1E-05 )</td>
<td>5.010 ( 9.5E-05 )</td>
<td></td>
<td></td>
</tr>
<tr>
<td>(-2.7)</td>
<td>11.002 ( b ) ( 3.0E-06 )</td>
<td>4.006 ( 1.6E-05 )</td>
<td></td>
<td></td>
</tr>
<tr>
<td>(-3.1)</td>
<td>8.5 ( E-04 ) ( 4.7E-07 )</td>
<td>5.002 ( 2.7E-06 )</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

\( ^a \) Significant difference \(( P < 0.001) \) between \( b = \) layer, \( c = \) canopy, and \( d = \) canopy and layer; 1-way ANOVA, Holm-Sidak method, significance level = 0.05.

Raafalub and Valeo (2009) calculated \( K(\psi_m) \) using the relationship:

\[
K(\psi_m) = K(\psi_m)(\theta)
\]

The saturated hydraulic conductivity \((K_s)\) was measured using the constant head approach (Klute 1986). The volumetric water content \((\theta)\) at different matric potentials was determined by a pressure plate apparatus. The \( \theta \) was fitted to the matric potential using the van-Genuchten model for the SWCC. The residual water content \((\theta_r)\) was set to zero following Weiss et al. (1998). The parameters \( \alpha \) and \( n \) that fitted the description of the SWCC were then employed to calculate \( K_r(\psi) \) as:

\[
K_r(\psi_m) = \theta_r + \frac{(1 - (x\psi_m)^{n-1}[1 + (x\psi_m)^n]^{-m})^2}{[1 + (x\psi_m)^n]^{3/2}}
\]

where \( m = 1 - 1/n \), and \( \psi_m \), which is by definition negative, was used as \((-\psi_m)\).

Statistical analysis was conducted using SigmaPlot for Windows V. 11.0. For the comparison with previous studies, \( K(\psi_m) \) is presented as 66% confidence limits because these were given by Lauren and Mannerkoski (2001). Similarly, 66% confidence limits were calculated for the curves of Raflaub and Valeo (2009) based on their original data.

Results and Discussion

The TSD \( K(\psi_m) \) curves of the pine and spruce F and H layers lie close to each other with their 66% confidence intervals often overlapping, and they lie mainly between the non-overlapping 66% confidence intervals of the upper and lower layer pine and spruce of Raflaub and Valeo (2009), hereinafter R&V) (Fig. 1). The large difference between R&V’s upper and lower layers may be due to the influence of \( \theta_r \) in the calculation while shrinkage was neglected. Sample volumes in the TSD decreased on average 5–8% with decreasing water content. The size of the TSD \( K(\psi_m) \) confidence intervals were similar to those of R&V. However, the TSD \( K(\psi_m) - \psi_m \) relations indicated more of a curvature with increasing \( \psi_m \) compared to R&V (Fig. 1, insert).

The layer-separated samples (TSD and R&V) have smaller sample numbers and a smaller variance resulting in a smaller confidence interval than the whole samples.

Table 2. Variance in bulk density of pine (p) and spruce (s) F and H layer

<table>
<thead>
<tr>
<th></th>
<th>( \text{Mean}^a )</th>
</tr>
</thead>
<tbody>
<tr>
<td>pF</td>
<td>0.12( ^b )</td>
</tr>
<tr>
<td>pH</td>
<td>0.15( ^b )</td>
</tr>
<tr>
<td>sF</td>
<td>0.11( ^b )</td>
</tr>
<tr>
<td>sH</td>
<td>0.16( ^b )</td>
</tr>
</tbody>
</table>

\( ^a \) Significant difference between \( b = \) layers \(( P < 0.001) \) 1-way ANOVA, Holm-Sidak method, significance level = 0.05. Note there was no significant difference between the same layers in the two different canopies.

