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Quantification of peatland water storage capacity using the water table fluctuation method

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1 Abstract

Peat specific yield (S_Y) is an important parameter involved in many peatland hydrological functions such as flood attenuation, baseflow contribution to rivers and maintaining groundwater levels in surficial aquifers. However, general knowledge on peatland water storage capacity is still very limited, due in part to the technical difficulties related to *in situ* measurements. The objectives of this study were to quantify vertical S_Y variations of water tables in peatlands using the water table fluctuation method (WTF) and to better understand the factors controlling peatland water storage capacity. The method was tested in five ombrotrophic peatlands located in the St. Lawrence Lowlands (southern Québec, Canada). In each peatland, water table wells were installed at three locations (up-gradient, mid-gradient and down-gradient). Near each well, a 1 m long peat core (8 cm x 8 cm) was sampled, and sub-samples were used to determine S_Y with standard gravitational drainage method. A larger peat sample (25 cm x 60 cm x 40 cm) was also collected in one peatland to estimate S_Y using a laboratory drainage method. In all sites, the mean water table depth ranged from 9 to 49 cm below the peat surface, with annual fluctuations varying between 15 and 29 cm for all locations. The WTF method produced similar results to the gravitational drainage experiments, with values ranging between 0.13 and 0.99 for the WTF method, and between 0.01 and 0.95 for the gravitational drainage experiments. S_Y was found to rapidly decrease with depth within 20 cm, independently of the within-site location and the mean annual water table depth. Dominant factors explaining S_Y variations were identified using ANOVA. The most important factor was peatland site, followed by peat depth and seasonality. Variations in storage capacity considering site and seasonality followed regional effective growing degree days and evapotranspiration patterns. This work provides new data on spatial variations of peatland water storage capacity using an easily implemented method that requires only water table measurements and precipitation data.

Key words: peatland, water storage, specific yield, water table fluctuation, drainage experiment

2 Introduction

Peatlands play important hydrologic functions by attenuating flooding by storing water during high precipitation events (Acreman and Holden, 2013), contributing to river base flows (Bourgault *et al.*, 2014) and maintaining groundwater levels in superficial aquifers (McLaughlin *et al.*, 2014). However, enhanced knowledge on quantification of water storage capacity is needed to better understand these peatland hydrological functions. In peatlands, peat storage capacity (S) strongly varies within the first meter and buffers water table fluctuations, flow velocities and evapotranspiration fluxes (White, 1932). For example, when the water table is high, flow velocities and evapotranspiration fluxes increase; the opposite happens during low water table periods.

In mineral aquifers, long-term water storage is also controlled by climatic forcing such as summer water deficits (Yeh *et al.*, 2006), by anthropogenic activities such as groundwater extraction, and to a more limited extent by land drainage which can reduce aquifer recharge (Winter *et al.*, 1998). Short-term changes occur mainly in response to rainfall, pumping, and evapotranspiration fluxes (Healy and Cook, 2002; Geris *et al.*, 2015). These processes are also active in peatland ecosystems. They are especially important due to the contrasted values of S between the acrotelm and the catotelm (Ingram and Bragg, 1984). In addition, peat S also changes due to expansion and compression, which is a seasonal effect of water content variation (also named *mire breathing*; Price and Schlotzhauer, 1999), ice expansion in the peat, or a longer time scale effect of organic matter oxidation. Therefore, water table fluctuation does not occur only when air enters the specific yield (S_Y) as the water table declines. However, as a first approximation S is usually assimilated to S_Y (Price, 1996).

Peat S_Y can vary by up to two orders of magnitude (0.01 – 1) within the first top 50 cm (Vorob'ev, 1963; Holden, 2009; Dettmann and Bechtold, 2016). This buffers peatlands against both inundation and excessive drying (Waddington *et al.*, 2015). S_Y has been quantified based on field measurements using porous disk infiltrometers (Holden *et al.*, 2001; Holden, 2009), rain-to-rise ratio (Letts *et al.*, 2000; McLaughlin and Cohen, 2014; Dettmann and Bechtold, 2016), tracer tests (Ronkanen and Klove, 2008), laboratory drainage experiments (Vorob'ev, 1963; Price, 1996; Rosa and Larocque, 2008), and pressure chamber measurements (Moore *et al.*, 2015). The rain-to-rise ratio method is equivalent to the water table fluctuation method (WTF; White, 1932) commonly used in aquifers to quantify groundwater recharge (Healy and Cook, 2002).

The WTF method is a simple alternative to laboratory measurements. It has significant potential as an easily implemented, low-cost method to determine peat S_Y. Because peat deposits are heterogeneous (Baird *et al.*, 2015) and compressible media where hysteresis is observed between water table rise and precipitation due to air encapsulation, gas bubble production, and unsaturated pore filling (Nachabe, 2002; Barton *et al.*, 2006; Ramirez *et al.*, 2015), we hypothesised that the WTF method is more adapted to peatland than conventional laboratory measurements. The use of the WTF method in peatlands, offers an excellent opportunity to upscale the understanding of water storage capacity using widely available data of water table and precipitation.

The objective of this research was to adapt the WTF method to quantify vertical S_Y variations in peatlands and better understand the factors controlling their water storage capacity. It is assumed that seasonal expansion and compression expansion of peat do not influence the short-term rain event-based calculation of S_Y. It is also assumed that changes in peat surface topography following a single rain event can be considered negligible. The WTF method was tested in five ombrotrophic peatlands located in the St. Lawrence Lowlands in southern Quebec (Canada), and results were compared to S_Y estimates from laboratory measurements on collected peat samples.

3 Study sites

The five studied peatlands (Large Tea Field – LTF, Sainte-Séraphine – SSE, Lac Cyprès – LCY, Victoriaville – VIC, Issoudun – ISO) are located in the southern part of the St. Lawrence Lowlands (Quebec, Canada) in three different watersheds (Châteauguay, Nicolet, and Du Chêne) (Figure 1). All sites are headwater peatlands formed in topographic depressions, except LCY, which is located on the flank of fine to medium aeolian sand deposits. All sites are characterized by a hummock and lawn microtopography without any surface pools. Hollows and mud bottom were found only at sites ISO and VIC.

The five sites are set in different geological contexts, characterized by quaternary surficial sediments (marine clay, fluvial sandy silt, clayey silty till, aeolian fine to medium sand, and regressive marine sand) deposited following the last deglaciation since 12,3 kaBP (Richard and Occhietti, 2004) (Table I). Peat thickness vary between 40 cm and 522 cm with maximum of 190 cm in LCY, 522 cm in SSE, 493 cm in LTF, 345 cm in VIC and 454 cm in ISO. Their surface range between 0.5 and 6.0 km^2 (Table 1) and they have developed as complexes with a central ombrotrophic section. Lateral minerotrophic conditions were found only at site SSE.

Mean annual precipitation (reference period: 1981 – 2010) for the Châteauguay (LTF), Nicolet (SSE, LCY, VIC), and du Chêne (Issoudun – ISO) watersheds varies between 965 mm (Châteauguay) and 1114 mm (Nicolet), with the driest conditions recorded in the LTF region specifically. For all sites (Figure 2), minimum monthly precipitation occurs during the winter, and maximum monthly precipitation occurs during the summer (Environment Canada, 2015). Mean annual temperature (for the same reference period as for mean annual precipitation) varies between 4.8 °C and 6.7 °C, with the lowest values in the ISO region. For all sites, minimum and maximum temperatures are recorded in January and July respectively (Figure 2). Effective growing degree days (GGD>0) (reference period: 1974-2000) varies between 1800 and 2000 for the Châteauguay watershed, between 1600 and 1800 for the Nicolet watershed, and between 1400 and 1600 for the du Chêne watershed (Atlas agroclimatique du Québec, 2012) (Table I).

Vegetation surveys performed at all sites show that *Sphagnum spp.* (*Sph* sp.), *Kalmia angustifolia* (*Kal ang*), and *Eriophorum vaginatum* (*Eri vag*) are the main species. *Andromeda glaucophylla* (*And gla*), *Aulacomnium palustre* (*Aul pal*), *Chamaedaphne calyculata* (*Cha cal*), *Carex spp.* (*Car* sp.), *Rhododendron groenlandicum* (*Rho gro*), and *Polytricum strictum (Pol str)* were also found, albeit sparsely (Larocque *et al.*, 2015; Lefebvre *et al.*, 2015; Pasquet *et al.*, 2015). Climatic conditions differ slightly from west to east, in terms of effective growing degree days and ecoregion vegetation assemblages, from the hickory and maple forest (*Carya cordiformis* and *Acer saccharum*) in the western section (LTF), to the lime tree and maple forest (*Tilia americana* and *Acer saccharum*) eastward, which supports the slightly colder and wetter conditions of the ISO site.

4 Methodology

4.1 Site instrumentation

Elevation data were obtained for the five sites from a Digital Elevation Model (DEM; 1 x 1 m resolution) derived from airborne light detection and ranging (LiDAR) surveys. Absolute errors on elevations vary between 5 and 48 cm (Hodgson and Bresnahan, 2004; Aguilar *et al.*, 2010), with the smallest errors for open areas. Based on the DEM, three locations were identified in each peatland (up-gradient, mid-gradient, and down-gradient) for the installation of wells (Figure 3). Distances between up-gradient and down-gradient wells vary between 123 and 760 m with mean slopes from 0.08% to 0.24% (Table 1).

