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Quantifying peat hydrodynamic properties and their influence on water table depths in peatlands of southern Quebec (Canada)

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Abstract

Water table depth in peatlands is strongly linked to physical properties of the peat, such as density (ρ_{dry}), peat composition and humification, hydraulic conductivity (K), and specific yield (-S_y-). Dry bulk density and peat depth are commonly used as indicators of K in eco-hydrological models. However, no mathematical relationship exists to quantify S_y based on K and ρ_{dry}. As a result, eco-hydrological models cannot explicitly reproduce the strong buffering capacity of peatlands. The objectives of this study were to analyze the literature-reported mathematical link between all the physical properties to develop new mathematical relationships between these parameters, and to evaluate whether variations in the physical properties of the peat control water table depth in peatlands. Seven peatlands located in the St. Lawrence Lowlands (Québec, Canada) were sampled, and 1 m-long peat cores were collected from up-gradient, mid-gradient, and down-gradient zones. All cores were used to measure ρ_{dry}, K, S_y, and to estimate peat composition and humification. Statistically significant correlations were found between: 1) K and S_y (log-log model), 2) K and depth (log-log model), 3) S_y and depth (log-log model), 4) ρ_{dry} and S_y (log model), and 5) ρ_{dry} and K (log model). No significant difference was found in either K or S_y between sites. However, significant differences

were found in water table depths. Because they provide a fuller description of the peat properties that control water table depths, these newly developed functions have the potential to improve the capacity of eco-hydrological models to simulate time-varying hydrological conditions.

Introduction

Peatlands are water-dependent ecosystems often connected to aquifers (Rossi et al., 2012) and rivers (Bourgault et al., 2014), and are characterized by an accumulation of organic matter that exceeds its decomposition. The connectivity of peatlands to aquifers and rivers, referred to as hydro-connectivity, and their capacity to accumulate and store carbon depends on the water table depth (Ise et al., 2008), which is strongly influenced by the physical properties of the peat (i.e., density (ρ_{dry}), peat composition and humification, hydraulic conductivity (K), and specific yield (Ise et al.); (Kelly et al., 2014).

The parameters ρ_{dry} (Radforth and Brawner, 1977) and depth (Young and Klaiwitter, 1968) are commonly integrated in eco-hydrological models as indicators of K (Frolking et al., 2010) to determine the facility with which water circulates through the organic deposit (Fetter, 2001). However, no mathematical equations are reported in the scientific literature to link ρ_{dry} and K to S_y. Even though S_y is known to vary strongly with depth (Bourgault et al., 2016), this parameter is either not integrated in eco-hydrological models (Frolking et al., 2010), or is considered constant (Morris et al., 2012). Since S_y controls the storage capacity of the peat (Dettmann and Bechtold, 2016) and its water table reactivity to precipitation (Bourgault et al., 2016), eco-hydrological models therefore cannot explicitly reproduce the strong buffering capacity of peatlands (Waddington et al., 2015). This limits their capacity to reproduce water table depths. The limited extent of literature-reported data partially explains the oversimplification in eco-hydrological models. For example, even if a handful of studies have reported measurements of K (Rosa and Larocque, 2008) and S_y (Lapen et al., 2000) across North America (Letts et al., 2000; Quinton et al., 2008) and Europe (Baird, 1997; Baird et al., 2016; Holden and Burt, 2003a), data are still extremely limited in eastern Canada, where peatlands occupy large surface areas..

The objectives of this study were to analyze the literature-reported mathematical link between ρ_{dry}, peat composition, humification, K, and S_y to develop new mathematical relationships between these parameters, and to evaluate whether variations in the physical properties of the peat control water table depths in peatlands. Measurements of ρ_{dry}, peat composition and humification, K and S_y were performed on 47 peat cores in seven peatlands located in the St. Lawrence Lowlands (southern Quebec, Canada). Water table variations were recorded over two summer periods at three locations (up-gradient, mid-gradient, and down-gradient) in all of the peatlands.

Site description

All seven studied peatlands (Covey Hill – CH, Large Tea Field – LTF, Sainte-Séraphine – SSE, Lac Cyprès – LCY, Victoriaville – VIC, Villeroy-VR, and Issoudun – ISO) are located in the St. Lawrence Lowlands, with the exception of CH, which located in the northernmost extension of the Adirondack Mountains (Figure 1). These peatlands are located in the Châteauguay (CH, LTF), Nicolet (SSE, LCY, VIC), Bécancour (VR), and Du Chêne (VR, ISO) watersheds, and are spread over a distance of 250 km in southern Quebec (Canada). Five of the seven studied peatlands (LTF, SSE, LCY, VIC, and ISO) have already been described in Bourgault *et al.* (2016), including their geological context, micro-topography, peat thickness, vegetation composition, humification, and hydro-climatic contexts.

The peatlands developed in different geological contexts, characterized by a wide variety of quaternary surficial sediments (marine clay, fluvial sandy silt, clayey silty till, aeolian fine to medium sand, and regressive marine sand) (Bourgault et al., 2016). The CH site is an exception, having developed on fractured Cambrian sandstone of the Potsdam Group (Levison et al., 2014).

Six sites (CH, LTF, SSE, VIC, VR, and ISO) are basin peatlands (National Wetlands Working Group-NWWG, 1997) and are set in headwater conditions. LCY is a slope peatland (as defined by NWWG, 1997) that developed on fine to medium sand dune deposits. The peatlands are characterized by a micro-topography of alternating hummocks and lawns. Hollows are only observed at ISO and VIC, while small shallow pools are observed at VR.

Vegetation surveys performed at all sites show that *Sphagnum* spp. (*Sph* sp.), *Kalmia angustifolia* (*Kal ang*), and *Eriophorum vaginatum* (*Eri vag*) were the main species for all sites. *Sphagnum* spp. (*Sph* sp.), *Kalmia angustifolia* (*Kal ang*), and *Rhododendron groenlandicum* (*Rho gro*) were the dominant species on hummocks. On lawns and hollows, *Sphagnum* spp. (*Sph* sp.), *Eriophorum vaginatum* (*Eri vag*), and *Carex* spp (*Car* sp.) were the dominant species. In shallow pools (only observed in VR), *Sphagnum cuspidatum (Sph cus*) was found. In sites CH, SSE and VR, minerotrophic vegetation was found at the margin of the peatlands and used to determine groundwater connectivity (Table 1). *Alnus rugosa* (Aln rug), *Iris versicolor* (Iri ver) and *Sphagnum* spp. (Sph sp.) were the common species of the minerotrophic zones.

All the peatlands began to accumulate following land emersion after the last deglaciation, between ca. 10 770 cal BP (Larocque et al., 2013) in VR, and ca. 13 450 cal BP in CH (Pellerin et al., 2007). Peatland areas range between 0.5 and 10.4 km^2, and peat thickness varies between 190 and 522 cm (Table 1). All the peatlands have central ombrotrophic sections, and some have lateral minerotrophic sections (CH, SSE, and VR). Rates of accumulation for the top meter of peat (only available for CH and VR) vary between 0.6 and 1.1 $mm.yr^{-1}$ for VR (Lavoie and Colpron-Tremblay, 2013) and between 0.01 and 4 $mm.yr^{-1}$ for CH (Lavoie et al., 2013), and includes the acrotelm, in which peat is partially decomposed.

Mean annual precipitation (1981 – 2010) varies between 929 mm (ISO) and 1114 mm (LTF) (MDDELCC, 2017). For all sites, the minimum monthly precipitation occurs during the winter, and the maximum is recorded during the summer. Mean annual temperature (1981-2010) varies between 4.8 (ISO) and 6.7 °C (LTF). Minimum and maximum temperatures are recorded in January and July respectively for the seven sites.

Methods

Field work was carried out between May 2014 and June 2016. Peat sampling sites were located along a transect covering up-gradient, mid-gradient, and down-gradient zones in all the peatlands. The three zones were identified using the digital elevation model (1 x 1 m resolution) derived from airborne light detection and ranging survey (LiDAR). Up-gradient was defined as the highest altitudinal zone, down-gradient the lowest altitudinal zone and mid-gradient an intermediate zone. Distances between up-gradient and down-gradient wells varied between 123 and 760 m with mean slopes from 0.08% to 0.24% (see Bourgault et al. 2016).

