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Aquifer–peatland connectivity in southern Quebec (Canada)

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Abstract

In areas where peatlands are abundant, they are likely to play a significant role in the hydrological and hydrogeological dynamics of a watershed. Although individual case studies are reported in the literature, there is a large range of aquifer–peatland interactions and there is a need to understand the controls of these interactions. The objectives of this study were 1) to better understand aquifer–peatland connections and how these may be predicted by geology and geomorphic location and 2) to provide a variety of reference sites for glacial geological settings. Slope and depression peatlands were studied in the Abitibi-Témiscamingue region and in the St. Lawrence Lowlands, two contrasting regions of southern Quebec. A total of twelve transects that span a shallow aquifer–peatland interface were instrumented with piezometers. Field investigations included peatland characterization, monthly water level monitoring, and continuous hydraulic head measurements with pressure transducers. The results indicate that 7 of the 12 transects receive groundwater from the surrounding shallow aquifer. At the peatland margin, four lateral flow patterns were identified and associated with slope peatlands (parallel inflow and divergent flow) and with depression peatlands (convergent flow and parallel outflow). Vertical hydraulic gradients suggest that water flows mainly downwards, i.e., from the peatland to the underlying mineral deposits. Vertical connectivity appears to decrease as the distance from the peatland margin increases. All of these exchanges are important components in the sustainability of peatland hydrogeological functions. The regional comparison of aquifer–peatland flow dynamics performed in this study provides a new set of referenced data for the assessment of aquifer–peatland connectivity.

Key words: peatland, aquifer, connectivity, geologic setting, southern Quebec (Canada)

1. Introduction

There is a need to understand regional variability in watershed hydrology, and how this may vary and be predicted by geology and geomorphic location. Wetlands in general and especially peatlands can play a significant role in the hydrological and hydrogeological dynamics of a watershed (Bullock and Acreman, 2003; Cohen and Brown, 2007). Minerotrophic peatlands (or fens) are usually connected to shallow aquifers. Ombrotrophic peatlands (or bogs) rely on precipitation and atmospheric deposition, and they often have a higher water table isolated from regional groundwater flow. However, groundwater can feed bogs as upward local groundwater flux (Drexler, 1999; Fraser *et al*., 2001). Bogs can also be connected to surface aquifers through minerotrophic peat margins and laggs. A better understanding of these dynamics can contribute to groundwater and wetland management.

Aquifer–peatland connections are influenced by peatland location within a local, intermediate, and regional flow system (Tóth, 1999; Winter, 2000; 2001; Winter and LaBaugh, 2003), as well as peatland development stage. For example, peatlands located on or at the base of hillslopes are known to be areas of regional or intermediate groundwater discharge (Todd *et al*., 2006) which generally supports persistent surface wetness in the peatland (Branfireun and Roulet, 1988). This context explains the vegetation diversity, elevated pH, alkalinity, and calcium concentrations found in minerotrophic peatlands (Bendell-Young and Pick, 1997; Bragazza and Gerdol, 2002). However, with currently available data it is difficult to extrapolate site-specific observations because of spatial variability of peatland geological settings (Whitfield *et*

al., 2010) and climate conditions. There is clearly a need to perform multi-site aquifer–peatland connection studies that could lead to a framework allowing such extrapolations (Price *et al.* 2005). These frameworks are not new for temperate wetlands and riparian zones (e.g., Brinson 1993), but are much less developed for peatland–upland interactions and in northern climates.

In the Canadian province of Quebec, peatlands cover an area of approximately 112,000 km^2, i.e., more than 7% of the territory (Daigle and Gautreau-Daigle, 2001), yet relatively little is known about their connections with surface aquifers. The objectives of this study were 1) to better understand aquifer–peatland connections and how these may be predicted by geology and geomorphic location and 2) to provide a multi-site comparison basis for aquifer–peatland connections in glacial geological settings. This study analyzed stratigraphy as well as spatio-temporal variations in water levels in twelve aquifer–peatland systems of the Abitibi and Centre-du-Quebec regions of southern Quebec.

2. Study sites

Surficial geology in the Abitibi region (Figure 1a) is characterized by an esker-moraine morphology surrounded by an extensive glaciolacustrine clay plain. These deposits cover metamorphosed sedimentary and volcanic rocks intruded by granitoids. Deposited when the region was submerged by the deep proglacial waters of Lake Barlow-Ojibway, this clay contributes to the highly productive aquifers found in eskers by retaining groundwater in the granular deposits (Nadeau, 2011). In the Abitibi region, 19% of the

study area comprises wetlands, most of which are peatlands (Ducks Unlimited Canada, 2009) essentially found on esker slopes. The peatlands selected for this study are slope bogs (as defined by NWWG, 1997) that have developed on the eskers. They form large peatland complexes, with a marginal fen at their upgradient limit and fingering organic deposits that drain naturally in small streams at the outer edge of the peatlands. The peatlands are geogenous (Mitsch and Gosselink, 2007), i.e., open to outside hydrologic flows other than precipitation, and most are flow-through systems.

Geology in the Becancour region (Figure 1b) consists of a series of sedimentary and metamorphic rocks, mainly schists and shales, covered with tills and permeable Quaternary marine deposits that form surface and semi-confined aquifers. Low-permeability tills and Champlain Sea clay deposits accumulated during and after the last glaciation have favored peat accumulation in topographic depressions (Godbout *et al.*, 2011). In low-lying areas, eolian deposits have been stabilized by the accumulation of peat (Filion, 1987). Peatlands comprise approximately 6% of the Becancour watershed (Avard *et al.*, 2013). The peatlands selected for this study are basin bogs (as defined by NWWG, 1997) surrounded by a minerotrophic lagg and are located at the head of small or intermediate watersheds. They all have more than one small stream outflow, and most are drained by artificial ditches. Many of the Becancour peatlands are topogenous peatlands, i.e., they have developed in topographic depressions with the possibility of local and intermediate scale groundwater connections (Mitsch and Gosselink, 2007).

Vegetation surveys performed on all the transects (Munger *et al*., 2014) have identified the presence of minerotrophic plant communities close to the shallow aquifer–peatland interface and a gradient towards ombrotrophic plant communities as the distance from the upland increases. This reflects the presence of a minerogenous hydrological system in the lagg or marginal fen portion of the peatlands and an ombrogenous system towards the inside of the peatland.

In the two regions, peatlands are bordered by sand and gravel deposits that extend, at least partly, under the organic deposits. Regional aquifer characterization studies (Larocque *et al.*, 2013a; Cloutier *et al.*, 2013) have shown that sand thickness can vary from 1 to 20 m at the peatland border (near the surface aquifer), allowing lateral hydrogeological connectivity. A hardened oxidized sand layer has been observed under Becancour peatlands near the water table, indicating a possible restriction in vertical flows. Towards the center of the peatlands, the organic deposits sometimes lie directly over either clay or low permeability compact till. Vertical flows are expected to be very limited in these sectors. In Abitibi, the slope peatlands are located within 250 to 3000 m of an esker crest. In Becancour, some depression peatlands are within 50 to 500 m of a local topographic crest, while other peatlands are far from any high topography region. These conditions define the Abitibi peatlands in a discharge position within an intermediate scale recharge-discharge setting. In Becancour, some peatlands are located in local recharge-discharge settings while others could be intermediate or even regional scale groundwater discharge sites.

Long-term average air temperatures are 1˚C and 5˚C in the Abitibi and Becancour regions respectively (Environment Canada, 2012). The long-term average annual precipitation is slightly lower in Abitibi (918 mm) than in Becancour (1193 mm). The proportion of snow precipitation (between November and April) is similar for the two regions, with 27% for Abitibi and 24% for Becancour. The May-November 2011 study period was especially dry in Abitibi, with 543 mm of rain (annual precipitation of 808 mm in 2011) compared to 954 mm in Becancour due to the Irene hurricane in late August (total 2011 annual precipitation 1388 mm). The year 2011 was warmer than average in both regions, with average temperatures of 3°C and 6°C in Abitibi and Becancour respectively. The May-November average monthly temperatures were above freezing in both regions (Figure 2). The potential evapotranspiration for the May-November 2011 period (calculated with the Oudin *et al*., 2005 formula) was 495 mm and 555 mm in Abititi and Becancour respectively. This leads to a very low net precipitation for the study period in Abitibi (48 mm) compared to a high net precipitation in Becancour (399 mm).