Water table variations were recorded at these three locations within each site using wells constructed from 3 cm OD PVC pipes, with 2 m long intakes perforated with 0.0254 cm slits from top to bottom, and sealed at their base. All wells were inserted into *Sphagnum* lawn microforms. Sites were also equipped with three level loggers (Solinst), a barometric logger (Solinst), and a rain gauge tipping bucket (Hobo). The level loggers and barometric loggers were attached to the well screw tops. Water table variations, barometric pressure, and precipitation were measured every 5 minutes from June 2014 to August 2015 (with the exception of the winter months between November 2014 and April 2015). Sites were also instrumented with a metal bar at down-gradient locations to monitor changes in topography due to peat expansion and contraction. These changes were monitored three times during the study period (spring, summer, and autumn) using a reference level located on the metal bars.

4.2 Small cube experiment

Five 1 m long peat cores were sampled using a Box corer (8 x 8 cm) (Jeglum, 1991) at the up-gradient location of each studied peatland. Sampling compression in the acrotelm was 10 cm for LTF, 12 cm for SSE, 20 cm for LCY, 8 cm for VIC, and 2 cm for ISO, and were proportional to the acrotelm thickness. Cores were cut into two 50 cm sections using a sharp knife, wrapped in cellophane, and stored at 4°C. Humification analysis was performed on 5 cm peat slices throughout the whole 5 cores. S_Y measurements were performed on 7 x 7 x 8 cm peat samples (14 cores in total; 3 for LTF, 3 for SSE, 2 for LCY, 3 for VIC and 3 for ISO) using gravity drainage experiments assuming that S_Y can be assimilated to its drainable porosity (Price, 1996).

Gravity drainage was performed in acrylic cubes (7 x 7 x 8 cm) and used to estimate S_Y following Eq. (1) (Freeze and Cherry, 1979),

$$S_Y = \frac{V_d}{A*\Delta h} \quad (1)$$

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). Peat samples were resized after 0.5 cm was cut from each side to remove any compression due to transportation. Samples were saturated for 24 hours and drained for an additional 24 hours. Each acrylic cube was connected at the bottom to a 1.3 cm plastic tube 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. Although slightly different from conventional drainage experiments, this method was specifically chosen so as to be comparable to the experimental tank method described in section 4.3.

For the less decomposed samples, the errors were proportional to the lost volume due to compression above the water table. Errors were calculated using the ratio between the loss of height and the mean annual water table depth since compression was limited to the unsaturated zone. Since compression was not evenly distributed throughout the core, errors on S_Y measurement were only applied to the upper 20 cm.

For the more decomposed samples (below 20 cm; all the sites), rapid outflow was observed, probably due to secondary porosity created during sample insertion into the acrylic cubes. The rapid outflow was measured at the beginning of each experiment and divided by the total volume of the acrylic cubes (7 x 7 x 8 cm) to quantify the maximum error associated with the method.

4.3 Experimental tank

The laboratory method developed by Rosa and Larocque (2008) to estimate S_Y was adapted to quantify the fine-scale, empirical relationship between S_Y and depth below the peat surface. Laboratory experiments were conducted in a 40 cm long, 25 cm wide, and 36 cm high experimental tank built using 4 mm thick clear acrylic panels (Figure 4). The peat sample was retrieved from the LTF peatland at the up-gradient location. The mean water table depth (26 cm) at this site is equivalent to that of the four other studied peatlands, making it representative of all sites for this experiment. No compression was observed during sampling.

In the laboratory, the two sides of the peat sample were supported with perforated stainless steel plates to create two experimental reservoirs. These reservoirs were connected using flexible 5.1 cm PVC tubing, and redirected to a single outlet to control water table elevation within the reservoirs. The tank was filled from the bottom with water collected in the field with 4 L Nalgene bottles. A neon lamp suspended 15 cm above the tank provided 12 h of daylight to maintain living vegetation conditions.

Drainage experiments were performed every centimetre between 0-20 cm, and every 2.5 cm between 20-36 cm. Drainage intervals were increased below 20 cm so as to reduce volumetric error measurements since S_Y and drained water decrease with depth below the peat surface. Drainage experiments were performed twice for the upper 20 cm to account for air encapsulation and unsaturated pore filling (Nachabe, 2002; Barton *et al.*, 2006). No compression or expansion resulting in a change of the peat elevation was observed during the drainage experiments.

S_Y estimates were obtained using Eq. 1, as defined in section 4.2 above, but with an A = 40 cm x 25 cm = 1000 cm^2. However, S_Y could not be estimated below 0.08, due to an increase in volumetric error measurements associated with the decreasing water volume released from the drainable porosity and to bottom sedimentation within the two reservoirs.

4.4 Water table fluctuation method

Using the WTF method, specific yield (S_Y) was calculated as follows:

$$S_Y = P/\Delta h \quad (2)$$

where P is the amount of precipitation, and Δh is the water level rise following a precipitation event. Eq. (2) assumes that the time lag between the end of each precipitation event and the maximum water level rise is sufficiently short for evapotranspiration, net subsurface flow and water table recession following P events (i.e., water reaching the saturated zone is entirely transferred into storage). The method also assumes that recharge is equal to precipitation (i.e., no runoff), that the static equilibrium water content profile within the unsaturated zone is attained instantaneously following a rain event and that any rain-to-rise ratio deviation from a theoretical model will be due to the presence of a capillarity fringe, air entrapment, peat expansion and contraction, net subsurface flow, water recession following P events and antecedent moisture content of the unsaturated zone.

A computation script written in the R language (R, 2008) was developed to identify the precipitation events to be considered and the maximum water table rise following each precipitation event. The program automatically calculated total precipitation during a given event (P), maximum water level rise following this event (Δh), and S_Y using three parameters: the time interval ($Time_{int}$), the maximum (max_{prec}) and minimum precipitation (min_{prec}). $Time_{int}$ was used to separate precipitation events. Max_{prec} and min_{prec} were used to determine which precipitation events to include in the S_Y calculation. Small precipitation events were excluded based on the assumption that a large proportion of the precipitation never reached the saturated zone during these events. Large precipitation events were also excluded since they induced large Δh with depth approximation error. Measurement errors on Δh were equal to 1 mm whereas P errors are estimated to be as high as 6.4 % of total P for small rain events (Chiah, 2003; Hodgkinson *et al.*, 2004). Therefore, precipitation events smaller than 1 mm and larger than 35 mm, and those associated with water table variations smaller than 10 mm were excluded, since the relative error on rain to rise ratio (equivalent to S_Y) was too large in these cases.

While calibrating the R program, variations with $Time_{int}$ were set between 1 and 10 hours, max_{prec} between 20-100 mm and min_{prec} between 0-10 mm. These intervals were chosen since precipitation events between 10 and 20 mm easily reached the saturated zone and were well constrained vertically. $Time_{int}$, max_{prec}, and min_{prec} were calibrated to minimize the residual sum of squared errors (RSSE) between the model estimation, using S_Y obtained from the WTF method, and the individual laboratory S_Y values, obtained using the small cube experiment and the experimental tank method, while seeking to retain a maximum number of precipitation events. A minimal value of $Time_{int}$ was used to support the hypothesis that subsurface flow was negligible and that the night-time recession period (4 to 9 hours) was greater than $Time_{int}$. This is based on the observation that the time lag between the end of a precipitation event and the maximum water table increase was less than 3 hours (mean of 2 hours) for all rainfall events.

For all-time series analysis, $Time_{int}$, max_{prec}, and min_{prec} were set to 3 hours, 35 mm and 7 mm, respectively. Time series were resampled at 10, 20, 30, 40, and 60 min, and one day time intervals to identify the maximum time step required to calculate S_Y. Modification of the selected time intervals had no effect on S_Y calculation, except for the one day time interval. To optimize calculations, the one hour time series interval was used for all S_Y calculations.

All S_Y calculated using the WTF method ($S_{Y\ WTF}$) were compared between sites, depths, location within the peatland, and seasonality, using one-way Analysis of Variance (ANOVA) implemented in R. Significant differences found among these variables were further analyzed using Tukey's Honest Significant difference (HSD), again in R. Finally, all S_Y and rates of S_Y decrease with depth obtained from the WTF, the experimental tank, and the small cube experiment methods were compared.

5 Results

5.1 Surface topography, hydrology and peat humification

At all locations in the five studied peatlands, the upper 5 cm was composed of living vegetation while peat was slightly humified between 10 and 20 cm below the surface (H3-H4; (Von Post, 1922). Peat humification increased toward the catotelm, with highly decomposed peat (H7- H8-H9) for sites VIC, LCY, LTF, and SSE, and slightly to moderately decomposed peat (H4-H5) for site ISO.

Throughout the five peatlands, water table depths (WTD) varied between 1 and 60 cm, with a maximum measured variation of 19 cm in LCY, 26 cm in SSE, 24 cm in LTF, 15 cm in VIC, and 19 cm in ISO. With the exception of VIC, WTD decreased from the up-gradient to the down-gradient locations (Figure 5). Mean WTD for all sites combined varied between 9 and 49 cm for up-gradient locations, between 12 and 33 cm for mid-gradient locations, and between 6 and 44 cm for down-gradient locations. Mean WTD for all locations in a given site in 2014 and 2015 were 41 cm in LCY, 37 cm in SSE, 26 cm in LTF, 19 cm in VIC, and 9 cm in ISO. Acrotelm thickness varied between 35 cm and 55 cm (comprised value of humification lower than H5) with mean acrotelm thickness equaled to 55 cm for LCY, 50 cm for SSE, 45 cm for LTF, 30 cm for VIC and 45 cm for ISO.

