Hydraulic Conductivity and Moisture Characteristics of Tropical Peatland - Preliminary Investigation

Lulie Melling¹, Ayob Katimon², Goh Kah Joo³, Lah Jau Uyo¹, Alex Sayok⁴ and Ryusuke Hatano⁵

¹Department of Agriculture, Jalan Badruddin, 93400, Kuching, Sarawak, Malaysia
²Faculty of Civil Engineering, Universiti Teknologi Malaysia, Skudai, Johor, Malaysia
³Advanced Agriecological Research Sdn Bhd, 47000, Sg. Buloh, Selangor, Malaysia
⁴Peat Swamp Forest Project UNDP/GEF Funded, FRIM, 52109 Selangor, Malaysia
⁵Graduate School of Agriculture, Hokkaido University, Sapporo, 060-8589 Japan,

ABSTRACT

The hydrological condition and its related moisture characteristics of the soil are important factors contributing to forest and plant growth in peatland ecosystem. These hydrological characteristics would also provide an indirect view point of the current management practices in the case of land cover other than natural forest. This paper reports our recent research findings on the behavior of field hydraulic conductivity (K) and moisture characteristics of peatlands typically found in Sarawak. The field hydraulic conductivity measurements were carried out on different forest types, namely mixed peat swamp, Alan forest and Padang Alan forest in the virgin peat swamp forest at Loagan Bunut National Park using auger hole and pumping method. The moisture characteristics of peat materials were obtained from samples taken from different areas in Sarawak representing different degrees of peat decomposition under various agronomic practices. The moisture characteristic determination was conducted in the laboratory using a combination of sand/kaolin box for suction pressure less than 500 cm (pF<2.7; < 0.5 bar) and pressure membrane apparatus for 500-15000 cm (pF 2.7-4.2 or 0.5-15 bar).

Peat materials from different ecosystems behaved differently in terms of its hydraulic conductivity. The hydraulic conductivity values depended on the hydraulic gradient and the degree of decomposition of peat. Generally, the higher the hydraulic gradient, the greater the K value. This implies that under shallower water table, the drainage process would occur slower thus more favorable to plant growth through maintaining the soil moisture status. However, it would also imply the higher likelihood of flooding. The K value was directly proportional to the degree of decomposition.

Keywords: Hydraulic conductivity, moisture curve, tropical peat, peat forest

INTRODUCTION

In principle, the growth performance of any type of natural forest vegetation, particularly on peatland, is closely related to water regime of the growing area (Hesikanen and Makitato, 2002). In drainage terms, the water regime of an area is largely controlled by
its soil drainage properties which can be described further using soil moisture retention characteristics curve and hydraulic conductivity (Silins and Rothwell, 1998). While soil moisture retention characteristics can provide detailed features on the capability of soil to hold water available for plant use, hydraulic conductivity on the other hand provides some general ideas on the water movement within the catchment areas in both directions, vertically and horizontally. As such, the dimensionality of water movement within the catchment area is somewhat associated with both hydraulic conductivity and soil moisture retention curve. Therefore the hydrological condition and its related moisture characteristics of the soil are important factors contributing to forest and plant growth. These hydrological characteristics would also indicate an indirect view point of the current management practices in the case of land cover other than natural forest.

About 1.6 million hectares of peatland are found in Sarawak. In terms of vegetation, there are 3 main types on peat i.e. mixed peat swamp forest, Alan and Padang Alan forest (Melling et al., 2006). Upon drainage, they, trigger the process of decomposition which oxidizes the original peat materials to hemic or sapric texture. In order to quantify the hydrological conditions of peat soil and their significant to plant growth, the relevant soil retention capability and hydraulic conductivity should be known.

The objectives of the present study are two folds. Firstly, to understand the hydrological behavior of different peat ecosystems using hydraulics conductivity data and secondly, to understand the moisture retention characteristics of peat soils with different degrees of decomposition.