3. Methods

3.1 Field instrumentation

The definition of peatland used in this study is the one from NWWG (1997), i.e., mainly anaerobic water-saturated ecosystems, where peat accumulation exceeds 40 cm. Six aquifer–peatland transects were instrumented in each region. Experimental sites were selected using wetland maps (Ducks Unlimited Canada, 2006; 2009) as well as aerial and satellite photographs. Undisturbed peatlands were preferred whenever possible. Five

peatlands were selected in Abitibi: La Belle (two transects: LB1 and LB2), La Coupe (LC), Saint-Mathieu-Berry (SMB), Sources Nord (SN), and Sources Sud (SS) and four were selected in the Becancour region: Lac Rose (two transects: LR1 and LR2), Mer Bleue (MB), Saint-Sylvère (SSY), and Villeroy (two transects: V1 and V2) (Figure 1).

In each peatland, one or two transects were positioned perpendicular to the peatland margin, in the direction of potential lateral groundwater flow. Transects in the same peatland were located at 690, 330, and 990 m apart for LB1/LB2, LR1/LR2, and V1/V2 respectively, and parallel to each other. All transects include six piezometric stations (Figure 3). Each piezometer is built of a 2.5 cm-ID-PVC pipe slotted over the lower 30 cm and sealed at the base. In the shallow aquifer (station no.1), the piezometers were installed using an auger and have depths ranging from 0.75 to 4.22 m, to ensure that they reach the water table. This piezometer station is located within 10 m from the peatland margin, while the other five stations (no.2 to 6) are located further into the peatland. Station no.2 is located as close as possible to the peatland margin, where peat thickness reaches 40 cm. Station no.3 is located where significant changes in vegetation are observed, indicating a transition from a fen vegetation to a bog vegetation. Stations no.4, 5, and 6 are approximately 50 m, 100 m, and 300 m away, respectively, from station no.3. The transects have an average length of 450 m.

Only one piezometer was installed in the surface aquifer, whereas nests of two piezometers were installed in the peatland. The nests were composed of a surface piezometer, at a maximum depth of 1.1 m in the peat, and a deep piezometer located at

40 cm below the mineral-peat interface (slotted section located in the underlying mineral deposits). This instrumentation was the best compromise for representing the surface water table, while avoiding surface flow (in the top 50 cm of the live organic deposits), therefore reflecting the true hydraulic gradients within the peatland. Transect surface and elevation of all the piezometers were surveyed using a differential GPS (R8 GNSS). The vertical precision of these measurements is approximately 1 cm in static mode (USGS, 2013). It is suspected however that the highly variable small-scale topography of the organic deposits probably induces a larger error. At four transects in the Becancour region (LR1, V1, V2, and SSY), the elevation of the shallow aquifer piezometer (no.1) was estimated from a LiDAR survey because deciduous trees prevented a precise measurement with the differential GPS. The vertical precision of the LiDAR measurements is estimated at 26 cm (Hodgson and Bresnahan, 2004).

3.2 Field measurements

The thickness of the organic deposits was determined using a standard Oakfield soil sampler every 50 m on all transects. At the time of sampling, the type of underlying mineral deposits was estimated in the field using a finger rub test. Fourteen holes were drilled using a portable pionjar drill in the Abitibi region close to station no.1 and between stations no.1 and 2 at the LB1, LC, SMB, SN, and SS sites to investigate the stratigraphy of the mineral deposits underneath the peatland. These pionjar holes reached a maximum of 8.5 m depth (LB1 and SMB sites). In the Becancour region, pionjar drilling was not able to penetrate below the organic deposits because of the presence of compact till or boulders.

Water levels were measured monthly in all piezometers from May to November 2011 using a manual water level tape (precision 0.5 cm). The water level surveys in each region were conducted within a span of 2-3 days. Campaigns started in early May 2011 (May 3rd in Abitibi and May 11th in Becancour) and ended in mid-November (November 13 in Abitibi and November 18 in Becancour). Water levels were therefore measured outside of the snow accumulation period (cf. Figure 2) and there was no ice in the organic deposits during the entire study period. Although an effort was made to perform the measurement campaigns during dry periods, there could have been occasional minor rain events. It is hypothesized that these did not bias the results. Lateral and vertical hydraulic gradients were calculated using the monthly head values:

$$i_{lat((i)-(i+1))} = (h_i - h_{i+1}) / L_{(i)-(i+1)} \quad (1)$$

$$i_{vert} = (h_M - h_P) / L_{M-P} \quad (2)$$

where i_{lat} is the lateral hydraulic gradient between the peat piezometers located at stations i and $i+1$ (m/m) (i_{lat} is positive from the aquifer to the peatland), h_i is the hydraulic head in the peat at station i and h_{i+1} is the hydraulic head in the peat at station $i+1$ (m), $L_{(i)-(i+1)}$ is the lateral distance between stations i and $i+1$ (m), i_{vert} is the vertical hydraulic gradient between the piezometer located in the peat and the piezometer located in the underlying mineral deposits (m/m) (i_{vert} is positive from the underlying mineral deposits to the peatland), h_P is head in the peat (m), h_M is the head in the underlying mineral deposits (m), and L_{M-P} is the vertical distance separating the two piezometers at one station (m).

Because of the error on the relative elevation of the peatland stations (+/- 1 cm) and on the head measurements (+/- 0.5 cm), a vertical hydraulic gradient is considered only if the head difference exceeds 2 cm.

Each transect had one piezometer nest equipped with pressure transducers (Solinst) recording hourly hydraulic heads in the peatland and in the underlying mineral deposits. These transducers were located at different positions in the transects to provide additional insight into the degree of vertical connectivity at various stations.

Slug tests were performed on eight of the twelve transects to measure peat hydraulic conductivity. Piezometers were temporally installed in the organic deposits to perform slug tests at different depths (0.50-0.75, 0.74-1.00, 1.00-1.25, and >1.25 m from the peat surface) between stations 2 and 3. A pressure transducer (INW PT2X, length 12 cm, diameter 1.9 cm) dropped inside the piezometer acted both as an inserted slug and as a logger of heads (initial heads were measured using the manual water level tape). The resulting head differences were small (on average 11.5 cm) and this was considered favorable to minimize potential compression effects. In total, 41 tests were performed, but only 21 provided data that could be interpreted. For the successful tests, hydraulic conductivity was calculated using the Bouwer and Rice (1976) method. In order to produce reliable estimates of hydraulic conductivity, slug test response-time curves were recorded until at least 90% recovery. The tests took between 12 and 5 870 sec to reach 90% completion.

4. Results and discussion

4.1 Stratigraphic contexts and hydraulic properties

The studied peatlands from the Abitibi region (Figure 4 a-f) have developed on the Saint-Mathieu-Berry esker slopes (SMB) or the Harricana Moraine slopes (SN, SS, LC, LB1, LB2). With the exception of the LB1 site, elevation decreases along the transects for all peatlands in this region. Maximum peat thickness on the six Abitibi transects is 4.5 m at the SS site. At SN, till was found only 1-1.5 m under the sand whereas the underlying sand is more than 20 m thick close to the peatland border at LB1 and LB2 according to a regional-scale geological model (Cloutier *et al.*, 2013). The SMB peatland is the only site where the glaciolacustrine clay was found directly under the peat deposits (Figure 4d). This is consistent with the upper limit of clay that rarely exceeds 320 m in the region (Nadeau, 2011). On transects LB1 and LC, and to a lesser extent on transect SMB, mineral deposits under the peat form plateaus close to the esker or moraine (e.g., Figure 4a, 4c, and 4d). These relatively flat plateaus start approximately 30 m from the peatland margin and extend 80 m (SMB) to 150 m (LC1) beyond station no.1. These plateaus and the irregularities in the peatland bottom observed in SN and SS sites (Figure 4e, and 4f) were created by eolian sand deposits (Nadeau, 2011).