Changes in peat surface topography throughout the study sites and within each peatland were on average 1.0 cm during the two monitored growing seasons. One extreme value of 5 cm change in peat surface topography was measured at the ISO site where ice was still partly presents following the record-cold winter 2014-2015.

5.2 Specific yield estimated using the small cube method experiment and experimental tank measurements

The S_Y values estimated using the cube (S_{Ycube}) and the tank (S_{Ytank}) methods varied from 0.01 and 0.95 within the first meter (S_{Ycube} and S_{Ytank} cannot exceed 1.0) (Figure 6). The mean S_{Ytank} and S_{Ycube} of the living and slightly humified peat layer comprised within the acrotelm was 0.69 and 0.35 for the two methods respectively. For the cube method, S_Y rates decreased with depth, varying between 0.001 and 0.030 cm^{-1}. The upper ~25 cm showed rates of decrease varying from 0.015 cm^{-1} to 0.030 cm^{-1}, whereas the rate of decrease between 25 cm and 100 cm is indistinguishable from 0 cm^{-1}. The average S_Y measurement error for the small cube experiment on the 0-20 cm samples was 0.49 for LCY, 0.32 for SSE, 0.38 for LTF, 0.42 for VIC and 0.22 for ISO, with an overall mean of 0.37. The average S_Y measurement error due to this manipulation was estimated to be 0.05 (n=40), with a maximum value of 0.11. For the experimental tank method, the rate of S_Y decrease with depth is 0.07 cm^{-1} between 10 and 25 cm, and 0.005 cm^{-1} for the bottom sections (25-30 cm). While modeling S_{Ytank} as a function of depth, S_{Ytank} between 0 and 10 cm were not considered due to the lack of variation with depth associated with the living vegetation.

Between 0 cm and 20 cm, S_{Ycube} measurements were considerably lower than S_{Ytank}, probably due to peat compression during coring for S_{Ycube} which varied between 2 and 20 cm. No compression was observed during sampling for the tank experiment. Hence, the S_{Ycube} measurements should be considered to represent the lower boundary of the true

S_Y values. Even if these data should not be used as absolute values, they suggest a non-linear trend of S_Y with respect to depth.

S_{Ytank} values for depth between 0 and 10 cm were relatively constant, and differed considerably from the values obtained at greater depth. This is consistent with the greater peat humification below 10 cm, which changed from poorly humified (H1-H2) above 10 cm to slightly humified (H3-H4) below.

Different regression models for the S_Y vs depth relationship (i.e., linear, log, and power law) were calculated. Similar to the work of Sherwood et al. (2013), the best fit model for both methods were power law models:

$$S_Y = \beta_0 depth^{-\beta_1} \quad (3)$$

where $\beta_0 =$ 1.45 and β_1= -0.75, with resulting RSSE = 0.62 for the small cube method, and where β_0 = 41.41 and β_1= 1.58, with resulting RSSE = 0.19 for the experimental tank method. These power law models are used henceforth to describe S_Y changes with depth. However, the rate of S_Y decrease with depth needs to be adjusted for each peatland since the mean water table depth and acrotelm thickness can vary between peatlands.

5.3 Specific yield estimated using the WTF method

During 2014 and 2015, a total of 1182 precipitation events were recorded, ranging between 1 and 57.2 mm, with a mean of 5 mm, and precipitation intensity varying between 0.2 to 27.6 mm/hour. During this period, Δh values varied from 10 to 178 mm. Following a rain event, the calculated $S_{Y\ WTF}$ varied between 0.02 and 2, with a mean of 0.59 (Figure 7). A total of 99 precipitation events (13%) generated $S_{Y\ WTF}$ values exceeding 1, 183 (24%) resulted in $S_{Y\ WTF}$ values between 0.59 and 1, and 465 (63%) resulted in S_Y values smaller than 0.59. Values of $S_{Y\ WTF}$ above 1 were not considered in the analysis since they did not respect the hypothesis that runoff was negligible.

$S_{Y\ WTF}$ values were highly variable between sites, with values between 0.32 and 0.99 for ISO, 0.18 and 0.99 for VIC, 0.13 and 0.99 for LTF, 0.25 and 0.90 for SSE, and 0.29 and 0.88 for LCY (Figure 8). The best fit power law equation for the S_Y-depth models used β_0 ranging from 6.69 to 2783.01 and β_1 from -0.94 to -2.23. Modeled rates of S_Y decrease with depth varied between 0.008 cm^{-1} and 0.06 cm^{-1} for all sites, with a higher rate of decrease when water table levels were high. The rate of S_Y decrease with depth shows similar patterns across all sites.

Results from the ANOVA showed that site, seasonality, within-site location, and depth have a significant effect on S_Y. Site ($p < 0.0001$), depth ($p < 0.0001$), and seasonality ($p = 0.007$) were the strongest factors, while location within the peatland was the weakest ($p = 0.05$; Figure 9).

Considering site (Figure 9a), LCY, VIC, and ISO show no significant difference in their median S_Y, whereas LTF and SSE, differ strongly from LCY, VIC, and ISO (confidence interval of 99%). For depth (Figure 9b), groups of 0-5, 5-10, and 10-15 cm show higher calculated S_Y than deeper groups. However, there are no systematic significant differences between all depth groups. For seasonality (Figure 9c), S_Y varies following the seasons and shows no significant difference during the wet periods (May, June, October, and November). Finally, the ANOVA results indicated that within-site location was not a dominant factor since no statistical difference was found between the up-gradient, mid-gradient, and down-gradient locations when comparing the different locations in a given peatland or when merging all the sites (Figure 9d).

6 Discussion

6.1 Specific yield measurements

The S_Y measurements and rates of decrease obtained in this study were generally consistent with the range of values reported for different types of wetlands (peatland, blanket peat, open water, constructed peatland, cutover bog) and using different methods (e.g., gravity drainage, moisture retention measurements, infiltration rate experiment, water table fluctuation method, tracer tests) (Table II). Using the WTF method, Moore et al. (2015), McLaughlin and Cohen (2014), and Dettmann and Bechtold (2016) reported S_Y values ranging from 0 to 1.1, from 0.13 to 1.05 and 0 to 0.9 within the first 50, 65 and 45 cm respectively. This was equivalent to rates ranging between ~ 0.007-0.013 cm^{-1}

(Moore *et al.*, 2015), 0.02 cm^{-1} (McLaughlin and Cohen, 2014) and ~ 0 – 0.08 cm^{-1} (Dettmann and Bechtold, 2016). Using pressure chamber experiment measurements as quantitatively equivalent to S_Y, Moore *et al.* (2015) found that S_Y varied between 0.1 and 0.7, at a rate ranging between 0.007 and 0.013 cm^{-1}. With infiltration measurements, Holden (2009) found that S_Y varied between 0.01 and 1.00 within the upper 20 cm, independently of the surface vegetation (with the exception of *Eriophorum*, where it reached 0.001). This is equivalent to a decrease in S_Y with depth of between ~ 0.02 and ~ 0.05 cm^{-1}. Finally, using gravity experiments, Vorob'ev (1963) investigated S_Y and the relationship between capillarity fringe and gravitational moisture in unforested low-lying swamps (the term used by the author to designate peatlands), and found that S_Y decreased non-linearly with depth, from ~0.09 to ~0.45, at a rate of ~0.04 to 0.06 cm^{-1} (Table II). In this study, S_Y varied between 0.13 and 0.99 using the WTF method and between 0.01 and 0.95 using the small cube and tank drainage experiments. These results are strong observational evidence of the sharp decrease of S_Y with depth. Moreover, results obtained using the WTF method show almost identical ranges and patterns obtained by Dettmann and Bechtold (2016).

6.2 Comparison of methods

In this work, the cube method and the experimental tank were combined to determine the fine scale variations of S_Y as a function of depth within the top peat deposit (experimental tank) and the general patterns of S_Y as a function of depth throughout the peat column (cube method). The sampling process can induce artificial modifications to the peat. For instance, the use of a box corer to sample peat is an imperfect method, especially in peatlands with a thick acrotelm layer that can be easily compressed. However, the box corer provides the capacity to sample deeper peat cores, thus providing insight into the values of S_Y lower within the peat column. Sampling the larger peat volume required for the experimental tank induces minimal peat compression, but addressed only on the top peat layer. Moreover, S_Y measurements are commonly performed directly in the laboratory on samples that have different volumes or in the field where it is hard to evaluate the scale of the measurements. In fact, strong heterogeneity of hydrodynamic properties are constantly encountered at very small scale and expected to modify measurements and induce a scale effect (Turner *et al.*, 2015). Hence, it is expected that S_Y obtained in the laboratory will disagree with S_Y measurements obtained with in situ methods.

Comparing results from the three different methods remains challenging also because they depart slightly from the S_Y definition. For example, the drainage experiments (small cubes and tank) measure drainage porosity which is an approximation of S_Y. Nevertheless, given the fact that the WTF method provided S_Y values similar to those of the cube method and of the experimental tank and that the results obtained in this study are almost identical to the results obtained by Dettmann and Bechtold (2016) using the same method, it is hypothesized that the assumption underlying the use of the WTF method are reasonable. In future research, the WTF method will need to be used in a wide variety of peatlands to fully constrain its validity.

