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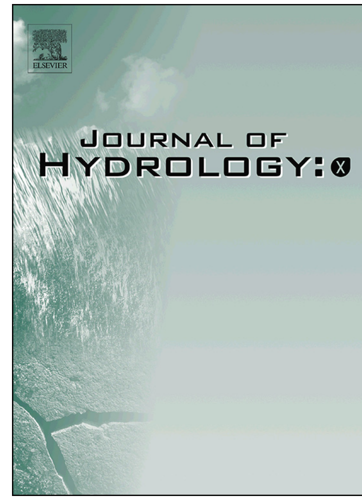

Review papers

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How do hydrogeological setting and meteorological conditions influence water table depth and fluctuations in ombrotrophic peatlands?

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Abstract

Peatlands are wetland ecosystems where net primary production exceeds organic matter decomposition. They are characterized by a near-surface water table controlled by a combination of internal and external processes, influenced by short-term meteorological and long-term climate variations among other factors. Site-specific conditions, such as peat hydrodynamic properties, surface vegetation patterns, and hydrogeological setting also substantially influence water table dynamics. The objective of this work was to characterize the influence of hydrogeological setting and meteorological conditions on water table depths (WTD) and on fluctuations therein in seven ombrotrophic peatlands in or near the St. Lawrence Lowlands (southern Quebec, Canada). Up-gradient, mid-gradient, and down-gradient locations were monitored in the seven peatlands, using dipwells with hourly WTD recordings. WTD was also monitored in the marginal

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minerotrophic zone found in three of the seven peatlands. Additionally, heads in the outflow (i.e., receiving diffused water from the peatland) and inflow (i.e., providing diffused water to the peatland) zones within the adjacent mineral deposits were monitored in seven and three peatlands respectively, using piezometers with hourly hydraulic head recordings. Hydraulic conductivities for the outflow zones ranged between $1.4*10^{-7}$ and $8.5*10^{-3}$ cm/s, whereas those of the inflow zones ranged between $5.6*10^{-7}$ and $3.9*10^{-6}$ cm/s. Evapotranspiration was shown to be the dominant factor controlling monthly cumulative water table decreases (MCD), while precipitation dominated the monthly cumulative water table increases (MCI). A strong correlation was found between mean peatland WTD and outflow zone hydraulic conductivity. Peatlands that were identified as being strongly connected with the adjacent mineral deposits in a diffuse underground outflow zone showed the greatest variations in water storage. This study highlights the importance of the connection between peatlands and adjacent mineral deposits in controlling WTD, as found for those located in the St. Lawrence Lowlands. The results show that water table fluctuations are strongly controlled by meteorological conditions, and that hydrogeological setting exerts a strong control on MCI and MCD. Moreover, this work shows that WTD in ombrotrophic peatlands is influenced by the hydraulic conductivity of the outflow zones, and confirms that aquifer – peatland connectivity influences peatland water storage variations, and therefore peatland vulnerability to disturbances in aquifer groundwater levels.

Keywords: peatland, aquifer, water table depth, water table fluctuation, hydrogeological setting, meteorological conditions, climate change, vulnerability

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Introduction

Peatlands are wetland ecosystems where net primary production exceeds organic matter decomposition. They are characterized by near-surface water tables controlled by many factors, including meteorological (short-term) and climate (long-term) conditions (Schonong et al., 2005; Charman, 2007; Charman et al., 2009), peat hydrodynamic properties (specific yield (S_y) and hydraulic conductivity (K_{sat})) (Kelly et al., 2014; Bourgault et al., 2016), hydrogeological setting (Glaser et al., 1997; Lukenbach et al., 2015), and autogenic ecological processes (Belyea and Clymo, 2001; Swindles et al., 2012). Net water balance (precipitation minus evapotranspiration) is recognized to strongly influence short-term water table fluctuations (WTF) (Labadz et al., 2010). Past water table depth (WTD), reconstructed using testate amoebae, has been found to correlate with mean annual temperature (Schonong et al., 2005; Payne, 2014), and summer moisture deficit has been shown elsewhere to best explain WTD over the long-term (Charman, 2007). Although the hydrogeological setting in which a peatland developed is also known to influence WTD (Winter, 1999; Winter, 2001; Dimitrov et al., 2014; Lukenbach et al., 2015), few studies have attempted to understand the concurrent relative influences of meteorological conditions and hydrogeological setting on peatland water table dynamics.

Peat hydrodynamic properties control the velocity of water circulating through the horizons (Morris et al., 2019). It has been shown that peat K_{sat} (Rosa and Larocque, 2008; Morris et al., 2015) and peat S_y (Vorob'ev, 1963; Moore et al., 2015; Bourgault et al., 2018) can markedly decrease with depth within the top meter. This vertical variability exerts a strong control on WTF (Waddington et al., 2015). For instance, as WTD

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increases, smaller amounts of rainfall are needed to trigger a water table increase. Inversely, when WTD is shallow, a larger amount of rainfall is needed to raise the water table, until a threshold is reached and additional precipitation cannot be stored. Bourgault et al. (2018) have shown that vertical variations in peat S_y and K_{sat} do not differ significantly between peatlands, and thus cannot explain the observed differences in WTD. This suggests that peatland connectivity to adjacent mineral deposits, determined by the hydrogeological setting in which the peatland developed, may be an important control of WTD.

The hydrogeological setting of a peatland is defined by the nature and hydraulic conductivity of the geological material adjacent to and underlying the organic deposits. Peatlands can exist in different geological settings, ranging from highly permeable Quaternary sand deposits (Rossi et al., 2012; Bourgault et al., 2014), to low-permeability sediments, such as silt, clay, or compact till (Ferlatte et al., 2015), to bedrock (Branfireun and Roulet, 1998; Levison et al., 2014). Peatlands can be found in a variety of geomorphic settings (National Wetlands Working Group-NWWG, 1997; Mitsch and Gosselink, 2007), which influence whether they receive water from the adjacent mineral deposits (e.g., Ferlatte et al.,2015; Levison et al., 2014), provide water to it (Rossi et al., 2012), or alternate between these two states (Devito et al., 1997).

In the literature, the influence of hydrogeological setting on peatland hydrology has been considered by identifying adjacent mineral deposit – peatland exchanges (Hokanson et al., 2016; Hokanson et al., 2018) using conceptual approaches (Ivanov, 1981; Sophocleous, 2002), numerical flow modelling (Winter, 1999; Bourgault et al., 2014; McLaughlin et al., 2014; Quillet et al., 2017), vegetation indicators (Dimitrov et

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al., 2014), or groundwater geochemistry (Larocque et al., 2016; Isokangas et al., 2017). Conceptual approaches explore different landscapes in which aquifer – peatland interactions arise, numerical flow modelling quantifies these interactions, and surface vegetation and geochemical indicators help to locate them.

Overall, some peatlands have been found to be groundwater dependent, while others are not (Ivanov, 1981; Kløve et al., 2011). Improved understanding of the factors that differentiate groundwater-dependent peatlands (GDP) (Kløve et al., 2011) from groundwater-independent peatlands (GIP) is crucial, since exchanged flows are expected to be an important control of peatland WTD. Connections between adjacent mineral deposits and a peatland can also be indirect, through pressure re-equilibration between the organic deposits and the adjacent mineral deposits. This process has been suggested to be an important mechanism to maintain peatland water levels (Ingram and Bragg, 1984). It has also been shown to control water levels in a superficial aquifer connected to geographically isolated wetlands (McLaughlin et al., 2014). Time series analysis is a useful tool to identify pressure-induced connectivity and causal relationships. This method has proven effective in different hydrogeological contexts, including karst aquifers (Larocque et al., 1998; Lee and Lee, 2000; Panagopoulos and Lambrakis, 2006) and alluvial aquifers (Cloutier et al., 2014; Larocque et al., 2016), but has not yet been used in peatlands.

The objective of this work was to characterize the influence of hydrogeological setting and meteorological conditions on WTD and WTFs in seven ombrotrophic peatlands located in or near the St. Lawrence Lowlands (southern Quebec, Canada). To

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attain this objective, precipitation, air temperature, and WTD time series were analyzed and compared over a range of climatic conditions.

Site descriptions

General information

The 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 or near the St. Lawrence Lowlands (southern Quebec, Canada; Figure 1), within a distance of 250 km on the south shore of the St. Lawrence River. They developed in four different watersheds (Châteauguay River, Nicolet River, Bécancour River, and Du Chêne River) and are set in headwater conditions on sub-watersheds of the main rivers. They are open ombrotrophic systems, with relatively similar surface vegetation assemblages (e.g., *Sphagnum spp.* (*Sph* sp.), *Kalmia angustifolia* (*Kal ang*), and *Eriophorum vaginatum* (*Eri vag*)). They are distinct with regards to their hydrogeological settings, elevation (above mean sea level), surface areas, presence or absence of a minerotrophic zone, acrotelm thickness, maximum peat thickness, physical properties of peat (e.g., dry bulk density (ρ_{dry}), K_{sat}, and S_y), and water storage variation (Table 1). Elevation data for the seven sites were obtained from a digital elevation model (DEM; 1 m × 1 m resolution) derived from airborne light detection and ranging surveys (LiDAR; (MFFP, 2017).