The LCY peatland does not include a mid-gradient location because of its small area (0.5 km^2). Twenty sampling locations were thus visited, and two 1 m-long peat cores were sampled at each site using a Box corer. One additional peat core was sampled in each of the up-gradient locations, for a total of 47 peat cores. Sampling compression was measured in the field and ranged between 2 and 20 cm for all sites and locations. Mean sampling compression was 4 cm for CH, 5 cm for LTF, 8 cm for SSE, 12 cm for LCY, 6 cm for VIC, and 2 cm for ISO. Peat gaps due to compression were not considered in the analyses. Cores were cut into two 50 cm sections using a sharp knife, wrapped into two half-cylinder PVC pipes (ρ_{dry} measurements) or rectangular plastic casings (K and S_y measurements) for transportation, and stored at 4°C. In the laboratory, one core per sampling location was used for ρ_{dry} measurements, one for K measurements, and one for S_y measurement (S_y measurements were performed only in up-gradient locations). Water table variations were recorded at the three locations within each site using wells constructed from 3 cm OD PVC pipes, with 2 m long intakes perforated with 0.254 mm slits equally spaced by 60 mm from top to bottom, and sealed at their base. All wells were equipped with level loggers (*Solinst*) that recorded water table variations at hourly intervals from June 2014 to May 2016.

Peat composition and humification

Peat composition and humification of the up-gradient core of each peatland were described. Degree of humification was assessed directly in the field using the standard von Post procedure (Von Post, 1922). In the laboratory, peat composition was describedat 4 cm intervals following the Troels-Smith (1955) method for up-gradient cores only. Peat composition was described using a stereoscopic microscope and classified within four groups, *Turfa bryophytica, Turfa lignosa, Turfa herbacea*, and *Detritus granosus*.

Dry bulk density (ρ_{dry})

Twenty 1 m-long peat cores (two for LCY) were used to perform ρ_{dry} measurements (Dean, 1974). To perform this analysis, all cores were frozen for three hours and then cut with a sharp knife at 2 cm intervals, corresponding to a volume of 44 cm^3. Each sliced section was weighed, dried overnight at 105 ˚C, and weighed again. ρ_{dry} was calculated using the following equation, where W is the slice weight after drying and V is its volume:

$$\rho_{dry} = \frac{W}{V} \quad (1)$$

For all cores, means were calculated at 8 cm intervals so as to be comparable to K and S_y measurements.

Hydraulic conductivity (K)

Twenty 1 m-long peat cores were cut into 343 cm^3 (7 cm x 7 cm x 7 cm) samples, for a total of 12 samples per core. In the laboratory, each cube was wrapped in a thin wax film and submerged into liquid paraffin, as required for the Modified Cube Method (MCM) (Surridge et al., 2005). The wax was removed from two sides of the cube to measure horizontal saturated hydraulic conductivity (K_h; equivalent to K_{sat}) and the samples were allowed to saturate overnight. The horizontal saturated hydraulic conductivity (hereafter called K) was measured using a constant head permeameter (Beckwith et al., 2003; Surridge et al., 2005). The waxed samples were placed on a funnel connected to a graduated cylinder, and a thin film of water was maintained on their upper face to produce a hydraulic gradient equal to one. By repeating the experiment on each sample, discharge (Q) from the peat sample was measured three times. Uncertainties between the three experiments were negligible for all samples (less than 2%). Mean K was calculated using Darcy's Law:

$$K = \frac{Q}{Ai} \quad (2)$$

where A (49 cm^2) is the cross-sectional area and i ($cm.cm^{-1}$) is the hydraulic gradient ($i = 1$) .

Storage coefficient (S_y)

Bourgault *et al.* (2016) previously reported S_y variations with depth for five of the studied peatlands (LTF, SSE, LCY, VIC, and ISO). The S_y values for the other two peatlands (CH and VR) are reported here. These cores were cut into 8 cm^3 samples for a total of 12 samples per core. S_y measurements were performed on these samples using the same gravity drainage experiments as those described in Bourgault *et al.* (2016).

Gravity drainage was performed in acrylic cubes (8 cm^3) and used to estimate S_y following Eq. (2) (Freeze and Cherry, 1979),

$$S_Y = \frac{V_d}{A * \Delta h} \quad (3)$$

where V_d is the drained water volume (cm^3), A is the area of the peat sample (7 cm x 7 cm = 49 cm^2), and Δh is the water table fluctuation (cm). The peat samples were soaked in water for 24 hours prior to the experiment, and then drained for 24 hours. Each acrylic cube was connected at the bottom to a plastic tube with a diameter of 1.3 cm attached to an adjustable base support to drain the samples. Each drainage experiment began by decreasing the height of the plastic tube to that of the bottom of the tested sample. S_y was measured twice on third of the sample to evaluate the experimental errors.

Data analysis

Tukey HSD analyses were performed to identify differences between peatlands and between site locations, using a 99% confidence interval. Linear regression and non-linear regression analyses were performed to identify relationships between K, S_y, ρ_{dry}, depth, and median water table depth. All the mathematical analyses were performed using the R statistical software (R environement, 2008)

Results

Water table depth

Water table depth for all the sites (CH, LTF, SSE, LCY, VIC, VR, and ISO) and locations (up-gradient, mid-gradient, and down-gradient), including winter months when snow accumulates at the surface, was between +25 cm (above peat surface) and -65 cm (below peat surface). Significant differences were found between sites (Figure 2), with median water table depths equal to -10 m for CH, -30 m for LTF, -35 m for SSE, -41 m for LCY, -16 for VIC, -5 for VR, and -1 for ISO. Two groups could be distinguished. The first group (CH, VIC, VR, and ISO), was characterized by shallow water table depths, and the second group (LTF, SSE, and LCY) was characterized by a deeper water table (Figure 2). However, no significant differences in water table depths were found within each of the seven peatlands (e.g., up-, mid-, and down-gradient).

Vegetation and humification

Acrotelm thickness (up-gradient locations) was 32 cm for CH, 57 cm for LTF, 57 cm for SSE, 56 cm for LCY, 28 cm for VIC, 21 cm for VR, and 24 cm for ISO, and was determined based on the minimum water table depth (Holden and Burt, 2003b) (Figure 3). In all sites, the acrotelm is mainly dominated by *Turfa bryophytica*, with varying percentages of *Turfa lignosa* (up to 40%) and/or *Turfa herbacea* (up to 30%) and/or *Detritus granosus* (up to 50%) (Figure 3). In the cores from CH, LTF, SSE, LCY, and VIC, a sharp transition from *Turfa bryophytica* to a highly decomposed *Detritus granosus* peat was observed. The transitions were characterized by an increase in humification from a non-decomposed *Sphagnum*-dominated fibric peat (≤ 20 cm) to a highly decomposed sapric peat (≥ 55 cm), which was expected to strongly affect ρ_{dry}, K, and S_y (Letts et al., 2000). The cores from VR and ISO were mainly composed of *Turfa bryophytica* for the entire sequence, with interspersed layers of *Turfa lignosa* between 66-74 for VIC and *Turfa herbacea* between 34-60 cm for VR.

Dry bulk density

ρ_{dry} results varied between 0.02 and 0.22 g/cm^3. Variance analysis of ρ_{dry} showed significant difference between sites, with median ρ_{dry} equal to 0.06 g/cm^3 for ISO, 0.08 g/cm^3 for VR, 0.10 g/cm^3 for VIC, 0.10 g/cm^3 for CH, 0.11 g/cm^3 for LTF, 0.11 g/cm^3 for SSE, and 0.14 g/cm^3 for LCY (Figure 4). In sites CH, LTF, SSE, LCY and VIC, a transition in slope was observed at a depth of 50 cm for CH, 20 cm for LTF, 35 cm for SSE, 35 for LCY, and 30 cm for VIC, and a maximum ρ_{dry} was reached at the depth of the transition (Figure 5). In VR and ISO, the maximum ρ_{dry} was found at the base of the cores (1 m depth). Two groups were distinguished, the first consisted of sites CH, ISO, and VR, and the second of sites LCY, LTF, and SSE, with the VIC site being between the two groups. No significant differences between site locations (up-gradient, mid-gradient, down-gradient) were recordedwith regards to ρ_{dry}.