The Becancour peatlands have developed in depressions within the surface deposits (Figure 4g-l). At several sites peat topography slightly increases from the shallow aquifer–peatland interface towards the peatland center (e.g., Figure 4g, 4h, and 4j). The maximum peat thickness on the six Becancour transects was 4.3 m at the SSY site where portions of the transect lied directly on clay deposits (Figure 4j). On all the other

Becancour transects, the organic deposits have accumulated on sand and gravel deposits. A regional-scale stratigraphic model developed by Larocque *et al.* (2013b) shows that the peatland at sites LR1 and LR2 (Figure 4g, and 4h) has developed on a 9 m thick sand deposit. At the MB and V1 sites, a 1 m layer of compact till was found underneath 6 to10 m of sands and gravel at the peatland margin (Figure 4i and 4k). At the V2 site (Figure 4l), the sand layer was very thin and the organic deposits were almost in direct contact with the compact till (see Larocque *et al*., 2013b for a detailed stratigraphic model of the Villeroy peatland). At the V1 and V2 sites, permeable Quaternary marine deposits are overlain by parabolic dunes of eolian deposits (Filion, 1987), whereas on the other Becancour region transects the Quaternary deposits are associated with glacial deposits (Larocque *et al.*, 2013a).

Hydraulic conductivities obtained with the slug tests range from 1.7×10^{-7} m/s (LC site in Abitibi at depth 0.75-1.00 m) to 1.2×10^{-4} m/s (MB site in Becancour at depth 0.50-0.75 m) (Table 1). Values from the Abitibi peatlands at 0.50-0.75 m depth appear to be lower than in the Becancour peatlands, but the sample size was too small to confirm a significant difference. Hydraulic conductivity in the top 0.5 m of organic deposits is expected to be much higher (e.g., Rosa et al., 2007; Levison et al., 2013). These upper peatland layers can have a large influence on runoff. Peat hydraulic conductivities generally decrease with depth from 0.5 m, and the lowest values were measured below 1 m. However, it is also possible that lower hydraulic conductivities occur closer to the bottom of the peat. In this case, the peat functions as a partially impermeable layer (Johansen *et al.*, 2011). The results showed clearly that hydraulic conductivities are

highly variable between transects and the connections could also vary significantly within each transect. Similar lateral and vertical heterogeneity in hydraulic conductivity has been observed in other peatlands (e.g., Fraser *et al*., 2001; Dempster *et al.*, 2006).

4.2 Lateral flow connections

The water table depths (wtd) within the organic deposits follow peat topography closely (Figure 4). Average depths ranged from -0.23 m (LC site) to 0.07 m (V2 site) relative to the ground surface (Table 2). The average wtd was negative (i.e., below the surface) for all the Abitibi transects. In the Becancour region, the average wtd was negative for all sites except at the MB site (at or near the peat surface) and at the V2 site (on average 0.07 m above the peat surface). Wtd were generally deeper in Abitibi than in Becancour peatlands. This could be linked to the more humid conditions that occurred in the Becancour region during the 2011 growing season, but it is also possible that the slope peatlands simply drain better than the depression peatlands.

Hydraulic heads in the shallow aquifer (station no.1) were higher than those of stations no.2 at LB2, SMB, SS, and SN (Abitibi), as well as LR1, LR2, and MB (Becancour) (see Figure 4). The average hydraulic heads in the shallow aquifer varied between -3.41 m below the surface at the V1 site and equal to the surface at the MB site. The amplitude of head variations in the shallow aquifer is maximum at the SN site (1.29 m) and minimum at the SMB site (0.14 m).

The average hydraulic gradients from May to November 2011 between stations no.1 and 2 ($i_{lat(1-2)}$) show that 7 out of the 12 transects (LB2, SMB, SS, and SN in Abitibi; LR1, LR2, and MB in Becancour) had flow directions from the shallow aquifer to the peatland. Sites LB1 and LC (Abitibi), as well as SSY, V1, and V2 (Becancour), had flow directions from the peatland to the shallow aquifer. The average hydraulic gradients between stations no.2 and no.3 ($i_{lat(2-3)}$) were towards the peatland center on 6 transects (LB1, LB2, LC, SMB, and SS in Abitibi; LR1 in Becancour). They were in the direction of the shallow aquifer on three transects (LR2, SSY, and V1 in Becancour), and equal to zero on three other transects (SN in Abitibi; MB and V2 in Becancour). The lateral gradients between the aquifer and the peatland were larger than the first gradients within the peatland with $i_{lat(1-2)}$ ranging from -0.016 (LB1) to 0.100 (LB2) and $i_{lat(2-3)}$ ranging from -0.007 (V1) to 0.004 (LB1 and SMB).

The lateral hydraulic gradients (i_{lat}) observed at the peatland margin i.e., between stations no.1 and 3, suggest four types of lateral flow (Figure 5): 1) parallel horizontal inflow (l_{par_in}) where groundwater flows from the shallow aquifer into the peatland, and towards the peatland center; 2) convergent horizontal flow (l_{conv}) where groundwater flows from the shallow aquifer to the peatland where it converges with water flowing from the peatland center to the peatland margin; 3) parallel horizontal outflow (l_{par_out}) where peatland water flows out of the organic deposits and into the shallow aquifer; and 4) divergent horizontal flow (l_{div}) where water flows both towards the peat and towards the surface aquifer, and flow from the peatland to the shallow aquifer is possible despite the inverse topographic gradient. The different types of lateral connections were generally

reflected by different geochemical signatures that assessed the degree (or lack) of connection between the surface aquifers and the peat water (see Ferlatte, 2014; results not reported here).

Four out of six transects in the Abitibi region (LB2, SN, SS, and SMB) showed l_{par_in} horizontal flow. At the SN site, despite the null-value of the lateral gradient between station no.2 and no.3, the hydraulic gradient beyond station no.3 was oriented towards the peatland center and suggests a horizontal inflow. This horizontal flow is representative of flow-through systems typical of slope peatlands (Kehew *et al.*, 1998). Peatlands located on esker and moraine slopes in Abitibi received water laterally from the shallow aquifer, and this water flows through the organic deposits towards small streams at the other edge of the peatland. Since all transects were set up parallel to the flow, the hydraulic gradients capture this flow pattern.

Three transects in the Becancour region showed l_{conv} flows (LR1, LR2, and MB). These depression peatlands have raised surface topography with piezometric mounds that drive water to flow towards the lower surrounding lagg. From that point, water generally stays above the peat surface and flows parallel to the shallow aquifer–peatland limit towards the surface flow outlet of the peatland.

The l_{par_out} flows were observed in three Becancour transects (SSY, V1, and V2), although they occasionally showed l_{conv}. As with the l_{conv} case, these depression peatlands have also raised surface topography with piezometric mounds that drive water towards

the peatland margins. However, water does not converge with inflowing groundwater from the aquifer, but rather flows into the surrounding sand deposits. These peatland outflows are not caused by local groundwater level drawdowns from pumping in the shallow aquifer (pumping for large volumes in these aquifers is unlikely because they do not represent significant reservoirs). They appear to be determined by intermediate scale groundwater flow directions driven by topography and hydrology. This type of flow direction was observed by Dempster *et al*. (2006).

The l_{div} flows were observed on only two transects in Abitibi (LB1 and LC). This type of flow is common in drier climates and with vegetation control of hydraulic depression on wetland edges (Winter, 2001). Ferone and Devito (2004) have reported similar conditions of divergent flow in a Boreal Plain depression peatland located close to a moraine. These conditions cannot be invoked exclusively for LB1 and LC since they are set in similar conditions to the other Abitibi sites. The observed divergent flows could be related to the presence of shallow peat depths over mineral plateaus observed at these two sites (cf. Figure 4).

No significant lateral flow reversals occurred during the study period, although they were locally and episodically observed at some stations in both regions (LB2, LC, SN, LR1, V1, and V2). These occasional changes are probably related to seasonal transitions from wet to dry periods (Ferone and Devito, 2004; Mouser *et al.*, 2005).

4.3 Vertical flow connections

Although peatland hydrology is mainly controlled by lateral hydraulic gradients, Reeve *et al*. (2000) have shown that aquifer–peatland systems can also receive water from or provide water to the underlying mineral deposits. Here, vertical hydraulic gradients between the peatland piezometer and the piezometer in the underlying mineral deposits are used to assess possible vertical flow connections. However, a vertical hydraulic head gradient does not necessarily indicate the presence of vertical flow, as the presence of peat layers with lower hydraulic conductivity can inhibit water flow.