**Field Hydraulic Conductivity**

Hydraulic conductivity is one of the most and foremost important soil parameters related to the water movement in a watershed system. In groundwater hydrology, hydraulic conductivity can be simply defined as the coefficient of permeability describing the rate at which water can move through a permeable medium (Fetter 1994). Under the saturated field condition as found in natural peat ecosystem, hydraulic conductivity is always referred to as saturated hydraulic conductivity. Hydraulic conductivity is basically governed by the pore size distribution of the soil materials. As a general guideline, the hydraulic conductivity increases as the median grain size increases. This is due to the larger pore openings of the soil materials. Another important related indicator is that unimodal (one dominant size) soil sample has a greater hydraulic conductivity than bimodal (two dominant sizes) samples. For peat, as the pore size distribution of the materials is yet clearly defined, its hydraulic conductivity could be associated with many other factors such as the degree of decomposition.

**Soil Moisture Characteristics**

Soil moisture characteristics curve is a graph giving the relationships between soil moisture tension or matric suction (unit cm of water or kPa or Bar) and soil moisture content (% volume). The curves are used for the following purposes:

- To determine the available moisture in soil that can readily absorbed by plant roots. As rule of thumb, the water available for plant can be estimated from the soil moisture retention curve data. The difference in volumetric soil moisture between water potential of 330 cm of water (330 kPa) and 15000
cm of water (150 kPa) is usually defined as the water holding capacity of the soil.

b) To determine the drainable porosity for drainage design and this closely related to hydraulic conductivity.

c) To estimate the height and rate of capillary rise (Lu and Likos, 2004) in the presence of water table.

MATERIALS AND METHODS

Data collection

Hydraulic conductivity measurements

Study site:

The study area was at Loagan Bunut National Park, Miri, Sarawak. This area has 3 main forest types i.e. mixed peat swamp, alan and padang alan forest as shown in Figure 1.

![Diagram showing the 3 different forest types on peat at Loagan Bunut National Park](Traverse 2A)

Figure 1  The 3 different forest type on peat at Loagan Bunut National Park (Traverse 2A)

Hydraulic conductivity tests:

The field tests for hydraulic conductivity were conducted using two different approaches, i.e. auger hole methods (slug test) and shallow well pumping method. These methods basically follow the same principle as described below.

While slug test uses PVC pipe of a known diameter to represent the auger hole size, pumping method on the other hand uses a dug pit of known size.
A hole (in the case of slug test method) is bored with an auger to a certain depth below the water table. In the case of pumping method, shallow dug well was used. In woody virgin peat, an auger hole can easily be prepared by pushing a sharpened young tree trunk, which can be found in the forest. When the water in the auger hole reaches equilibrium with the groundwater part of it is removed through bailing process. The groundwater then begins to enter the hole (radial seepage) and the rate at which it rises is measured. The hydraulic conductivity of the soil is computed with a formula describing the mutual relationship between the rate of rise, the groundwater conditions and the geometry of the hole.

![Figure 2](image)

**Figure 2** Measurement of the auger-hole method
As reported by Bouwer and Jackson (1974), Ernst developed the following equation for the K-value of the soil which depends on the average rate of rise of the water level in the hole (Figure 1) as follows:

\[ K_s = C \frac{(H_0 - H_t)}{t} \]  \hspace{1cm} (1)

Where

- \( K_s \) = hydraulic conductivity of the saturated soil (m/d)
- \( C \) = a factor defined in Equation (2) or (3)
- \( t \) = time elapsed since the first measurement of the level of the rising water in the hole (s)
- \( H_t \) = depth of the water level in the hole below reference level at time \( t \) (cm)
- \( H_0 \) = depth of the water level in the hole below reference level at time \( t=0 \)

The \( C \)-factor depends on the depth of an impermeable layer below the bottom of the hole \( (D) \) and the average depth of the water level in the hole below the water table \( (h') \) as follows:

When \( D > 0.5 D_2 \), then

\[ C = \frac{4000r / h'}{(20 + D_2 / r)(2 - h'/D_2)} \]  \hspace{1cm} (2)