Hydraulic conductivity

Hydraulic conductivity results show strong variation in K, over nearly six orders of magnitude between sites (Figure 6). Experimental errors on K were less than 2% and considered negligible. The median K was 6.9×10^{-3} cm/s for CH, 5.1×10^{-4} cm/s for LTF,

8.0×10^{-5} cm/s for SSE, 4.0×10^{-4} cm/s for LCY, 6.4×10^{-4} cm/s for VIC, 2.3×10^{-3} cm/s for VR, and 3.5×10^{-3} cm/s for ISO, and show no significant difference between the sites. The highest K value is 1.4 cm/s at site SSE, while the lowest is 0.000003 cm/s at site LCY, with an overall median K value of 0.067 cm/s.

Similar to ρ_{dry}, two distinct rates of K decrease with depth were observed: a rapid decrease observed within the upper part of the acrotelm, and a small decrease corresponding to the catotelm (Figure 7). Regression models were used to represent the decrease in measured K with depth. Models for log (K) – depth (see figure 7; blue lines) and log (K) - log (depth) (see figure 7; black lines) were compared. Results show that the log (K) - depth model best described CH (R^2=0.88) and VR (R^2=0.42), whereas the log (K) - log (depth) model best described LTF (R^2=0.55), SSE (R^2=0.78), LCY (R^2=0.86), VIC (R^2=0.66), and ISO (R^2=0.60). However, the difference in R^2 between the two models for CH and VR is not significant compared to the difference in R^2 between the two models for LTF, SSE, LCY, VIC and ISO. Therefore, all sites are considered best described using log (K) - log (depth) models.

Comparing figure 3 and figure 7, an increase in K is observed in *Turfa bryophytica* peat layers between 22 and 34 cm and 60 and 82 cm for VR and in *Turfa herbacea* between 66 and 74 cm for VIC. This pattern was not observed at the other sites. Finally, no significant difference was observed between the different site locations, with the exception of SSE and VR, where the Tukey HSD test (CI = 99%) identified a significant difference for the down-gradient locations.

Storage coefficients

Result of S_y using the MCM method varied between 0.01 and 0.82 (Figure 8). Similarly to K, a rapid change in rates of decrease is observed for all peat cores (Figure 9). This rapid decrease is restricted to the acrotelm, with a median S_y of 0.27 for all sites, whereas a slow decrease is observed in the catotelm, with a median S_y of 0.05 for all sites. Median S_y were 0.16 for CH, 0.05 for LTF, 0.03 for SSE, 0.38 for LCY, 0.05 for VIC, 0.06 for VR, and 0.09 for ISO, and showed significant differences only between LCY and ISO. Based on previous results from Bourgault *et al.* (2016), no significant differences in S_y were observed across locations (i.e., up-gradient, mid-gradient, and down-gradient) in sites LTF, SSE, LCY, VIC, and ISO.

Mathematical relationships between ρ_{dry}, K, S_y, and peat depth

Strong correlations were found between median water table depth and ρ_{dry} (Figure 10), K and depth (see figure 11), S_y and depth (see figure 12), K and ρ_{dry} (see figure 13), ρ_{dry} and S_y (see figure 14), and S_y and K (see figure 15). No correlation was found between median water table depth and K (R^2 = -0.05), or median water table depth and S_y (R^2=0.13). K-depth (figure 11), S_y-depth (figure 12), and S_y-K (figure 15) relationships were best modelled using log-log functions:

$$\log(y) = \alpha * \log(x) + \beta \quad (3)$$

where y is the dependant variable (e.g. S_y, K), x is the independent variable (e.g. depth, ρ_{dry}) and α and β are constants controlling the curvature of the relationship. Calculated α and β varied respectively from -3.74 to -2.56 and from 1.26 to 3.17 for K-depth relationship (figure 11), from 0.32 to 0.40 and from 0.28 to 0.56 for S_y-depth relationship (figure 12), and from 0.33 to 0.40 and from -0.19 to 0.02 for S_y-K relationship (figure 15). K-ρ_{dry} (figure 13) and S_y-ρ_{dry} (figure 14) were best modelled using semi-log functions:

$$y = \alpha * \log(x) + \beta \quad (4)$$

where calculated α and β varied respectively from -33.90 to -25.01 and from 0.57 to 0.29 for K-ρ_{dry} relationship (figure 13) and from -10.20 to -5.87 and from -0.53 to -0.12 for S_y-ρ_{dry} relationship (figure 14). Results from this study were compared to the K-ρ_{dry} relationship developed by Radforth and Brawner (1977) and included in the Holocene peat model (HPM; Frolking et al., 2011) (figure 13), and the model of K-depth developed by Young (1968), which is included in the Digibog model (Baird et al., 2012) (figure 11).

Discussion

Functional correlations between K, S_y, ρ_{dry}, and depth

K, S_y, and ρ_{dry} values measured in this study were well within the ranges of values reported in the literature. Baird et al. (2016) showed that K can vary between 10^{-1} cm/s and 10^{-5} cm/s within the first meter of peat sequences. From their data compilation, Dettmann and Bechtold (2016) have shown that S_y varies between 0.01 and 0.95 within the first 50 cm of peat. Compiled values of ρ_{dry} reported by Loisel et al. (2014) for different types of peatlands around the world vary mainly between 0.05 and 0.20 g/cm^3, with a mean value of 0.10 g/cm^3.

The strong correlations for the K-depth, Sy-depth, and K-ρdry, relationships are consistent with the equations used in models (Baird et al., 2012; Frolking et al., 2010) and field data based studies (Bourgault et al., 2016; Dettmann and Bechtold, 2016; Morris et al., 2015). The equation used in the HPM for the K-ρ_{dry} relationship overestimates results from this study (see figure 13). This is explained by the fact that the K-ρ_{dry} relationship used in the model was derived from sites that might not have been located in a similar hydrogeological context. Moreover, because K has been shown to be a sensitive parameter in the HPM (Quillet et al., 2013), it would be advisable to include the possibility for a region-specific or site-specific K-ρ_{dry} relationship to be used. The exponential function of Young (1968), describing the K-depth relationship, underestimates K values of the present study in the top 10 cm and overestimates K values between 20 and 60 cm (see figure 11). This underestimation of surface K could have an important effect on simulated peatland hydrodynamics, since the surface layer controls water table variations, and therefore water flow velocities. Additionally, figure 15 shows a strong positive correlation of S_y as a function of K. This is also important, as it demonstrates a quantitative relationship between these two parameters in peatlands. Finally, a relationship was identified to link S_y and ρ_{dry} (figure 14) that could be included in models using ρ_{dry} as an indicator of K and S_y.

However, higher K at the surface and lower K at the bottom of a peatland is not always observed (see figure 7). As explained by Baird et al. (2016), stratigraphic changes in vegetation assemblages and decomposition, within the catotelm, can modify the peat pore structure and result in K values equal to or exceeding values usually found in shallow, near-surface peat. In the present study, this was observed at VR, with higher K values found between 22 and 34 cm and 60 and 82 cm (see figure 7.f), where peat was less decomposed and dominated by *Turfa bryophytica*. These conditions can favor local peatland-aquifer connectivity.

Additionally, in VR and SSE, K values were lower in down-gradient locations (i.e., close to the peatland margin; see figure 7.c). This reinforces the results from Lapen et al. (2005), which raised the importance of this lower peatland margin in maintaining an elevated water table within the peat deposits. According to Baird (2016), the finding of significant difference regarding the hydraulic properties between the different locations within the peatlands is crucial because it shows the importance of different-scale features (e.g. micro-topography, patterning, raised bog, margin) in the understanding of peatlands function both hydrologically and ecologically.

Therefore, the quantitative relationships developed in this paper should be used cautiously considering that spatial heterogeneity in peatlands is common. The different functions and their parameters variability could be tested using models. Additionally, the similarity between the relationships developed in this work and the relationships available in the literature suggests that generalization is conceivable. A community effort to assemble existing unpublished data should be considered to validate the newly developed relationships.

