A graphical approach for documenting peatland *hydrodiversity* and orienting land management strategies

Eric Rosa[1,2]*, Pierre-Luc Dallaire[1], Simon Nadeau[1], Vincent Cloutier[1,2], Jean Veillette[1], Simon van Bellen[2], Marie Larocque[3]

[1]Groundwater Research Group, Institut de Recherche en Mines et en Environnement, Université du Québec en Abitibi-Témiscamingue, 341 Principale Nord, Amos, Québec, Canada (J9T 2L8)

[2] GEOTOP Research Center, Université du Québec à Montréal, C.P. 8888 succ. Centre-ville, Montreal, Québec, Canada

[3] Département des sciences de la Terre et de l'atmosphère & GEOTOP Research Center, Université du Québec à Montréal, C.P. 8888 succ. Centre-ville, Montreal, Québec, Canada

Email addresses:

*** Corresponding author**
Eric Rosa : eric.rosa@uqat.ca
Phone: 819-732-8809 (#8229)
Cell.: 819-442-3978

Pierre-Luc Dallaire: pierre-luc.dallaire@uqat.ca
Simon Nadeau: simon.nadeau@uqat.ca
Vincent Cloutier: Vincent.cloutier@uqat.ca
Jean Veillette: jjveillette@gmail.com
Simon van Bellen: simonvanbellen@gmail.com
Marie Larocque: larocque.marie@uqam.ca

Keywords:

1. **Peatland Hydrology**
2. **Geographic Information System (GIS)**
3. **Peatland-aquifer interactions**
4. **Geomorphology**
5. **Land management**
6. **Peatland hydrodiversity**

Abstract

This study focuses on the development of an approach to document the hydrological characteristics of peatlands and understand their potential influence on runoff processes and groundwater flow dynamics. Spatial calculations were performed using geographic information systems (GIS) data in order to evaluate the distribution of peatlands according to (1) neighboring hydrogeological units, and (2) their position within the hydrographic network. The data obtained from these calculations were plotted in a multiple trilinear diagram (two ternary plots projected into a diamond-shaped diagram) that illustrates the position of a given peatland within the hydrogeological environment. The data allows for the segregation of peatlands according to groups sharing similarities as well as the identification of peatlands that are most likely to have similar hydrological functions. The approach was tested in a 19 549 km^2 region of the southern portion of the Barlow-Ojibway Clay Belt (in Abitibi-Témiscamingue, Canada) and lead to a conceptual model representing the hydrological interactions between peatlands, aquifers and surface waters. This approach allows for a GIS-based differentiation of headwater peatland complexes that are likely to interact with aquifers and to supply continuous baseflow to small streams from lowland peatland complexes of the clay plain that are isolated from surrounding aquifers but that can act as storage reservoirs within the hydrographic network. The typology is further used to discuss land management strategies aimed at preserving peatland *hydrodiversity* within the study region. The proposed approach relies on widely applicable hydrogeological and hydrographic criteria and provides a tool that could be used for assessing peatland *hydrodiversity* in other regions of the planet.

1. Introduction

Peatlands are essential ecosystems in a variety of regions across planet and play key functions in the cycling of water and carbon (Gorham, 1991; Holden, 2005). They are also widely recognized as environments that are prone to hydrological interactions with surrounding aquifers (Rossi et al., 2012; 2014; Levison et al., 2014) and surface waters (Spence et al., 2011). Peat deposits are characterized by high porosities and a two-layer structure comprising the acrotelm (upper layer) and the catotelm (bottom layer). Both layers possess distinct physical and hydraulic properties, with the acrotelm generally having a higher hydraulic conductivity than the catotelm (Ingram, 1983; Clymo, 1983, Hilbert et al, 2000; Holden and Burt, 2003a; 2003b; Rosa and Larocque, 2008). Peatland water mainly circulates within interconnected pools and streams at the surface, as well as underground within the acrotelm, macropores and piping networks (e.g. Holden and Burt, 2002; Holden, 2005). The water table fluctuates within the acrotelm, which can present changes in water content (in time and space), while the catotelm remains constantly saturated in response to a positive water balance. Peatlands can play key functions in the water cycle through hydrological interactions with the atmosphere (evapotranspiration), surface waters (runoff generation processes) and aquifers (heads and groundwater flow dynamics). These functions are likely to vary in time and space according to the local hydrogeological setting and to climatic conditions.

Key studies have documented runoff generation processes in wetlands and associated drainage basins (e.g. see Richardson et al., 2012 and references therein). Among others, Roulet and Woo (1986) suggested that the loss of water from a wetland located in the continuous permafrost zone (Northwest Territories, Canada) through surface flow occurred primarily in the spring whereas the peat storage capacity increased during the summer due to water losses through evaporation. Kværner and Kløve (2008) also highlighted temporal changes in summer runoff generation from a flat fen located in Southern Norway where two distinct hydrological regimes were observed; with water originating from peat storage *vs* upland areas during low-flow and storm-flow events, respectively. In a study focusing on a site located near Schefferville, Quebec (Canada), Quinton and Roulet (1998) highlighted that the storage capacity of patterned wetlands can vary with time owing to changes in the hydrological connectivity between the pools found within the wetlands. The hydraulic connectivity between wetlands also significantly influences runoff generation processes, especially in low relief areas such as the Boreal Plain of Canada (Devito et al., 2005). Spence et al. (2011) further stressed that the position of a wetland within a watershed influences its hydrological functions and that regional hydrological models of the boreal region should include an assessment of the position of wetlands within the hydrographic network (i.e. headwater vs lower reaches). Overall, such studies reveal that climatic conditions and the intrinsic characteristics of peatlands and their position within the hydrogeological environment can influence runoff generation processes.

The interactions between peatlands and surrounding aquifers have also been the focus of scientific studies over the last years. Rossi et al. (2012; 2014) studied the hydrological interactions between a drained fen and the Rokua esker in Northern Finland. The authors concluded that groundwater from the esker is feeding the drained fen and highlighted that peat drainage can impact groundwater levels within the aquifer. Similarly, Levison et al. (2014) modeled the hydrological interactions between a headwater peatland in Southern Québec (Canada) and the surrounding bedrock aquifer and they concluded that the peatland was fed by the bedrock aquifer and supplies continuous baseflow to streams. At both locations, peatland-groundwater interactions were closely related to the position of the peatland within the hydrogeological environment and to its contact with surrounding aquifers.

Despite the advances discussed above, peatland environments present a significant diversity in terms of hydrology, geomorphology and biology and thus it remains challenging to propose generalized conceptual models for discussing their role within the water cycle at various scales. Similarly, the dynamics of peatland-aquifer interactions will largely depend on the characteristics of the hydrogeological setting, which are likely to vary significantly from site to site, even within a given region. This issue is of major concern in vast and remote areas, such as of Northern Canada where peatlands are abundant and where field data acquisition is costly and complex. In these regions, there is a crucial need to develop robust conceptual models of peatland hydrology in order to discuss local results (i.e. field data acquired within different peatland sites) and propose generalized interpretations including the hydrological functions of peatlands at various scales.

Interpreting the hydrological diversity of peatlands at the regional scale and identifying systems that are most likely to share similarities is central to the development of these generalized models. Classification systems (e.g. Cowardin et al., 1979, Brinson 1993;

Smith et al., 1995; Semeniuk and Semeniuk, 2011; Tiner, 2015) are useful because they allow for the regrouping peatlands/wetlands into categories according to various characteristics, and provide a framework that highlights similarities and differences between specific environments (Tiner, 2015). Among others, the *hydrogeomorphic* approach (Brinson, 1993) is of particular interest because it allows for the segregation of wetlands according to both geomorphological and hydrological criteria. GIS-based calculations can help to implement these classification schemes because they provide the data required to develop regional-scale inventories that account for spatial attributes such as peatland area, morphology, slope and vegetation patterns (e.g.: Dvorett et al., 2012).

The concept of *hydrodiversity* has been used in the scientific literature for discussing the hydrology of rivers and lagoons, among others (e.g.: see Graf, 2001; Ferrarin et al., 2014). Here, the concept of peatland *hydrodiversity* is defined as the diversity in peatlands hydrological functions as indicated by interactions with the atmosphere, surface waters and aquifers. The parameters included in this definition relate to the main components of the water budget of peatlands:

$$P + G_I + S_i - ET - G_O - S_O = \Delta S \qquad \textbf{Equation 1}$$

where the subscripts I and O represent inflows and outflows, P is precipitation, G is groundwater, S is surface water, ET is evapotranspiration and ΔS is the difference in water storage. The factors driving peatland *hydrodiversity* include (A) intrinsic characteristics, (B) spatial attributes and (C) temporal fluctuations. Intrinsic peatland characteristics include parameters such as (A1) hydraulic conductivity, (A2) specific yield and (A3) geomorphology (e.g.: slope, area, peat thickness). These parameters can directly affect the G_I, S_i, G_O, S_O and ΔS components of Equation 1 through a control on water flow dynamics within the peatland. Peatlands spatial attributes are related to their position within (B1) the hydrogeological environment (influence on G_I, G_O), (B2) the hydrographic network (influence on S_I, S_O) and (B3) the climate setting (influence on P, ET). Spatial attributes are important for assessing *hydrodiversity* because peatlands sharing similar intrinsic characteristics can exert distinct hydrological functions according to the extent of their connection with surface waters and aquifers. Finally, temporal fluctuations are likely to drive peatlands hydrological functions through their influence on (C1) precipitation (P), (C2) peat moisture content (influence on G_I, S_i, G_O, S_O and ΔS), (C3) evapotranspiration (ET), (C4) hydrological connectivity (influence on S_I, S_O) and (C4) peat compression and gas content (likely to affect hydraulic conductivity and specific yield).

Fitting in the pre-established context, this study aims at proposing a GIS-based approach for evaluating peatland *hydrodiversity*. The focus is set on the evaluation of the spatial attributes of peatlands, and more specifically their position within (1) the hydrogeological environment and (2) the hydrographic network. The approach is applied and tested within a 19 549 km^2 region located in the southern portion of the Barlow-Ojibway Clay Belt (Abitibi-Témiscamingue region, Québec, Canada). Ultimately, the results allow discussing the hydrological functions of peatlands and proposing land management strategies oriented towards the protection of peatland *hydrodiversity*. The approach described here stems from the previous work of Cloutier et al., (2015; 2016).

2. Study area

2.1. Geological framework and environmental setting

The study region is part of the Quebec/Ontario Clay Belt and covers a total area of 19,549 km^2 (Figure 1). It is included in a territory that was extensively studied in recent years due to the regional groundwater inventory projects supported by Québec's ministry of Environment and regional partners (Cloutier et al., 2013; 2015). The regional geomorphology is inherited from the rugged Precambrian Shield topography, covered in places by thick accumulations of glacial, glaciofluvial and glaciolacustrine deposits (Nadeau et al., 2015; 2017). Surface elevations range between 570 m and 174 m, with a regional average of 304 m. The region encompasses the continental water divide between the St. Lawrence River and James Bay basins (Figure 1). At the Mont-Brun meteorological station (Environment Canada station #7085106) located near the center of the study area, annual rainfall and snowfall average approximately 705 mm and 281 mm, respectively, whereas daily average air temperatures range between approximately -18 °C in January and 17 °C in July (Environment Canada, *1981 to 2010 Canadian Climate Normals station data*).