When \( D = 0 \), then

\[ C = \frac{3600r / h'}{(10 + D_2 / r)(2 - h'/D_2)} \]  \hspace{1cm} (3)

where,

- \( D \) = depth of the impermeable layer below the bottom of the hole (cm)
- \( D_2 \) = depth of the bottom of the hole below the water table (cm), with the condition, \( 20 < D_2 < 200 \)
- \( r \) = radius of the hole (cm), \( 3 < r < 7 \)
- \( h' \) = average depth of the water level in the hole below the water table (cm), with the condition, \( h' > D_2/5 \)

when \( 0 < D < 0.5D_2 \), one must interpolate between the results of the above two equation. The value of \( h' \) can be calculated from,

\[ h' = 0.5 (H_0 + H_n) - D_1 \]  \hspace{1cm} (4)

where,

- \( D_1 \) = depth of the water table below reference level (cm)
- \( H_n \) = depth pf the water level in the hole at the end of the measurement (cm)
Moisture Retention Curves and other physical parameters

**Peat samples:** Undisturbed peat samples were taken from different peat ecosystems using standard soil core rings. They were taken from the same site as the hydraulic conductivity test which were representative of sapric and fine hemic peat. To obtain undisturbed samples, core ring samplers were inserted and cut slowly around them to a desired soil depth and then took them out carefully. They were brought to the laboratory for further analysis.

*Plate 1*  
Sand/Kaolin box for soil determination at low suction head

*Plate 2*  
Pressure ceramic plate for soil determination at higher suction head

**Moisture curves test:** Each core sample of size 50 mm diameter and 50mm high was covered with nylon cloth at the bottom face before soaking overnight for saturation process. The saturated core samples were then transferred into sand/kaolin box (*Plate 1*) to determine the soil moisture retention at low range suction pressure from 10 cm to 500 cm. Upon completion of 10 - 500 cm suction range, the same samples were transferred into the moisture pressure plate chambers (*Plate 2*) for soil moisture determination at higher soil pressure 500 cm (0.5 bar) to 15000 cm (15 bar). A total of seven different suction heads (1, 100, 330, 500, 1000, 3000, 5000, 10000 and 15000 cm)
of water) were applied to the samples in order to obtain a complete water retention curve of the sample. After obtaining the soil moisture retention curve, we can then estimate the water holding capacity and capillary movement of soil.

**Bulk density:** The undisturbed bulk density of each sample representing the actual bulk density of the field was tested using the same sample that had undergone the moisture retention curve analysis. At the end of the 15000 cm suction head, the sample was oven dried at 60°C followed by 105°C to determine the dry weight of the samples. The dry bulk density can be easily computed by dividing the dry weight to the volume of the core (the volume was 98.1875 cm³ based on 5cm diameter and 5cm height).

**RESULTS AND DISCUSSION**

*Hydraulic conductivity analysis*

**Measured K-value**

A total of 73 experimental runs representing 59 slug runs and 14 pumping test runs were conducted to cover the three different types of peat ecosystem found at the study site. Having known the geometry of the auger holes and peat pit and static water table condition of the field, $K_s$ values were calculated using Equations 1, 2 and 3 shown earlier.

Table 1 summarized the $K_s$ value of the study catchment based on 59 slug tests. The average $K_s$ values at Padang Alan, Alan and mixed peat forest were 0.379 cm s⁻¹ (32.76 m day⁻¹), 9.36 cm s⁻¹ (59.06 m day⁻¹) and 6.33 cm s⁻¹ (33.77 m day⁻¹), respectively. As indicated by their standard deviation, there was a large variation in the $K_s$ values obtained from the slug auger holes tests indicating that the peat materials at the study site were decomposing non-uniformly.