Meteorological conditions

In southern Quebec, mean annual temperature ranges from 4 to 7°C, and total precipitation from 900 to 1200 mm/year (MDDELCC, 2017). Mean annual precipitation (reference period 1981 – 2010) for the Châteauguay (CH, LTF), Nicolet (SSE, LCY,

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VIC), Bécancour (VR), and du Chêne (VR, ISO) watersheds varies between 929 and 1114 mm, with the lowest value recorded in the southernmost region (LTF). For all sites, minimum monthly precipitation occurs during the winter, and maximum monthly precipitation occurs during the summer (Environment Canada, 2016). Mean annual temperature (reference period 1981 – 2010) varies between 4.8 and 6.7°C, with the lowest value occurring in the northernmost region (ISO). For all sites, minimum and maximum temperatures are recorded in January and July respectively.

For the study period, hourly precipitation and temperature data are available from 2014-04-01 to 2016-06-01. Hourly temperature was retrieved from the closest meteorological stations (MDDELCC, 2017), and hourly precipitation from rain gauge tipping buckets (Hobo) installed at each site. For all sites, monthly precipitation (P_{month}) (excluding winter periods, snowfall, and months with more than 20% missing values) varied between 24 and 180 mm, with maximum values recorded in June and minimum values recorded in April and September (see supplementary material Table 2). Monthly temperatures (T_{month}) show a slight northeast-southwest gradient, with a minimum of -18.7°C recorded at ISO (April 2015) and a maximum of 32.9 ºC at LTF (July 2014; see supplementary material Table 3). Mean yearly temperature in 2014 was lower than that in 2015 for all sites. For the same period, potential evapotranspiration (PET) was calculated using the method of Oudin et al. (2005) (supplementary material Table 4). Annual PET varied between 607 and 684 mm, with minimum values obtained for ISO (595 mm in 2014) and maximum values for LTF (663 mm in 2015). No significant difference in PET was found between 2014 and 2015. High PET occurred during the summer months (June, July, and August), varying between 107 and 137 mm/month. Low PET occurred during

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the spring and autumn months (April, October, and November), varying between 9 and 48 mm/month.

Hydrodynamic properties of the studied peatlands

K_{sat} and S_y were measured by Bourgault et al. (2016) in 1 m peat cores retrieved from the present-day surface of each peatland using the modified cube method (Surridge et al., 2005) and a gravity drainage experiment (Bourgault et al., 2016). WTD was measured by Bourgault et al. (2018). K_{sat} varied over nearly six orders of magnitude between sites. The median K_{sat} values were $6.9*10^{-3}$ 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 between-site differences were not found to be significant. Median S_y was 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, with significant differences between LCY and ISO (Bourgault et al., 2018). For all sites, S_y varied between 0.01 and 0.82, decreasing rapidly with depth (Bourgault et al., 2016). Power law models were found to best describe S_y versus depth, and were used to quantify maximum storage variations, equal to 74 mm for CH, 192 mm for LTF, 127 mm for SSE, 124 mm for LCY, 133 mm for VIC, 65 mm for VR, and 60 mm for ISO (Bourgault et al., 2016) (see Table 1).

Hydrogeological settings

Six of the studied peatlands developed over Quaternary sediments (LTF, SSE, LCY, VIC, VR, and ISO) and one (CH) developed directly over the bedrock. The peatlands all have distinct characteristics (Figure 2), and are described here from southwest to northeast (Figure 1 and 2). CH (0.5 km^2; 310 m asl) is characterized by a central ombrotrophic section surrounded by a minerotrophic section adjacent to the bedrock (Fournier, 2008;

Levison et al., 2014). It has developed in a depression on the Cambrian sandstone of the Potsdam Group (Figure 2a). Year-round continuous base flow is provided to its outlet, even during dry periods. These groundwater-surface water exchanges are greater than those of the other ombrotrophic systems in the St. Lawrence Lowlands. LTF (6.0 km^2; 51 m asl) is an ombrotrophic peatland that developed on marine clay deposits from the postglacial Champlain Sea (Figure 2b). Before the peatland was intensively drained, its area was estimated to be 51 km^2 (Payette and Rochefort, 2001), which is more than eight times greater than its current size. SSE (4.9 km^2; 84 m asl) is a peatland complex composed of a central ombrotrophic section surrounded by a minerotrophic section. It has developed in a geomorphic context of alternating littoral marine sediment (silt sand and clayey silt) and clayey silt diamicton (Figure 2c). LCY (0.5 km^2; 106 m asl) is an ombrotrophic peatland that developed within a sandy dune swale, where a discontinuous indurated horizon was found at the mineral-organic contact (Figure 2d). VIC (2.6 km^2; 118 m asl) is an ombrotrophic peatland that developed on exondated fine silty marine sediment (Figure 2e). VR (10.4 km^2; 124 m asl) is a peatland complex composed of a central ombrotrophic section surrounded by a minerotrophic section (Larocque et al., 2015). It has formed on alternating aeolian medium and fine sands, silt, clayey silt, and reworked diamicton from glacial deposits (Figure 2f). Finally, ISO (2.8 km^2; 117 m asl) is an ombrotrophic peatland, which developed over a diamicton dominated by a clayey silt matrix (Figure 2g).

Methodology

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Water level monitoring and hydraulic testing

The peatlands composed of a central ombrotrophic section surrounded by a minerotrophic section (sites CH, SSE, and VR) were divided into six zones: up-gradient (1), mid-gradient (2), down-gradient (3), minerotrophic (4), inflow (5), and outflow (6) (see Figure 2a). The ombrotrophic peatlands with no minerotrophic section (sites LTF, LCY, VIC, and ISO) were divided into four zones: up-gradient (1), mid-gradient (2), down-gradient (3), and outflow zones (6) (see Figure 2e). Within each peatland, up-gradient (highest altitude) and down-gradient (lowest altitude) zones were located along a longitudinal transect, while the mid-gradient zone was located halfway between the two. All of the zones were identified by manual water table and hydraulic head measurements. The inflow zones were located outside the peatlands in the adjacent mineral deposits, typically at a higher elevation and characterized by a higher water table than that of the peatland. They were found exclusively where minerotrophic zones were present, and were therefore used as a criterion to identify GDPs. Minerotrophic zones were identified using surface vegetation nutrient and pH indicators during field work (Rydin and Jeglum, 2006). The outflow zones were also located outside the peatlands, and were characterized by a lower water table compared to the peatland. Both inflow and outflow zones were identified using manual water table measurements in the adjacent mineral deposits. WTD was not measured in the inflow zone of CH (see Figure 2a), because of the technical difficulties related to the fractured bedrock aquifer. At LTF (see Figure 2b), the WTD of the outflow zone was not measured, because it was located in impervious clay. At LCY (see Figure 2d), the WTD was not measured in the mid-gradient zone, because of the small distance between the up-gradient and down-gradient zones. WTD was therefore

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measured at six locations at SSE and VR (see Figure 2c and 2f), at five locations at CH (see Figure 2a), at four locations at VIC and ISO (see Figure 2e and 2g), and at three locations at LTF and LCY (see Figure 2b and 2d).

WTD was measured in dipwells constructed from 3 cm outside diameter PVC pipes, with 2 m-long intakes perforated with 0.254 mm slits spaced equally every 60 mm from top to bottom, and sealed at the base. In the up-gradient, mid-gradient, and down-gradient zones, the wells were inserted into *Sphagnum* lawn microforms. The altitude of the dipwells was surveyed multiple times during the study and no drift was measured. The piezometers were inserted into the adjacent mineral deposits 500 m from the edge of the peatland. The piezometers were constructed from 3 cm outside diameter steel pipes sealed at the base with a 30 cm *Solinst* drive point. They were driven into the mineral sediments using a Manual Slide Hammer, with the exception of at CH, where the piezometer was installed in a borehole drilled as part of a previous study (Levison et al., 2014). The piezometers were installed 2 m below the field-measured WTD (see red well screens in Figure 2). WTFs in the peatland dipwells and head variations in the outflow and inflow zone piezometers were monitored hourly using level loggers (*Solinst*) from June 2014 to May 2016. To compare the different sites, water level measurements in the outflow and inflow zones were normalized using z-scores, and WTFs in the peatlands were reported relative to the peat surface at measurement locations.