2.2. Hydrogeological framework

Six main regional hydrogeological units (RHU, labeled as RHU-A to RHU-F in Figure 1) were identified within the study area by Cloutier et al., (2013; 2015) based on the stratigraphy of the unconsolidated deposits inherited from the last glacial cycle (Veillette, 1996). RHU-A corresponds to the fractured rocks of the Canadian Shield. Vast rock outcrops are generally restricted to the sectors characterized by the highest elevations, whereas point outcrops are sporadically distributed at lower levels within the region. RHU-B corresponds to the till deposits. These heterometric glacial sediments are characterized by a matrix consisting of silt and sand. Till outcrops generally occur in the vicinity of rock outcrops, whereas buried till patches are generally assumed to be associated with bedrock depressions. RHU-C is comprised of sand and gravel deposits that are associated with glaciofluvial formations, mainly eskers and moraines. This unit hosts the most productive aquifers of the region (Nadeau et al., 2015). Sectors associated with this unit constitute the main recharge zones and are generally located in the upstream portions of regional flow paths. RHU-D is associated with the glaciolacustrine, fine-grained deep water sediments which compose the Barlow-Ojibway Clay Belt. This unit is considered as an aquitard within the studied region. RHU-E corresponds to littoral, aeolian, and alluvium sediments. This unit mainly corresponds to sand and gravel that have been redistributed in the periphery of glaciofluvial ridges. RHU-F corresponds to organic deposits, predominantly peatlands. In RHU-F, it is assumed that water preferentially circulates within the acrotelm, macropores, and piping networks. The hydrological framework of the study area is further described in Nadeau et al., (2017) and Rey et al., (2017).

The focus hereafter is on the organic deposits as outlined on the surficial geology maps (1: 100 000 scale) from the Geological Survey of Canada (GSC) (Veillette, 1986a,b, maps 1639A, 1642A; Veillette, 1987a,b,c, maps 1640A, 1641A, 1643A; Veillette and Daigneault, 1987, map 1644A; Veillette, 2004, map 2019A; Thibaudeau et Veillette, 2005, map 1996A; Paradis, 2005, map 1991A; Paradis, 2007, map 2017A). Because these organic deposits mainly correspond to peatlands, which are spatially associated with other types of wetlands (mainly swamps), the term «peatland complexes» is used hereafter.

3. Methods

3.1. Concept of the graphical approach

The proposed graphical approach for segregating peatland complexes relies on the construction of a multiple trilinear diagram that shows the position of peatlands within the hydrogeological environment. It is inspired from the well-known Piper's method (Piper, 1944), with the difference being that spatial attributes are evaluated instead of geochemical attributes. The approach and associated multiple trilinear diagram are conceptualized in Figure 2. Two main criteria are considered for documenting the position of a peatland within the hydrogeological environment. Criterion #1 relates to the contact between the peatland and surrounding hydrogeological units (Table 1). Criterion #2 relates to the position of the peatland with respect to the hydrographic network (Table 2).

Criterion #1 was addressed by evaluating the proportions of the peatland perimeter that are shared with neighboring RHUs. Three groups of spatially associated RHUs are proposed in Table 1, and the length of perimeter shared with the bedrock/till (BT), sand/gravel (SG), and silt/clay (SC) units must be calculated for each peatland. The proportions of these lengths (normalized to 100%) are reported in a ternary plot where the BT, SG, and SC units define the vertices (Figure 2; left ternary plot). Table 3 provides a summary of the potential aquifer-peatlands interactions that can be proposed based on Criterion #1.

Criterion #2 was addressed through an assessment of the position of the peatland within the hydrographic network, as described in Table 2, which was inspired from the classification scheme proposed by Tiner (2015). For each peatland, the length of outflow (O) and flow through (F) stream segments and the extent of the perimeter shared lakes or large rivers (L) is evaluated. The proportions of these lengths (normalized to 100%) are reported in a ternary plot where the O, F and L components define the vertices (Figure 2; right ternary plot). Table 4 provides a summary of the potential surface waters-peatlands interactions that can be proposed based on Criterion #2.

Eight different peatlands are represented in Figure 2; peatland #4 is used as an example and discussed in more details. This peatland shares 70% of its perimeter with the SC unit and 30% with the BT unit. Based on this calculation, a data point corresponding to peatland #4 is plotted in Figure 2 on the left ternary plot of the diagram. Similarly, peatland #4 is spatially associated with F and O stream segments (as depicted in table 2), which account for 70% and 30% of peatland/stream contacts in terms of lengths, respectively. Based on this calculation, a data point corresponding to peatland #4 is plotted in Figure 2 on the right ternary plot of the diagram. The two ternary plots are subsequently used jointly to project the data into a diamond shaped surface, providing a joint representation of the data from the two ternary plots.

3.2. Criteria evaluation and GIS-based calculations

The criteria evaluation process essentially relies on GIS-based calculations. A four-step GIS-based approach was applied using ArcGIS. The first step is related to data preparation. A homogeneous dataset covering the whole area must be available for the method to be applicable. Moreover, the cartographic polygons delimiting the peatland complexes must be entirely contiguous with the peripheral geological units. It follows that the use of two separate data sources for the mapping of peatland complexes and other surficial deposits may result in increased complexity within the proposed approach. Additionally, a homogeneous dataset representing the structured hydrographic network is required for evaluating the position of peatland complexes within the hydrographic network. For the purposes of this study, two main datasets were used for GIS-based treatments; i.e. surficial geology maps from the Geological Survey of Canada (1:100,000 scale) and features of the hydrographic network dataset (*Cadre de référence hydrologique du Québec*, 1:20,000 scale). Prior to performing calculations, the gaps at the junction of GSC cartographic sheets were filled. For this purpose, the polygons were converted to 5 × 5 m grids and subsequently reconverted to polygons. This procedure enabled merging of the polygons from adjacent cartographic sheets, thus providing a homogeneous and continuous dataset. In addition, the polygon features of the hydrographic network were used to clip the polygons of the surficial deposits maps in order to avoid the superposition of data.

The second step is related to the evaluation of the position of peatlands with respect to neighboring hydrogeological units (left ternary diagram of Figure 3). For each peatland polygon entirely included within the study area, the proportion of its perimeter shared with each of the three RHU groups defining the vertices of the ternary diagram was evaluated. These calculations were used to add data points to the left ternary plot (Figure 3).

The third step is related to the evaluation of the position of peatlands within the hydrographic network (right ternary diagram of Figure 3). For calculation purposes, linear features of the hydrographic network dataset were considered as stream segments (O and F vertices), whereas polygons are systematically considered as part of the lacustrine/riverine (L) vertex. When alluvium deposits were observed between the peatland and a feature of the hydrographic network, the length of the contact between peat deposits and alluvium was evaluated. These calculations were used to add data points in the right ternary plot (Figure 3).

The fourth step is related to zonal statistics with respect to area and elevation. The average elevation of each peatland is evaluated from a digital elevation model (DEM) constructed on 10×10 m mesh (Cloutier et al., 2013; 2015). The intrinsic elevation extent of each peatland, defined here as the difference between the maximum and minimum elevation within a peatland, is also evaluated using the DEM. Finally, the average elevations are also used to define four subdivisions. These subdivisions allow sharing the data in equal proportions (each subdivision contains approximately 25% of the peatlands). Such subdivisions will be useful for illustrating the variations in peatland characteristics as a function of elevation. Finally, the elevations of the contacts between peatlands and glaciofluvial formations are based on a digital elevation model constructed on a 100 × 100 m mesh (Nadeau et al., 2017).

4. Results

Following GIS-based data treatment, the organic deposits defined 6 303 distinct polygons which were included entirely within the study region and were in contact with at least one of the RHUs defined in Table 1. These polygons ranged in size from 5×10^{-5} to 73 km^2 and altogether covered 2 243 km^2. Basic regional observations related to the spatial distribution and attributes of peatland complexes are summarized in Tables 5 and 6. Figures 4 and 5 illustrate the distribution of peatland complexes with respect to neighboring RHUs and within the hydrographic network, respectively, whereas the multiple trilinear diagrams presented in Figure 6 provide an integrated representation of the distribution of peatlands within the hydrogeological environment. In each case, four ternary plots are proposed based on subdivisions related to elevation ranges. These subdivisions are used to illustrate the differences in the characteristics of peatlands according to elevation (each plot contains approximately 25% of the data).

The first key regional observation relates to the segregation of peatland complexes according to their elevation. An increase in the proportion of peatland complexes in contact with the BT and SG units is observed with increasing elevation. This can be seen in Figure 4 where the distribution of data gradually migrates from the SC vertex towards the BT vertex with increasing elevation. This is also shown in Table 5, where the average elevation of peatlands found on the BT and SG vertices and corresponding edge are significantly higher (> 320 m) than that of other types of peatlands (< 311 m). The relationship between elevation and the position of peatlands within the hydrographic network is less clear (Figure 5). Nevertheless, Table 6 reveals that the peatland complexes corresponding to the O vertex display the highest average elevation within the region, whereas those plotting on the edge between the F and L vertices display the lowest average elevation. This suggests that, within the study region, outflow peatland complexes that share boundaries with the BT and SG units are generally located at the head of regional hydrological/hydrogeological flow paths. In contrast, lacustrine/riverine peatland complexes set on silt/clay deposits are generally found in the lower reaches of the basins. The relationship between peatland distribution and elevation is also displayed in Figure 6, which shows that the bulk of data points migrates from the right quarter towards the upper quarter of the diamond-shaped zone of the diagram with increasing elevation.

The second key observation relates to the segregation of peatland complexes according to their area. The data reveals increasing average areas for peatland complexes according to the following trend within the ternary diagrams: vertices < edges < intermediate plane (Tables 5 and 6). This reveals that, owing to the heterogeneity of the regional hydrogeological framework, larger peatland complexes are more likely to intercept a wider range of geological units and components of the hydrographic network than smaller ones.