6.3 Factors influencing storage capacity variations

Many authors (Moore *et al.*, 2015; Thompson and Waddington, 2013; Holden, 2009; Price, 1996) have demonstrated that peatlands vary significantly in terms of microtopography (hummock, lawn, hollow, pool), disturbances (fire, drainage), hydrogeological context, and hydroclimatic environment (Geris *et al.*, 2015). These are all factors that have been recognized as affecting storage capacity. Fires have been shown to decrease S_Y, which increases the flashiness of water table fluctuations (Sherwood *et al.*, 2013). S_Y differ between hummocks and hollows as these tend to dry up more rapidly and retain more water than hummocks (Moore *et al.*, 2015). Hydrogeological contexts control the connectivity of peatlands to aquifers, limiting water table fluctuations (i.e., minerotrophic peatland), and hydroclimatic conditions modify precipitation regimes, evapotranspiration, and soil moisture dynamics, exerting a control on water storage (Geris *et al.*, 2015).

In this study, observed S_Y differences could not be explained by the presence of disturbances or variations in microform, since vegetation assemblages did not show strong evidence of perturbation and microforms did not differ significantly within and between sites. Additionally, the hydrogeological context, which was found to differ strongly from site to site (Table I) could not explain the increasing S_Y trend observed in Figure 9a. LCY and VIC have both developed on fine to medium sand (high permeability), whereas ISO formed on glacial clayed silt (low permeability), yet no statistical difference was found between their means.

Between site locations, differences in storage capacity are better explained by the decreasing trend in effective growing degree days registered from the south-west to the north-east St. Lawrence Lowlands. Higher numbers of effective growing degree days increase overall evapotranspiration rates. Sites characterized by greater evapotranspiration tend to have water tables closer to their respective minimum annual water table position, where humification is higher. Therefore, under similar precipitation regimes, those sites experiencing higher evapotranspiration rates will have lower $S_{Y\ WTF}$. However, their dynamic storage capacity will be higher, since more space is available before reaching a threshold water-table depth.

Large variations in S_Y with depth within the peat profile (Figure 9b) have also been reported in the literature (Moore *et al.*, 2015; Holden, 2009; Vorob'ev, 1963), and correspond to the increasing degree of peat decomposition with depth. For instance, a S_Y of greater than 0.13 is equivalent to a Von Post degree of decomposition between H1 and H5, whereas a S_Y of less than 0.13 is equivalent to a degree of decomposition between H6 and H9. This link between S_Y and degree of decomposition has also been reported by Letts *et al.* (2000), where S_Y decreased from 0.66 to 0.13, with peat type changing from fibric to sapric, and by Boelter (1964), who reported S_Y as high as 0.80 in undecomposed peat and as low as 0.10 in highly decomposed peat. However, results from the current study show that depth is not a systematic explanatory factor when all sites were considered together. Similar $Sy_{\ WTF}$ distributions with depth were observed for all sites, independently of the mean annual WTD of each. For example, at LCY where mean annual WTD is 41 cm, $Sy_{\ WTF}$ is almost identical to that of ISO, where mean annual WTD is only 9 cm. Therefore, mean annual WTD should not be considered to be a proxy of peatland water storage capacity.

Seasonality is another important control on dynamic storage capacity (Figure 9c). Indeed, median $S_{Y\ WTF}$ is higher during wet periods compared to dry periods. This is explained by the fact that evapotranspiration rates are higher during dry periods compared to wet periods. Moreover, these results are consistent with recent findings by Geris *et al.* (2015), showing that tree cover temporarily increases the dynamic storage capacity during summer due to higher evapotranspiration.

The absence of a within-site location effect on $S_{Y\ WTF}$ in this study (Figure 9d) has strong implications for future research. The absence of spatial variation within the studied sites suggests that a single S_Y-depth model could be sufficient to represent a given site. However, more research is needed to better understand the vertical S_Y variation of the water table fluctuation layer, due to the various hydrogeological contexts and microforms.

6.4 Implications for peatland understanding and management

Results from this study have many hydrological implications in terms of hydrological modelling, evapotranspiration feedback, WT-climate linkage, and understanding peatland water storage capacity at the local and global scales. Many authors have studied overland and rapid/slow subsurface flow within peatlands to quantify peatland-surface water interactions (Devito *et al.*, 1997; Reeve *et al.*, 2000; Reeve *et al.*, 2001; Holden *et al.*, 2008). The WTF method provides a means to quantify the S_Y, and therefore to better understand the timing and the transition between overland and subsurface flow within peatlands. Two previously established (McLaughlin and Cohen, 2014) S_Y ranges were also observed in this study: greater than 1, and between 0 and 1. S_Y values greater than 1 indicate additional water input from uphill or from the redistribution of precipitation within the peatland. When S_Y is between 0 and 1, precipitation accumulates within the pore spaces until a threshold, where pore sizes of undecomposed peat are too large to hold more water (Holden, 2009). Somewhat counterintuitively, this can be interpreted as indicating that the water table does not need to reach the surface to be characterized by a $S_{Y\ WTF}$ of greater than 1.

Peatland water storage capacity is an important component of flood mitigation (Acreman and Holden, 2013). The results obtained with the WTF method offer new data that could be very useful for short term transient hydrological/hydrogeological models. A single model of vertical S_Y could be used in physically-based models to simulate peatland dynamics (Reeve *et al.*, 2006). This could lead to more accurate estimates of the delay between precipitation and river floods in watersheds containing large peatland coverage. However, using long-term transient hydrological models requires a thorough understanding of the effect of swelling/shrinking peat soils on water storage capacity (Camporese *et al.*, 2006) which is rarely available.

7 Conclusion

The objective of this study was to adapt the WTF method in order to quantify vertical S_Y variations in peatlands and to better understand the factors controlling peatland water storage capacity. This objective was achieved by comparing results from laboratory experiments on small and intermediate-size peat samples with results from the WTF method. The methods were carried out on five peatlands of the St. Lawrence lowlands, at three different locations within each peatland.

Although uncertainties in S_Y were identified for the cube samples in the upper peat layers, similar relationships describing vertical variations with depth reported in the literature suggest that results from the WTF are reasonable. Results show that this method is a promising tool to quantify S_Y and its vertical variation within the water table fluctuation layer of peatlands. The power law apparently provides the best description of S_Y-depth variations.

Moreover, site location and seasonality are dominant controls upon water storage capacity, suggesting that both hydroclimatic context and evapotranspiration are of primary importance to understanding peatland water storage capacity. This research has shown that within-site location plays a minor role in S_Y variations, suggesting that the WTF method could be used to quantify water storage capacity using a single dip well. However, further studies are needed to investigate the influence of microforms (i.e., hummocks, hollows and pools) and hydrogeological context on water storage capacity.

The WTF method is non-invasive, inexpensive, and can easily be used in a wide variety of contexts, since hourly precipitation and peatland water table fluctuation data are commonly measured in peatland monitoring projects. This method provides a relatively simple means of improving the available data on peatland water storage capacity in different conditions, thus contributing to better understand peatland hydrological functions.

8 Acknowledgments

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Table I Site descriptions: coordinate, altitude, area, distance and mean slope between up-gradient and down-gradient location, watershed, lithology, dominant species, annual evapotranspiration and difference between precipitation (P) and evapotranspiration (ETP).

site	Lat	Long	Altitude (m)	Area (km^2)	Distance (m):slope (%)	Watershed	Lithology	Dominant species	Annual ETP (mm)	P-ETP
LTF	45.132	-74.217	51	6.0	697:0.08	Chateauguay	Marine clay	Sph sp, Kal Ang, Eri Vag, Rho Ca, Pol Str, Aul Pal	640 - 710	neg
SSE	46.042	-72.345	84	4.9	760:0.20	Nicolet	Fluvial silt/Glacial clayey silt	Sph sp, Kal Ang, Eri Vag, Cha Cal	575 - 701	pos /neg
LCY	45.950	-72.187	106	0.5	123:0.24	Nicolet	Eolian fine to medium sand	Sph sp, Kal Ang, Cha Cal, Rho Gro	575 - 701	pos /neg
VIC	46.023	-72.077	118	2.6	593:0.16	Nicolet	Marine exondated fine sand	Sph sp, Kal Ang, Eri Vag, Pol Str, Cha Cal, Rho Gro	575 - 701	pos /neg
ISO	46.579	-71.597	117	2.8	454:0.23	du Chene	Glacial clayey silt	Sph sp, Kal Ang, Eri Vag, Car sp, And Gla, Cha Cal	548 - 611	pos

Table II Specific yield measurements in wetlands as reported in the literature.