The vertical hydraulic gradients (i_{vert}) observed can indicate three types of vertical flow: 1) the head gradient between the underlying mineral deposits and the peat is downwards, suggesting peatland water flowing towards the underlying mineral deposits (v_{down}); 2) the head gradient between the mineral and organic deposits is upwards, suggesting vertical groundwater flow from the underlying mineral deposits to the peatland (v_{up}); and 3) the head difference between the mineral and organic deposits is close to zero and vertical flow is considered negligible (v_0).

The vertical flow connections calculated from all piezometric stations and for all seven months are dominated by v_{down} at all sites except at the LR1, SMB, and V2 transects (Table 3). The v_{up} vertical flow is observed at three sites (LB2, SMB, and LR1) and was only recorded on one occasion at V1 (May) and LR2 (November). Most of the v_{up} flows were recorded near the shallow aquifer, in sites with l_{par_in}, l_{par_out}, and l_{conv} lateral flow connections. Stations without vertical hydraulic gradients (v_0) were more frequent at the sites with l_{conv} lateral flow conditions. Settings with v_{down} occurred at all transect stations.

Figure 4 shows that hydraulic heads in the underlying mineral deposits were generally lower than the peatland heads in the Abitibi region. Heads in the underlying mineral deposits are not available for stations 3, 4, and 5 at SMB because the organic deposits lie on clay deposits. In the Becancour region, hydraulic heads in the underlying mineral deposits are lower than those in the peatland at LR2, SSY, and V1. They were mostly equal at LR1 and MB, and slightly lower at V2. Hydraulic head variations in the underlying mineral deposits from May to November were generally larger than those in the peatland, especially at sites LB1, LB2, LR2, V1, and V2. The average i_{vert} was downwards for 11 of the 12 transects (the exception is at LR1). The average gradients vary from -0.524 (LR2) to 0.023 (LR1) (Table 2). These high vertical hydraulic gradients are likely to be the result of the larger hydraulic conductivity in the underlying mineral deposits (Reeve *et al.*, 2000). The highest hydraulic gradients could also indicate confined flow conditions in the underlying mineral deposits, caused by the low hydraulic conductivity of the more decomposed peat layers found at the bottom of the peatland.

The v_{up} conditions can be explained in part by the transect location within local or intermediate scale recharge–discharge conditions (Tóth, 1999; Winter and LaBaugh, 2003). For all Abititi sites, recharge occurs at the esker crest (250-3000 m upgradient) and the peatland is a lateral inflow discharge area. When vertical peat-mineral hydraulic connectivity exists, upward flow can occur in these conditions. In Becancour, three transects show upward flows. LR1 and LR2 are not located near a topographic high, while V1 is a lateral outflow discharge area. These upwad flows could be due to

intermediate-scale discharge conditions. Since vertical flow conditions can occur at any station, the morphology of the underlying deposits and the presence of macropore flow (Rossi *et al.*, 2012) probably also play an important role.

Vertical flow reversals can occur when there is a change in the water table head relative to the head in the underlying mineral deposits (Siegel *et al.*, 1995; Devito *et al.*, 1997). This condition generates exchanged water. Flow reversals can also occur when there is a change in water table head relative to a no-flow lower boundary such as clay (Fraser *et al.*, 2001), but does not include a vertical water flow. In this study, flow reversals were observed many times at the LR1 site (all stations except no.6), but also occurred at least once at LB2, LR2 and V2, from May to November. Several authors noticed vertical flow reversals during sustained dry periods (e.g., Fraser *et al.*, 2001). This was not what happened at LB2 where flow was almost always upwards, except in August and September where it was downwards. Lower heads in the esker aquifer late in the summer were probably responsible for these flow reversals. The humid meteorological conditions in the Becancour region are unlikely to have triggered flow reversals. They could have resulted from ephemeral local scale groundwater upward flow equilibrating with a local and temporary water deficit in the upper peat (Reeve *et al.*, 2001). A larger number of flow reversals might have been identified had the water depth survey been conducted more frequently than once a month.

If the peatland is disconnected from the underlying mineral deposits, head variations in the underlying mineral deposits should not be correlated with head variations in the peat

(Mouser *et al*., 2005). To verify whether this was the case in the studied peatlands, hourly head time series from the piezometer nest instrumented with a data logger were compared on all the transects. A simultaneous reaction of peatland and mineral heads to rain events near the peatland margins can be either related to direct transmission of a pressure pulse within the peat to the underlying deposits, or to simultaneous but independent transmission from the shallow aquifer of a pressure pulse within the peat and within the mineral deposits. To assess when a connection was probable, linear regressions were calculated between head time series from the peatland and head time series from the underlying mineral deposits. R^2, considered a measure of the intensity of the hydraulic connection, varied from 0.23 at station no.6 of the LC site to 1.00 at station no.2 of the LR1 site (Table 4). The largest R^2 values were observed in the Becancour region, with the exception of the V2 site where vertical connections were apparently lower (0.71). As the distance from the peatland margin increases, head variations tend to become less synchronized, and the responses to precipitation events were lessened and delayed (see Figure 6 for examples at LB1 station no.6 and LR2 station no.2). This trend holds true for all sites except SMB and LR1. It could result from the generally decreasing sand/gravel thickness underneath the peatland, from the increasing peat thickness along the transects, and from the decreasing peat hydraulic conductivity with depth.

Darcy's law was used to estimate the amount of vertical flow across the peat–sand interface. The average hydraulic conductivity from all transects at depths larger than 1 m and the average vertical hydraulic gradient for stations no.2 and 3 where the highest connectivity was observed were used to calculate the vertical flows. The results showed

average outflows from the peatland to the underlying aquifer of 28 mm in Abitibi and of 38 mm in Becancour over the May-November 2011 period under study. These values appear to be very high, especially in Abitibi where net precipitation was 48 mm from May to November 2011 (net precipitation over this same period was 399 mm in Becancour).

4.4 Implications for peatland management

The stratigraphic contexts of the 12 studied transects indicate that peatlands are often underlain by permeable material. In these conditions, the decreasing thickness of the deposits and the low permeability of the bottom peat layers could limit exchanged vertical flows. This limited vertical connectivity, combined with the possible presence of oxidized sand below the peatland, could explain how peat accumulation was initiated and maintained through the centuries. These results have important implications for peatland management since they indicate that a majority of slope and depression peatlands are connected to surface aquifers. Lowering groundwater levels within a surface aquifer (e.g. from increased pumping) could impact the peatland water budget, either through reduced groundwater inflow (l_{par_in} and l_{conv}) or through increased peatland outflow (l_{par_out} and l_{div}).

The results of this study show very clearly that the Abitibi slope peatlands are located in an intermediate scale recharge–discharge setting and are connected to groundwater reservoirs in esker aquifers. Vertical inflow to these peatlands was observed only on two transects. Most transects show downward flow from the organic deposits to the aquifer,

with a decreasing connectivity with distance from the peatland margins. This difference with the presence of vertical inflows for slope peatlands suggested by Winter (2001) probably stems from the highly permeable esker deposits that favor horizontal groundwater inflow, and that in turn translate to a dominance of l_{par_in} lateral inflow conditions.

In the Becancour depression peatlands, the SSY, V1, and V2 transects are located in local discharge settings and feed the shallow aquifer with l_{par_out} flow conditions. In these peatlands, precipitation is probably the main water source for peatland development and maintenance. This corresponds to the typical definition of a bog. The other Becancour transects (LR1, LR2, and MB) are clearly discharge sites from the neighboring mineral deposits, but could also receive intermediate scale groundwater discharge. This translates into l_{conv} lateral flow conditions where only the lagg portion of the peatland receives groundwater. In these peatlands, lateral groundwater inflow probably represents an important water source for peatland development and maintenance. The distinction between the two flow types in depression peatlands probably depends on the intermediate scale groundwater flow directions driven by topography and hydrology.

It is evident that peatland and surface aquifers must be managed in a conjunctive manner to prevent lowering of heads either in the surface aquifer or in the peatland. For example, lowering of heads in the surface aquifer, due to a succession of dry periods or to pumping increases, could have a direct impact on most of the studied peatlands. The marginal fen portions of the Abitibi slope peatlands are probably least vulnerable to a long dry period

because of the significant buffering capacity of the large groundwater flow systems represented by eskers (Winter, 2000). In contrast, the lagg portions of some of the Becancour depression peatlands are likely very vulnerable to such a change because of the local recharge–discharge setting. The ombrotrophic portions of the peatlands in both regions depend primarily on precipitation for their water supply and are probably highly vulnerable to climate change (Winter, 2000). In other wetland settings, differences in sources of water to wetlands could imply that they would require different techniques to protect their water supply and water quality (Winter *et al*., 2001).