5. Discussion

5.1. Peatland-aquifer interactions

The position of peatlands with respect to surrounding hydrogeological units (Figure 4) is used for discussing potential peatland-aquifers interactions (as initially proposed in Table 3). Overall, it is assumed here that the peatlands associated with BT and SG vertices are prone to interactions with surrounding aquifers. This hypothesis is consistent with observations made elsewhere for peatlands set on bedrock units (e.g. Levison et al., 2014) and on the flanks of glaciofluvial formations (e.g.: Rossi et al., 2012; 2014). The peatlands that are spatially associated with glaciofluvial formations (eskers/moraines; SG vertex) most likely contribute to the rise of groundwater levels within the associated unconfined granular aquifers. Within the study area, the maximum elevation of groundwater within eskers and moraines is constrained by the elevation of the silt/clay deposits (RHU-D; SC vertex) found on their flanks. This was first empirically observed by Champagne (1988) who reported that point specific groundwater exfiltration zones (groundwater springs) set on the flanks of eskers are found at an elevation that is higher than that of the surrounding fine-grained glaciolacustrine sediments (RHU-D). This was followed by a detailed survey of springs which confirmed Champagne's observation and led to the development of a typology for the eskers and associated unconfined aquifers of the region (Veillette et al., 2004). This is supported by the contrast in hydraulic conductivity (K) between the sand and gravel deposits of the eskers/moraines (recharge areas with high K) and that of the silt and clay unit (low K). Further support was provided by observations made in groundwater monitoring wells completed in eskers and moraines of the region (Nadeau et al., 2015). Here, the elevations of the lines defining the contacts between eskers and peatlands were compared with the elevation of the surface of the silt/clay unit (RHU-D; SC vertex) as evaluated by Nadeau et al., (2017) (Figure 7). The data reveals that the peatland/esker contacts of the region are on average 5.5 m above the elevation reached by RHU-D. In this context, it seems realistic to propose that the peatland's catotelm acts as a low-K barrier that can contribute to raising groundwater levels within eskers to elevations that are higher than that of the silt/clay unit (RHU-D; SC vertex). Combined with recharge from precipitation, the continuous supply of water from the glaciofluvial formations is most likely responsible for maintaining permanent saturation within the catotelm at the margin of the peatland, even in the absence of an impervious inorganic unit at the base of the peat deposits. Under such conditions, the acrotelm most likely acts as an outflow that routes groundwater and precipitation inputs towards the hydrographic network and supplies continuous baseflow to small streams. Similar processes could be observed within peatlands set on the bedrock (RHU-A; BT vertex), however a more complex pattern of peatland-aquifer interactions is expected given the influence of structural discontinuities in the bedrock on groundwater flow dynamics. It is further proposed that the peatlands associated with the silt/clay unit (RHU-D; SC vertex) are most likely disconnected from regional aquifers owing to the low hydraulic conductivity of these deposits (Cloutier et al., 2015). The hydrological interactions of these systems are most likely restricted to exchanges with the atmosphere and with surface water reservoirs (including diffuse surface runoff).

Devito et al., (2005) stressed that hydraulic and topographic gradients can diverge in environments such as the Canadian Boreal Plain (as exemplified by the work of Ferone and Devito, 2004 and Smerdon, 2005). One important consideration highlighted by Devito et al., (2005) is that in areas of coarse-grained deposits, the hydraulic gradient is likely to be controlled by the morphology of the impermeable base of the aquifer, rather than by surface topography. These authors further stressed that hydrological exchanges from organic soils towards inorganic soils located at higher elevations can occur owing to the higher moisture contents maintained in peat during dry periods. Such observations stress the need to cautiously examine the interpretations developed above for explaining peatland-esker interactions in the southern Barlow-Ojibway Clay Belt. Here, it was proposed that groundwater mainly flows from eskers towards peatlands. Nevertheless, further work aimed at evaluating hydraulic gradients between eskers and peatlands of the study region seem much needed to evaluate spatial and temporal changes in the magnitude and direction of hydrological exchanges between these two hydrogeological units.

5.2. Peatland-surface water interactions

The position of peatlands within the hydrographic network (Figure 5; Table 4) is used for discussing potential peatland-surface water interactions. Owing to their headwater positions, the peatlands associated with the outflow (O) vertex are most likely responsible for routing part of their hydrological inputs (mostly diffuse surface runoff, precipitation and groundwater inflow) towards the hydrographic network, thus supplying continuous baseflow to small streams that are in the upper reaches of the basins. In addition, depending on their water balance, the peatlands associated with the flow through (F) and lacustrine/riverine (L) vertices are likely to act as transient storage reservoirs for surface waters. This is particularly true during the summer, when evapotranspiration drives water losses from the peat deposits and increases the storage capacity within the acrotelm. This interpretation is consistent with the concepts discussed by Roulet and Woo (1986), despite the difference between the studied environmental settings. Such systems might also supply continuous baseflow to streams, rivers and lakes, especially if groundwater supplies are significant.

5.3. Peatland hydrological functions at the regional scale

The information associated with the diamond-shaped portion of the multiple trilinear diagrams is reported in the conceptual model shown in Figure 8. Nine main zones are shown in this conceptual model (labeled as rows 1 to 3 and columns A to C). Since this diamond-shaped portion of the diagram corresponds to the data projected from the two associated ternary plots, two general trends are identified: (1) the proportion of perimeter shared with the SC vertex increases from row 1 to row 3 and (2) the proportion of O-type stream segments decreases from column A to column C.

The peatland complexes found in row 1 (A-B-C) are described here as headwater systems that are most likely in contact with surrounding unconfined bedrock and sand/gravel aquifers. The average elevation of these peatlands (ranging from 317 m to 322 m for zones 1C and 1A, respectively) are slightly higher than those of the other peatlands of the region (Figure 8). The peatlands found in row 3 (A-B-C) are most likely isolated from surrounding aquifers owing to the silt/clay unit. With average elevation ranging between 293 and 299 m in zones 3C and 3A, respectively, these sites are located in the lower reaches of the regional basins within the clay plain. The peatlands complexes found in row 2 (A-B-C) are considered as hybrid systems between zones 1 and 3. Overall, within row 2, the sites plotting closer to row 1 are more likely to have significant interactions with surrounding aquifers than those plotting closer to row 3.

The peatland complexes found in column A (1-2-3) are outflow systems that are most likely responsible for supplying baseflow to small headwater streams. Given that these peatland complexes are essentially outflow systems, they are unlikely to store significant amounts of water from streams and rivers at the regional scale. Conversely, the peatland complexes found in column C (1-2-3) are flow through and lacustrine/riverine systems that are most likely acting as transient storage reservoirs for surface waters. Among these peatlands, the sites associated with large lakes or rivers are most likely found within the lower reaches of basins. Finally, the peatlands found in Column B (1-2-3) are considered as hybrid systems between columns 1 and 3.

5.4. Land management strategies: protecting peatland *hydrodiversity*

Peatlands are increasingly affected by direct and indirect human impacts and the development of land management strategies aimed at preserving their hydrological functions is critical. Within the study region, the main indirect human impacts on peatlands are groundwater abstraction (e.g.: for open pit mining and/or water supply) and surface water flow control. Direct human impacts in the region are primarily peat harvesting and peatland infilling (e.g.: for roads and various construction) activities. In the province of Québec (Canada), the protection of wetlands is addressed in the Environmental Quality Act (L.R.Q., Chapter Q2). More recently, the Québec's Ministry of the Environment adopted Bill 132, which specifically addresses the protection of wetlands. Among other aspects, this bill suggests that the rareness of a wetland or the exceptional interest of its biophysical characteristics can stand as criteria for designating sites where additional protection is required. Nevertheless, the land management strategies relating to the protection of peatlands are most often based on the preservation of the biodiversity of associated ecosystems, whereas the diversity of the hydrological functions of peatlands is rarely accounted for, although both are likely to be closely related. It therefore seems of foremost importance to include criteria in land management strategies that are related to the protection of peatland *hydrodiversity* (in addition to biodiversity). This would allow for better preservation of the hydrological functions of peatlands, which are likely highly sensitive to human pressures.

The new GIS-based graphical approach presented in this study provides a tool that could be used to support such land management strategies. For a given project that is likely to generate a direct or indirect impact on a peatland site, the multiple trilinear diagram (Figure 6) provides an evaluation of the commonness (or rareness) of the potentially impacted peatland. Based on this diagram, and considering the area and elevation of the site, regional stakeholders can evaluate how many comparable peatlands can be found at the regional scale. With the objective of ensuring the conservation of peatland *hydrodiversity*, it is proposed that sites that are less common at the regional scale should systematically be privileged for conservation. However, if systematic conservation is not an option, recommendations associated with the implementation of a monitoring program can be proposed based on the peatland-aquifer and peatland-surface waters interactions as discussed in section 5.3.

In the case of an indirect impact due to groundwater abstraction, hydrological monitoring is recommended. This is especially important for peatland complexes plotting in row 1 (A-B-C) of Figure 8 because these systems are most likely to interact with surrounding aquifers. The water levels within the impacted peatland complexes should be monitored in order to quantify the impact of the nearby groundwater abstraction. In the case of an indirect impact caused by modifications in surface water flowrates upstream of a peatland, surface water monitoring is recommended. This monitoring is particularly important for sites found in column C of Figure 8 because such flow through systems are most likely to host hydrological exchanges with surface waters. Among the key aspects, water levels within the impacted peatland and flowrates upstream and downstream of the impacted site should be monitored in order to quantify the impact induced by surface water flow control. The peatland complexes found in zones 3B and 3C are assumed to be most vulnerable to such impacts because buffering by groundwater is considered unlikely in such environments.

In the case of a direct impact caused by peat harvesting, groundwater monitoring in the surrounding shallow unconfined aquifers is recommended for peatlands found in row 1 of Figure 8 because these environments are most likely to interact with surrounding aquifers. Surface water monitoring is recommended for all peatlands that are connected to a stream in order to evaluate the impact of peat harvesting on surface water flow rates and quality. Finally, in the case of a direct impact caused by infilling, surface water monitoring is recommended for all peatlands that are connected to a stream in order to evaluate the impact of infilling on surface water flow rates and quality. Groundwater monitoring is recommended mainly for peatlands found in row 1 of Figure 8.

5.5. Comparison with a statistical analysis

The GIS-based graphical approach developed herein is used to propose groups of peatlands that are likely to exert similar hydrological functions within the study region (section 5.3). A direct comparison with a discrete statistical analysis such as clustering is challenging because the two criteria used in the approach (see section 3) do not provide the normal distribution required for statistical analyses as multivariate techniques (Brown, 1998). As shown in tables 5-6, several peatlands plot on the vertices and edges of the ternary plots, meaning that the dataset associated with the two criteria used in the proposed approach contains several values equal to zero and one, making it unfit for multivariate statistical analyses. Nevertheless, the results presented here allowed identifying relationships between the position of peatlands within the multiple trilinear diagrams and their elevation, intrinsic elevation extent and area (also reported in tables 5-6). Therefore, a hierarchical cluster analysis (HCA) was conducted using peatland elevation, intrinsic elevation extent and area. This provides a framework for comparing the graphical approach developed herein with an independent statistical approach allowing classification of peatland complexes.