Table 2 summarized the Ks values measured using pumping test. The size of the pit varied but the equivalent hydraulic radius was about the same. Based on the average hydraulic head used during the pumping tests, the Ks values were in the following order: Alan Forest (32.6 m/day) > Padang Alan (36.5 m/day) > mixed peat forest (3.26 m/day). Compared to those obtained from the slug test, it seemed that the pumping test provided more reliable data in the sense that they followed the general hypothesis that Alan and Padang Alan should gave similar results as they occurred at almost the same ecosystem whereas the mixed peat forest undergone substantial drainage process as it was located close to Loagan Bunut water body. As such, peat found in mixed forest had more decomposed materials thus producing a lower Ks value. This finding was further supported by data obtained from other parts of Malaysia, which have mostly decomposed or developed peat. For comparison, the $K_s$ values in other peat areas are presented in Table 3.
### Table 1. Summary of the result using slug auger test

<table>
<thead>
<tr>
<th>Forest type</th>
<th>No of test</th>
<th>Mean value (m/day)</th>
<th>Range Max (m/day)</th>
<th>Range Min (m/day)</th>
<th>Standard deviation (m/day)</th>
<th>Standard deviation (cm/sec)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mixed Peatswamp</td>
<td>15</td>
<td>33.77 (cm/sec)</td>
<td>86.50</td>
<td>4.60</td>
<td>33.77</td>
<td>6.33</td>
</tr>
<tr>
<td>Alan</td>
<td>12</td>
<td>59.06 (cm/sec)</td>
<td>140.21</td>
<td>21.83</td>
<td>59.06</td>
<td>9.36</td>
</tr>
<tr>
<td>Padang Alan</td>
<td>32</td>
<td>32.76 (cm/sec)</td>
<td>174.86</td>
<td>0.94</td>
<td>32.76</td>
<td>0.3790</td>
</tr>
</tbody>
</table>

### Table 2. Summary of the result using pumping test

<table>
<thead>
<tr>
<th>Forest type</th>
<th>Size of pit (cm²)</th>
<th>Equivalent radius, r</th>
<th>Initial water table depth (cm)</th>
<th>Hydraulic conductivity (m/day)</th>
<th>Hydraulic conductivity (cm/s)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mixed peatswamp</td>
<td>20335</td>
<td>45.385</td>
<td>20</td>
<td>3.26</td>
<td>0.0038</td>
</tr>
<tr>
<td>Alan</td>
<td>23195.5</td>
<td>48.475</td>
<td>27.5</td>
<td>32.66</td>
<td>0.0378</td>
</tr>
<tr>
<td>Padang Alan</td>
<td>21025</td>
<td>46.075</td>
<td>33.5</td>
<td>36.49</td>
<td>0.0422</td>
</tr>
</tbody>
</table>

### Table 3. Saturated hydraulic conductivity of peat from different part in Malaysia and the world

<table>
<thead>
<tr>
<th>Site</th>
<th>Hydraulic conductivity, Ks (m/day)</th>
<th>References</th>
</tr>
</thead>
<tbody>
<tr>
<td>Dun Moss, England</td>
<td>0.86 – 0.09</td>
<td>Rycroft et al., (1975)</td>
</tr>
<tr>
<td>Alberta, Canada</td>
<td>0.40 – 3.47</td>
<td>Silins and Rothwell (1998)</td>
</tr>
<tr>
<td>Minnesota, USA</td>
<td>4.28</td>
<td>Boelter (1969)</td>
</tr>
<tr>
<td>Pontian, Malaysia</td>
<td>0.05 – 2.30</td>
<td>Salmah (1994)</td>
</tr>
<tr>
<td>Klang, Malaysia</td>
<td>0.48 – 4.90</td>
<td>Ayob and Mutalib (1997)</td>
</tr>
<tr>
<td>Pulau Brui, Malaysia</td>
<td>2.39 – 24.70</td>
<td>Zailon (1999)</td>
</tr>
<tr>
<td>Kalimantan, Indonesia</td>
<td>0.86 – 0.09</td>
<td>Takahashi and Yonetani (1995)</td>
</tr>
<tr>
<td>Kushiro, Japan</td>
<td>0.052</td>
<td>Takahashi and Yonetani (1995)</td>
</tr>
<tr>
<td>Mixed Peat swamp, Malaysia</td>
<td>33.77</td>
<td>Melling et al, 2006</td>
</tr>
<tr>
<td>Alan forest, Malaysia</td>
<td>59.06</td>
<td>Melling et al, 2006</td>
</tr>
<tr>
<td>Padang Alan, Malaysia</td>
<td>32.76</td>
<td>Melling et al, 2006</td>
</tr>
</tbody>
</table>
Moisture retentivity analysis