The main anthropogenic threat to the Abitibi peatlands is probably a reduction in esker piezometric heads that would lead to less groundwater discharge through springs and seepages areas. A reduction of this sort could be induced by pumping large volumes of water from the highly productive esker aquifers that are already solicited for drinking water purposes and water bottling (Cloutier *et al*., 2013). In the Becancour region, threats to peatlands are mostly from changes in land use (Avard *et al*., 2013), such as draining agricultural fields (this can limit aquifer recharge) and cranberry farming (this can modify local recharge patterns). Drainage within a peatland can also have a significant impact on aquifer–peatland interactions. Direct drainage is observed mostly in the Becancour region, in connection with the expansion of intensive agriculture and cranberry production. A lowering of peatland heads due to peat drainage can trigger tree growth (Frankl and Schmeidl, 2000; Pellerin and Lavoie, 2003) and limit or stop peat development. If groundwater levels in the shallow aquifer were to be significantly reduced, peatlands could transition to the parallel horizontal outflow (l_{par_out}) category.

5. Conclusion

The objectives of this research were 1) to better understand aquifer–peatland connections and how these may be predicted by geology and geomorphic location and 2) to provide a multi-site comparison basis for aquifer–peatland connections in glacial geological settings. Twelve transects were instrumented, characterized, and monitored through a seven-month period in the Abitibi and Becancour regions of southern Quebec. Four types of lateral flow connections were identified, l_{par_in} with parallel groundwater inflow and peatland flow within the organic deposits, l_{conv} with convergent lateral flow connections, l_{par_out} with parallel horizontal outflow, and l_{div} with diverging flow, both towards the peatland and towards the surface aquifer. Esker slope peatlands in Abitibi were predominantly l_{par_in} type, while 50% of the depression peatlands in Becancour were l_{par_out} and 50% were l_{conv} type. Seven of the twelve transects receive water from the shallow aquifer. Downward hydraulic gradients between the peat and the underlying mineral deposits suggest the presence of predominantly downward vertical flow, with decreasing vertical connectivity as the distance from the peatland margins increases.

These results have important implications for peatland management. Because a majority of peatlands are connected to surface aquifers and most of the water input is from lateral groundwater inflow, a decrease in groundwater levels surrounding the peatland will have a direct impact on hydrological conditions within the peatland. This decrease could be triggered by multi-year dry conditions, increased pumping, or land use changes. Over the long term, such changes could impact peat development and sustainability.

The twelve transects studied here were intended to represent conditions in two geologically and climatically contrasted areas. They illustrate the wide range of hydrogeomorphological settings of peatlands in southern Quebec. This study presents an entirely new data set that can serve as a basis for systematic extrapolation of peatland connectivity in southern Quebec. It is reasonable to assume that other peatlands in similar geomorphological and climate settings would exhibit similar connectivity with the surrounding shallow aquifer. Complementary work is underway on the studied transects to confirm the results presented here with groundwater flow modelling.

Acknowledgements

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References

Avard K, Larocque M, Pellerin S. 2013. Perturbations des tourbières de la région de Bécancour, Centre-du-Québec, entre 1966 et 2010. *Le Naturaliste Canadien* **137 (1)**: 8-15.

Bendell-Young L, Pick F. 1997. Base cation composition of pore water, peat and pool water of fifteen Ontario peatlands: Implications for peatland acidification. *Water, Air, and Soil Pollution* **96** : 155-173.

Bouwer H, Rice RC. 1976. A slug test for determining hydraulic conductivity of unconfined aquifers with completely or partially penetrating wells. *Water Resources Research* **12** : 423-428.

Bragazza L, Gerdol R. 2002. Are nutrient availability and acidity-alkalinity gradients related in Sphagnum-dominated peatlands? *Journal of Vegetation Science* **13** : 473-482.

Branfireun BA, Roulet NT. 1998. The baseflow and storm flow hydrology of a precambrian shield headwater peatland. *Hydrological Processes* **12 :** 57-72.

Brinson MM. 1993. Changes in the functioning of wetlands along environmental gradients. *Wetlands* **13**: 65-74.

Bullock A, Acreman M. 2003. The role of wetlands in the hydrological cycle. *Hydrology and Earth System Sciences* **7 :** 358-389.

Cloutier V, Blanchette D, Dallaire PL, Nadeau S, Rosa É, Roy M. 2013. *Projet d'acquisition de connaissances sur les eaux souterraines de l'Abitibi-Témiscamingue (partie 1). Rapport final déposé au Ministère du Développement durable, de l'Environnement, de la Faune et des Parcs dans le cadre du*

Programme d'acquisition de connaissances sur les eaux souterraines du Québec. Rapport de recherche P001, Groupe de recherche sur l'eau souterraine et Institut de recherche en mines et en environnement, Université du Québec en Abitibi-Témiscamingue. 135 p.

Cohen MJ, Brown MT. 2007. A model examining hierarchical wetland networks for watershed stormwater management. *Ecological Modelling* **201** : 179-193.

Daigle JY, Gautreau-Daigle H. 2001. *Canadian Peat Harvesting and the Environment*. Sustaining wetlands, Issues Paper no. 2001-1, North American Wetlands Conservation Council Comittee, Ottawa, Ontario, Canada. 45 p.

Dempster A, Ellis P, Wright B, Stone M, Price J. 2006. Hydrogeological evaluation of a southern Ontario kettle-hole peatland and its linkage to a regional aquifer. *Wetlands* **1** : 49-56.

Devito KJ, Waddington JM, Branfireun BA. 1997. Flow reversals in peatlands influenced by local groundwater systems. *Hydrological Processes* **11** : 103-110.

Drexler JZ, Bedford BL, Scognamiglio R, Siegel DI. 1999. Fine-scale characteristics of groundwater flow in a peatland. *Hydrological Processes* **13** : 1341-1359.

Ducks Unlimited Canada (2006). *Conservation plan for wetlands and their adjacent uplands in the administrative region of Centre-du-Québec*. Quebec 55 p.

Ducks Unlimited Canada (2009). *Conservation plan for wetlands and their adjacent uplands in the administrative region of Abitibi-Témiscamingue*. Quebec 76 p.

Environment Canada. 2012. *National Climate Data and Information Archive*. Accessed in February 2012. Online: climat.meteo.gc.ca/climateData/canada_f.html.

Ferlatte M. 2014. *Hydrogéochimie des systèmes aquifère-tourbière et traceurs des processus d'échange dans deux contextes géo-climatiques du Québec méridional*. MSc thesis, Université du Québec à Montréal, Département des sciences de la Terre et de l'atmosphère, 77 p.

Ferone JM, Devito KJ. 2004. Shallow groundwater–surface water interactions in pond–peatland complexes along a Boreal Plains topographic gradient. *Journal of Hydrology* **292** : 75-95.

Filion L. 1987. Holocene development of parabolic dunes in the central St. Lawrence Lowland, Québec. *Quaternary Research* **28** : 196-209.

Frankl R., Schmeidl H. 2000. Vegetation change in a south German raised bog: ecosystem engineering by plant species, vegetation switch or ecosystem level feedback mechanisms? *Flora* **195** : 267-276.

Fraser CJD, Roulet NT, Lafleur M. 2001. Groundwater flow patterns in a large peatland. *Journal of Hydrology* **246** : 142-154.

Godbout PM, Lamothe M, Horoi V, Caron O. 2011. *Synthèse stratigraphique, cartographie des dépôts quaternaires et modèle hydrostratigraphique régional, secteur de Bécancour, Québec* Montréal, Québec. 37 p.

Hodgson, M.E., Bresnahan, P. 2004. Accuracy of airborne Lidar-derived elevation: empirical assessment and error budget. *Photogrammetric Engineering & Remote Sensing* **70**(3) : 331-339.

Johansen OM, Pedersen ML, Jensen JB. 2011. Effect of groundwater abstraction on fen ecosystems. *Journal of Hydrology* **402**(3–4): 357-366.