The HCA was conducted using Statistica 13.3 (TIBCO Software Inc.) on 6 277 peatland polygons. Twenty-six out of the 6 303 distinct polygons were excluded from the dataset because their intrinsic elevation extent is equal to zero. Data preparation for the HCA includes log-transformation of average area and intrinsic elevation extent to reduce the deviation from normality of their distribution. The distribution of peatland average elevation was close to normal. The two lognormal and one normal distributions were then standardized by subtracting the mean of the distribution from each peatland and dividing by the standard deviation of the distribution (Davis, 2002), thus ensuring that each variable is weighted equally. The HCA was performed by using the Euclidean distance as the distance measure between peatlands, and the Ward's method as the linkage rule. The visual inspection of the resulting dendrogram allowed the classification of the peatlands by drawing a vertical cut-off line (phenon line) at a linkage distance of ~ 400, with peatlands grouped at a linkage distance below 400 belonging to the same cluster (Figure 9). The HCA allowed defining five clusters according to peatland elevation, area and intrinsic elevation extent. Figure 10 provides a comparison of the cluster analysis with the graphical approach developed herein. Overall, the results suggest that cluster-1 is dominant for the «hybrid» systems in both of the ternary plots of Figure 9. Cluster-2 dominates for the «outflow» and «flowthrough» peatlands associated with the «silt/clay» vertex, while cluster-5 is rather associated with the «bedrock/till» and «sand/gravel» vertices. Finally, cluster-3 is dominant for «lacustrine» peatlands, while cluster-4 is not dominant in any zone of the multiple trilinear diagram. The coherence between the cluster analysis and the multiple trilinear diagram is also shown in the diamond shaped portion of the diagram (figure 10), where clusters 2 and 5 correspond to the zones 1 and 3 as illustrated in Figure 8. Although a direct quantitative comparison between the statistical and graphical approaches is not possible, the observations discussed above suggest coherent results.

5.6. Advantages and limits of the GIS-based graphical approach

The proposed approach provides valuable insights for identifying the potential hydrological functions of peatlands. It documents the hydrological diversity of peatlands using basic geological and hydrological data. This makes the approach widely applicable, adaptable, and provides a complement to existing classification schemes (e.g. see Brinson, 1993 Smith et al., 1995; Semeniuk and Semeniuk, 2011; Tiner, 2015). The proposed vertices allow coverage of a wide range of hydrogeological settings and can be adapted for various types of environments. The approach also represents the data over a continuum in a way that could not be achieved through the use of a discretized classification approach. If a discrete classification is needed for simplifying the work of end users such as regional stakeholders, discrete classes can be defined in the diamond shaped portion of the diagram for segregating peatlands into groups, as illustrated in Figure 8. Therefore, the approach proposed here can be used over a continuum or based on discrete classes, depending on the needs of the user. Additional peatland characteristics such as area, elevation, surface slope, water quality, and vegetation cover could also be illustrated through the use of color (or size) codes for data points within the diagrams. An evaluation of the distribution of bogs, fens, and patterned wetlands could also be included in the proposed graph. If used as a complement to other classification schemes, the approach could provide a tool for establishing groups of peatlands that exert similar hydrological functions. From a scientific perspective, the approach could be used for targeting reference (see Brinson, 1993) peatlands within a given region. In that sense, the graphical approach provides a framework for upscaling interpretations based on data acquired at the local scale and for constructing regional-scale generalized conceptual models associated with the «reference» peatlands. These models are needed to better understand peatland hydrological functions. Given the potential sensitivity of peatlands to climate change (Ise et al., 2008), addressing this issue is critical, especially in Northern Canada and other parts of the world where climate change and related hydrological effects are anticipated (e.g.: Déry et al., 2005; 2009).

The proposed approach also has some limitations. First, as suggested by Dvorett et al., (2012), the quality of the results obtained from GIS-based calculations are a function of the quality of the input data. This is a challenge because data sources might contain inconsistencies related to scale, age, and quality. Errors related to automated GIS-based calculations are, therefore, likely to occur if the data sources are not cautiously examined. Some of the errors associated with the numerical data layers are visible in the Google Earth file provided as supplementary material, where peatland polygons sometimes only roughly correspond to the shape of peatland that can be interpreted from the satellite images. Second, the graphical approach does not allow for a quantitative evaluation of the hydrological exchanges between peatlands, surrounding aquifers, and the hydrographic network, but rather provides an evaluation of the contact between these entities. Third, the proposed approach evaluates the extent of perimeter shared with neighboring RHUs, but does not provide a precise evaluation of the underlying material. Nevertheless, in the case study discussed here, it was assumed that the general geology obtained from the surficial maps was reliable and that this issue did not significantly affect the proposed interpretations. Fourth, the proposed approach, as applied in this study, did not allow accounting for key characteristics of peatlands such as piping (e.g. Holden, 2004; 2005, Holden et al., 2012; Smart et al., 2013) and hydrological connectivity and patterning (e.g. Quinton and Roulet, 1998; Richardson et al., 2012) among others. Finally, the proposed approach does not allow representing peatlands that are not connected to the hydrographic network.

6. Conclusion

This study proposed a regional-scale conceptual model of interactions between peatlands, surface waters and aquifers within the Barlow-Ojibway Clay Belt. The data revealed that the headwater peatlands in the study region are mainly set directly on the bedrock or on the flank of glaciofluvial formations (eskers and moraines). The peatlands set on the flanks of eskers and moraines likely contribute to raising groundwater levels within the associated shallow, unconfined granular aquifer. Headwater peatland complexes acting primarily as outflow systems are interpreted as being responsible for routing groundwater and precipitation towards the hydrographic network, thus providing continuous baseflow to small streams. In contrast, flow through and lacustrine/riverine peatland complexes of the clay plain, in the lower reaches of the regional basins, are interpreted as transient reservoirs which store surface waters during the summer period, when evaporation losses increase the storage capacity of the acrotelm. The proposed approach provides a framework that can be used for (1) developing land management strategies aimed at preserving peatland *hydrodiversity* at the regional scale and (2) orienting the design of hydrogeological monitoring programs in relation to human impacts on peatlands.

From a broader scientific perspective, the proposed approach could help identify reference peatlands for upscaling interpretations based on field and/or modeling data acquired at the local scale, given an appropriate knowledge of the regional scale hydrogeological setting. The identification and documentation of these reference peatlands in various regions of the planet is much needed in order to better understand the regional-scale response of peatland-aquifers and peatland-surface water exchanges to climate and land use change. Overall, the proposed approach could allow assessing peatland *hydrodiversity* in different regions of the planet because the geological and hydrographic criteria used for constructing the multiple trilinear diagrams allow covering a wide range of hydrogeological settings.

Acknowledgments

This research was conducted through the *Projet d'Acquisition de Connaissances sur l'Eau Souterraine de l'Abitibi-Témiscamingue* (PACES-AT2). The research was supported by the partners of a regional initiative for sustainable development of groundwater in Abitibi-Témiscamingue, including the Government of Québec (*Ministère du Développement durable, de l'Environnement et de la Lutte contre les changements climatiques,* MDDELCC) and the Regional Conference of Elected Officials of Abitibi-Témiscamingue (CRÉAT). The authors also acknowledge the financial contribution of the Québec Ministry of the Environment (MDDELCC) through the Groundwater Knowledge Acquisition Program (PACES), with significant contributions from regional partners involved in the program, including the Regional County Municipalities (Abitibi, Vallée-de-l'Or, Abitibi-Ouest, Ville de Rouyn-Noranda, Témiscamingue) and the CRÉAT. This publication was possible due to funding from the *Fondation de l'Université du Québec en Abitibi-*

Témiscamingue (FUQAT). The authors thank Magalie Roy and Daniel Blanchette for their help in this project.

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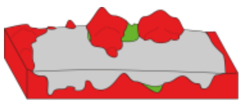
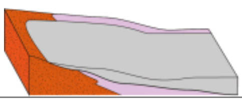
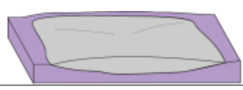
Proposed vertices	Description
Hydrogeological units A and B (bedrock / till) 	RHU-A and RHU-B as identified in Figures 2 and 3. The latter are known to be spatially associated and it is assumed that the main aquifers associated with these units are found within the fractured bedrock. The conceptual diagram illustrates a peatland (shown in gray) sharing a portion of its perimeter with the «Bedrock / Till» group (shown in red and green).
Hydrogeological units C and E (sand / gravel) 	RHU-C and RHU-E (sublittoral sands) as identified in Figures 2 and 3. The latter are spatially associated and it is assumed that the main aquifers associated with these units are found within eskers and moraines. The conceptual diagram illustrates a peatland (shown in gray) sharing a portion of its perimeter with the «Sand / Gravel» group (shown in orange and light purple).
Hydrogeological unit D (silt / clay) 	RHU-D as identified in Figures 2 and 3. This unit is assumed to present a lower hydraulic conductivity than the other RHU (Cloutier et al., 2013; 2015). The conceptual diagram illustrates a peatland (shown in gray) sharing a portion of its perimeter with the «Silt / Clay» group (shown in dark purple).

Table 1 Groups of units proposed for classifying peatland complexes according to their position within the hydrogeological environment. A single peatland could be spatially associated with the three components described in this table (see Figure 3). The diagrams shown in the left column are adapted from Cloutier et al., 2015.

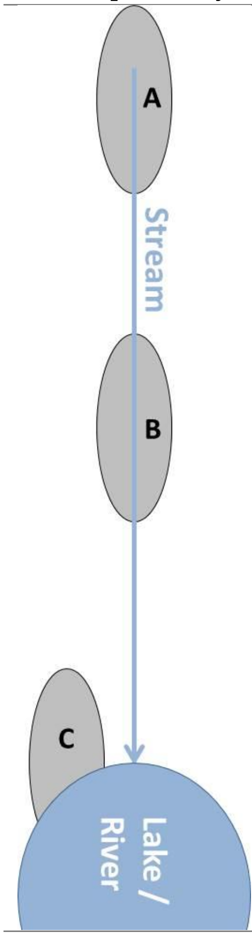
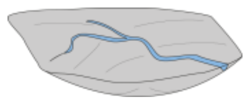
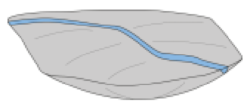
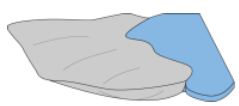
Concept / theory	Proposed vertices	Description
	**(peatland A) «outflow» component** 	For peatland A, the stream is considered an «outflow» segment of the hydrographic network because its starting point is located within the peatland.
	(peatland B) «flow through» component 	For peatland B, the stream is considered a «flow through» segment of the hydrographic network because its starting point is located upstream of the peatland.
	(peatland C) «lacustrine/riverine» component 	Peatland C is considered as a lacustrine/riverine peatland because it is sharing a portion of its perimeter with a large water surface.

Table 2 Surface water components proposed for classifying peatland complexes according to their position within the hydrographic network. A single peatland could be spatially associated with the three components as described in this table (see Figure 3). The diagrams shown in the left column are adapted from Cloutier et al., 2015.

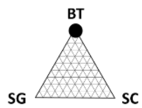
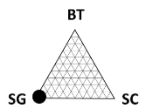
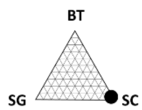
Positions within the ternary plot	Proposed interpretations with respect to peatland – aquifer contacts
	Peatland complexes that are likely to be in contact with surrounding fractured bedrock and/or granular unconfined aquifers. The peatland complexes associated with the «sand/gravel» (SG) vertex are generally located on the flanks of eskers and moraines, which host major unconfined aquifers in the region (Nadeau et al., 2017; Rey et al., 2017). The hydrological exchanges between peatlands and the bedrock aquifer will strongly depend on the hydraulic properties of the bedrock.
	
	Peatland complexes that are unlikely to be in direct contact with surrounding aquifers, mainly because the regional «silt/clay» unit is considered as an aquitard (Nadeau et al., 2017; Rey et al., 2017).