Laboratory test

The characteristics of the soil moisture held by different peat samples from various peat ecosystems are summarized in Tables 4 and 5. Before a further discussion can be made, the following detailed explanation is required. Unlike for clayey soil (using disturbed, air dried, crushed and pounded), all the laboratory measurements carried out using both sand box and pressure plate were based on undisturbed core samples. Also, the bulk densities were estimated from dry weight basis. The volumetric moisture content at saturation, field capacity (FC) and permanent wilting point (PWP) were estimated based on matric suction at 100 cm (10 kPa or 0.1 bar), 330 cm (33 kPa or 0.33 bar) and 15000 cm (1500 kPa or 15 bar). The water holding capacity (WHC) or the available water to plant was estimated from the different volumetric moistures between FC and PWP. For comparative purpose, Table 6 shows the WHC values of different soil texture other than peat. Figures 3 shows the water retention curves of the studied samples compared to sand and clay loam.

In terms of soil porosities as indicated by their bulk densities, the following order was obtained:

sapric > hemic > mixed peat swamp > Alan

The trend between WHC characteristics and their bulk densities was in very close agreement especially for sapric, hemic, Alan forest and cleared mixed forest.

Table 4 Moisture retention characteristics of the sapric and hemic characteristics

<table>
<thead>
<tr>
<th>Type of peat</th>
<th>Bulk density (g/cm³)</th>
<th>Moisture content (% vol)</th>
<th>Matric suction (cm)</th>
<th>Water holding capacity (%) vol cm/m rootzone depth</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sapric</td>
<td>0.2365</td>
<td></td>
<td>0.8535</td>
<td>0.7207</td>
</tr>
<tr>
<td>Fine Hemic</td>
<td>0.1621</td>
<td></td>
<td>0.8981</td>
<td>0.6960</td>
</tr>
</tbody>
</table>

In Table 4, the moisture content is shown in percentage volume. The matric suction values are given in centimeters. The water holding capacity values are given as percentage volume. The cm/m rootzone depth values are also provided.
Table 5  Moisture retention characteristics of alan and mixed peatswamp forest peat

<table>
<thead>
<tr>
<th>Forest type</th>
<th>Soil depth (cm)</th>
<th>Bulk density (g/cm³)</th>
<th>Moisture Content (% vol)</th>
<th>Water Holding Capacity</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td>Matric Suction (cm)</td>
<td>Field Capacity</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Saturation</td>
<td></td>
</tr>
<tr>
<td>Alan 0 - 25</td>
<td>0.1105</td>
<td>0.5850</td>
<td>0.3344</td>
<td>0.1888</td>
</tr>
<tr>
<td>Alan 25 - 50</td>
<td>0.0846</td>
<td>0.8334</td>
<td>0.5188</td>
<td>0.3355</td>
</tr>
<tr>
<td>Mixed peatswamp 0 - 25</td>
<td>0.1096</td>
<td>0.7950</td>
<td>0.5789</td>
<td>0.3985</td>
</tr>
<tr>
<td>Mixed peatswamp 25 - 50</td>
<td>0.0759</td>
<td>0.9026</td>
<td>0.4508</td>
<td>0.2872</td>
</tr>
</tbody>
</table>