Slug tests were performed to measure the K_{sat} of the mineral deposits in the inflow and outflow zones, using the Hvorslev method (Hvorslev, 1951). A minimum of ten slug tests were performed for each piezometer. In the outflow zones, slug tests were performed at depths of 300 cm for CH, 205 cm for SSE, 193 cm for LCY, 281 cm for

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VIC, 423 cm for VR, and 161 cm for ISO. These depths were chosen to vary between sites to be close to the maximum WTD recorded at each site during outflow zone monitoring that took place during summer 2013. In the inflow zones, slug tests were performed at a depth of 300 cm for SSE and 220 cm for VR. K_{sat} values for the fractured bedrock at CH are those reported in Levison et al. (2014).

Time series analysis

Every water table increase linked to a single precipitation event, and every water table decrease initiated by PET and lateral water circulation was isolated using the techniques described in Bourgault et al. (2016). First, a computation script written in the R programming language (R environement D.C.T., 2008) was used to identify the maximum water table rise following each precipitation event. The code calculated total precipitation during the event (P_{event}), the maximum water level rise following the event (Δh_{rise}), and the time interval between P_{event} and Δh_{rise}. Water table decreases were isolated by removing time periods between P_{event} and Δh_{rise} from each water table time series. The difference between the maximum and minimum water table height ($\Delta h_{drawdown}$) was computed. Δh_{rise} and $\Delta h_{drawdown}$ were cumulated monthly, leading to two new variables, the monthly cumulative increase (MCI) and the monthly cumulative decrease (MCD). The data were analyzed to evaluate whether T_{month} and P_{month} could be used as indicators of MCI and MCD. In Dargie et al. (2017), MCI correlated strongly with P_{month} for WTDs above the peat surface. However, MCI has never been used for peatlands where WTD is below the surface. Likewise, the use of MCD as an indicator of the effect of PET (considered to be proportional to air temperature) has never been

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reported in the literature. Linear correlations were performed between T_{month} and MCD, and P_{month} and MCI.

Autocorrelation (r(k)) and cross-correlation ($r_{xy}(k)$) functions were calculated using the hourly water table measurements over periods of 25 days (600 hours), from June 2014 to June 2016. The autocorrelation functions were calculated for both the ombrotrophic sections of the peatlands and the outflow zones of the adjacent mineral deposits. The autocorrelation function is useful to differentiate water table reactivity (i.e., a rapid decrease of r(k) over time is associated with a reactive water table). The time lag equivalent to an r(k) value of 0.7 was arbitrarily used to compare the slopes of the autocorrelation functions of the seven sites. The $r_{xy}(k)$ functions were calculated between WTD in the up-gradient zone of the peatland (zone 1 in Figure 2) and WTD in the outflow zone of the adjacent mineral deposits (zone 6 in Figure 2). The lag time between the two time series is quantified as the maximum value of the cross-correlation.

Results

Water table depths and water table fluctuations

Results from this study and from data compiled from Bourgault et al. (2018) reveal significant differences (ANOVA p-value = 10^{-14}; Tukey's test p-value < 10^{-10}) between WTDs of the seven studied peatlands. For all peatlands, WTD varied between -54 cm (below peat surface at LCY; Figure 3) and 1 cm (above peat surface at ISO; Figure 3), with WTF varying between 21 cm (ISO) and 38 cm (LCY). WTDs were closer to the surface in April and were deeper in August and September (see supplementary material Table 5).

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WTD in the minerotrophic zones of CH, SSE, and VR was between 22 cm and -17 cm, and WTF varied between 11 and 22 cm (Figure 4). Similar to the levels within the ombrotrophic section of the peatland, water tables in the minerotrophic zones were higher in April and deeper in August and September (see supplementary material Table 6). No significant differences were found between peatlands.

In the inflow zones, hydraulic heads varied between 0 cm (VR in April 2016) and -131 cm (SSE in July 2014), while the fluctuations varied between 27 cm at VR in 2014 and 115 cm at SSE (see supplementary material Table 7). The mean annual hydraulic head was -34 cm (SD = 31 cm) for SSE and -48 cm (SD = 23 cm) for VR. When normalized (standard score; Figure 5), the hydraulic heads at VR varied more strongly than at SSE. As for the peatlands, the hydraulic head in the adjacent mineral deposits was closer to the surface in April and deeper in August and September.

In the outflow zones, the hydraulic heads varied between 0 and -374 cm, while fluctuations varied between 11 and 95 cm (see supplementary material Table 8). The mean annual hydraulic head was -78 cm (SD = 14 cm) for CH, -42 cm (SD = 26 cm) for SSE, -46 cm (SD = 26 cm) for LCY, -69 cm (SD = 23 cm) for VIC, -350 cm (SD = 20 cm) for VR, and -13 cm (SD = 4 cm) for ISO. When normalized (standard score; Figure 6), hydraulic head at VR and at ISO showed the largest variation, whereas hydraulic head at LCY varied the least.

Aquifer hydraulic conductivity

The K_{sat} of the outflow zones varied by four orders of magnitude, ranging between $1.4*10^{-7}$ and $8.5*10^{-3}$ cm/s (LTF was excluded, because the K_{sat} of the outflow zone was not measured), whereas the K_{sat} of the inflow zones varied by only one order of

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magnitude, ranging between 5.6*10^{-7} and 3.9*10^{-6} cm/s. The median K_{sat} of the outflow zones was 3.6*10^{-4} cm/s for CH (Fournier, 2008), 5.0*10^{-9}cm/s for LTF (Desaulniers and Cherry, 1989), 1.3*10^{-4} cm/s for SSE, 2.9*10^{-3} cm/s for LCY, 2.6*10^{-5} cm/s for VIC, 1.4*10^{-5} cm/s for VR, and 4.4*10^{-7} cm/s for ISO. The median K_{sat} of the inflow zones was 1.3*10^{-6} cm/s for SSE, and 1*10^{-7} cm/s for VR.

With the exception of LTF, the K_{sat} of the outflow zones correlated negatively with mean WTD at the up-gradient well (zone 1, ombrotrophic section), with an R^2 of 0.7 (Figure 7). This suggests that WTD in the ombrotrophic section of the peatlands was closer to the surface when the K_{sat} of the outflow zone was low, and that WTD decreases as the K_{sat} of the outflow zone increases. No significant correlation was found between the mean WTD of the ombrotrophic section and the K_{sat} measured in the inflow zone (not shown).

Time series analyses

MCI varied between 61 mm (LCY) and 451 mm (LTF), with the highest MCI occurring during the highest evaporative period (May to August) and the lowest MCI occurring during low evaporative periods (March, April, and November; Figure 8). MCD varied between 44 and 542 mm for all peatlands, with the highest MCD (at LTF) occurring during the highest evaporative period (July and August) and the lowest MCD (at ISO) occurring during the lowest evaporative period (October and November) (Figure 9).

MCI and P_{month} were strongly correlated for all peatlands, with R^2 values of 0.8 for CH, 0.8 for LTF, 0.6 for SSE, 0.8 for LCY, 0.7 for VIC, 0.6 for VR, and 0.8 for ISO (Figure 8). The associated slopes varied between 1.0 and 4.2 mm of MCI per mm of

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precipitation, with the highest slope for LTF (slope = 4.2), LCY (slope = 2.3) and SSE (slope = 2.9), and the lowest slope for VR (slope = 1.0) and ISO (slope = 1.4). MCD and T_{month} were also strongly correlated for all peatlands, with R^2 values of 0.7 for CH, 0.7 for LTF, 0.8 for SSE, 0.9 for LCY, 0.7 for VIC, 0.8 for VR, and 0.8 for ISO (Figure 9). The associated slopes varied between 8 and 18 mm MCD per ^{o}C, with the strongest slope calculated for LTF (slope = 18 mm/°C), LCY (slope = 15 mm/°C), and SSE (slope = 10 mm/°C), and the weakest slope calculated for VR and ISO (slope = 8 mm/°C in both cases). LTF, LCY, and SSE showed the strongest variation in both MCI and MCD, whereas VR and ISO showe the weakest variation in MCI and MCD. WTD was not found to correlate significantly with either P_{month} or T_{month} (not shown).

For the peatlands, r(k) reached a value of 0.7 after 430 h for CH, 451 h for LTF, 167 h for SSE, 135 h for LCY, 158 h for VIC, 154 h for VR, and 485 h for ISO (Figure 10a). The most rapid decrease in r(k) was observed for LCY, whereas the slowest decrease was observed for ISO (see Figure 10a). In the adjacent mineral deposits (Figure 10b), r(k) reaches a value of 0.7 after 245 h for CH, 492 h for SSE, 570 h for LCY, 301 h for VIC, 326 h for VR, and 139 h for ISO (Figure 11). The most rapid decrease in r(k) was observed for ISO, and the slowest decrease was observed for LCY (see Figure 10b).

Cross-correlation functions between the outflow zone and the peatland (up-gradient zone) were calculated for all sites (Figure 11), except for LTF, because of its hydrogeological setting. Maximum $r_{xy}(k)$ was 0.62 for CH, 0.67 for SSE, 0.65 for sie LCY, 0.69 for VIC, 0.37 for VR, and 0.30 for ISO. Time lags were similar for all sites, and were less than 16 hours.