Table 3 Summary of interpretations related to potential peatland – aquifer interactions. SG: «sand/gravel vertex»; BT: «bedrock/till» vertex; SC: «silt/clay» vertex. The diagrams shown in the left column are adapted from Cloutier et al., 2015.

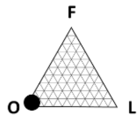
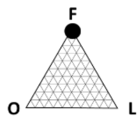
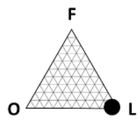
<table>
<tr><th>Positions within the ternary plot</th><th>Proposed interpretations with respect to peatland – surface water contacts</th></tr>
<tr><td>
</td><td>Outflow systems are most likely responsible for routing part of their hydrological inputs (mostly diffuse surface runoff, groundwater inputs and precipitation) towards the hydrographic network. These peatland complexes supply continuous baseflow to small streams that are in the upper reaches of the basins.</td></tr>
<tr><td>
</td><td rowspan="2">The peatlands associated with the flow through («F») and lacustrine («L») are likely to act as potential storage reservoirs for surface waters, especially during summer when evapotranspiration drives water losses from the peat deposits, increasing the storage capacity within the acrotelm.</td></tr>
<tr><td>
</td></tr>
</table>

Table 4 Summary of interpretations related to potential peatland – surface water interactions. O: «Outflow vertex»; F: «Flow through» vertex; L: «Lacustrine/riverine» vertex. The diagrams shown in the left column are adapted from Cloutier et al., 2015.

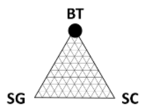
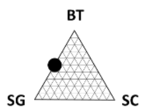
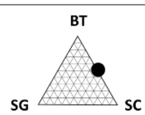
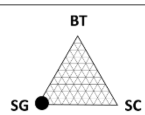
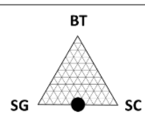
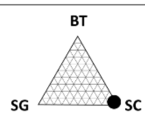
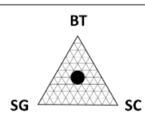
Positions within the ternary plot	Regional observations			
	Number of polygons	**Average area (km^2)**	**Average elevation (m)**	**Average intrinsic elevation extent (m)**
	1 054	0.09	324.5	9.2
	367	0.34	322.7	11.3
	1 076	0.44	300.3	11.1
	769	0.16	321.2	5.5
	319	0.56	305.1	7.8
	2 467	0.16	295.7	5.0
	251	3.42	310.3	18.3

Table 5 Distribution of peatlands with respect to neighboring hydrogeological units. The intrinsic elevation extent of a peatland is defined here as the difference between the maximum and minimum elevation measured within a peatland. Average values are provided in this table. SG: «sand/gravel vertex»; BT: «bedrock/till» vertex; SC: «silt/clay» vertex. The diagrams shown in the left column are adapted from Cloutier et al., 2015.

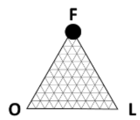
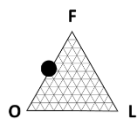
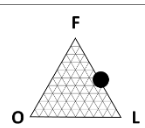
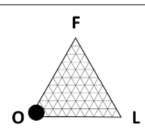
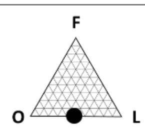
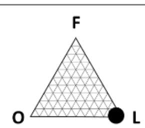
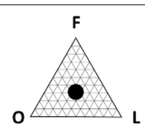
Positions within the ternary plot	Regional observations			
	Number of polygons	Average area (km^2)	Average elevation (m)	Average intrinsic elevation extent (m)
	1 577	0.16	304.5	8.6
	623	0.95	303.9	11.4
	744	0.21	300.0	10.4
	503	0.24	309.7	7.0
	36	0.37	305.3	9.4
	489	0.03	304.7	4.3
	347	2.67	303.5	16.9

Table 6 Distribution of peatlands within the hydrographic network. The intrinsic elevation extent of a peatland is defined here as the difference between the maximum and minimum elevation measured within a peatland. Average values are provided in this table. O: «Outflow vertex»; F: «Flow through» vertex; L: «Lacustrine/riverine» vertex. Note that 31% of peatlands at the regional scale are entirely disconnected from the hydrographic network. These systems are not accounted for in this table. The diagrams shown in the left column are adapted from Cloutier et al., 2015.

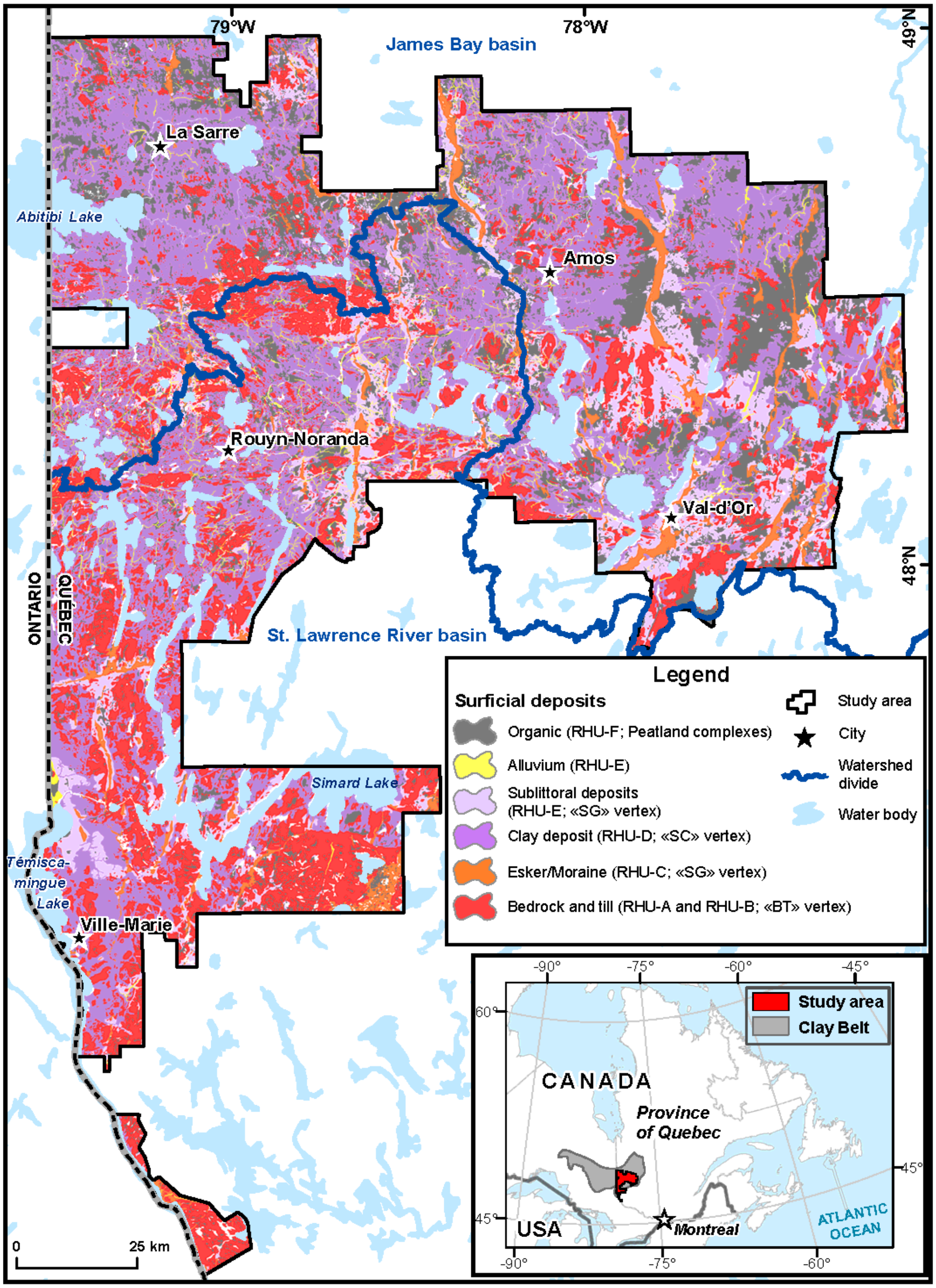


Figure 1 Study area. The mapped peatland complexes correspond to the organic deposits identified from the geological maps of the Geological Survey of Canada (see section 2). The «organic deposits» correspond to accumulations of peat and plant debris ranging from 0.5 to 5 m in thickness. SG: «Sand/Gravel» vertex; BT: «Bedrock/Till» vertex; SC: «Silt/Clay» vertex. O: «Outflow vertex»; F: «Flow through» vertex; L: «Lacustrine/riverine» vertex.