Kehew AE, Passero RN, Krishnamurthya RV, Lovett CK, Bettsc MA, Dayharsh BA. 1998. Hydrogeochemical interaction between a wetland and an unconfined glacial drift aquifer southwestern Michigan. *Ground Water* **36** : 849-856.

Larocque M, Gagné S, Tremblay L, Meyzonnat G. 2013a. *Projet de connaissance des eaux souterraines du bassin versant de la rivière Bécancour et de la MRC de Bécancour. Rapport final déposé au Ministère du Développement durable, de l'Environnement, de la Faune et des Parcs dans le cadre du Programme d'acquisition de connaissances sur les eaux souterraines du Québec*. Montréal, Québec. 219 p.

Larocque M, Colpron-Tremblay J, Lavoie M, Tremblay L. 2013b. *Écohydrologie de la grande tourbière de Villeroy. Rapport d'activités*. Report submitted to the Ministère du Développement durable, de l'Environnement, de la Faune et des Parcs. 61 p.

Levison JK, Larocque M, Fournier V, Gagné S, Pellerin S, Ouellet MA. 2013. Dynamics of a headwater system and peatland under current conditions and with climate change. *Hydrological Processes* **28** : 4808-4822.

Mitsch WJ, Gosselink JG. 2007. Wetlands. Wiley. 600 p.

Mouser PJ, Hession WC, Rizzo DM, Gotelli NJ. 2005. Hydrology and Geostatistics of a Vermont, USA Kettlehole Peatland. *Journal of Hydrology* **301** : 250-266.

Munger J, Pellerin S, Larocque M, Ferlatte M. 2014. Espèces indicatrices des échanges d'eau entre aquifère et tourbière. *Le Naturaliste Canadien* **138**(1) : 4-12.

Nadeau S. 2011. Estimation de *la ressource granulaire et du potentiel aquifère des eskers de l'Abitibi-Témiscamingue et du sud de la Baie-James (Québec)*. MSc thesis, Université du Québec à Montréal, Département de Géographie, 161 p.

NWWG (National Wetlands Working Group). 1997. The Canadian wetland classification system. Second edition. University of Waterloo, Waterloo, Ontario, Canada. 68 p.

Pellerin S, Lavoie C. 2003. Reconstructing the recent dynamics of mires using a multi-technique approach. *Journal of Ecology* **97** : 1008-1021.

Price JS, Braunfireun B, Waddington JM, Devito JK. 2005. Advances in Canadian wetland hydrology, 1999–2003. *Hydrological Processes* **19** : 201–214

Reeve AS, Siegel DI, Glaser PH. 2000. Simulating vertical flow in large peatlands. *Journal of Hydrology* **227** : 207-217.

Reeve AS, Warzocha J, Glaser PH, Siegel DI. 2001. Regional ground-water flow modeling of the Glacial Lake Agassiz peatlands, Minnesota. *Journal of Hydrology* **243** : 91-100.

Rosa É, Larocque M. 2008. Investigating peat hydrological properties using field and laboratory methods: application to the Lanoraie peatland complex (Southern Quebec, Canada). *Hydrological Processes* **22** : 1866-1875.

Rossi PM, Ala-aho P, Ronkanen AK, Kløve B. 2012. Groundwater–surface water interaction between an esker aquifer and a drained fen. *Journal of Hydrology* **432-433** : 52-60.

Siegel DL, Reeve AS, Glaser PH, Romanowicz EA. 1995. Climate-driven flushing of pore water in peatlands. *Nature* **374** : 531-533.

Todd AK, Buttle JM, Taylor CH. 2006. Hydrologic dynamics and linkages in a wetland-dominated basin. *Journal of Hydrology* **319** : 15-35.

Tóth J. 1999. Groundwater as a geologic agent: An overview of the causes, processes and manifestions. *Hydrogeology Journal* **7**: 1-14.

USGS (United States Geological Survey). 2013. *USGS Global positioning application and practice*. http://water.usgs.gov/osw/gps/.

Waddington JM, Roulet NT. 1997. Groundwater flow and dissolved carbon movement in a boreal peatland. *Journal of Hydrology* **191** : 122-138.

Whitfield CJ, Aherne J, Gibson JJ, Seabert TA, Watmough SA. 2010. The controls on boreal peatland surface water chemistry in Northern Alberta, Canada. *Hydrological Processes* **24** : 2143-2155.

Winter TC. 2000. The vulnerability of wetlands to climate change. *Journal of the American Water Resources Association* **36**(2) : 305-311.

Winter TC. 2001. The concepts of hydrologic landscapes. *Journal of the American Water Resources Association* **37**(2) : 335-349.

Winter TC, Rosenberry DO, Buso DC, Merk DA. 2001. Water source to four U.S. wetlands: Implications for wetland management *Wetlands* **21** : 462-473.

Winter TC, LaBaugh JW. 2003. Hydrologic considerations in defining isolated wetlands *Wetlands* **23** : 532-540.

Table 1. Hydraulic conductivities (m/s) of peat material

Region	Site	Depth (m)			
		0.50 – 0.75	**0.75 – 1.00**	**1.00 – 1.25**	**> 1.25**
Abitibi	**LB1**	--	--	--	--
Abitibi	**LB2**	--	--	--	--
Abitibi	**LC**	2.5×10^{-7}	1.7×10^{-7}	--	--
Abitibi	**SMB**	5.5×10^{-6}	1.1×10^{-6}	6.9×10^{-7}	--
Abitibi	**SN**	--	--	4.4×10^{-6}	--
Abitibi	**SS**	--	--	--	--
Becancour	**LR1**	7.9×10^{-6} (1)	1.1×10^{-6}	6.6×10^{-7}	--
Becancour	**LR2**	3.6×10^{-7}	7.0×10^{-7}	8.2×10^{-7}	--
Becancour	**MB**	1.2×10^{-4}	5.7×10^{-7} (1)	8.1×10^{-7}	--
Becancour	**SSY**	--	--	--	--
Becancour	**V1**	3.1×10^{-5}	--	--	--
Becancour	**V2**	3.5×10^{-5}	--	3.9×10^{-6}	1.2×10^{-6} (1)

(1) The value is the arithmetic average of results from the two tests performed at this location. All other locations had only one slug test.

Table 2. Average water table depth (wtd) within the peatland, average lateral hydraulic gradients between piezometer stations no.1 (shallow aquifer) and no.2 ($i_{lat(1-2)}$), average lateral hydraulic gradient within between piezometer stations no.2 and no.3 ($i_{lat(2-3)}$), and average vertical hydraulic gradients within the peatland (i_{vert}). See Figure 3 for location of piezometer stations.

Region	Site	wtd[(1)] (m)	$i_{lat(1-2)}$[(2)] (m/m)	$i_{lat(2-3)}$[(2)] (m/m)	i_{vert}[(3)] (m/m)
Abitibi	LB1	-0.17 (0.19)[(4)]	-0.016 (0.003)	0.004 (0.001)	-0.468 (0.285)
Abitibi	LB2	-0.15 (0.17)	0.100 (0.036)	0.001 (0.002)	-0.112 (0.233)
Abitibi	LC	-0.23 (0.13)	-0.006 (0.005)	0.003 (0.005)	-0.352 (0.319)
Abitibi	SMB	-0.11 (0.13)	0.078 (0.002)	0.004 (0.002)	-0.038 (0.167)
Abitibi	SN	-0.07 (0.09)	0.022 (0.005)	0.000 (0.001)	-0.129 (0.090)
Abitibi	SS	-0.04 (0.08)	0.007 (0.004)	0.004 (0.001)	-0.086 (0.058)
Becancour	LR1	-0.07 (0.12)	0.009 (0.007)	0.002 (0.003)	0.023 (0.177)
Becancour	LR2	-0.07 (0.05)	0.028 (0.001)	-0.001 (0.000)	-0.524 (0.462)
Becancour	MB	0.00 (0.05)	0.002 (0.001)	0.000 (0.001)	-0.262 (0.476)
Becancour	SSY	-0.21 (0.25)	-0.001 (0.001)	-0.001 (0.001)	-0.378 (0.358)
Becancour	V1	-0.20 (0.20)	-0.024 (0.007)	-0.007 (0.003)	-0.181 (0.104)
Becancour	V2	0.07 (0.04)	-0.003 (0.005)	0.000 (0.000)	-0.073 (0.101)

[(1)]A negative wtd indicates average wtd below the peatland surface and a positive wtd indicates a wtd above the peatland surface.