Discussion

Influence of hydrogeologic setting on aquifer – peatland connections

Aquifer – peatland connections can be categorized into four distinct conditions (Figure 12), including the typical lateral flow suggested by Ferlatte et al. (2015) based on static groundwater levels. Direct aquifer – peatland connections are characterized by water flowing from the adjacent mineral deposits towards the peatland (Figure 12a), water flowing from the peatland toward permeable adjacent mineral (Figure 12b, and 12c) or water flowing from the peatland toward impermeable adjacent mineral (Figure 12d).

In the literature, water flowing from the aquifer to the peatland and from the peatland to the aquifer corresponds to converging flow zones (Ferlatte et al., 2015) or minerotrophic zones (Siegel and Glaser, 1987; Glaser et al., 2006). When water flows from the aquifer toward the peatland, groundwater fluxes contribute to maintaining the peatland water table close to the surface and limit WTF (Morris and Waddington, 2011). In the current study, this type of aquifer – peatland connection (Figure 12a) was observed at the margin of the CH, SSE, and VR peatlands, and was characterized by WTF that never exceeded 15 cm/year. Surprisingly, the presence of these zones did not correlate with near-surface WTD in the up-gradient zone. For instance, WTD and WTF monitored in the up-gradient zone of SSE was found to be comparable to those of sites where no convergent zone was observed (Figure 3; green line and Figure 7; green point).

Converging flow conditions are important for peatlands, because they can contribute substantially to the total annual peatland water budget, and can maintain flow in streams and rivers that are located at peatland outlets during dry periods (Holden and Burt, 2003). For example, Bourgault et al. (2014) (Lanoraie peatland complex,

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St. Lawrence Lowlands) and Levison et al. (2014) (CH, this study) quantified groundwater inflows as contributing more than 50% of the annual peatland water budget, and convergent zones as contributing to more than 70% of the peatland surface outflow measured during dry periods.

The influence of the marginal portion of the peatland on WTD and WTF was not restricted to convergent flow conditions. As summarized in Figure 12b, 12c, and 12d, results from this study suggest that WTD and WTF in the marginal portion of the peatlands are also controlled by the hydraulic conductivity and the presence of drainage in the outflow zone. More importantly, it was found that the control of WTD and WTF exerted by the outflow zone is not restricted to the marginal portion of the peatland, but instead extends to the up-gradient zone. Other studies have emphasised the importance of hydrogeological setting on peatland hydrology (Ivanov, 1981; Glaser et al., 1997; Winter, 2001; Lukenbach et al., 2015). However, this is the first report whereby the influence of hydrogeological setting on WTD and WTF is directly demonstrated by *in situ* field measurements (K_{sat}, WTD and WTF) and time series analysis (autocorrelation, cross-correlation, MCI and MCD).

Overall, the results show that, for all the studied peatlands, with the exception of the heavily disturbed LTF, the underlying mechanisms controlling WTD and WTF in the peatlands is the K_{sat} of the outflow zone (see Figure 7). The results also show that, when water flows from the up-gradient zone towards the down-gradient zone and the peatland is in contact with a low-K_{sat} adjacent mineral deposit (Figure 12b), WTD is close to the surface everywhere in the peatland and less reactive to rain events (i.e., low WTF) (CH, VR and ISO; Figures 2a, 2f and 2g). When water flows from the up-gradient toward the

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down-gradient zone and the peatland is in contact with a high-K_{sat} adjacent mineral deposit (Figure 12c) or with a peat margin that has been heavily disturbed by intensive human activities (e.g., LTF) (Figure 12d), WTD is deeper everywhere in the peatland and more reactive to rain events (i.e., high WTF).

These results are also important, because they suggest that peatlands that have limited connectivity with the aquifer (Figure 12b) have lower WTF, and could be less vulnerable to drawdowns in the aquifer induced by land use changes (e.g., pumping or reduced recharge) than peatlands that are more strongly connected to aquifers and have larger WTF (Figures 12a and 12c). Consequently, any such perturbation (e.g., pumping) in the outflow zone of a peatland that was formed on highly permeable sediment should be considered to be a potential threat to the peatland, even if up-gradient zones have traditionally been assumed to only be impacted by precipitation.

Meteorological controls on WTD and WTF

The effect of precipitation and temperature on peatland WTF on a monthly time scale was quantified using MCI and MCD. For the seven peatlands, MCI correlated strongly with P_{month} (Figure 8), and MCD correlated strongly with T_{month} (Figure 9). With the exception of LTF (the heavily disturbed site), the sites characterized by the strongest changes in MCI and MCD, LCY and SSE, had developed on mineral sediments with the highest K_{sat} (from $2.9*10^{-3}$ cm/s to $1.3*10^{-4}$ cm/s). On the other hand, VR and ISO, characterized by the weakest changes in MCI and MCD, had developed on materials that have the lowest K_{sat} (ranging from $1.4*10^{-5}$ cm/s to $4.4*10^{-7}$). These two new indices, MCI and MCD, are easily accessible indicators of peatland vulnerability to meteorological conditions in different hydrogeological settings, and can be relatively

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easily implemented. Their usefulness will need to be confirmed on other peatlands and on decadal and longer periods.

Additionally, the autocorrelation function of WTD and heads (Figure 10) could be used as a proxy of MCD, while the cross-correlation function between WTD in the up-gradient zone and heads in the outflow zone (Figure 11) could be used as a proxy of mineral deposit – peatland connection. For example, it was found that ISO, which developed on low-K_{sat} sediment, has the weakest MCD, the weakest decrease in r(k) (see yellow line on Figure 10a), and the weakest cross-correlation (yellow line on Figure 11). LCY, which developed on the highest K_{sat} sediment, has the highest MCD and the highest decrease in r(k) (see blue line on Figure 10a), with one of the strongest cross-correlations (blue line on Figure 11). Interestingly, this influence on drawdown was observed when time series were analyzed at both daily and monthly time scales.

It therefore appears that meteorological conditions have variable effects on WTD and WTF in peatlands, depending on their hydrogeological setting. This is an important result in light of the current changing climate conditions and in the context of increasing pressure on groundwater resources from changing land uses. More investigation will be needed to delineate protection zones within the mineral deposits adjacent to peatlands in different climate conditions to better protect these ecosystems.

Identification of groundwater-dependent and groundwater-independent peatlands

The classification of peatlands as GDP or GIP is important, because GDPs contribute to the maintenance of good quality groundwater (Moss, 2008). GDPs are one type of ecosystem (Kløve et al., 2011), often recognized for their rich biodiversity (Murray et al., 2003). In this work, GDPs and GIPs were identified using head

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measurements in the adjacent mineral deposits. GDPs were characterized by inflow zones, where heads in the aquifer were higher than the water table in the peatlands. GIPs were entirely surrounded by outflow zones, where the water tables were lower than those of the peatlands. CH, SSE, and VR were confirmed to be GDPs, as suggested by the presence of a marginal minerotrophic zone surrounding the ombrotrophic section. LTF, LCY, VIC, and ISO were identified to be GIPs. Others (e.g. Lukenbach et al. 2015) have previously shown that GDPs tend to have WTDs closer to the surface in their ombrotrophic section. However, this was not observed in the current study and peatland WTD did not distinguish GDPs from GIPs. Additionally, as previously demonstrated by the influence of the outflow zone on peatland WTD and WTF, the definition of GDPs and GIPs needs to be revisited to include pressure-induced connectivity, in addition to exchanged fluxes.

Clarification of the influence of hydrogeological setting on distinguishing GDPs and GIPs is therefore needed. The hydrogeological setting determines the presence of groundwater inflows, which distinguishes GDPs (Kløve et al., 2011), for example in eskers (Isokangas et al., 2017) or in sandy deltaic environments (Bourgault et al., 2014). However, GDPs can also be found in association with low-K_{sat} sediments, such as glacial deposits (e.g., VR), marine silts (e.g., SSE), and in fractured bedrock aquifers (e.g., CH). GDPs are therefore not restricted to specific geological settings. However, it is suggested that groundwater-fed peatlands could be linked with the surrounding local topography. In this study, minerotrophic zones were located within a maximum distance of 500 m, and with an elevation of between 2 and 4 m higher than that of the peatlands. Inversely, peatlands that were not groundwater-fed were the highest topographic features (within a

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500 m distance), which makes them easy to identify using high resolution topographic maps.