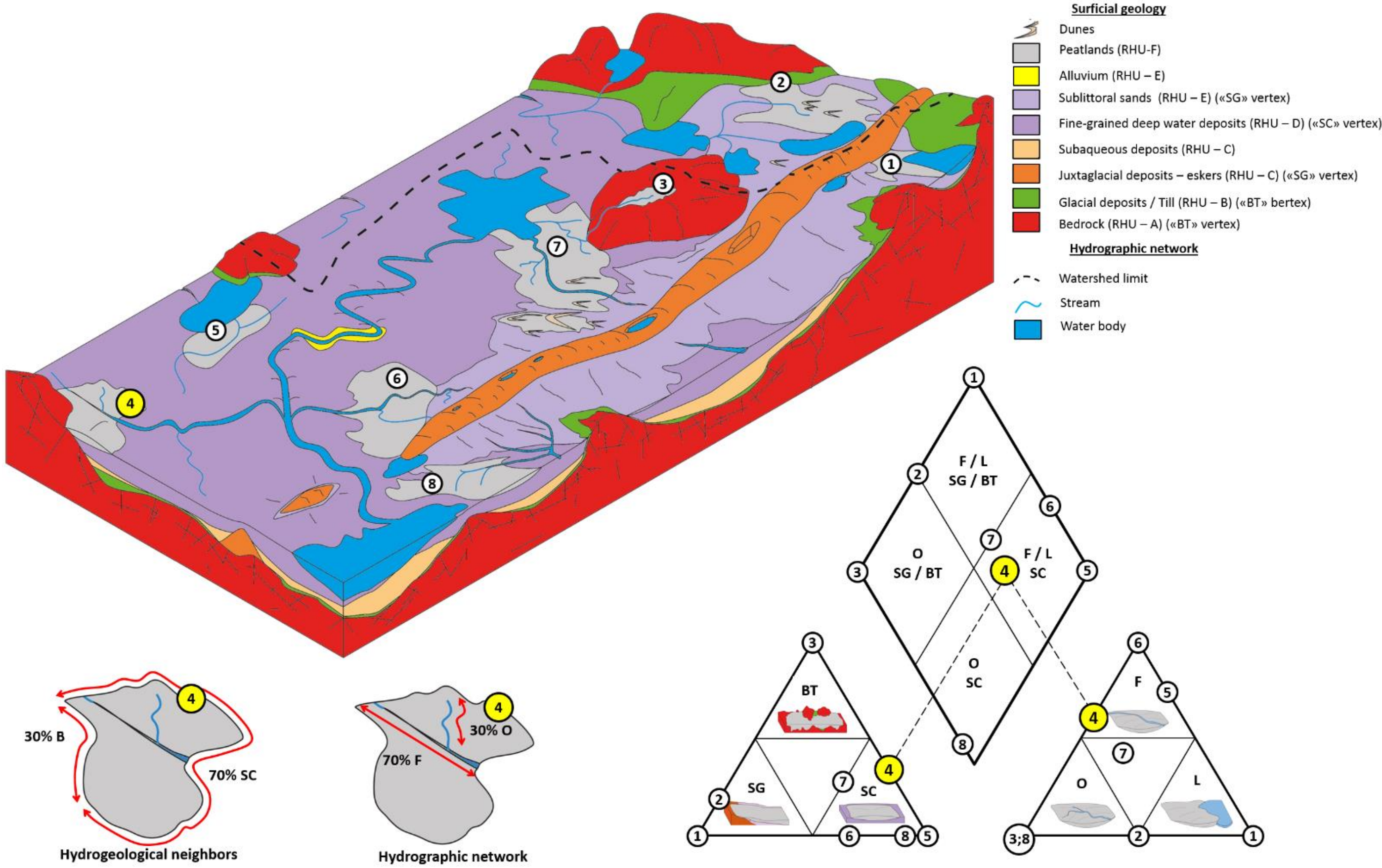


Figure 2 Schematic representation of the proposed graphical approach. The numbers (1-8) associated with each peatland complex shown within the conceptual model correspond to those reported within the graph shown in the lower right side of the Figure. For the purpose of this simplified conceptual example, only eight cases are targeted and the positions of data within the ternary plots are only approximate. Calculations associated with case #4 are illustrated by mean of example. SG: «Sand/Gravel» vertex; BT: «Bedrock/Till» vertex; SC: «Silt/Clay» vertex. O: «Outflow vertex»; F: «Flow through» vertex; L: «Lacustrine/riverine» vertex. Adapted from Cloutier et al., 2015; 2016; reproduced by permission of the *Presses de l'Université du Québec*.

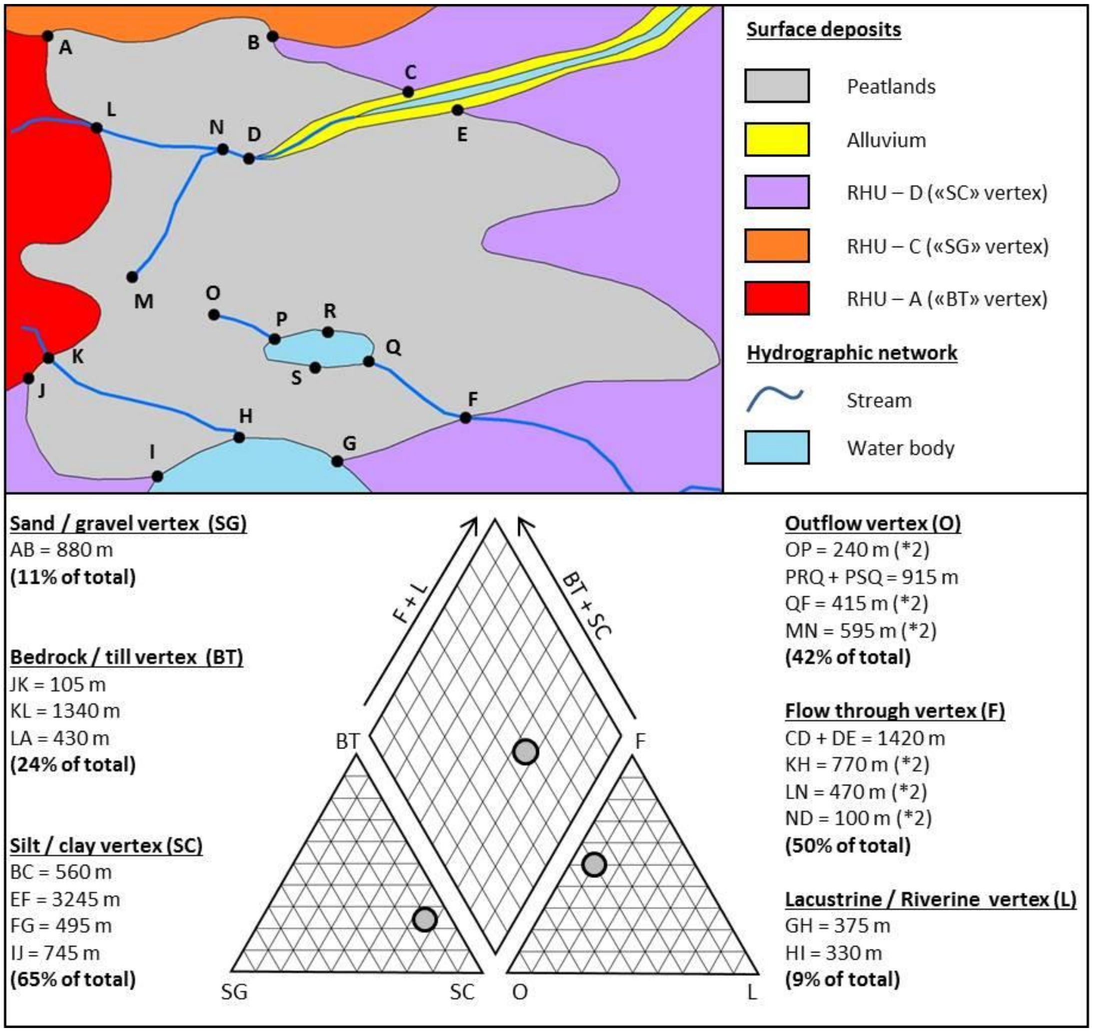


Figure 3 Theoretical example of the GIS-based and graphical approaches. The lengths of curvilinear segments are evaluated between each of the points appearing on the map (labeled A to Q). The lengths of perimeter shared with neighboring hydrogeological units defining the vertices of the ternary plot on left side of the diagram are shown on the left side of the Figure. Similarly, the lengths of contacts between the peatland and the components of the hydrographic network defining the vertices of the ternary plot on the right side of the diagram are shown on the right side of the Figure. In both cases, proportions (normalized to 100%) are calculated for plotting the data within the ternary diagrams. The lengths of the «line» features associated with the hydrographic network must be multiplied by a factor of two, assuming that the contact between peat and water will occur on both sides of the stream. This multiplication factor does not need to be applied for «polygon» features of the hydrographic network.

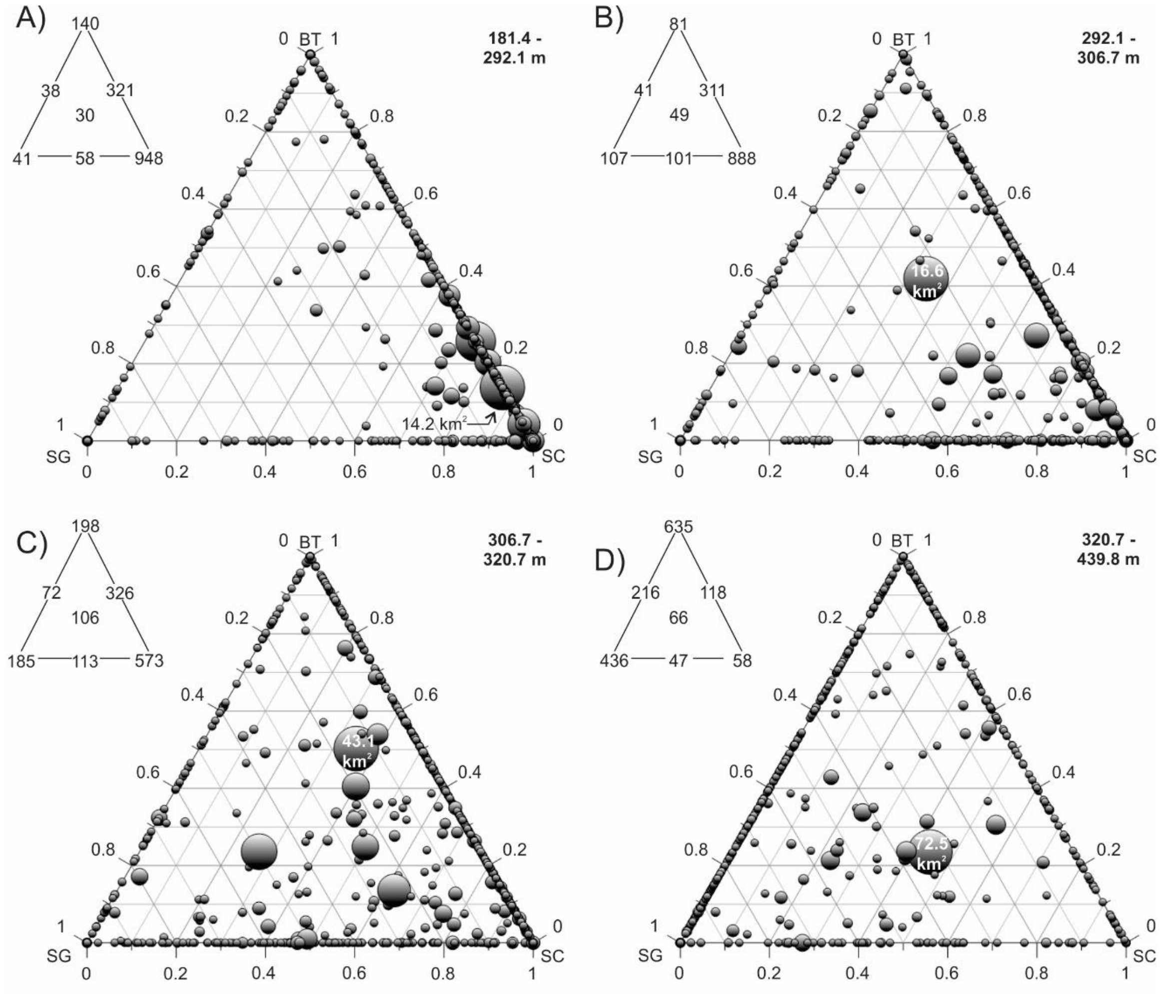


Figure 4 Distribution of peatlands with respect to neighboring hydrogeological units. The elevation ranges are shown on the upper right side of each diagram. Four ternary plots are proposed based on subdivisions related to elevation ranges, with increasing values from A to D. These subdivisions allow sharing the data in approximately equal proportions (each plot contains approximately 25% of the data). The smaller ternary plots in the upper left side show the number of data points plotting on the vertices, edges and within the intermediate plane of the ternary diagrams. The size of data points corresponds to the area of the peatland complexes. For simplicity, only the maximum area is reported in the ternary diagram. SG: «Sand/Gravel» vertex; BT: «Bedrock/Till» vertex; SC: «Silt/Clay» vertex.