Water table depth in peatlands

In modelling studies, peatlands are generally conceptualized with a highly conductive upper layer, corresponding to the acrotelm (high K, high S_y, low ρ_{dry},and low humification), and a low conductivity bottom layer, corresponding to the catotelm (low K, low S_y, high ρ_{dry}, and high humification) (Baird et al., 2008). In this study, the transition was observed within the top 50 cm of peat, similar to what has been reported in the literature (see figure 11 and figure 12). For many authors, this strong vertical variation in hydrodynamic properties is crucial to understanding differences in water table depth. Peatlands characterized by a more conductive upper layer are expected to have a lower median water table depth and peatlands with a less conductive upper layer is expected to have a higher median water table depth. However, this is not what was observed in this study.

352 In this study, significant differences in ρ_{dry} and water table depths were found between sites, but no significant differences in K and S_y were observed. Moreover, no correlation was found between the hydrodynamic properties and water table depth. This suggests that factors other than K and S_y of peat (e.g., hydro-connectivity, climate) are probably involved in the control of water table depth. Moreover, since all sites are located in a similar climatic context, it is hypothesized that the connectivity between each peatland and a neighbouring river or superficial aquifer should be considered and included as control factors of water table depth (Winter, 2001).

Implications for eco-hydrological models

As discussed in Baird *et al.* (2016), a physically based representation of peat hydrology should account for both K and S_y. In indicator-based models, such as the HPM, K is quantified using ρ_{dry} and is used to model the yearly variation in water table depth. However, S_y is not represented. In models solving the Darcy flow equation (e.g., Modflow, Digibog), K_{sat} is vertically discretized as a function of depth and only Digibog has integrated S_y (constant value). The absence or the simplification of S_y limits the ability of eco-hydrological models to quantify water table fluctuations in peatlands, and therefore to reproduce their daily and monthly hydrodynamics. And, since peat accumulation and decomposition processes are highly dependent on water table depth (Belyea and Clymo, 2001; Blodau and Moore, 2003; Moore and Dalva, 1993), simulating carbon dynamics without adequately describing the vertical changes of S_y with depth poses a challenge. This is especially true when considering that droughts, which occur on a short time scale, can transform a temperate peatland from a carbon sink to a carbon source (Fenner and Freeman, 2011). Moreover, S_y is a necessary component of transient modelling. Therefore, the quantification of S_y should be a priority in any modelling application aiming to downscale eco-hydrological models. Such downscaling is becoming more and more important, because peatlands store large amount of carbon (Fenner and Freeman, 2011) and can be strongly affected by extreme climatic events, such as drought and extreme precipitation.

This work provides new functions that could be included in eco-hydrological models. For example, the HPM, which describes the accumulation and decay of peat with a definition

382 of annual peat layers (Frolking et al., 2010), could integrate the newly developed relationship between S_y and ρ_{dry} (see figure 14). Using this function would allow to the water table depth to be better determined following precipitation, and therefore the model to be temporally downscaled. Users of models based on the groundwater flow equation or Darcy's law, such as Digibog (Baird et al., 2012), could use the new equation describing S_y as a function of depth (see figure 12) to better discretize the vertical variation of S_y within the peat profile. If K values are available, they could be used to estimate unavailable S_y values (see figure 15). The use of these new equations would facilitate model calibration, provide more reliable peatland hydrology models, and contribute to a better understanding of peat accumulation and decomposition on short time scales (Belyea and Clymo, 2001; Blodau and Moore, 2003; Moore and Dalva, 1993).

393 However, as demonstrated in this study, describing the hydrodynamic properties that control water table fluctuations in peatlands and which are strongly linked to density profiles, is not sufficient to fully understand differences in water table depths between different sites. It is thus crucial to better understand how the connectivity of peatlands with aquifers and rivers can influence peatland hydrology.

398 **Conclusion**

399 The objectives of this study were to quantify relationships between ρ_{dry}, depth, K, and S_y, to be used in eco-hydrological models, to develop new functions that could improve eco-hydrological models, and to evaluate whether differences in water table depths of peatlands located in the St. Lawrence lowlands could be linked to vertical variations in hydrodynamic properties. The first and the second objectives were achieved by revisiting two functions (K-ρ dry; K-depth) and developing three new functions (K-Sy; Sy-depth; Sy-ρ dry) that could be integrated in future eco-hydrological models. These functions could lead to better model calibration, and alleviate the necessity for intensive laboratory measurements, while including peatlands in regional models and improving existing steady-state models. Importantly, in eco-hydrological models, these functions could contribute to downscaling models to include processes occurring at smaller time scales and to improving models to better describe flow dynamics within peatlands by including S_y. The third objective was achieved by comparing the statistical relationships between

water table depth and ρ_{dry}, depth, K, and S_y, and evaluating the strength of the correlation between all variables. A significant relationship between ρdry and water table depth was found, but there was no significant difference in K or Sy between the sites. A good linear correlation (R2 = 0.57) was found between ρdry and water table depth, but this is not the result of a difference in hydrodynamic properties. It is therefore crucial to better understand how the connectivity of peatlands with aquifers and rivers can influence water table depth in peatlands, although considerable improvements to hydrological modelling of peatlands are expected using the current results.

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Table

Table 1 Site description: coordinates, altitude, surface area, watershed, hydrogeology, peat thickness, microform, and presence or absence of groundwater input

site	Lat	Long	Altitude (m)	Area (km²)	Watershed	Hydrogeology	Peat thickness (cm)	Microform	Groundwater fed
CH	45.008	-73.828	310	0.5	Chateauguay	Fractured Cambrian sandstone	322	Hummock/hollow/pools	Yes
LTF	45.132	-74.217	51	6.0	Chateauguay	Marine clay	493	Hummock/lawns	No
SSE	46.042	-72.345	84	4.9	Nicolet	Fluvial silt/Glacial clayey silt	522	Hummock/lawn	Yes
LCY	45.950	-72.187	106	0.5	Nicolet	Eolian fine to medium sand	190	Hummock/lawn	No
VIC	46.023	-72.077	118	2.6	Nicolet	Marine exondated fine sand	360	Hummock/hollows	No
VR	46.376	-71.838	124	10.4	Becancour/du Chene	Eolian sand/Glacial clayey silt	491	Hummock/hollow/pools	Yes
ISO	46.579	-71.597	117	2.8	du Chene	Glacial clayey silt	454	Hummock/hollow/pools	No

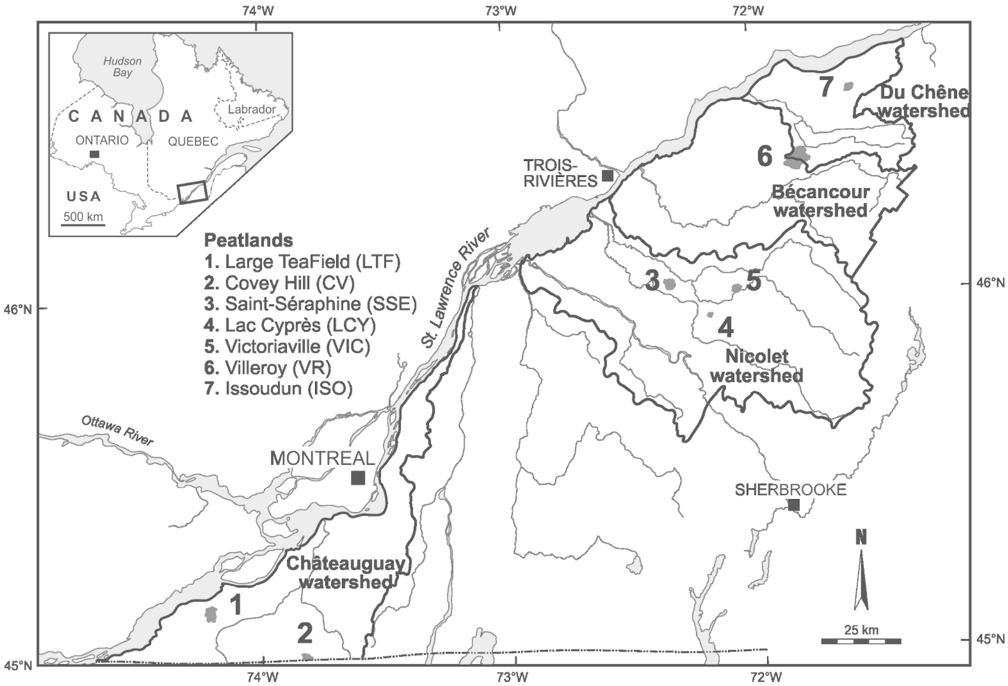

Figure 1. Locations of the seven studied peatlands in the Châteauguay (1-CH and 2-LTF), Nicolet (3-SSE, 4-LCY, and 5-VIC), Bécancour (6-VR), and Du Chêne (7-ISO) watersheds of southern Quebec (Canada).