Sy	Rate decrease (cm^{-1})	Method	Author	Main objective	Wetland type	depth (cm)	year
0 – 0.9	≈ 0 - 0.08	WTF	Dettmann and Bechtold 2016	methological development	peatland	0 - 45	2016
0 - 1.1	0.007 – 0.013	WTF	Moore et al. 2015	site-depth-microforms	peatland	0 - 65	2015
0.1 - 0.7	0.007 – 0.013	Pressure chamber	Moore et al. 2015	site-depth-microforms	peatland	0 - 50	2015
0.13 - 1.05	0.02	WTF	McLaughlin and Cohen 2014	evapotranspiration and groundwater exchange estimation	open water	50 - 0 (above surface)	2014
0.05 - 0.4	NA	WTF	McLaughlin and Cohen 2014	evapotranspiration and groundwater exchange estimation	open water	60 – 0 (above surface)	2014
0 - 0.85	NA	Pressure chamber	Thompson and Waddington 2013	microforms-depth-density-wildfire alteration	peatland	0 - 45	2013
0.01 - 1	0.02-0.05	Infiltrometer	Holden 2009	depth-cover type	upland blanket peat	0 - 20	2009
0.23	NA	Gravity (experimental tank)	Rosa and Larocque 2008	peat hydrological properties	peatland	0 - 40	2009
0.75-0.99	NA	Tracer tests	Ronkanen and Klove 2008	modelling of water treatment wetlands	contructed peatland	NA	2008
0.13 - 0.66	NA	Gravity	Lett et al 2000	depth - humification - modelling WT variation	peatland	0 - 35	2000
0.25 - 0.55	≈ 0.01	Gravity	Price, 1996	effect of peat harvesting on water balance	peatland	0 - 55	1996
0.04-0.06	≈ 0	Gravity	Price, 1996	effect of peat harvesting on water balance	cutover bog	0 - 62	1996
0.1 - 0.55	≈ 0 - 0.015	Gravity	Price 1992	water budget - hydrological processes	blanket bog	0 - 250	1992
0.09 - 0.45	0.04 - 0.06	Gravity	Vorob.ev. 1963	depth-cover type	swamp (peat)	0 - 20	1963

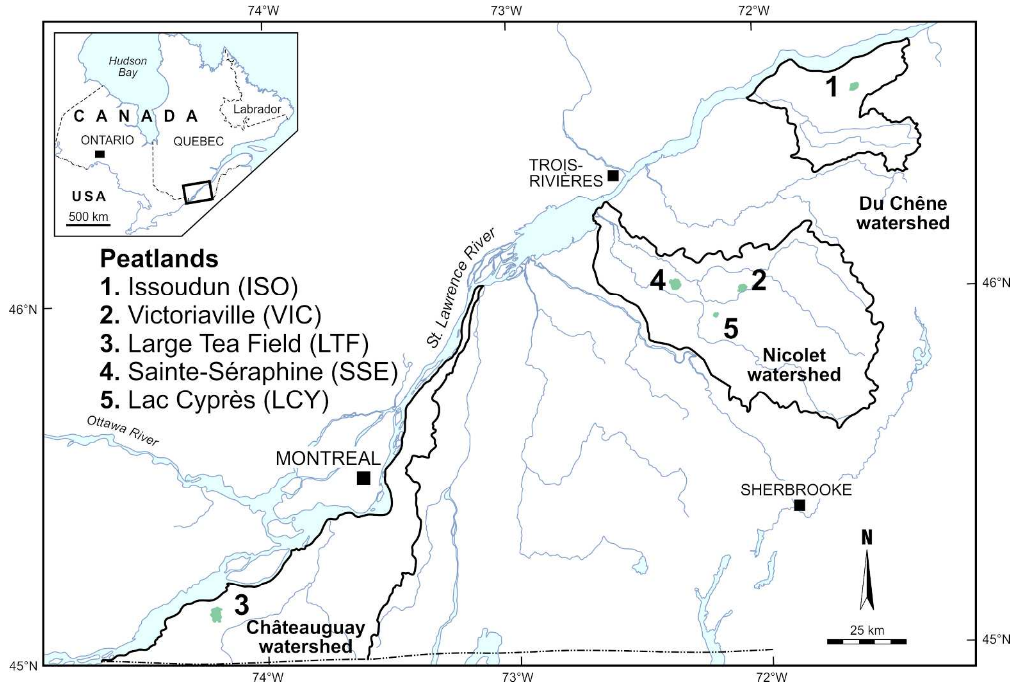

Figure 1 Locations of the five studied peatlands in the Châteauguay (LTF), Nicolet (SSE, LCY, and VIC), and Du Chêne (ISO) watersheds of southern Québec (Canada).
Figure 1
223x150mm (300 x 300 DPI)

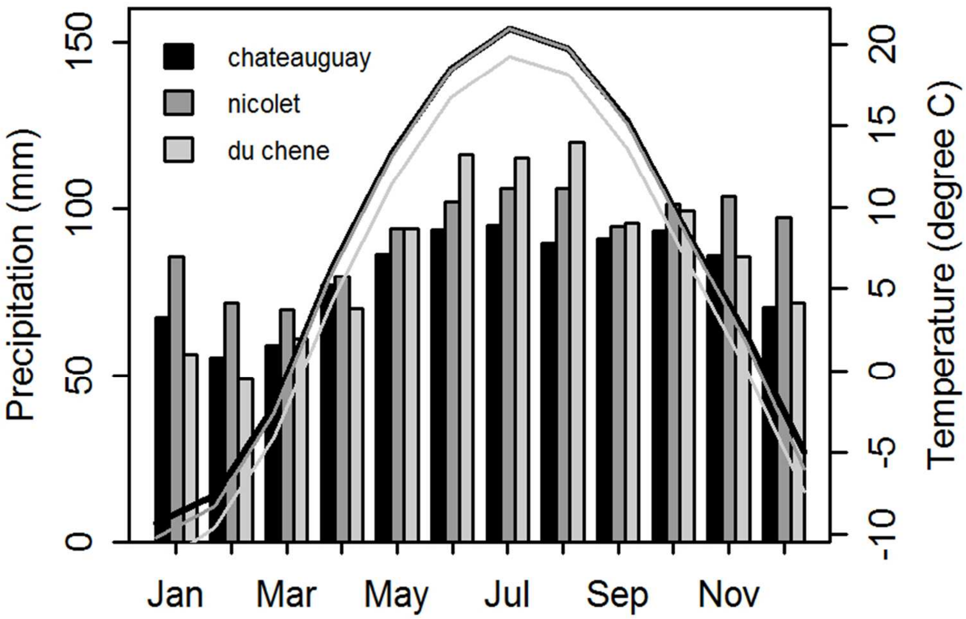

Figure 2 Mean monthly precipitation (bars) and temperature (lines) between 1981 and 2010 for Châteauguay (black), Nicolet (grey), and du Chêne (light grey) watersheds. Note that temperatures curves for Châteauguay and Nicolet overlap or nearly overlap for much of the year.
Figure 2
76x60mm (300 x 300 DPI)

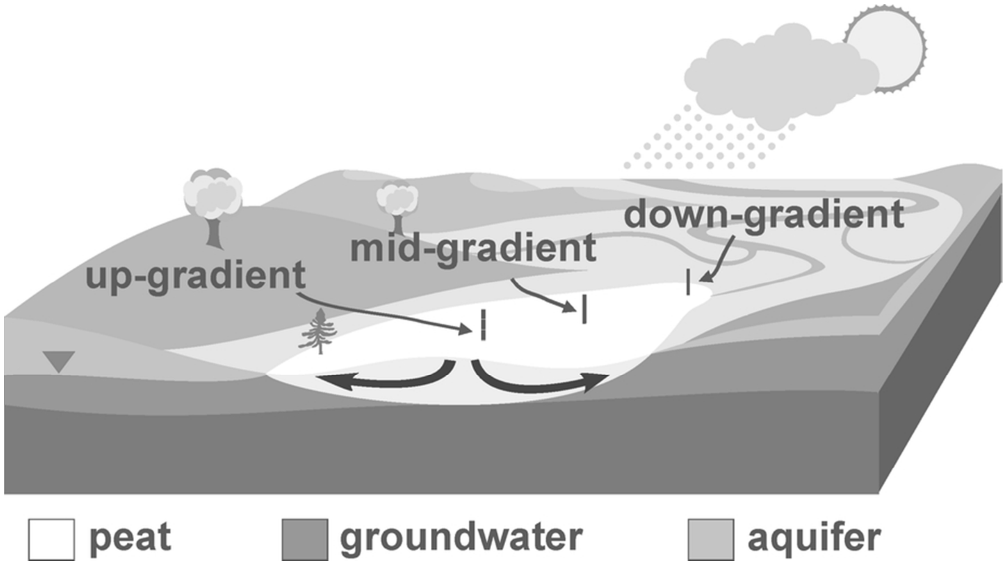

Figure 3 Up-gradient, mid-gradient, and down-gradient locations of the instrumented wells in the studied peatlands. Black arrows show general water circulation patterns.
Figure 3
39x21mm (600 x 600 DPI)

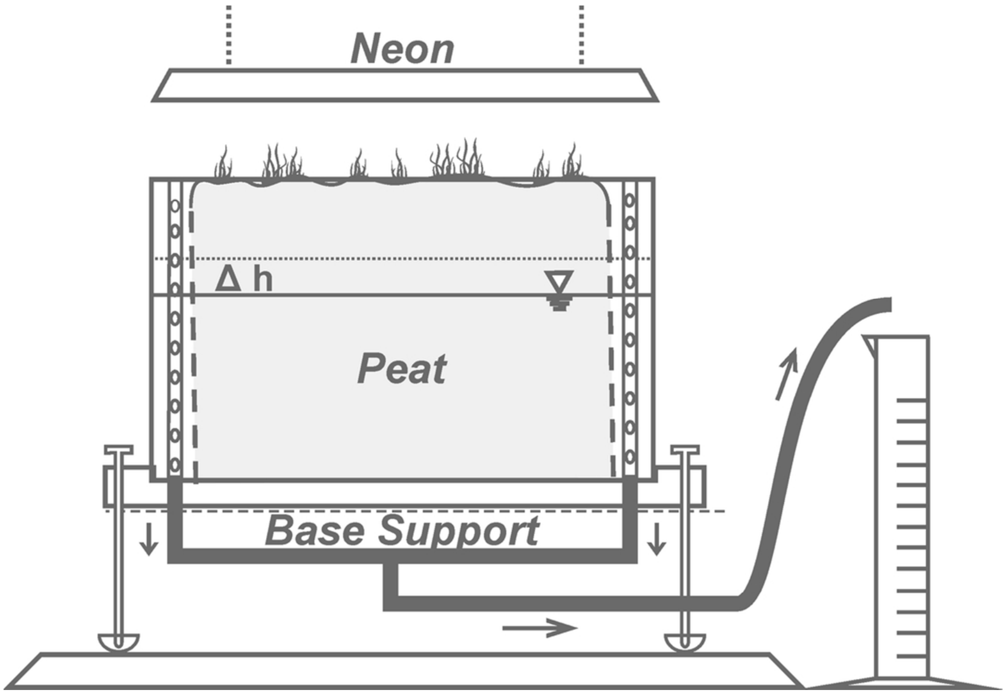

Figure 4 Design of the experimental tank with an impermeable base support built for the drainage experiment to calculate specific yield variations with depth (modified from Rosa and Larocque, 2008).
Figure 4
45x31mm (600 x 600 DPI)