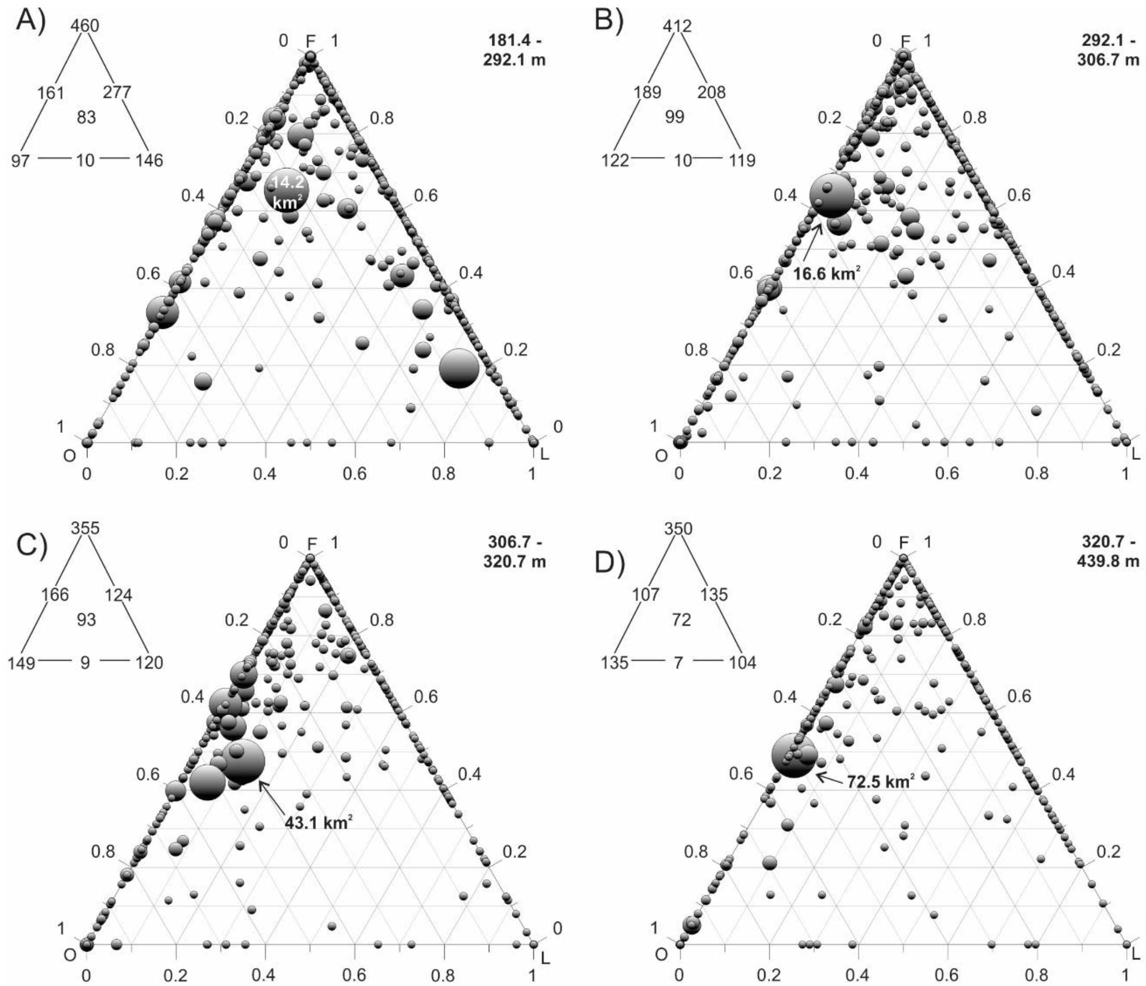


Figure 5 Distribution of peatlands within the hydrographic network. The elevation ranges are shown on the upper right side of each diagram. Four ternary plots are proposed based on subdivisions related to elevation ranges, with increasing values from A to D. These subdivisions allow sharing the data in approximately equal proportions (each plot contains approximately 25% of the data). The smaller ternary plots in the upper left side show the number of data points plotting on the vertices, edges and within the intermediate plane of the ternary diagrams. The size of data points corresponds to the area of the peatland complexes. For simplicity, only the maximum area is reported in the ternary diagram. Note that 31% of peatlands at the regional scale are entirely disconnected from the hydrographic network. These systems are not presented in the ternary plots. O: «Outflow vertex»; F: «Flow through» vertex; L: «Lacustrine/riverine» vertex.

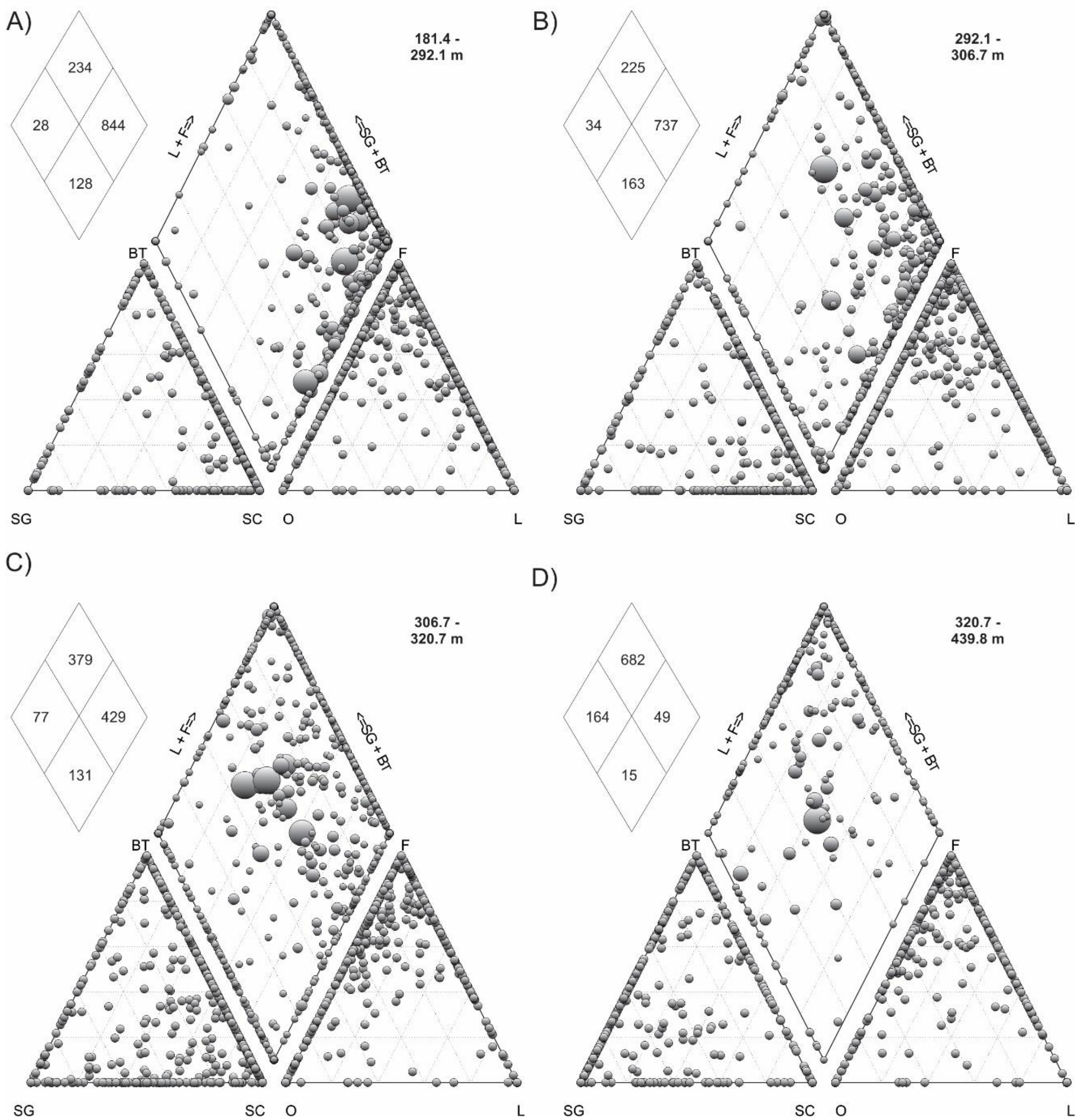


Figure 6 Graphical representation of regional data. The elevation ranges are shown on the upper right side of each diagram. Four ternary diagrams are proposed based on subdivisions related to elevation ranges, with increasing values from A to D. These subdivisions allow sharing the data in approximately equal proportions (each plot contains approximately 25% of the data). The smaller diamond-shaped plots in the upper left side show the number of data points plotting in each of the four identified graphical sectors. The size of data points corresponds to the area of the peatland complexes, with values corresponding to those reported in Figures 5 and 6. SG: «sand/gravel vertex»; BT: «bedrock/till» vertex; SC: «silt/clay» vertex. O: «Outflow vertex»; F: «Flow through» vertex; L: «Lacustrine/riverine» vertex. Note that 31% of peatlands at the regional scale are entirely disconnected from the hydrographic network. These systems are not presented in the left side ternary plots and in the diamond-shaped portion of the diagram.

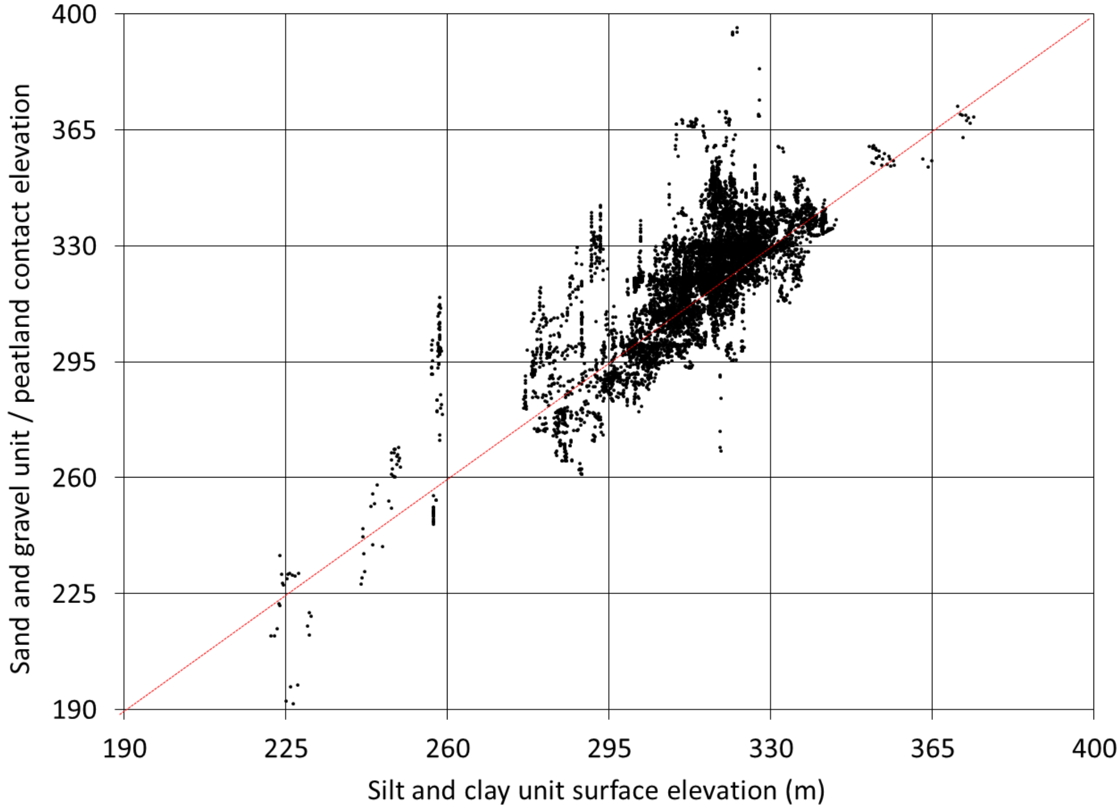


Figure 7 Comparison between the elevation of the contacts between peatlands and the sand/gravel unit (RHU-C; «SG» vertex) on the y-axis and that of the regional silt/clay unit (RHU-D; «SC» vertex) on the x-axis. Each point in the graph corresponds to one 100 m x 100 m cell of the regional grid as described in Nadeau et al., (2017). The data reveals that numerous contacts are found at an elevation greater than that of the RHU-D. This suggests that peatlands might play a key hydrological role at the regional scale by raising groundwater levels within glaciofluvial formations (eskers and moraines).