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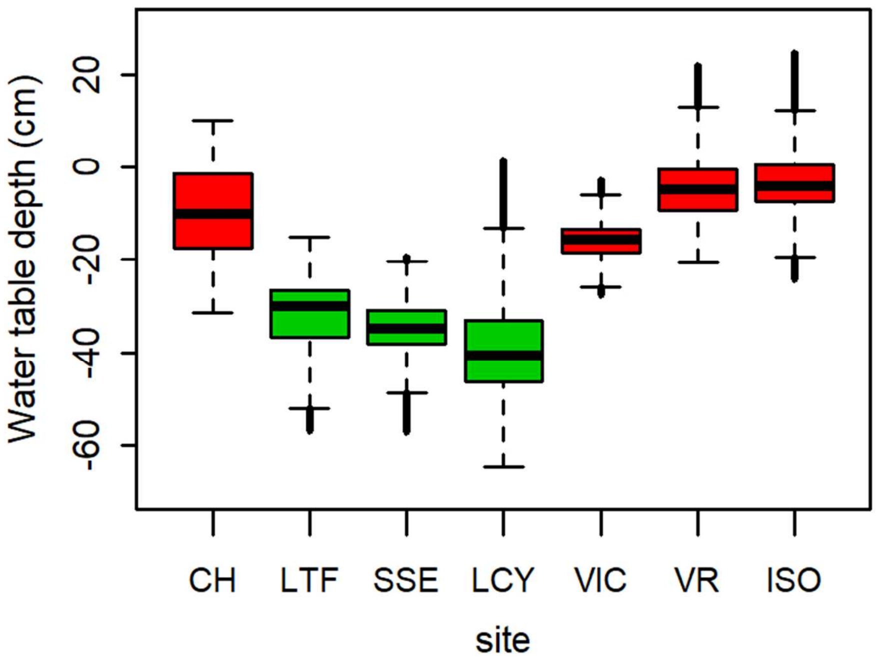

Figure 2 Water table depths (WTD) for all locations (up-gradient, mid-gradient, down-gradient) of the seven sites (CH, LTF, SSE, LCY, VIC, VR, and ISO) from June 2014 to May 2016. Colors show significant differences in WTD between the sites. Red boxplots show the significant different group composed of CH, VIC, VR, and ISO whereas green boxplots show the second group composed of LTF, SSE, and LCY.

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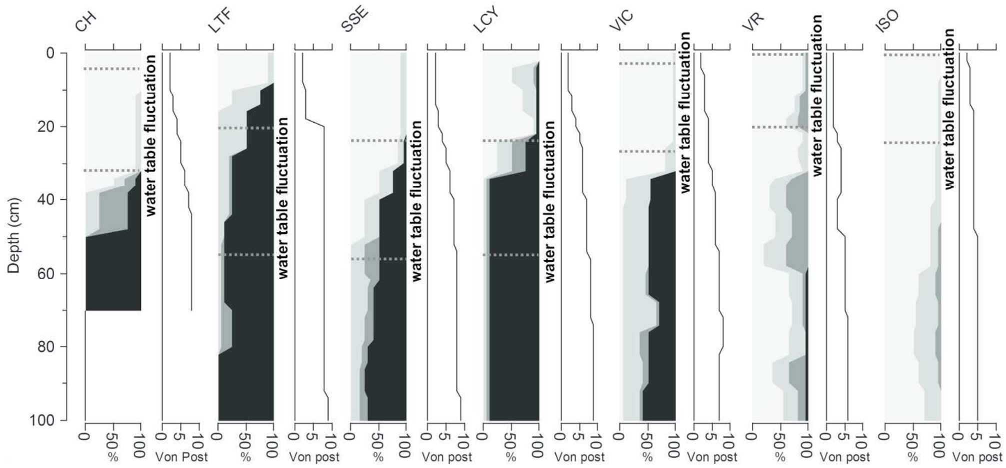

Figure 3. Description of peat composition (shading), peat humification, maximum and minimum water table depths (dark grey dashed lines), and degree of humification(von Post; black line) from one core (up-gradient) of each of the seven sites (CH, LTF, SSE, LCY, VIC, VR, and ISO). Black = Detritus granosus ; dark gray = Turfa herbacea ; grey = Turfa lignosa and light grey = Turfa bryophytica.

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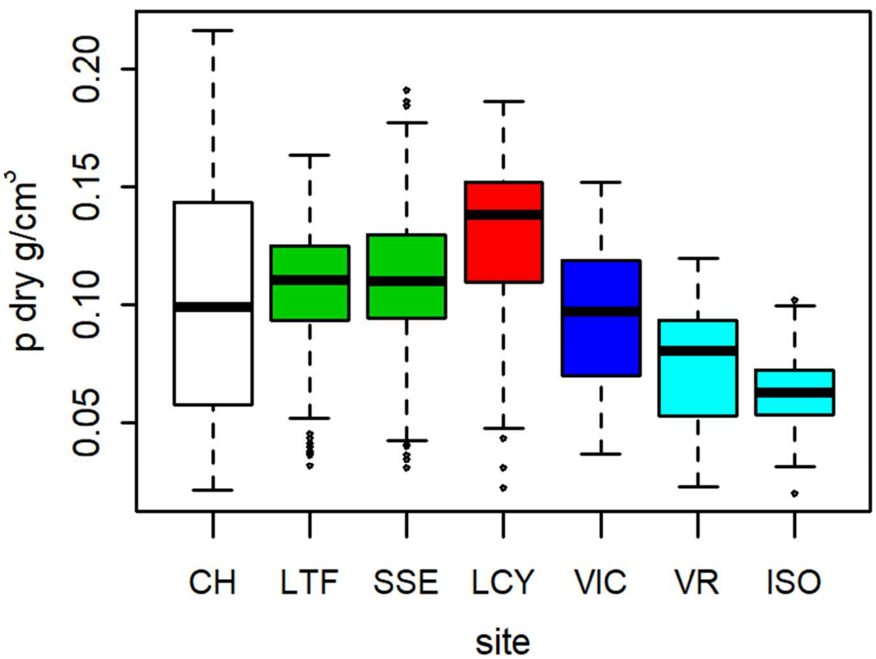

Figure 4 Bulk dry density variation for all locations (up-gradient, mid-gradient, down-gradient) of the seven sites (CH, LTF, SSE, LCY, VIC, VR, and ISO). Colors show significant differences in bulk dry density between the sites. Red shows the group with the highest ρ dry and light blue the group with the lowest ρ dry. The group shown in white show both similarities with the green group and the dark blue group.