The method described by Price et al. (2008) applied to undecomposed peat mosses and it required standardization relative to the measurements of the F and H organic layer. (1) Air-dry samples were submerged for 12 h prior to measurement, i.e., the time necessary to reach a constant weight in the saturated samples. (2) It was critical to record the equilibrating outflow, i.e., \( \theta \) adjusting to \( \psi_m \) until net flow without head difference stopped, because the time period for this equilibration increased with increasing \( \psi_m \) up to several hours.

Lauren and Mannerkoski (2001) measured temporal changes in \( \psi_m \) and determined the SWCC from differential tensiometer readings employed in the instantaneous profile technique and from measurements using a pressure plate apparatus, respectively. The van-Genuchten (1980) model for the SWCC was fitted to the pressure-plate derived \( \kappa - \psi_m \) relation. This allowed calculation of the discharge

\[
\frac{dQ}{dt} = \theta t - \theta_{t+1}
\]

for each discrete time interval corresponding to tensiometer-derived changes of \( \psi_{t+1} - \psi_{t+1} \). \( K(\psi_m) \) was calculated as:

\[
K(\psi_m) = \frac{dQ}{dt} = A \frac{\partial(\psi_m)}{\partial \psi_{m+1}}
\]

where \( \frac{dQ}{dt} \) is the difference in \( \theta \) between two periodically read tensiometer means, and \( A \) and \( \partial(\psi_m) / \partial \psi \) are, respectively, the surface area and the matric potential gradient for the tensiometer sample.
of Lauren and Mannerkoski (2001), hereinafter L&M), which comprise a larger sample number, and thus must include a larger variance based on their confidence intervals (Fig. 1). L&M found that between-sample variance was significant, whereas the between-stand variance was not significant. The TSD did not show significant differences in $K(\psi_m)$ between samples at the smaller $\psi_m$, i.e., when the largest pores conduct the bulk of water. But $K(\psi_m)$ developed to significant differences between both layer and canopy with increasing $\psi_m$ (Table 1). The comparison of layer (TSD, R&V) and whole sample results (L&M) corroborates L&M’s suggestion that vertical heterogeneity increases the between-sample variation.

The ranges of $\psi_m$ in L&M’s and the present study did not overlap but included a gap of $>3$ kPa (Fig. 1). In spite of the gap the TSD $K(\psi_m)$ curves reached similar $K(\psi_m)$ values as the L&M study, because $K(\psi_m)$ of all four canopy-layer groups showed consistent trends to a larger decrease at $\psi_m < -2$ kPa. This indicates a misalignment between TSD data and the conductivities plotted from the data of L&M. In agreement with the study by L&M, and in contrast to R&V, the TSD $K(\psi_m)$ values were higher in spruce than in pine layers, except for $K(\psi_m)$ at $\psi_m = 0.3$ kPa and for the spruce H layer at $\psi_m$ of $-2.3$ kPa, $-2.7$ kPa, and $-3.1$ kPa (Table 1).

Differences in bulk densities ($D_B$) were not likely responsible for the different curvature in the compared $K(\psi_m) - \psi_m$ relations. L&M found significantly greater $D_B$ in the lower (l) than the upper (u) layer in both pine (P) and spruce (S) forests ($D_B$, g cm$^{-3}$; Pu 0.12, Su 0.10, Pl 0.15, and Sl 0.16). Mean $D_B$ (g cm$^{-3}$) of TSD F and H layer samples were very similar to those of the L&M study (Table 2). A possible cause for the deviation between results of $K(\psi_m) - \psi_m$ of the TSD and those of L&M is the curve fitting in which L&M allowed parameters to vary between individual samples and no values were available for small $\psi_m$. However, L&M also linked the time component in $K(\psi_m)$, i.e., from evaporation-driven tensiometer differential measurements, with the volume component derived from $\psi_m - 0$ values of pressure plate measurements. The TSD restricts evaporation and measures $K(\psi_m)$ directly; thus, the comparison suggests that the high end of the TSD range marks the significant change in the relative contribution of vapor vs. liquid transport. This is consistent with the understanding that progressing drainage increases the connected pore volume conducting vapor diffusion while at the same time inhibiting liquid diffusion.

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