[(2)]A positive lateral gradient is from the shallow aquifer to the peatland and a negative gradient is from the peatland to the shallow aquifer.

[(3)]A positive vertical gradient is from the underlying mineral deposits to the peatland and a negative gradient is from the peatland to the underlying mineral deposits.

[(4)] Values in parenthesis are standard deviations.

Table 3. Percentage of occurrence of the three types of vertical gradients considering all fen and bog sites.

Region	Site	v_{down} (%)*	v_{up} (%)	v_0 (%)
Abitibi	LB1	100	--	--
Abitibi	LB2	82	18	--
Abitibi	LC	88	--	12
Abitibi	SMB	43	50	7
Abitibi	SN	97	--	3
Abitibi	SS	86	--	14
Becancour	LR1	47	35	18
Becancour	LR2	83	3	14
Becancour	MB	76	--	24
Becancour	SSY	87	--	13
Becancour	V1	96	4	--
Becancour	V2	49	--	51

*: Percentages calculated for all the stations where a piezometer nest exists, using data from May to November 2011.

Table 4. Regression coefficients between heads in the peat and heads in the underlying mineral deposits

Region	Site	Station no.	Type of lateral gradient	R^2
Abitibi	LB1	6	l_{div}	0.64
Abitibi	LB2	5	l_{par_in}	0.58
Abitibi	LC	6	l_{div}	0.23
Abitibi	SMB	2	l_{par_in}	0.46
Abitibi	SN	4	l_{par_in}	0.81
Abitibi	SS	3	l_{par_in}	0.86
Becancour	LR1	6	l_{conv}	0.97
Becancour	LR2	2	l_{conv}	1.00
Becancour	MB	2	l_{conv}	0.93
Becancour	SSY	2	l_{par_out}	0.99
Becancour	V1	3	l_{par_out}	0.94
Becancour	V2	3	l_{par_out}	0.71

Figure captions

Figure 1. Location of individual peatlands at the two study sites a) Abitibi, b) Becancour.

Figure 2. May-November 2011 monthly precipitation, evapotranspiration, and air temperature.

Figure 3. Typical instrumented aquifer–peatland transect.

Figure 4. Stratigraphy and piezometric heads for the 12 aquifer–peatland transects. On panels a) to f): Abitibi sites and on panels g) to l): Becancour sites.

Figure 5. Typical lateral flow connections a) l_{par_in}, b) l_{conv}, c) l_{par_out}, and d) l_{div}.

Figure 6. Vertical flow connections based on hourly head measurements in the peatland (P) and in the underlying mineral deposits (UMD) from May to November 2011 in a) Abitibi (station no.6, LB1) and b) Becancour (station no.2, LR2).