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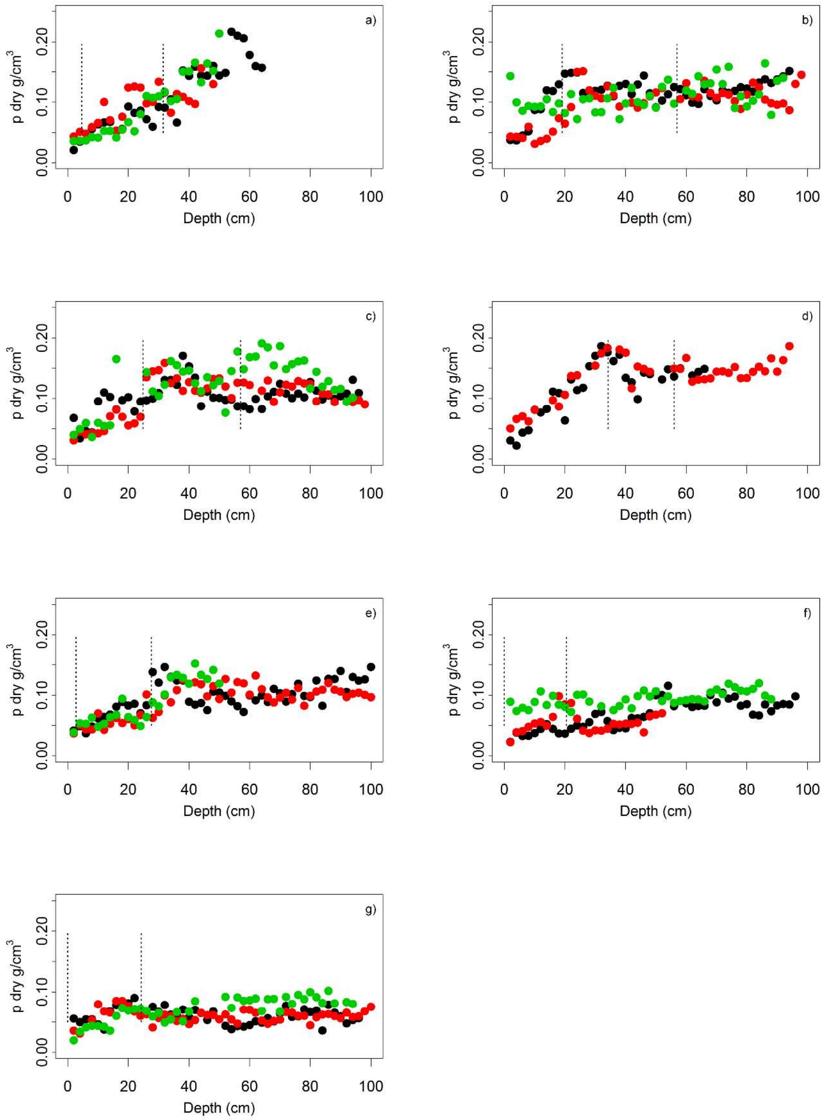

Figure 5 Variations in dry bulk density (ρdry) with depth in the up-gradient (black), mid-gradient (red), and down-gradient locations (green) of a) CH, b) LTF, c) SSE, d) LCY, e) VIC, f) VR, and g) ISO. Black vertical dashed lines represent maximum and minimum water table depths in the up-gradient location.

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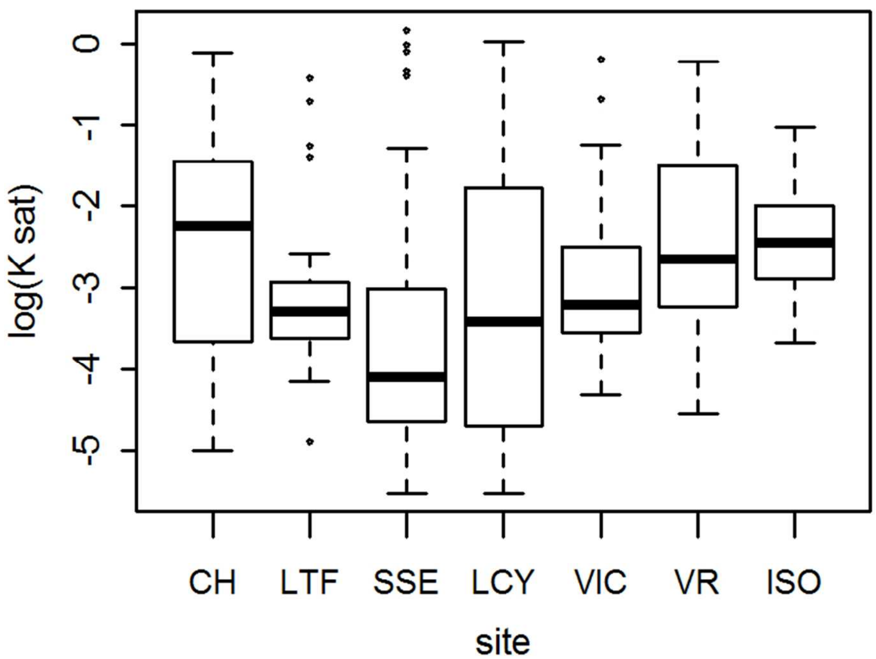

Figure 6 Hydraulic conductivity variations for all locations (up-gradient, mid-gradient, down-gradient) of the sites (CH, LTF, SSE, LCY, VIC, VR, and ISO).

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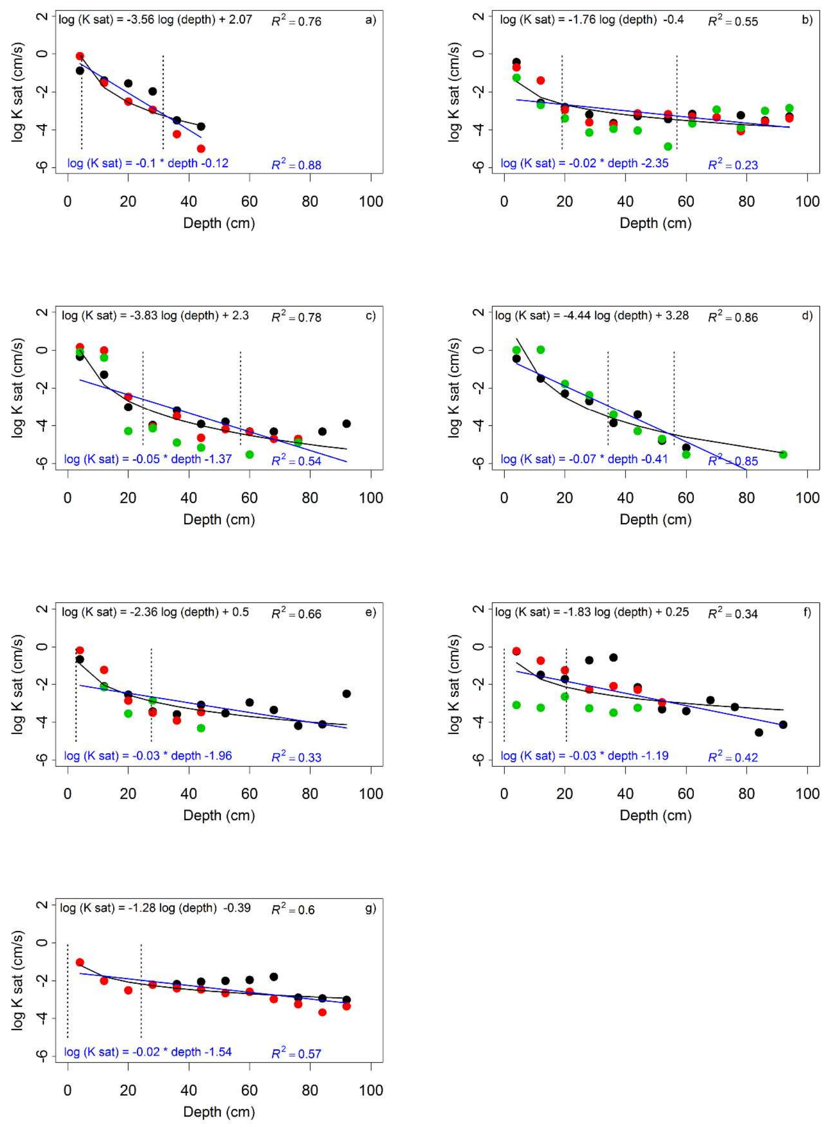

Figure 7 Log Ksat variation with depth in the up-gradient (black), mid-gradient (red) and down-gradient locations (green) of a) CH, b) LTF, c) SSE, d) LCY, e) VIC, f) VR, and g) ISO, including the log-log model (black line) and the log model (blue line), and the R2 of each. Black vertical dashed lines represent the maximum and minimum water table depths in the up-gradient locations.