Conclusion

The comparison of monthly WTDs in peatlands and in their adjacent mineral deposits has revealed a significant relationship between the K_{sat} of the outflow zones and the mean annual WTD for all studied peatlands, with the exception of the heavily impacted LTF. Sites where peatlands are strongly connected with their aquifer show significant differences between MCD and MCI compared to weakly connected sites. Peatlands that were strongly connected with their outflow zone show the strongest correlations and water storage variation, suggesting that hydrogeological setting does have some influence on peatland WTD and WTF. This mechanism should be further explored to better understand the long-term WTD responses of peatlands to climate and anthropogenic pressures. By providing new insights regarding peatland hydrology where adjacent mineral deposits play a dominant role, the methods developed in this study provide a strong basis from which to further investigate the impacts of variations in such pressures on peatlands. This study also provides important new data with which to include hydrogeological setting in numerical models attempting to simulate peatland WTD and WTFs.

Two new indicators, MCI and MCD, were calculated and compared with monthly precipitation (P_{month}) and monthly temperature (T_{month}). Strong correlations enabled the quantification of the effects of monthly temperature and monthly precipitation changes on WTD. The results show that a 1°C change in monthly temperature imposes a change of between 8 and 18 mm in monthly WTD, and that a 1 mm change in monthly

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precipitation imposes a change of between 1.3 and 4.3 mm in monthly WTD. This method should be validated in different climatic contexts and hydrogeological settings to further document the vulnerability of peatlands to climate change.

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Figure captions

Figure 1. Location of the seven studied peatlands (green areas) 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 (black lines), including the major rivers (blue lines) in southern Quebec, Canada.

Figure 2 Hydrogeological setting for a) Covey Hill (CH), b) Large Tea Field (LTF), c) Sainte-Séraphine (SSE), d) Lac Cyprès (LCY), e) Victoriaville (VIC), f) Villeroy (VR), and g) Issoudun (ISO), including instrumented dipwells and piezometers of all sites. Mean monitored water table variations, ± minimums and maximums are illustrated for the June 2014 to June 2016 period and for all monitored zones (1-up-gradient, 2-mid-gradient, 3-down-gradient, 4-minerotrophic, 5-inflow, and 6-outflow).

Figure 3. Temporal evolution of water table depth in the up-gradient dipwell (dipwell 1 in Figure 2) of each studied peatland, from June 2014 to June 2016.

Figure 4. Water table depth in the minerotrophic zone (dipwell 4 on Figure 2) of the peatland for CH, SSE, and VR, from June 2014 to June 2016.

Figure 5. Normalized (standard score) hydraulic heads in the inflow zones (piezometer 5 in Figure 2) of the aquifer for SSE and VR, from June 2014 to June 2016.

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Figure 6. Normalized (standard score) hydraulic heads in the outflow zones (piezometer 6 on Figure 2) of the aquifer for CH, SSE, LCY, VIC, VR, and ISO, from June 2014 to June 2016.

Figure 7. Median (point), minimum (lower bar), and maximum (upper bar) hydraulic conductivity of the outflow zone, as a function of the median water table depth in the up-gradient dipwell (zone 1, ombrotrophic section). Black = CH, red= LTF, green= SSE, dark blue=LCY, light blue= VIC, pink= VR, and yellow=ISO.

Figure 8. Monthly cumulative water table increase (MCI) as a function of monthly precipitation for the seven sites: a) Covey Hill (CH), b) Large Tea Field (LTF), c) Sainte-Séraphine (SSE), d) Lac Cyprès (LCY), e) Victoriaville (VIC), f) Villeroy (VR), and g) Issoudun (ISO). Numbers associated with each point indicate the month for which the MCI was calculated (i.e., 3 = March – 11 = November). Symbols indicate the year for which the MCI was calculated (open circle = 2014, triangle=2015, cross=2016).

Figure 9. Monthly cumulative water table decrease (MCD) as a function monthly mean temperature for the seven sites: a) Covey Hill (CH), b) Large Tea Field (LTF), c) Sainte-Séraphine (SSE), d) Lac Cyprès (LCY), e) Victoriaville (VIC), f) Villeroy (VR), and g) Issoudun (ISO). Numbers associated with each point indicate the month for which the MCD was calculated (i.e., 3 = March – 11 = November). Symbols indicate the year for which the MCI was calculated (open circle = 2014, triangle=2015, cross=2016).

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Figure 10. Autocorrelation function (r(k)) of water table depth as a function of time lag (hours) a) at the position of the up-gradient dipwell (dipwell 1 in Figure 2) and b) in the outflow zone (piezometer 5 in Figure 2).

Figure 11. Cross-correlation function (rxy(k)) between the dipwell in the up-gradient portion (dipwell 1 in Figure 2) and the piezometer in the outflow zone (piezometer 5 in Figure 2).

Figure 12. Four distinct cases regarding the relationship between flow direction, hydrogeological setting, and the WTD in the down-gradient and upgradient zones. a) convergent flow in the minerotrophic zone; peatland is in contact with both low-Ksat and high-Ksat sediment, b) outflow; peatland in contact with with low-Ksat sediment, c) outflow; peatland is in contact with high-Ksat sediment and d) outflow; peatland is surrounded by drainage.

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Site	Latitude	Longitude	watershed	Altitude (m)	Area (km^2)	Maximum peat thickness (m)	Hydrogeological setting	Acrotelm thickness (cm)	Minerotrophic zone	Mean annual temperature (°C)	Mean annual precipitation (mm)	Median ρ dry (g/cm^3) (max, min)	Median K (cm/s) (max, min)	Median Sy (max, min)	Water storage variation (mm)
1-CH	45.008	-73.828	Chateauguay	310	0.5	322	Fractured cambrian sandstone	32	Yes	6.1	929	0.10 (0.02 – 0.22)	$6.9x10^{-3}$ $(0.8 – 1x10^{-6})$	0.16 (0.05 – 0.82)	74
2-LTF	45.132	-74.217	Chateauguay	51	6.0	493	Marine clay	57	No	6.7	965	0.11 (0.03 – 0.16)	$5.1x10^{-4}$ $(0.4 – 1x10^{-5})$	0.05 (0.02 – 0.54)	192
3-SSE	46.042	-72.345	Nicolet	84	4.9	522	Fluvial silt/ glacial clayey silt	57	Yes	6.4	1114	0.11 (0.03 – 0.19)	$8.0x10^{-5}$ $(1.4 – 3x10^{-6})$	0.03 (0.01 – 0.56)	127
4-LCY	45.950	-72.187	Nicolet	106	0.5	190	Eolian sand	56	No	6.4	1114	0.14 (0.02 – 0.19)	$4.0x10^{-4}$ $(1.1 – 3x10^{-6})$	0.38 (0.01 – 0.69)	124
5-VIC	46.023	-72.077	Nicolet	118	2.6	360	Marine exondated silt	28	No	6.0	1114	0.10 (0.04 – 0.15)	$6.4x10^{-4}$ $(0.6 – 5x10^{-5})$	0.05 (0.01 – 0.49)	133
6-VR	46.376	-71.838	Becancour/ du Chene	124	10.4	491	Eolian sand/ glacial clayey silt	21	Yes	5.0	1037	0.08 (0.02 – 0.12)	$2.3x10^{-3}$ $(0.6 – 3x10^{-5})$	0.06 (0.01 – 0.59)	65
7-ISO	46.579	-71.597	du Chene	117	2.8	454	Glacial clayey silt	24	No	4.8	1037	0.06 (0.02 – 0.10)	$3.5x10^{-3}$ $(0.1 – 2x10^{-4})$	0.09 (0.02 – 0.38)	60

Table 1 Characteristics of the studied peatlands: abbreviated site name, latitude, longitude, watershed, altitude, area, maximum peat thickness, hydrogeological setting, acrotelm thickness, presence of minerotrophic zone, mean annual temperature (°C) and precipitation (mm), and median dry bulk density (ρ dry), hydraulic conductivity (K), storage coefficients (Sy), and storage variation (from Bourgault et al. 2016).