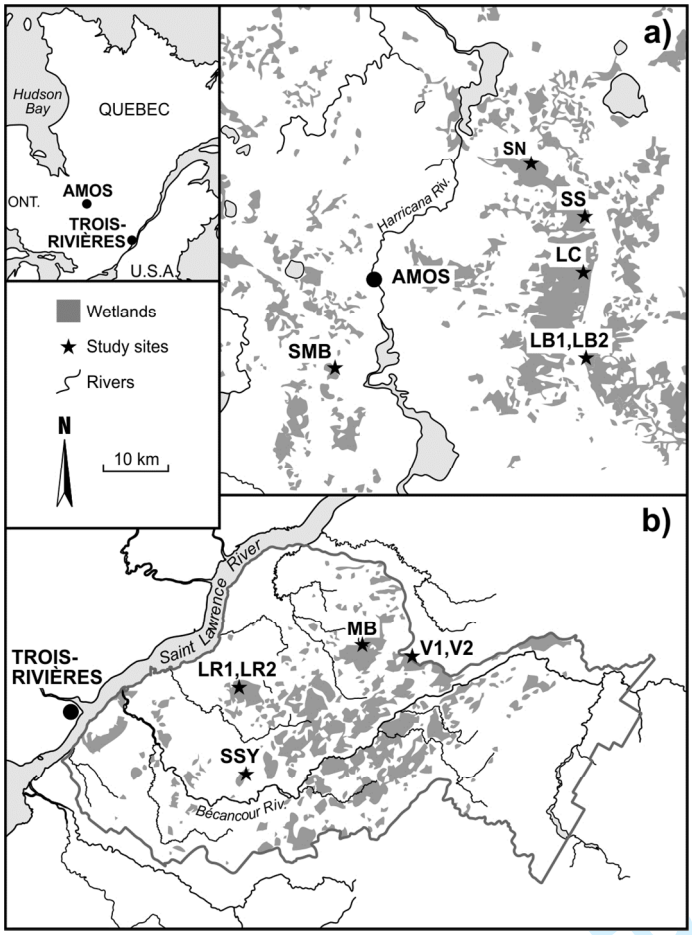


Figure 1
Ferlatte et al., 2014
Hydrological Processes

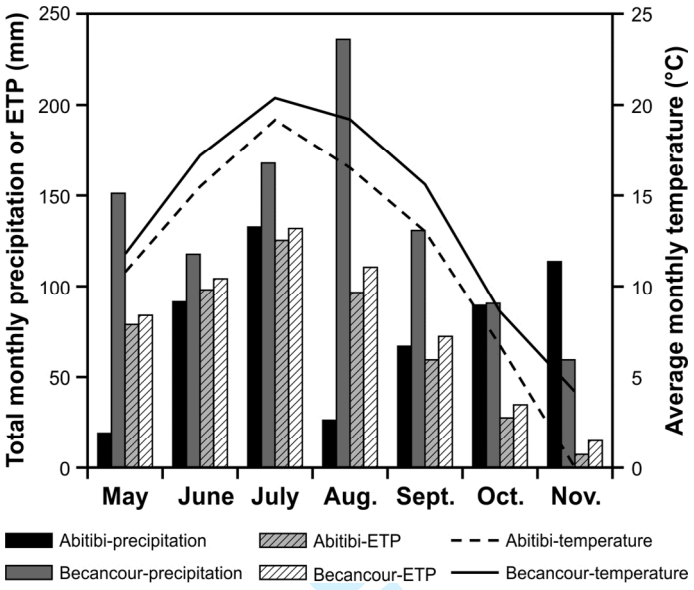


Figure 2
Ferlatte et al., 2014
Hydrological Processes

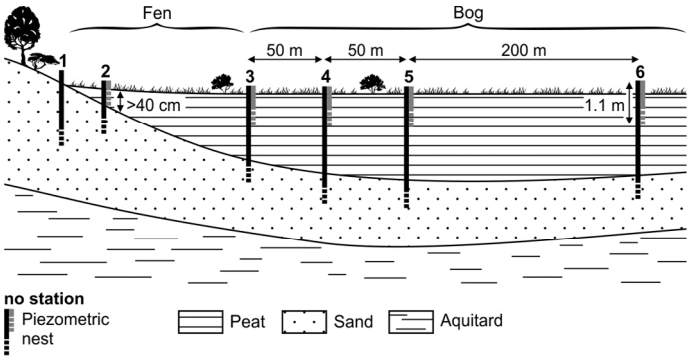
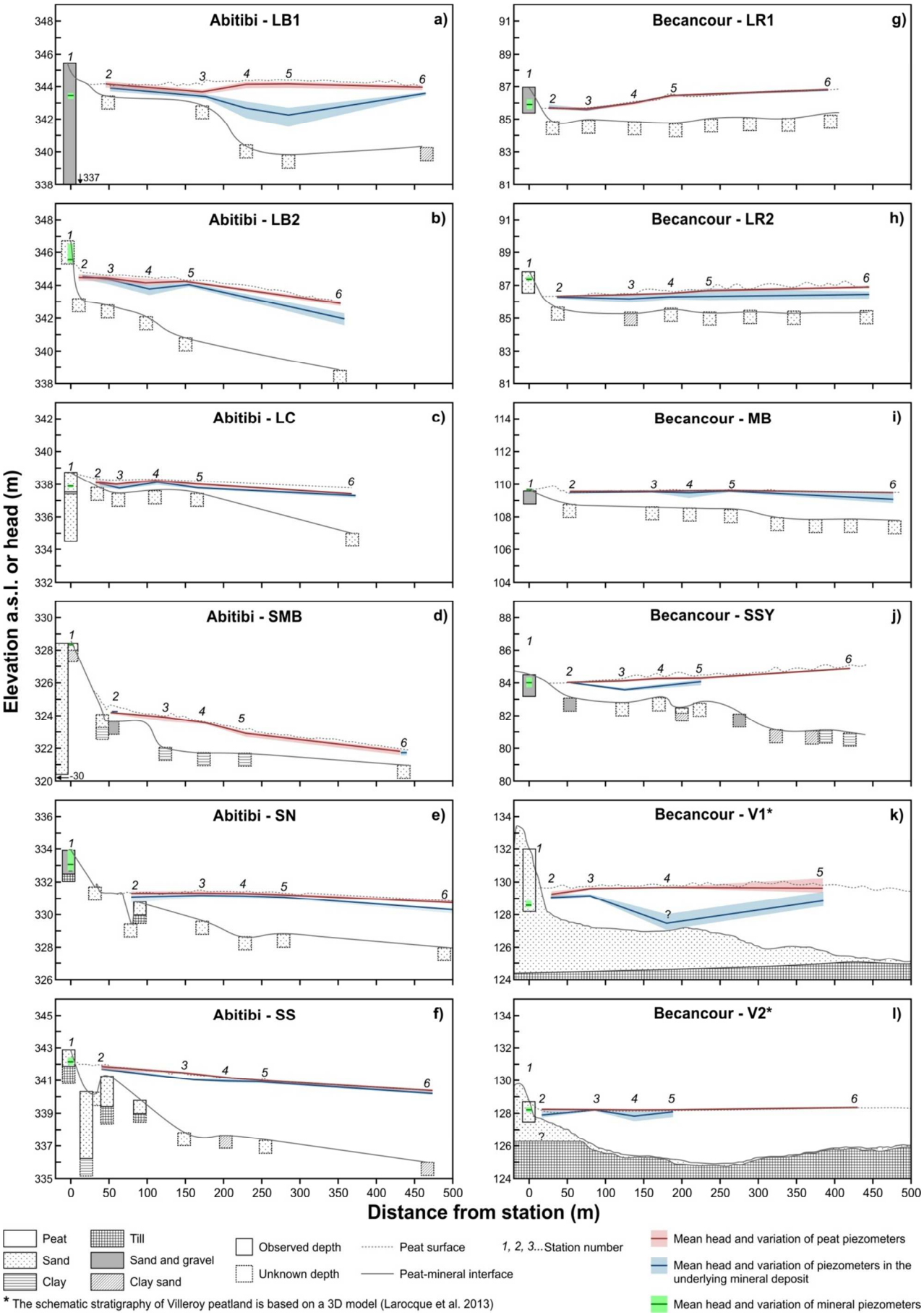
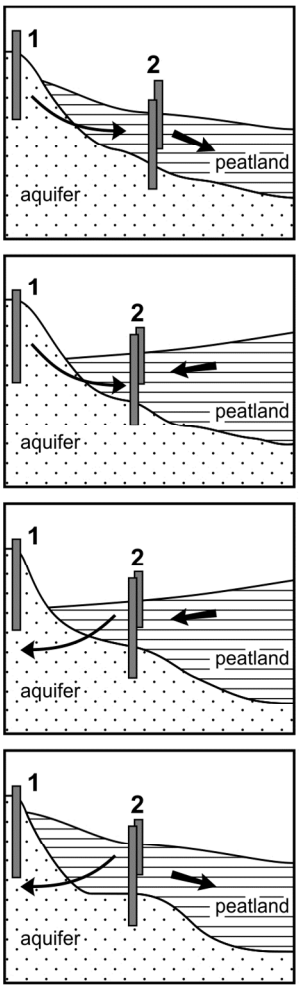


Figure 3
Ferlatte et al., 2014
Hydrological Processes


Abitibi - LB1
a)
Abitibi - LB2
b)
Abitibi - LC
c)
Abitibi - SMB
d)
Abitibi - SN
e)
Abitibi - SS
f)
Becancour - LR1
g)
Becancour - LR2
h)
Becancour - MB
i)
Becancour - SSY
j)
Becancour - V1*
k)
Becancour - V2*
l)
Elevation a.s.l. or head (m)
Distance from station (m)
Peat
Sand
Clay
Till
Sand and gravel
Clay sand
Observed depth
Unknown depth
Peat surface
Peat-mineral interface
1, 2, 3...Station number
Mean head and variation of peat piezometers
Mean head and variation of piezometers in the underlying mineral deposit
Mean head and variation of mineral piezometers
* The schematic stratigraphy of Villeroy peatland is based on a 3D model (Larocque et al. 2013)



a) $I_{par\text{-}in}$: parallel horizontal inflow
Groundwater from the shallow aquifer flows into the peatland and peatland water flows in the same direction (LB2, SMB, SS, SN)

b) I_{conv}: convergent horizontal flow
Groundwater flows from the shallow aquifer to the peatland where it converges in the lagg with water flow from the peatland center to the peatland margin (LR1, LR2, MB)

c) $I_{par\text{-}out}$: parallel horizontal outflow
Peatland water flows out of the organic deposits and into the shallow aquifer (SSY, V1, V2)

d) I_{div}: divergent horizontal flow
From a piezometric mound at station 2, peatland water flows into the shallow aquifer and towards the peatland center (LB1, LC)

Figure 5
Ferlatte et al., 2014
Hydrological Processes

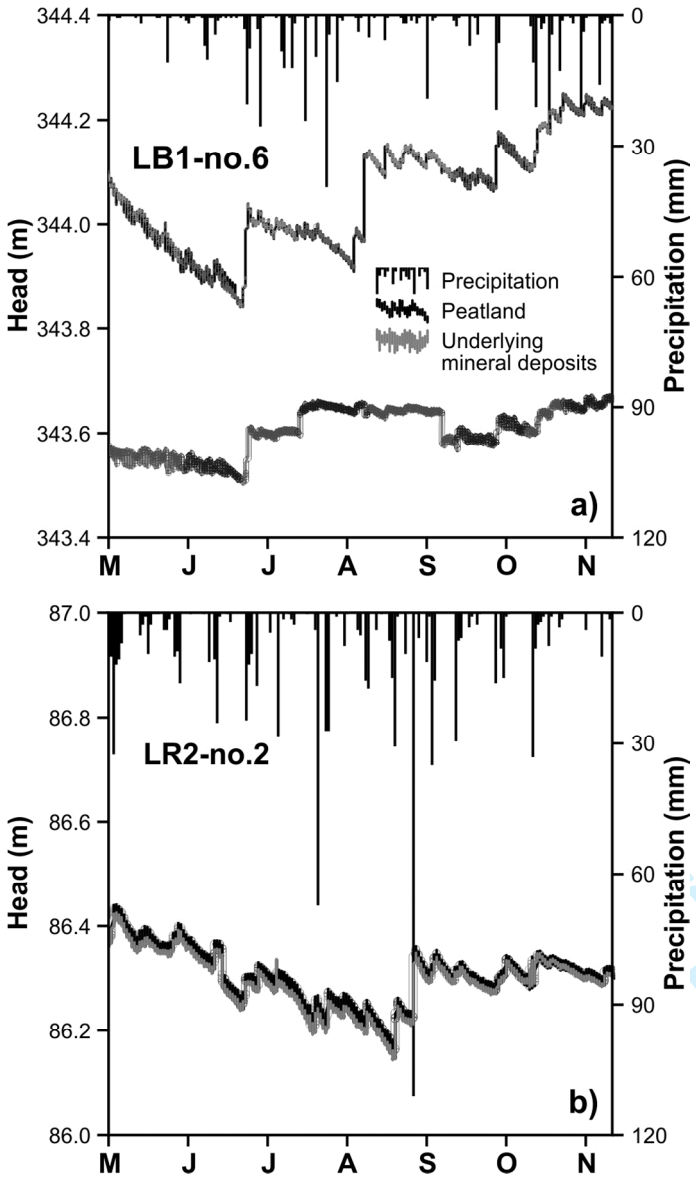


Figure 6
Ferlatte et al., 2014
Hydrological Processes