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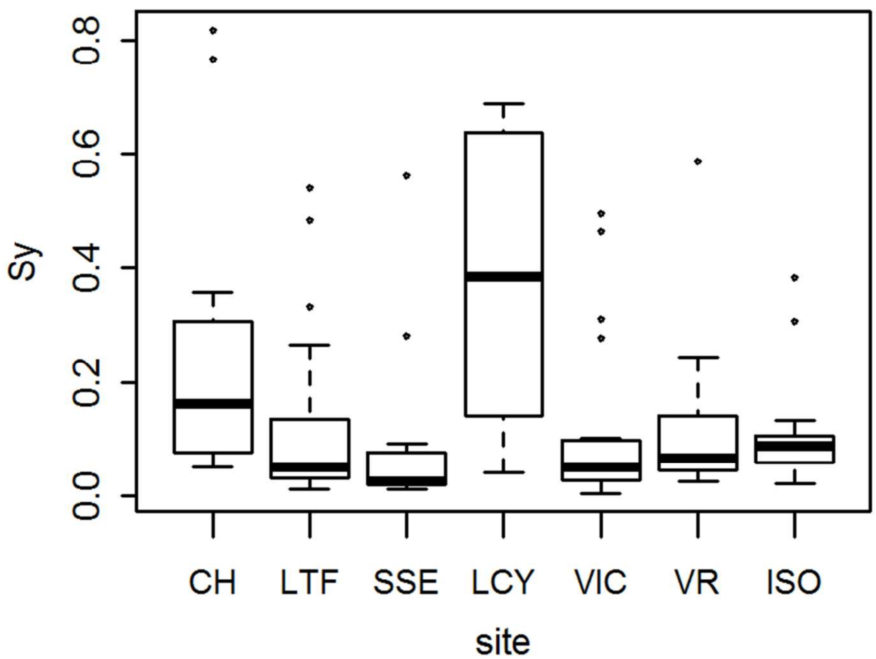

Figure 8 Specific yield (Sy) variations for all locations (up-gradient, mid-gradient, down-gradient) of the sites (CH, LTF, SSE, LCY, VIC, VR, and ISO).

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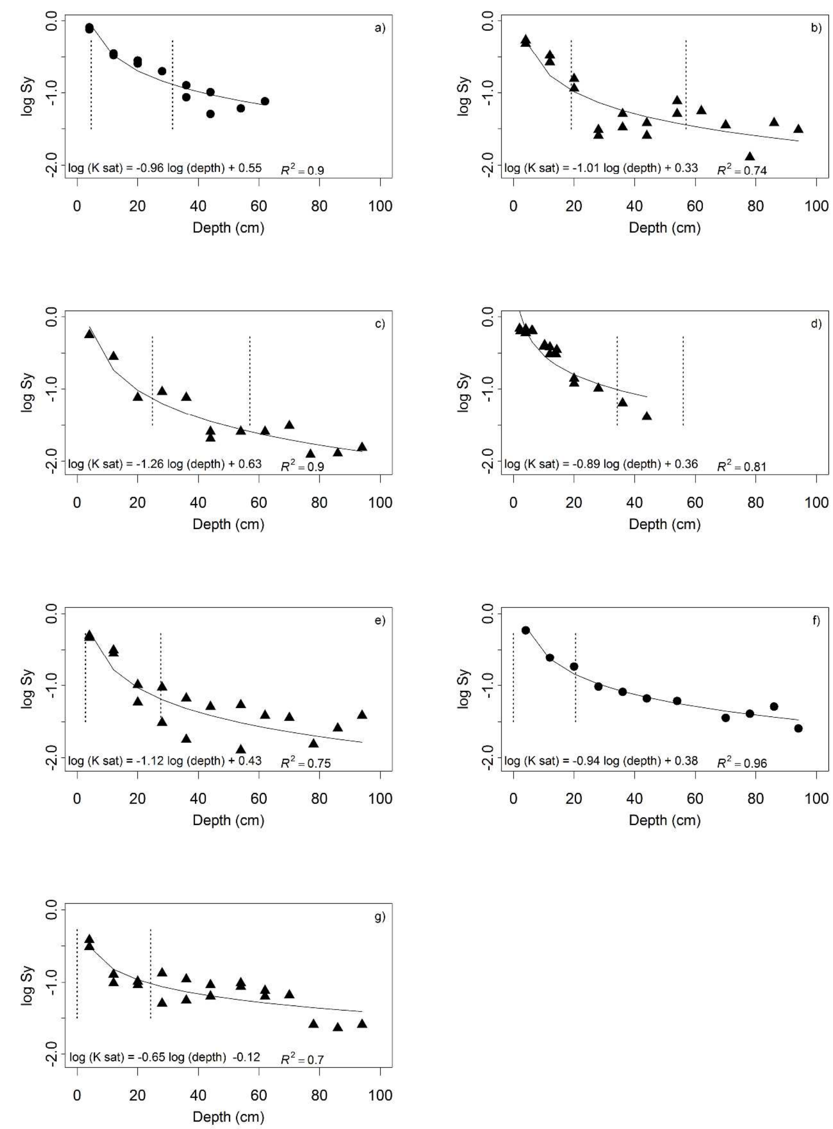

Figure 9. Log-log model (black line) of Sy variations with depth in the up-gradient (black) location of the seven peatlands . The circles correspond to new data from this study, and the triangles to data from Bourgault et al. (2016). Black vertical dashed lines represent the maximum and minimum water table depths in the up-gradient locations.

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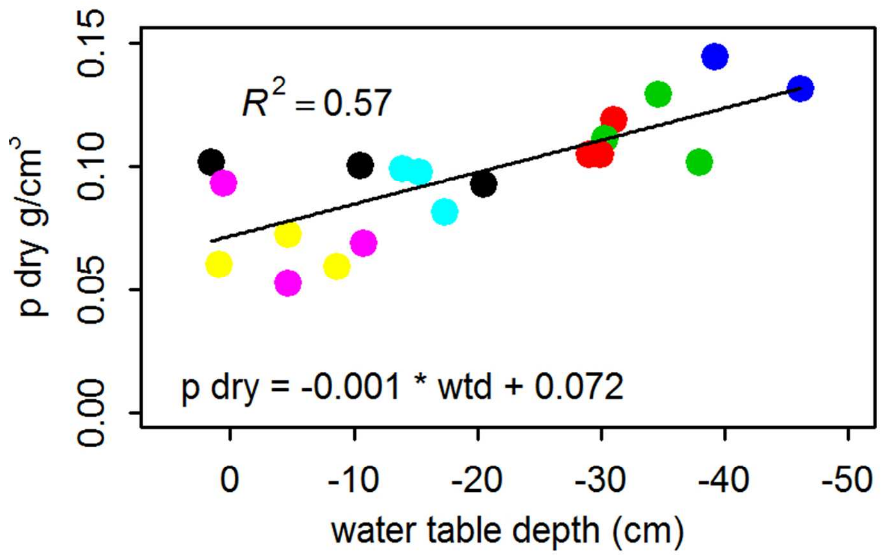

Figure 10 ρdry as a function of median water table depth for all locations in the seven peatlands. Black = CH, red= LTF, green= SSE, dark blue=LCY, light blue= VIC, pink= VR, and yellow=ISO. The black line shows the linear regression model.

76x50mm (300 x 300 DPI)

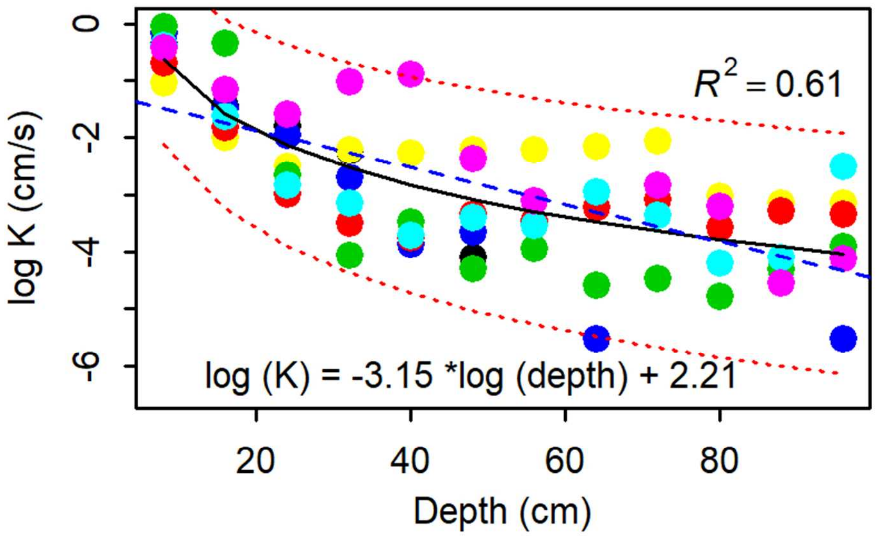

Figure 11. log K as a function of depth for all locations in the seven peatlands (Black = CH, red= LTF, green= SSE, dark blue=LCY, light blue= VIC, pink= VR, and yellow=ISO). The black line shows the log-log model developed in this paper, the dashed red lines show the upper and the lower log-log model calculated using a confidence interval of 95% on the parameters α and β, and the dashed blue line shows the semi-log model developed by Young (1968) and used in the Digibog model (Baird et al., 2012).