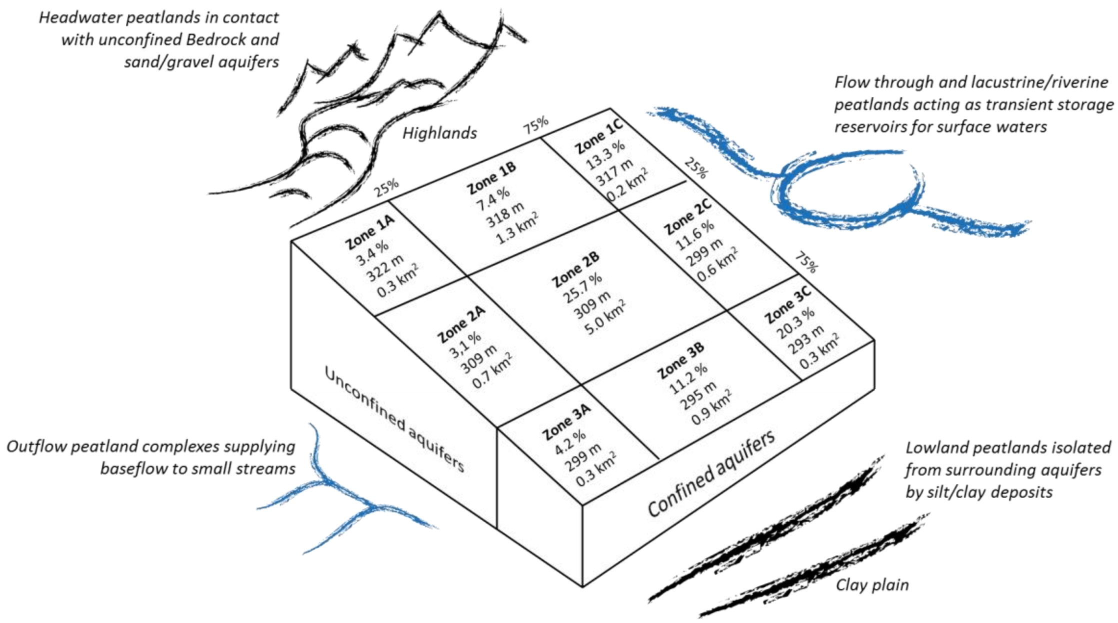


Figure 8 Comprehensive interpretation of the hydrological functions of peatlands within the regional landscape. The central scheme corresponds to the diamond shaped portion of the multiple trilinear diagram. The lines separating the different zones are set at 25% and 75% in terms of proportion with respect to the corresponding ternary plots. The percentages shown in each zone correspond to the proportion (in terms of area) occupied by the peatlands at the regional scale. The numbers with units of meters (m) and square kilometers (km^2) correspond to the regional average elevation and area of peatlands in each zones, respectively.

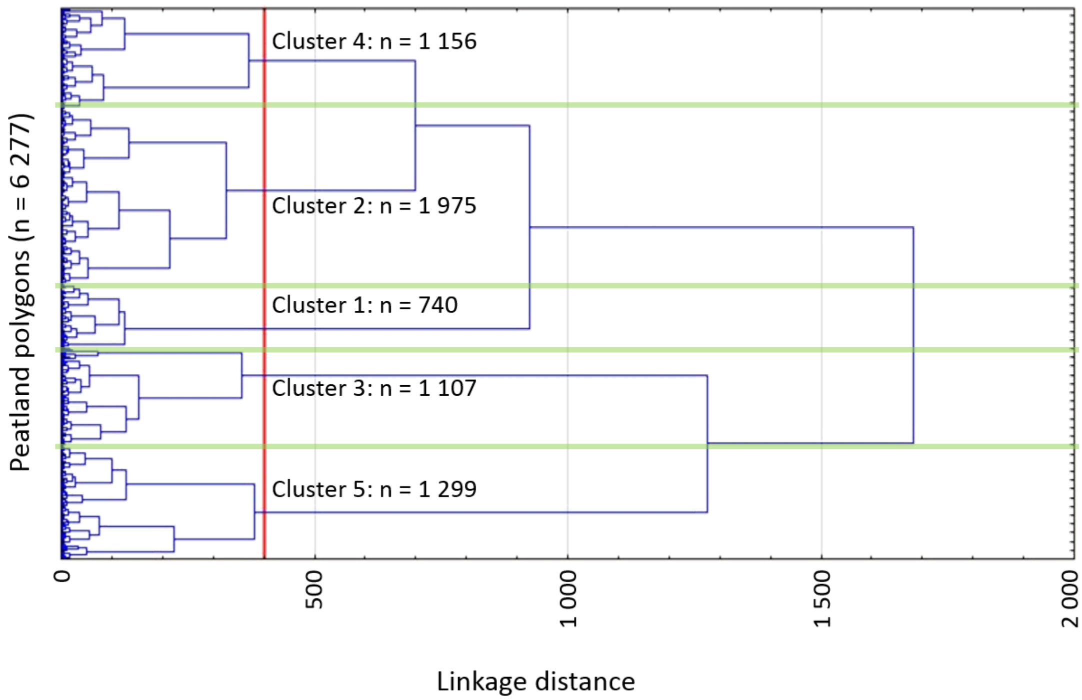


Figure 9 Results of the hierarchical cluster analysis (HCA). The analysis uses the Euclidean distance as the distance measure between peatlands, and the Ward's method as the linkage rule. The phenon line is drawn at a linkage distance of about 400, with peatlands grouped at a linkage distance below 400 belonging to the same cluster.

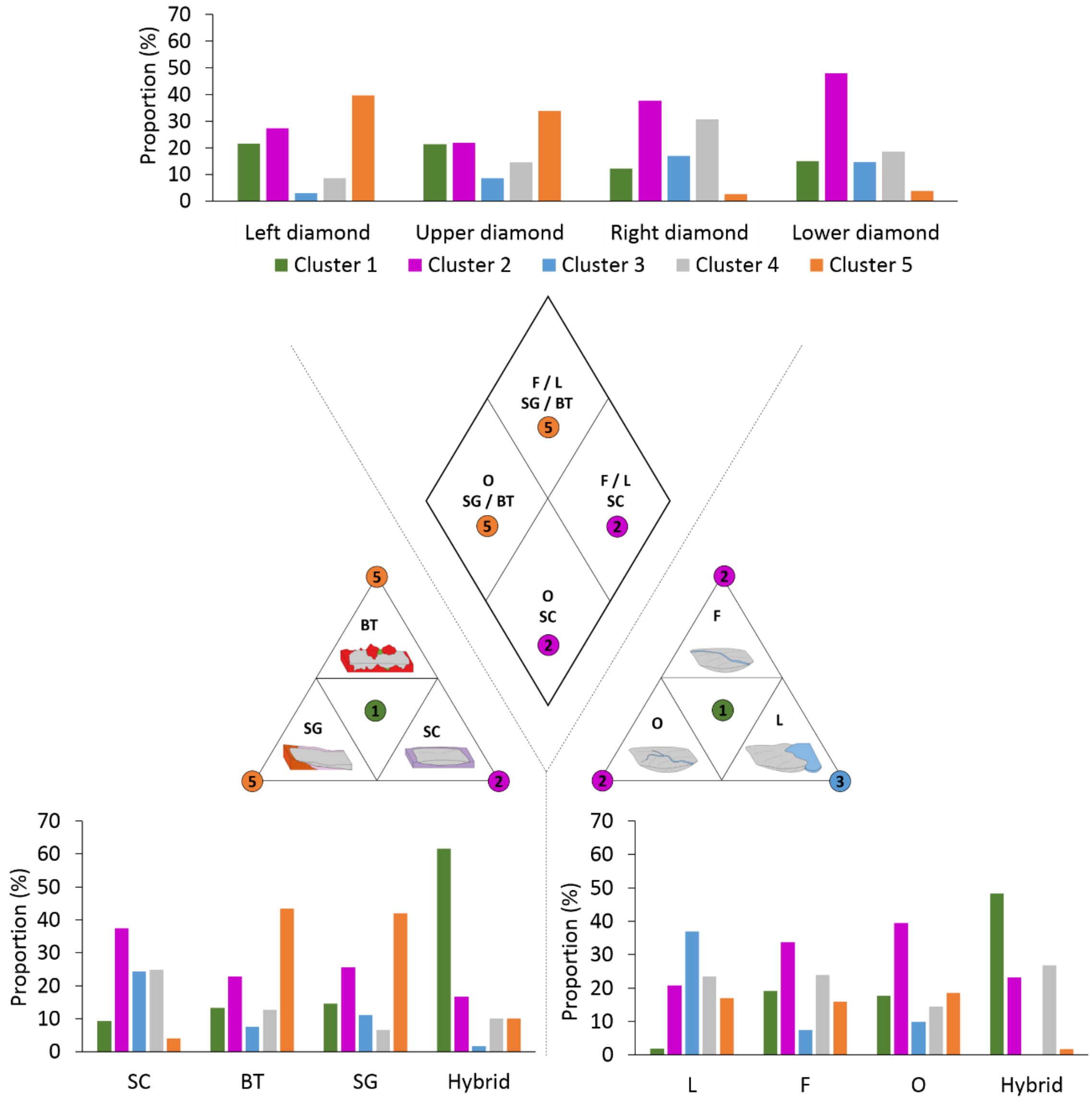


Figure 10 Comparison of the cluster analysis with the graphical approach. The colors included in the histograms correspond to clusters, as reported in the legend found below the uppermost histogram. The numbers shown in color-filled circles in the multiple trilinear diagram correspond to the dominant cluster plotting in each zone. The cluster analysis and the multiple trilinear diagram provided coherent results, as shown in the diamond shaped portion of the diagram, where clusters 2 and 5 are associated with the peatlands of zones 1 and 3 as reported in Figure 8. See text for further details about clusters 1-3-4. SG: «sand/gravel» vertex > 50%; BT: «bedrock/till» vertex> 50%; SC: «silt/clay» vertex> 50%. O: «Outflow vertex»> 50%; F: «Flow through» vertex> 50%; L: «Lacustrine/riverine» vertex> 50%.