Table 6  Water holding capacity by texture

<table>
<thead>
<tr>
<th>Textural Classes</th>
<th>Water holding capacity (Vol/Vol)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Coarse sand</td>
<td>0.02-0.06</td>
</tr>
<tr>
<td>Fine sand</td>
<td>0.06-0.08</td>
</tr>
<tr>
<td>Loamy sand</td>
<td>0.09-0.10</td>
</tr>
<tr>
<td>Sandy loam</td>
<td>0.10-0.12</td>
</tr>
<tr>
<td>Fine sandy loam</td>
<td>0.13-0.17</td>
</tr>
<tr>
<td>Silt loam</td>
<td>0.17-0.21</td>
</tr>
<tr>
<td>Silty clay loam</td>
<td>0.15-0.17</td>
</tr>
<tr>
<td>Silty clay</td>
<td>0.13-0.14</td>
</tr>
<tr>
<td>Clay</td>
<td>0.10-0.14</td>
</tr>
<tr>
<td>Sapric Peat</td>
<td>0.15</td>
</tr>
<tr>
<td>Hemic Peat</td>
<td>0.09</td>
</tr>
<tr>
<td>Alan Forest *</td>
<td>0.16</td>
</tr>
<tr>
<td>Mixed Peatswamp Forest *</td>
<td>0.18</td>
</tr>
</tbody>
</table>
Another issue pertinent to the relationship between soil water characteristics and plant growth on peat is the capillary water rise potential. In water management system of areas with shallow water table as found in peat swamp, water supply from the capillary rise is very critical. The capillary rise potential is an estimated value which can be deduced using Terghazi (1943) formulation based on Darcy’s Law (Lu and Likos, 2004) as follows:

\[ i = \frac{h_c - z}{z} \]  

where

\( i \) - hydraulic gradient responsible for capillary rise,
\( h_c \) - ultimate height of capillary rise,
\( z \) - distance measured positive upward from water table.

The magnitude of \( h_c \) represents the drop in pressure head across the air-water interface at the wetting front of the water retention curve (Figure 4)
In this particular study, the issue is on how to estimate the amount of irrigation supply from the capillary rise of various peat materials from different depths. Estimating the capillary water supply from the water table is not a straightforward method as it requires knowledge in hydraulic conductivity of unsaturated soil condition above the water table ((Lu and Likos, 2004; Raes and Deproost, 2003). Related to such issue, Raes and Deproost (2003) has developed a model dubbed UPFLOW to estimate steady upward flow (capillary rate) from the water table. Beside the water retention curve of the soil, another main input to the model is a graph or table showing the relationship between hydraulic conductivity and matric suction (K-h). With the absence of K-h curve of peat samples of the study site, an equivalent value was estimated based on the nearest equivalent soil texture. Referring to Tables 4 and 5, the following equivalent WHC values may apply. Sapric and Alan forest were equivalent to silty clay loam, hemic equivalent to loamy sand, cleared forest equivalent to silt loam and mixed forest equivalent to maximum value of silt loam. Figure 4 shows the computer image of input fields in the main menu of UPFLOW software.
CONCLUSIONS

1. In general, the K value of peat under Padang Alan was higher than Alan forest, while mixed peat forest had the lowest K value. Nevertheless, the field K values varied according to several factors as follows:
   a. Method of measurement
   b. Size of pit (equivalent well radius)
   c. Hydraulic head and water table depth
2. The K values were closely related to the drainage performance of the areas thus the compactness or bulk density of the soil.
3. The water holding capacity of the peat materials varied according to the silviculture practiced at the site. In general, a more developed peat such as sapric held more water compared to hemic layer. Mixed forest planted with oil palm would hold more water compared to other types of peat due to soil compaction at planting. Similarly, developed Alan forest is capable of holding as much water as cleared mixed, drained forest.
4. The water retention curves of the tested peat samples had similar shape to that of sand and clay loam but had higher volumetric water content under high matric suction. This indicates that peat soils have smaller capillary rise potential even when they are still quite moist. This might be expected since they were porous.
ACKNOWLEDGEMENT

The field assistances of Wan Laeng, Lai Poh Luke, Donny Sudid, Johncar Nyadek and Gan bin Haip are very much appreciated for their loyal support, sacrifices and hardwork during the course of all these field surveys. We also wish to thank Edward Baran for the assistance in the laboratory.

REFERENCES


Ivanov, K. E. (1953). “Gidrologiya Bolot (Hydrology of bogs).” Leningrad: Gidromeoizdat Translated from Russian