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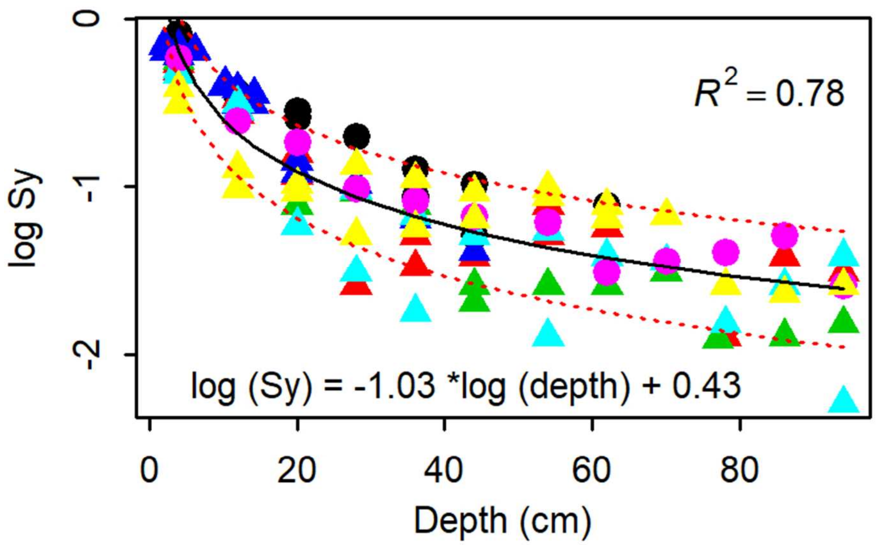

Figure 12. Sy as a function of depth for all locations in the seven peatlands (Black = CH, red= LTF, green= SSE, dark blue=LCY, light blue= VIC, pink= VR, and yellow=ISO). The black line shows the model developed in this paper. The dashed red lines show the upper and the lower log-log model calculated using a confidence interval of 95% on the parameters α and β. The circles correspond to new data from this study and the triangles represent data from Bourgault et al. (2016).

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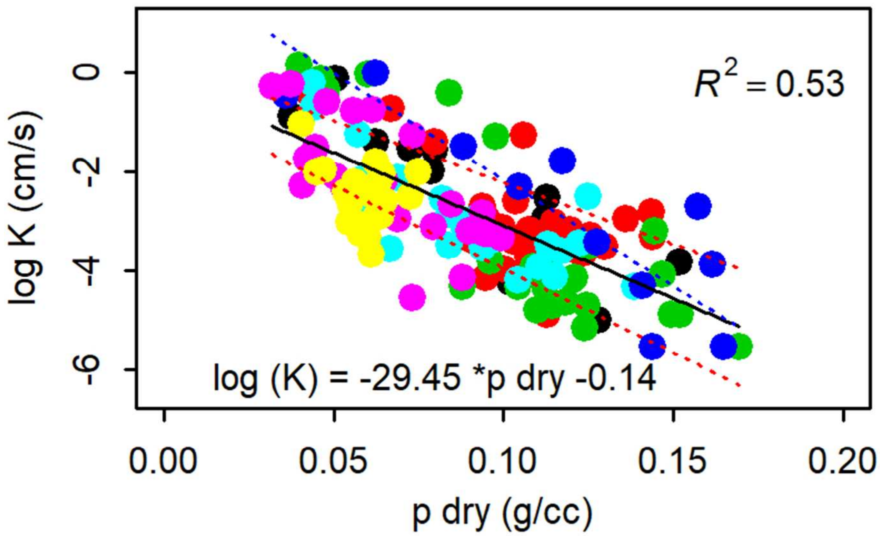

Figure 13 Log K as a function of ρdry for all locations in the seven peatlands. Black = CH, red= LTF, green= SSE, dark blue=LCY, light blue= VIC, pink= VR, and yellow=ISO. The black line shows the semi-log model developed in this paper, the dashed red lines show the upper and the lower log model calculated using a confidence interval of 95% on the parameters α and β, and the dashed blue line shows the semi-log model developed by Radforth and Brawner (1977) and used in the Holocene Peat Model (Frolking et al., 2011).

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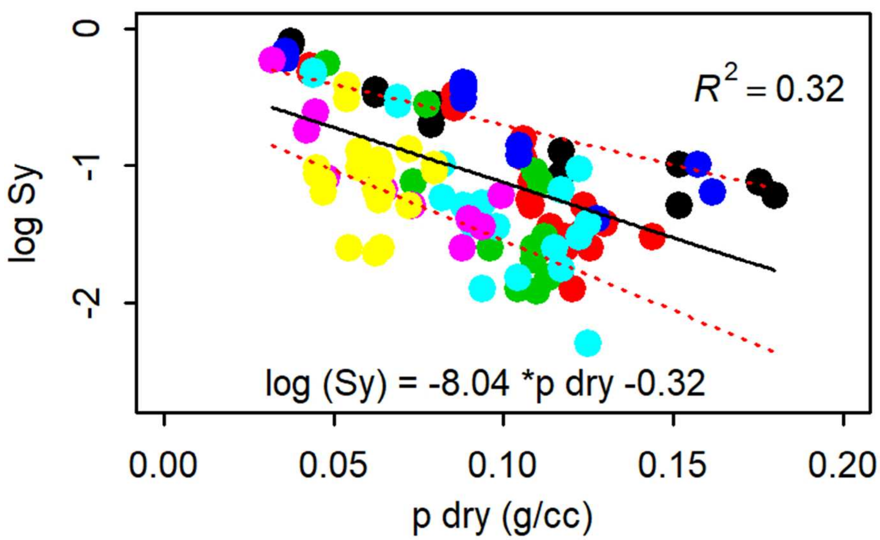

Figure 14 Sy as a function ρdry for all locations in the seven peatlands (Black = CH, red= LTF, green= SSE, dark blue=LCY, light blue= VIC, pink= VR, and yellow=ISO). The black line shows the model developed in this study. The dashed red lines show the upper and the lower log model calculated using a confidence interval of 95% on the parameters α and β.

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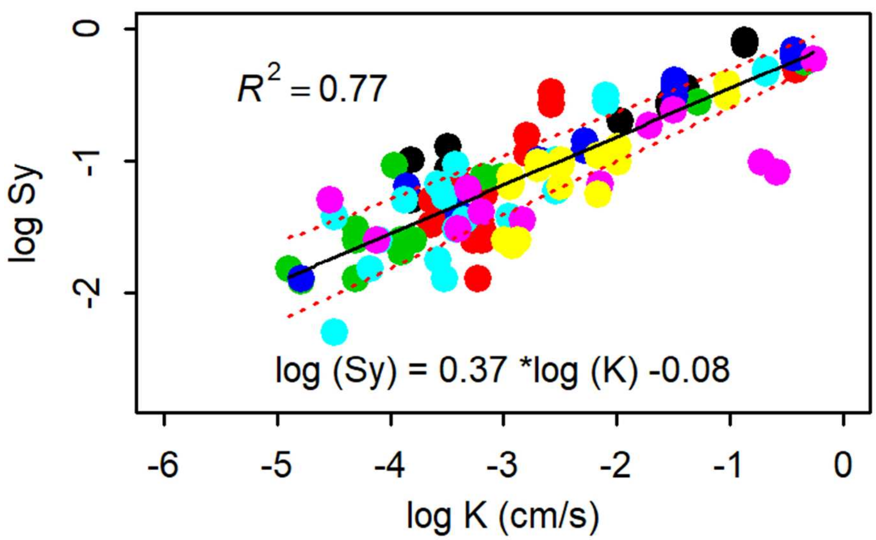

Figure 15 Sy as a function K for all locations in the seven peatlands (Black = CH, red= LTF, green= SSE, dark blue=LCY, light blue= VIC, pink= VR, and yellow=ISO). The black line shows the model developed in this study. The dashed red lines show the upper and the lower log-log model calculated using a confidence interval of 95% on the parameters α and β.

76x50mm (300 x 300 DPI)