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Highlights

- Meteorological conditions have variable effects on peatland WTD and WTF, depending on peatland hydrogeological setting
- K_{sat} of the adjacent mineral controls the WTD of the ombrotrophic section of peatland
- Groundwater connected peatlands show low WTD and strong WTF
- Monthly cumulative variation in peatland WTD is linearly correlated to monthly precipitation and monthly temperature

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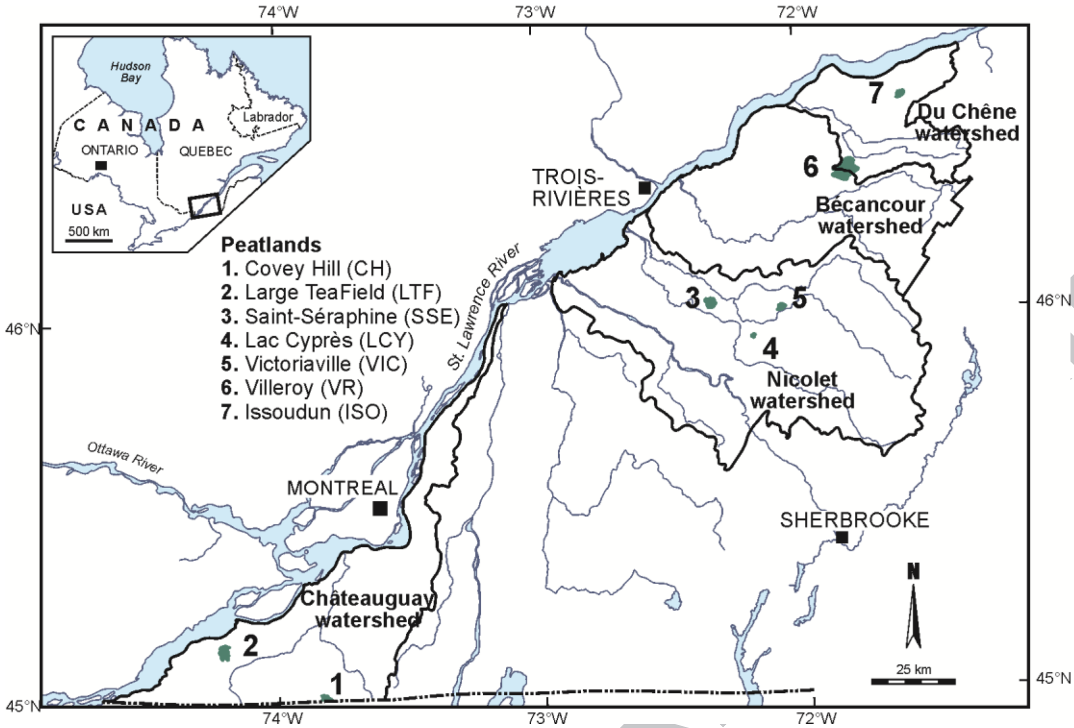

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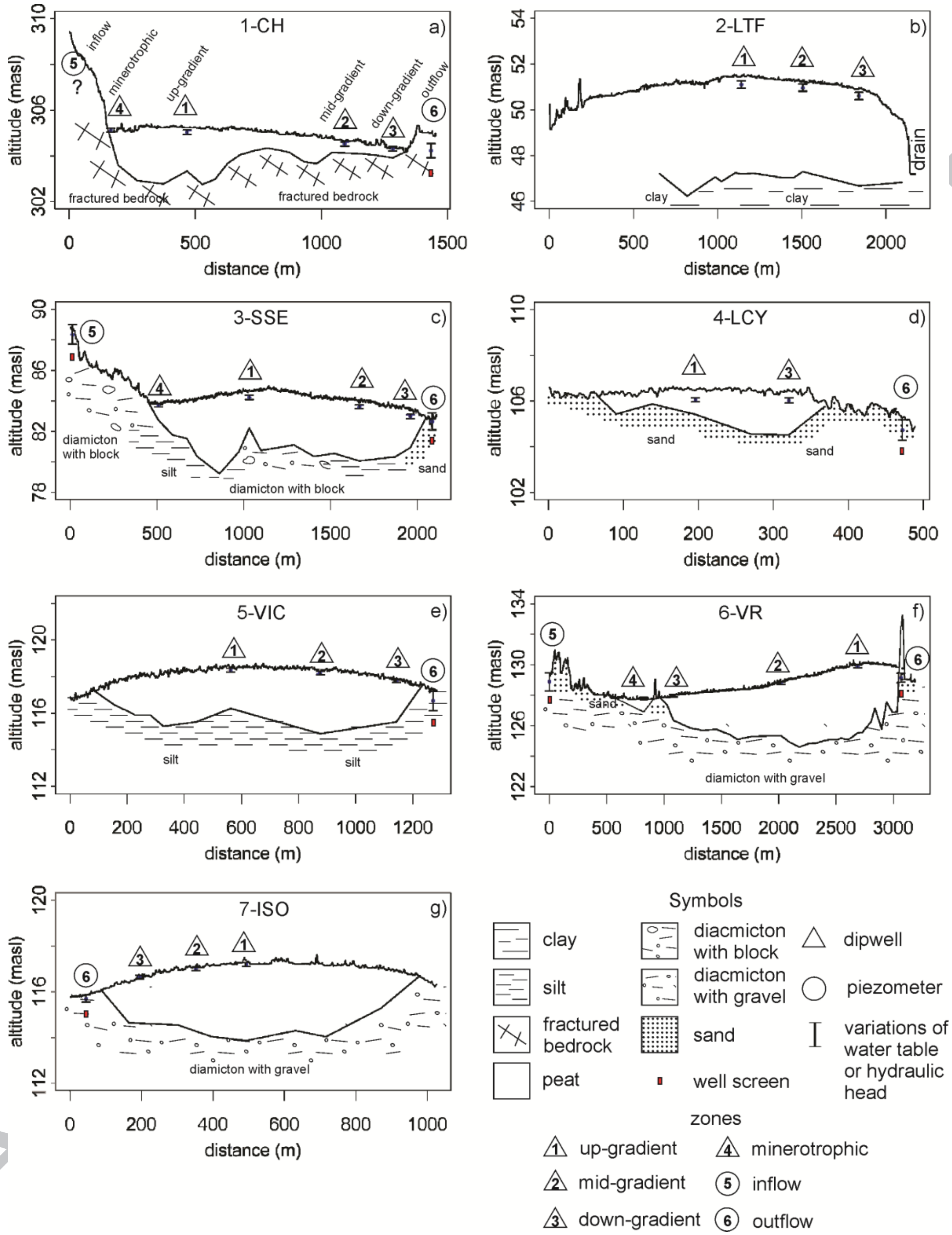

1-CH
a)
inflow
minerotrophic
up-gradient
mid-gradient
down-gradient
outflow
fractured bedrock
fractured bedrock
altitude (masl)
distance (m)
2-LTF
b)
drain
clay
clay
3-SSE
c)
diamicton with block
silt
diamicton with block
sand
4-LCY
d)
sand
sand
5-VIC
e)
silt
silt
6-VR
f)
sand
diamicton with gravel
7-ISO
g)
diamicton with gravel
Symbols
clay
silt
fractured bedrock
peat
diacmicton with block
diacmicton with gravel
sand
well screen
dipwell
piezometer
variations of water table or hydraulic head
zones
up-gradient
mid-gradient
down-gradient
minerotrophic
inflow
outflow

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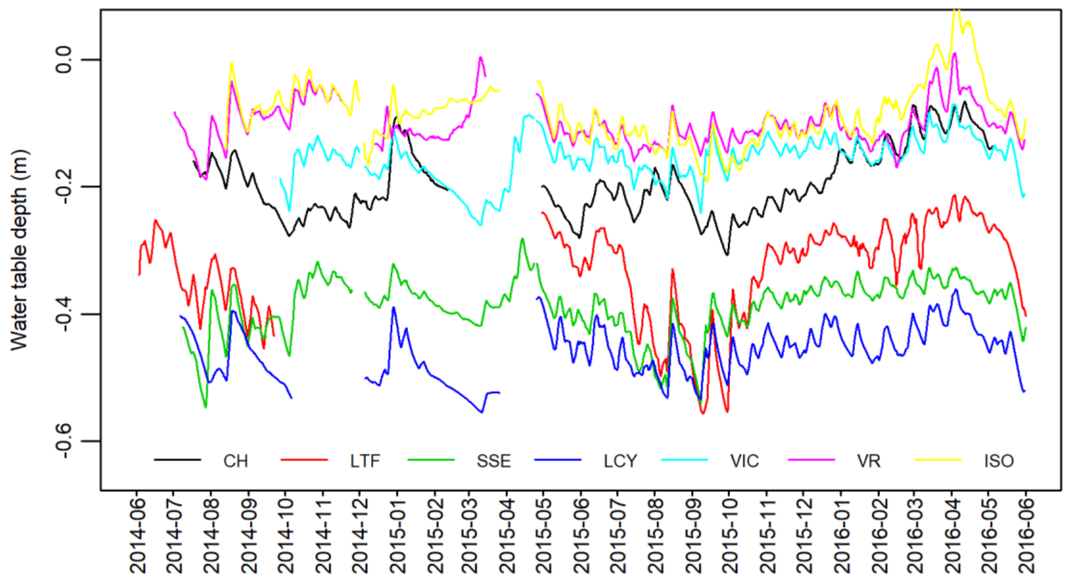