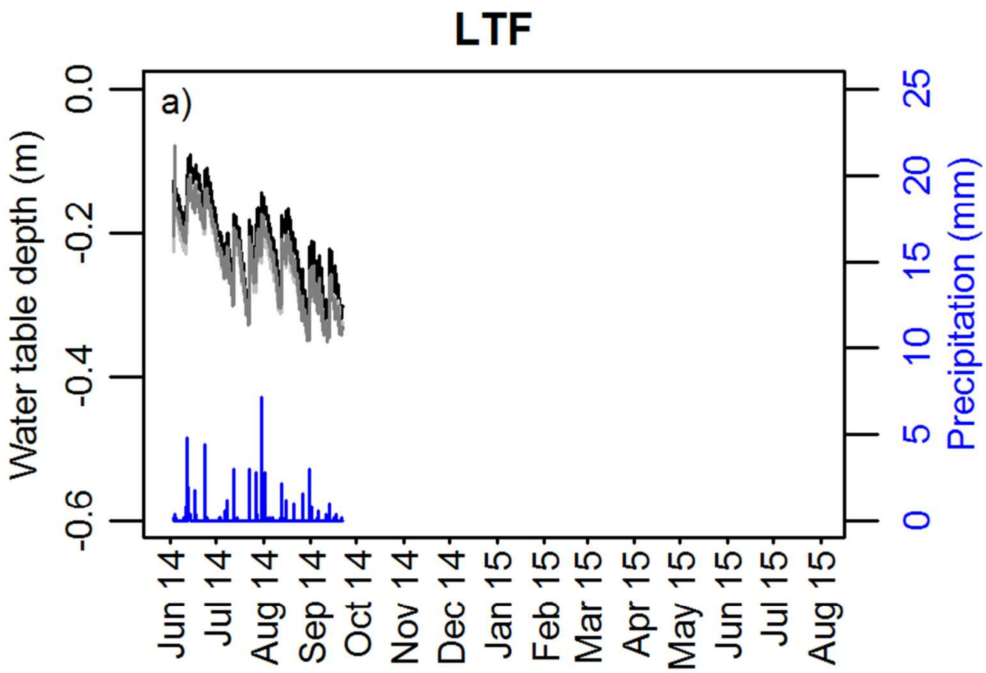

Figure 5 Water table depths and precipitation from June 2014 to August 2015 at the up-gradient (black), mid-gradient (grey), and down-gradient (light grey) locations at a) Large Tea Field (LTF), b) Sainte-Séraphine (SSE), c) Lac Cyprès (LCY), d) Victoriaville (VIC), and e) Issoudun (ISO). The period without data corresponds to the winter season. The LTF time series is only from June to September 2014 due to technical difficulties with the pluviometer in the summer 2015.
Figure 5
76x60mm (300 x 300 DPI)

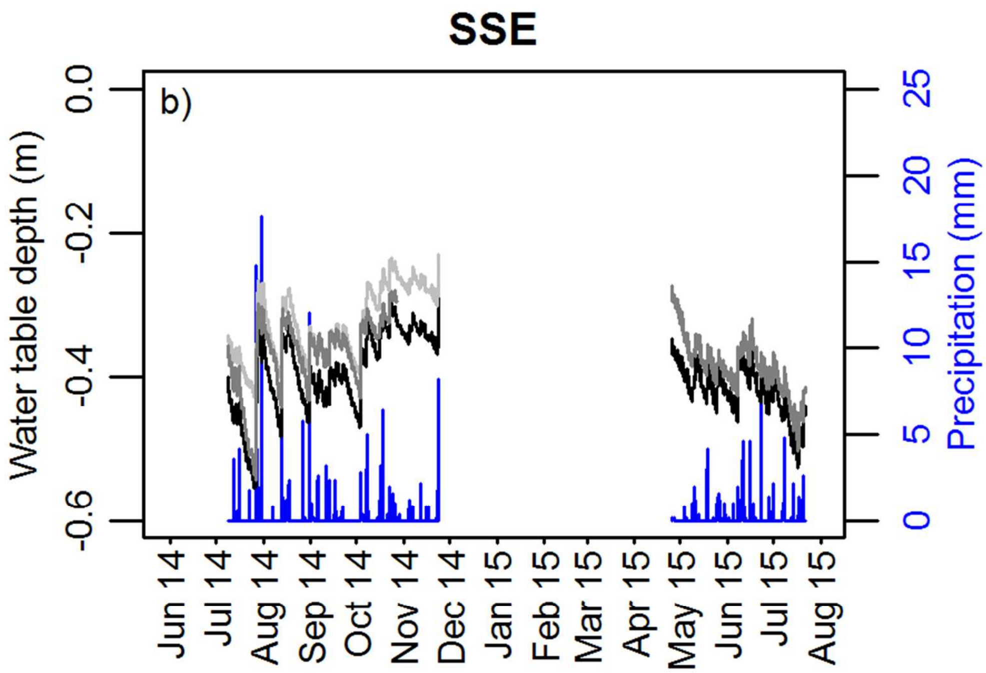

Figure 5 Water table depths and precipitation from June 2014 to August 2015 at the up-gradient (black), mid-gradient (grey), and down-gradient (light grey) locations at a) Large Tea Field (LTF), b) Sainte-Séraphine (SSE), c) Lac Cyprès (LCY), d) Victoriaville (VIC), and e) Issoudun (ISO). The period without data corresponds to the winter season. The LTF time series is only from June to September 2014 due to technical difficulties with the pluviometer in the summer 2015.
Figure 5
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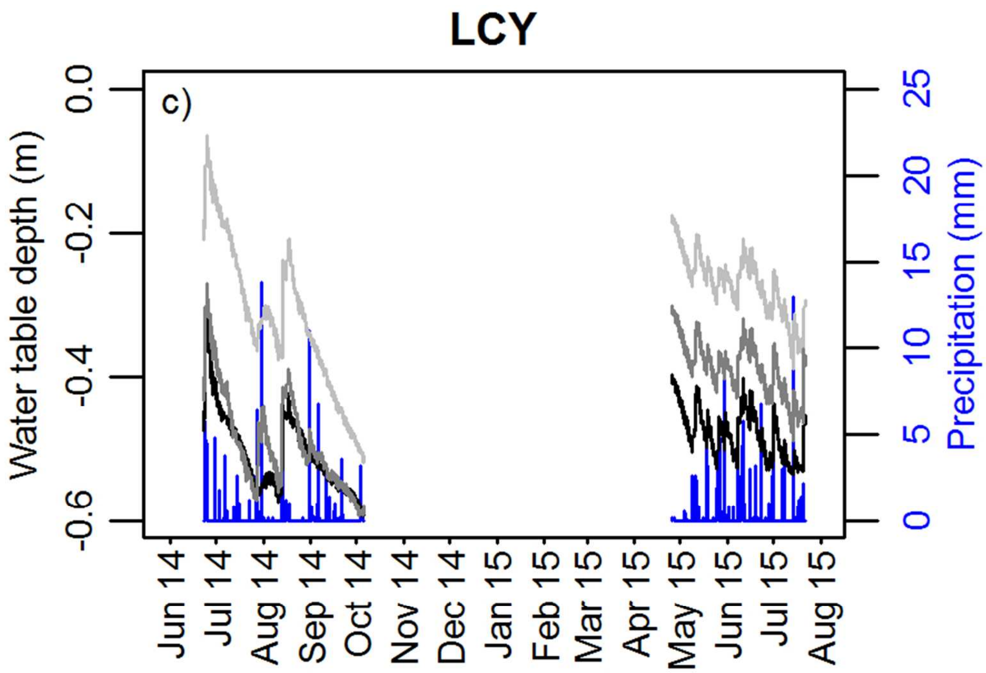