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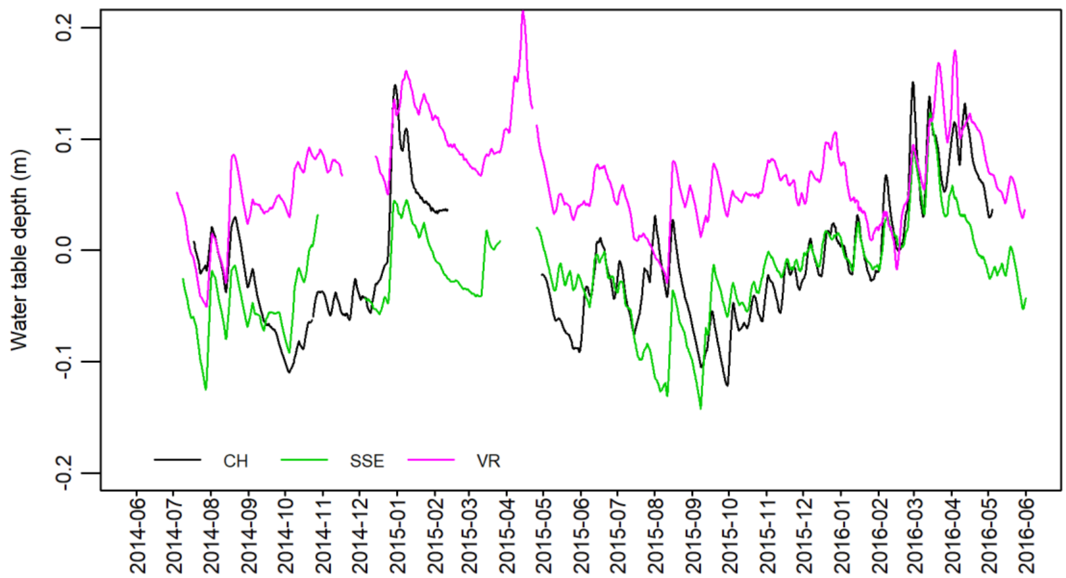

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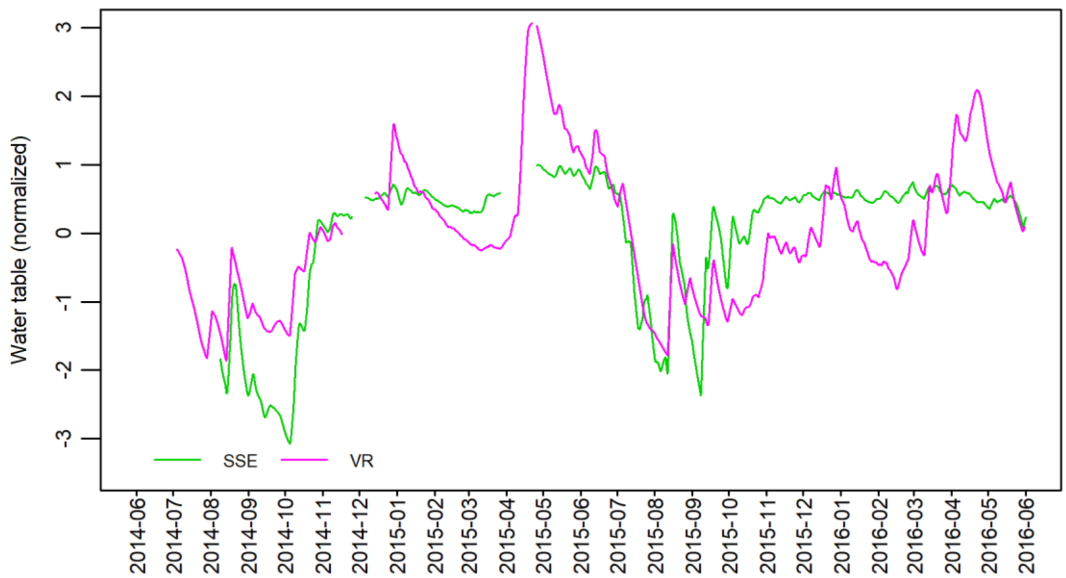

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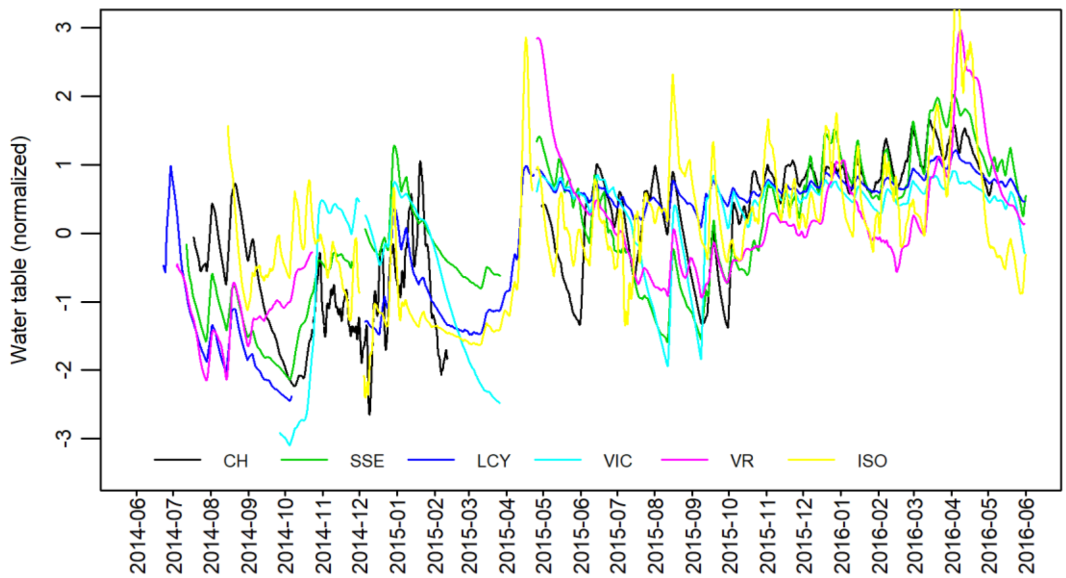

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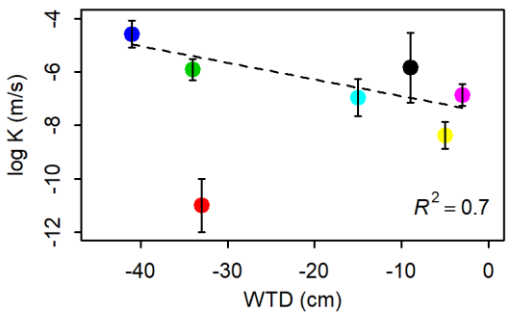

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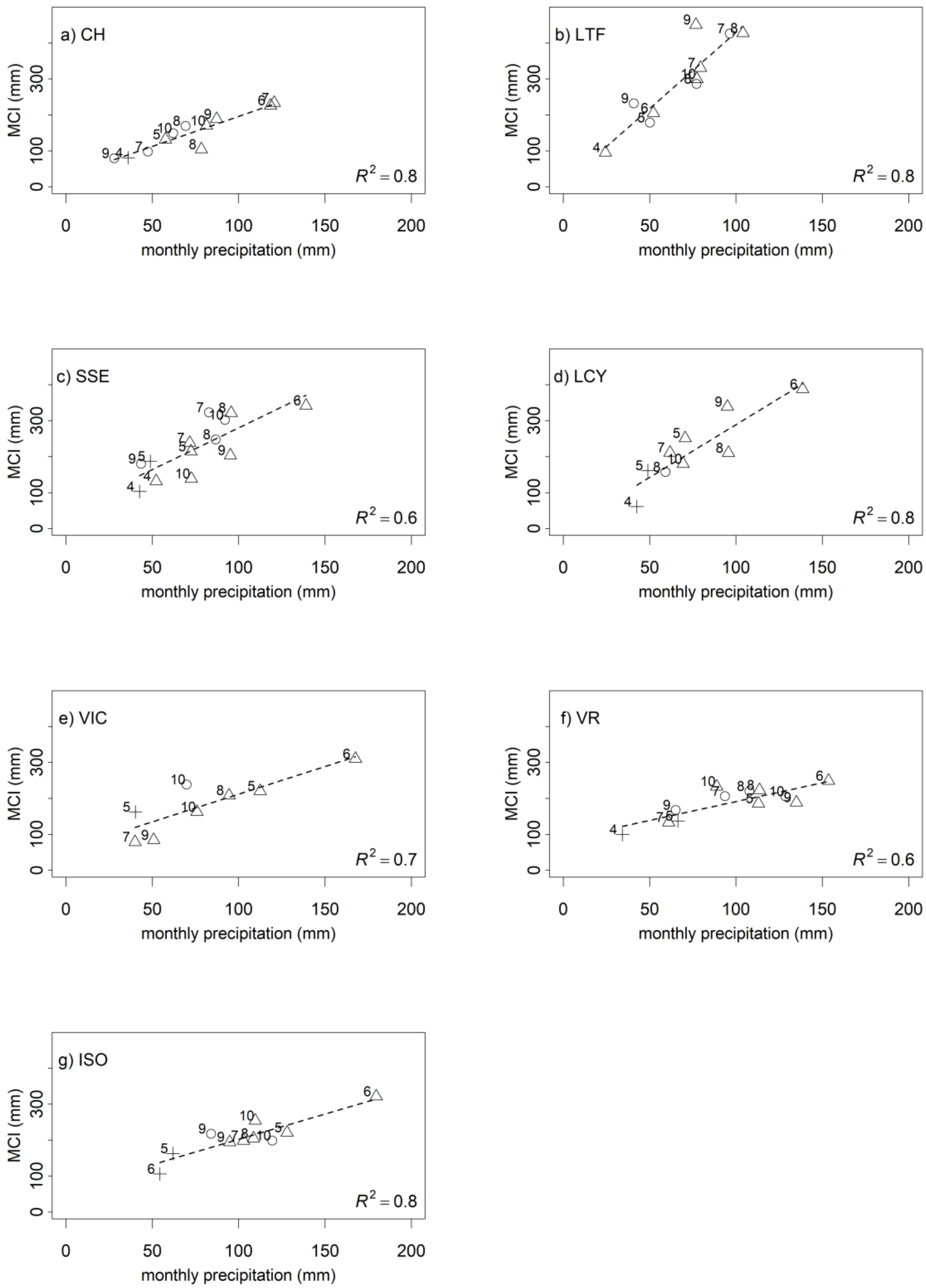