Figure 5 Water table depths and precipitation from June 2014 to August 2015 at the up-gradient (black), mid-gradient (grey), and down-gradient (light grey) locations at a) Large Tea Field (LTF), b) Sainte-Séraphine (SSE), c) Lac Cyprès (LCY), d) Victoriaville (VIC), and e) Issoudun (ISO). The period without data corresponds to the winter season. The LTF time series is only from June to September 2014 due to technical difficulties with the pluviometer in the summer 2015.
Figure 5
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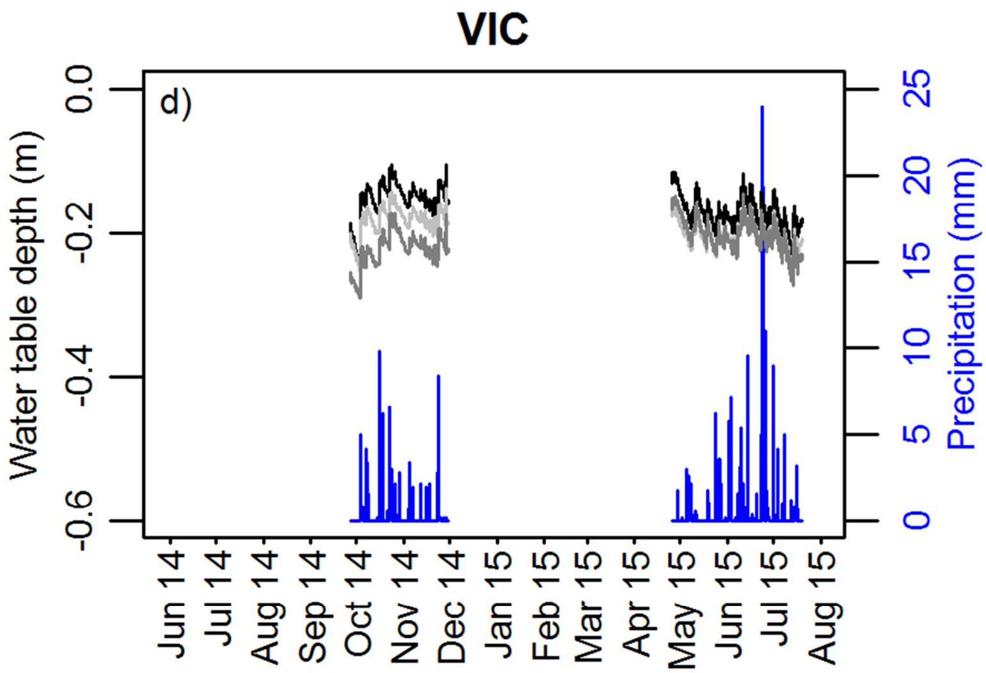

Figure 5 Water table depths and precipitation from June 2014 to August 2015 at the up-gradient (black), mid-gradient (grey), and down-gradient (light grey) locations at a) Large Tea Field (LTF), b) Sainte-Séraphine (SSE), c) Lac Cyprès (LCY), d) Victoriaville (VIC), and e) Issoudun (ISO). The period without data corresponds to the winter season. The LTF time series is only from June to September 2014 due to technical difficulties with the pluviometer in the summer 2015.
Figure 5
76x60mm (300 x 300 DPI)

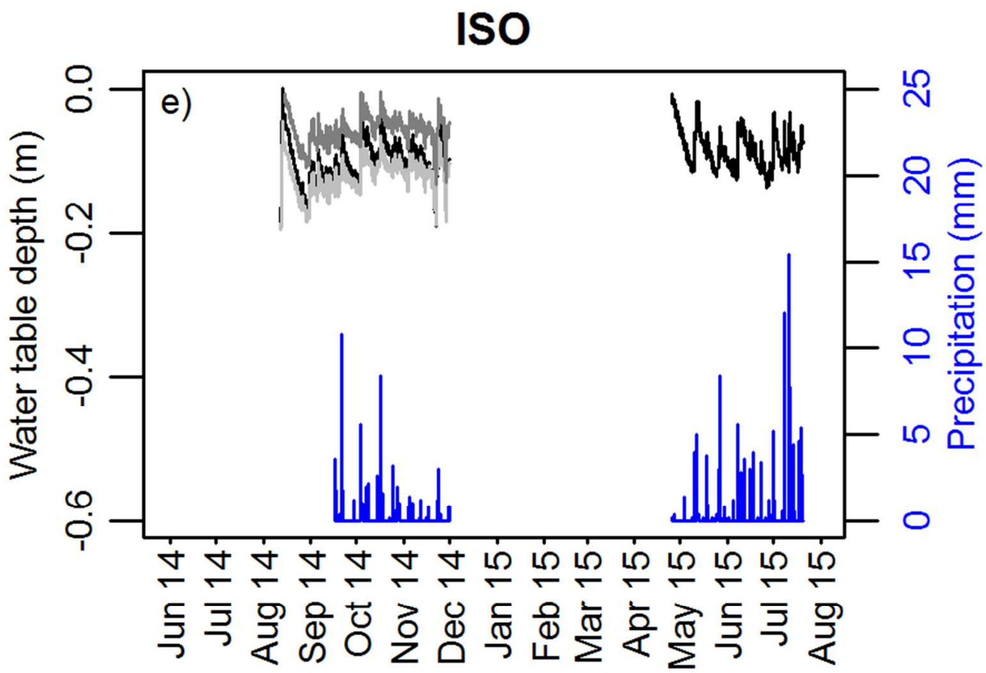

Figure 5 Water table depths and precipitation from June 2014 to August 2015 at the up-gradient (black), mid-gradient (grey), and down-gradient (light grey) locations at a) Large Tea Field (LTF), b) Sainte-Séraphine (SSE), c) Lac Cyprès (LCY), d) Victoriaville (VIC), and e) Issoudun (ISO). The period without data corresponds to the winter season. The LTF time series is only from June to September 2014 due to technical difficulties with the pluviometer in the summer 2015.
Figure 5
76x60mm (300 x 300 DPI)

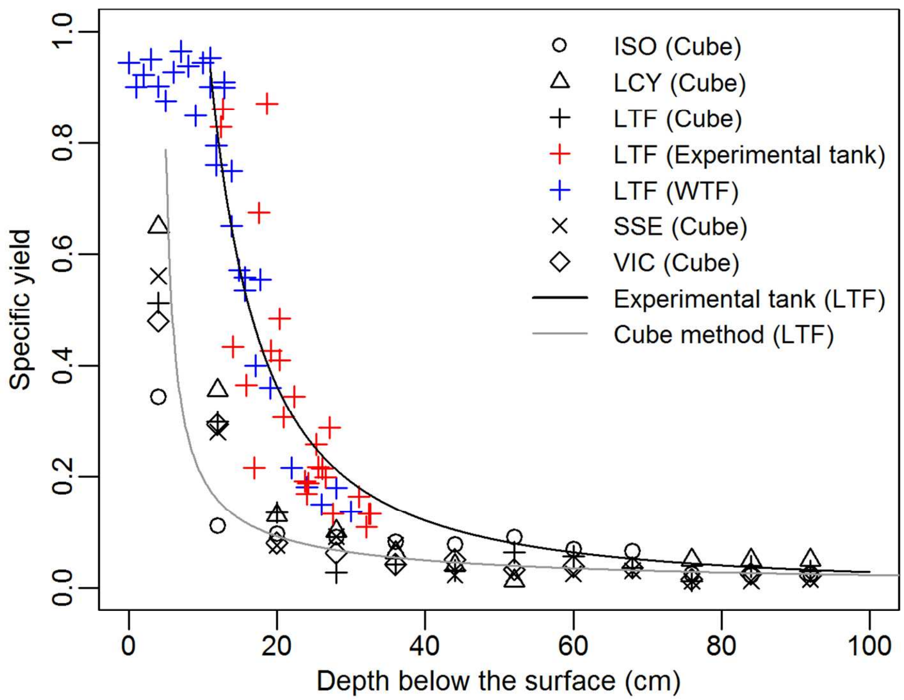

Figure 6 Variation in specific yield (SY) with depth using the small cube (mean values are plotted for each site), experimental tank (LTF only) and WTF (LTF only) methods. The black line shows the SY-depth relationship using the experimental tank method (LTF) and the grey line shows the logarithmic SY-depth relationship using the cube method (LTF).
Figure 6
127x101mm (300 x 300 DPI)

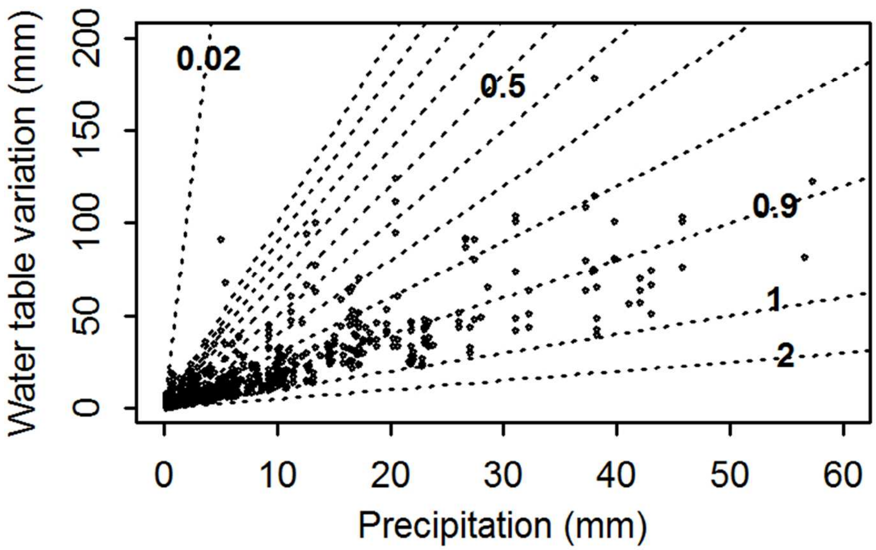

Figure 7 Water table variation (Δh) as a function of precipitation (P) for all sites and locations. Each point represents a single precipitation event. Dashed lines and associated value represent the ratio of P/Δh equivalent to SY.
Figure 7
76x50mm (300 x 300 DPI)

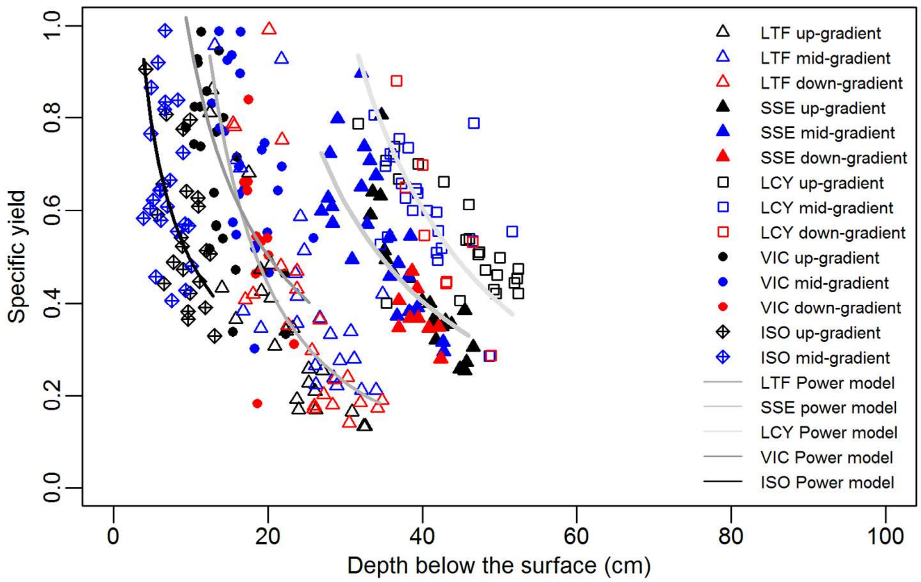

Figure 8 Variation in specific yield estimated using the power law model applied to the WTF method as a function of depth below the surface for all peatlands and all locations (up-gradient, mid-gradient and down-gradient).
Figure 8
152x101mm (300 x 300 DPI)

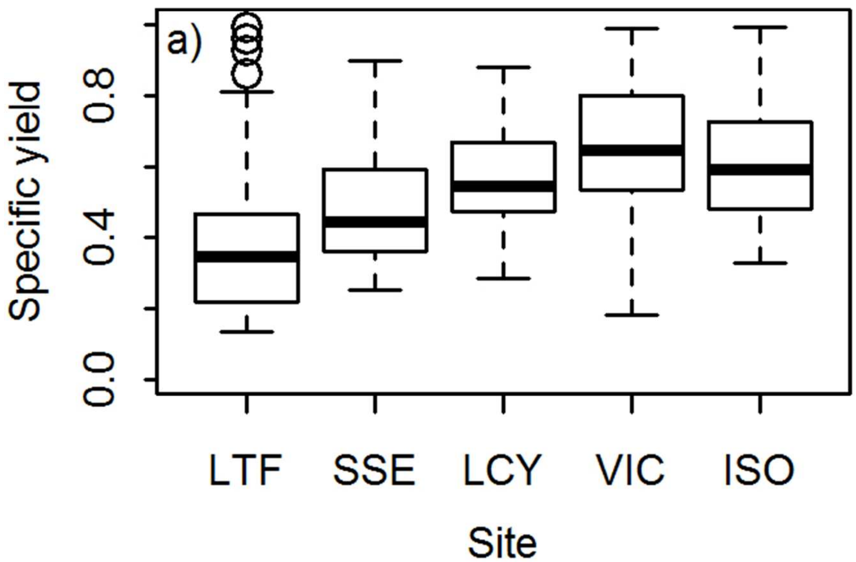

Figure 9 Influence of a) site, b) depth below the surface, c) seasonality (May to November), and d) within-site location on specific yield found using the WTF method. Each box plot shows the minimum (lower bar), the first quartile (lower portion of the box), the median (bold black line), the third quartile (higher portion of the box), the maximum (upper bar), and the outliers (circles).
Figure 9
66x50mm (300 x 300 DPI)

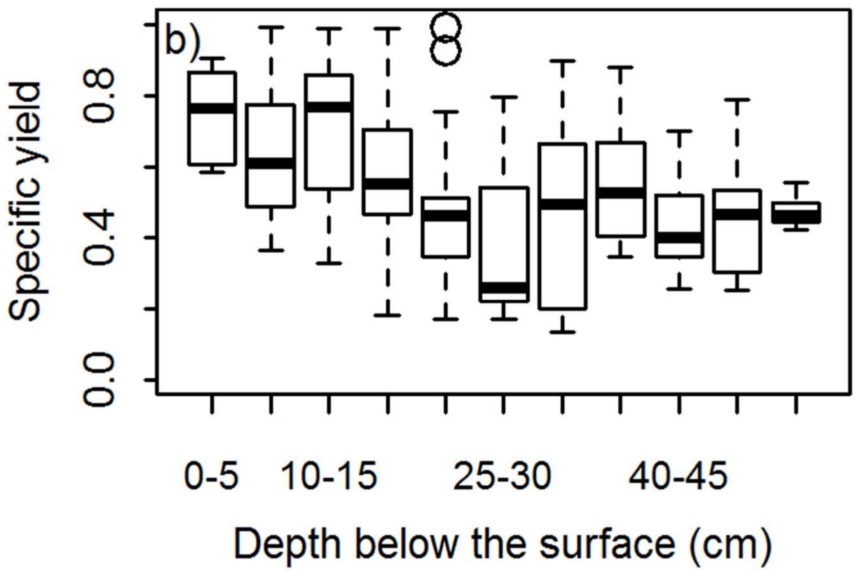

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Figure 9
66x50mm (300 x 300 DPI)

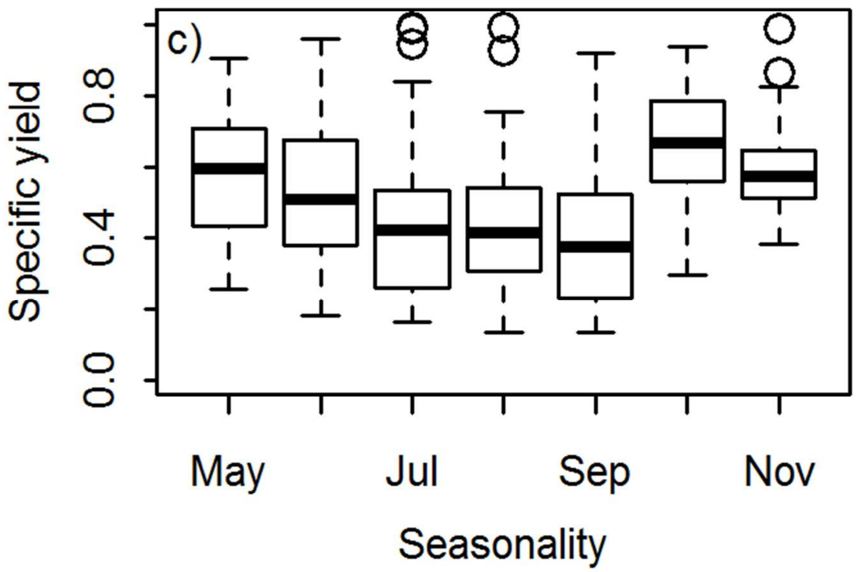

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Figure 9
66x50mm (300 x 300 DPI)

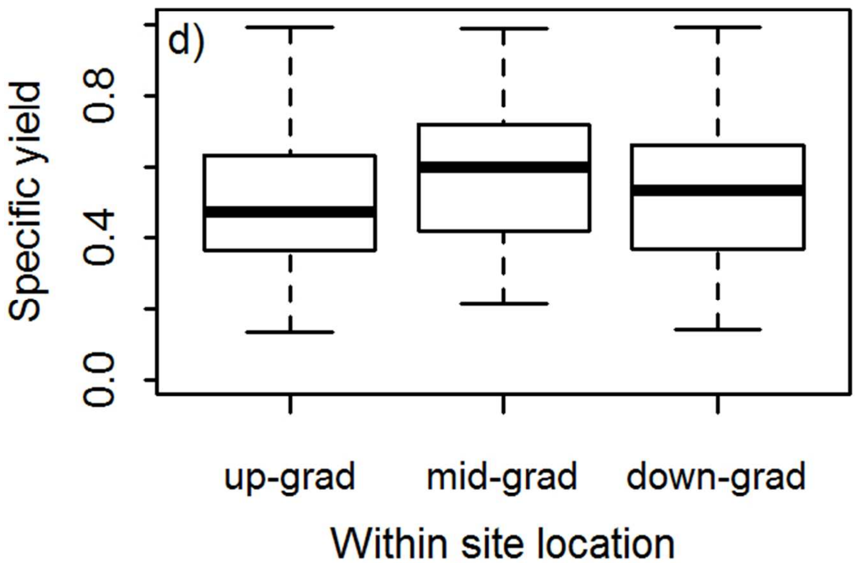

Figure 9 Influence of a) site, b) depth below the surface, c) seasonality (May to November), and d) within-site location on specific yield found using the WTF method. Each box plot shows the minimum (lower bar), the first quartile (lower portion of the box), the median (bold black line), the third quartile (higher portion of the box), the maximum (upper bar), and the outliers (circles).
Figure 9
66x50mm (300 x 300 DPI)