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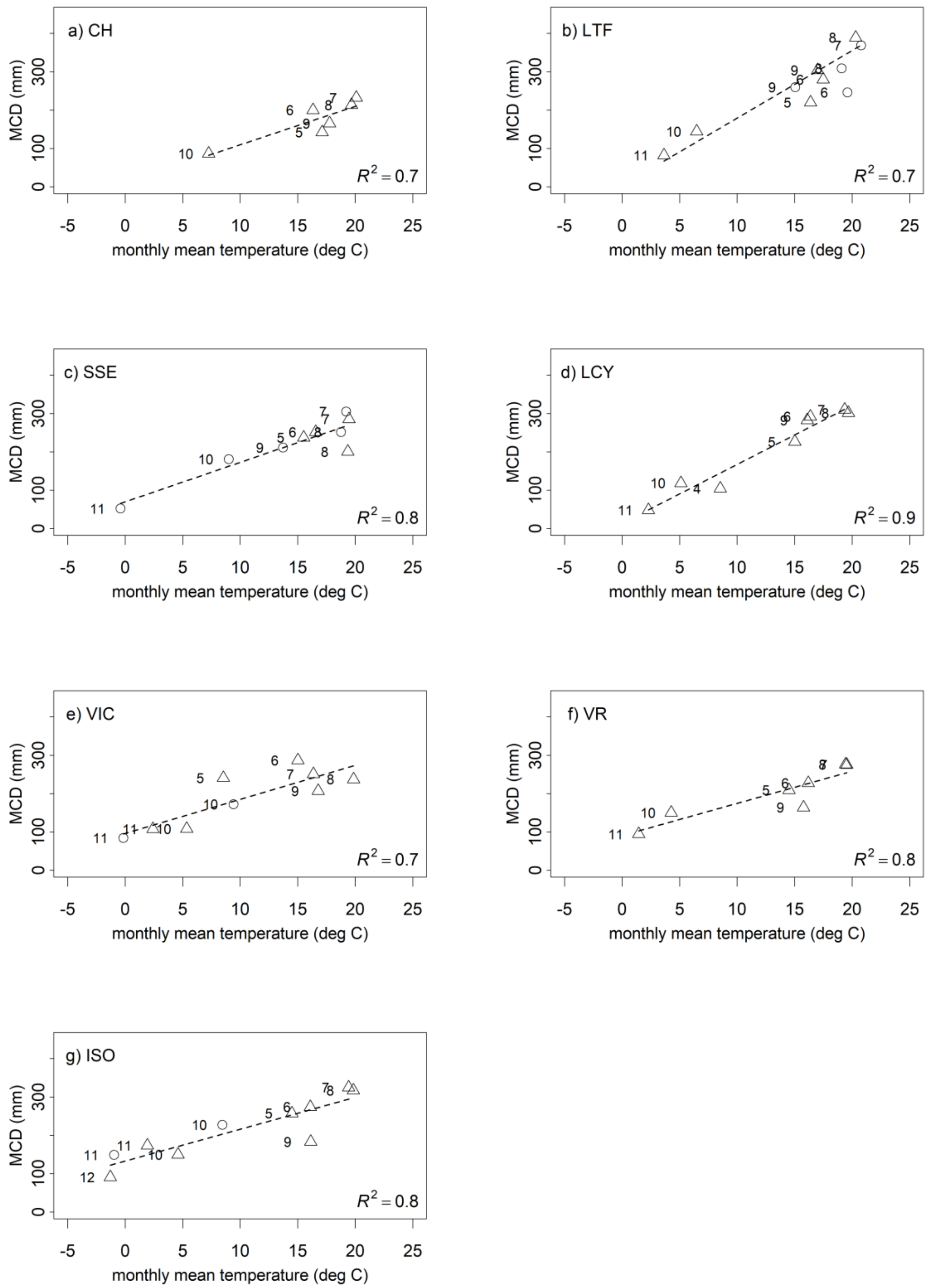

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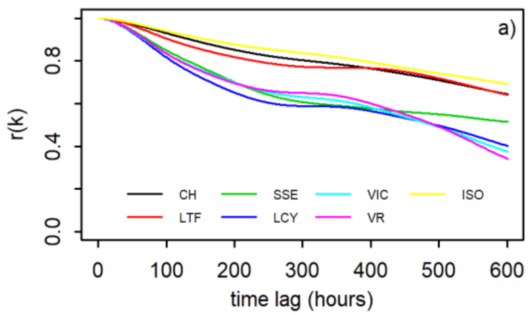

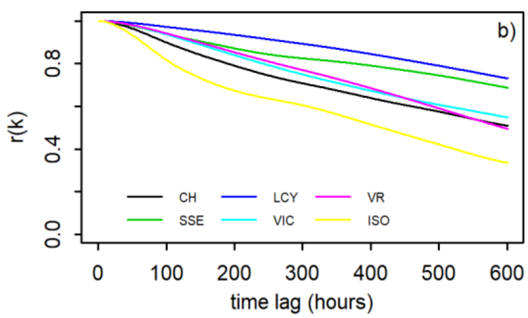

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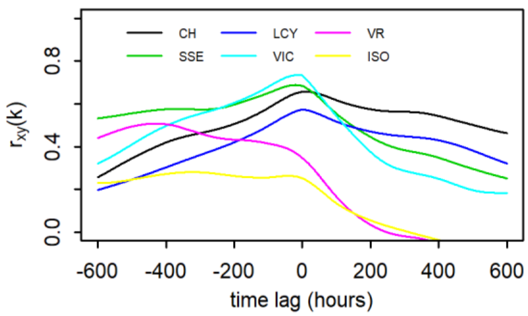

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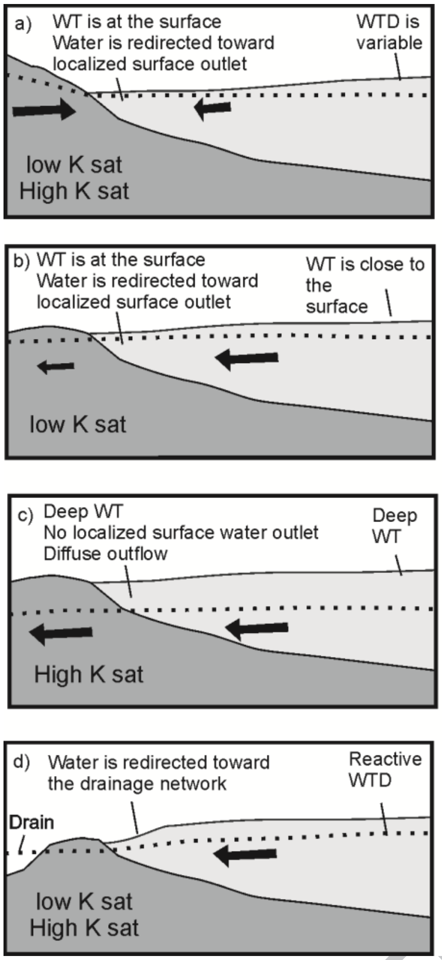

- Similar to CH, SSE and VR
-WTD in the convergent zone is at the surface
-WTD in up-gradient zone is variable
-Low WTF in the downgradient zone
-Groundwater-fed peatland

- Similar to CH, VR and ISO
-WTD in down-gradient zone is at the surface
-WTD in up-gradient zone is close to the surface
-Low WTF in up- and down-gradient zone
-Weak connectivity with the adjacent mineral

- Similar to VIC, SSE and LCY
-WTD in down-gradient zone is not close to the surface
-WTD in up-gradient zone is not close to the surface
-High WTF in up- and down-gradient zone
-Strong connectivity with the adjacent mineral

- Similar to LTF
-WTD in up- and down-gradient zone is in intermediate situation
-High WTF in up- and down-gradient zone
-No connectivity with the adjacent mineral
-No equilibrium with the hydrogeological setting

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