An assessment of the hydrogeological functions of peatlands on the basis of cartographic and geophysical data

Pierre-Luc Dallaire*, E. Rosa, S. Nadeau, V. Cloutier, D. Blanchette and M. Roy
Groundwater Research Group, Université du Québec en Abitibi-Témiscamingue, Campus d'Amos, Québec, Canada
*corresponding author: pierre-luc.dallaire@uqat.ca

1. Introduction

Peatlands (**Figure 1a; b**) are environments where the processes related to organic matter accumulation prevail over decomposition and humification mechanisms (**Payette and Rochefort, 2001**) and where the water table fluctuates near the surface (within the acrotelm) in response to a positive water balance (**Mitsch and Gosselink, 2000**). Covering approximately 3% of the earth's surface, it is estimated that northern peatlands store approximately 5×10^{17} g of carbon (**Gorham, 1991**). Due to their relatively high porosity (≈ 90%), peatlands are also likely to constitute a significant component of the water cycle within watersheds, depending both on their hydrogeological properties and geomorphological attributes. However, the acquisition of quantitative hydrogeological data through field and laboratory experiments is generally realized at the local scale. The evaluation of the hydrogeological functions of peatlands at the regional (watershed) scale therefore often requires generalizations to be proposed. In this context, the present study aims at documenting the potential hydrogeological functions of peatlands solely on the basis of geographic and geophysical data. It is intended to allow classifying peatlands according to their spatial and geomorphological attributes in an effort to identify key environments for the acquisition of quantitative hydrogeological data that could subsequently be used for proposing robust regional scale interpretations.

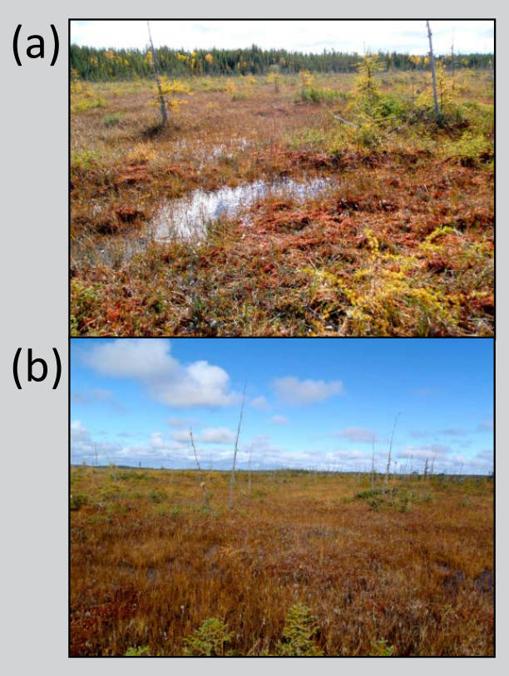

Figure 1. Landscape patterns in peatlands

2. Study area

The study area (**Figure 2**) covers 19 397 km² and encompasses the Barlow-Ojibway Clay Belt region in western Quebec, Canada. The geomorphological features of the region are inherited from the Canadian Shield irregular surface and from the sediments deposited during and following the last glaciation (**Figure 3**). A detailed description of the regional hydrogeological setting can be found in **Cloutier et al., 2013a; 2013b**. Here, the focus is set on peatlands, the latter covering approximately 7.9% of the study area.

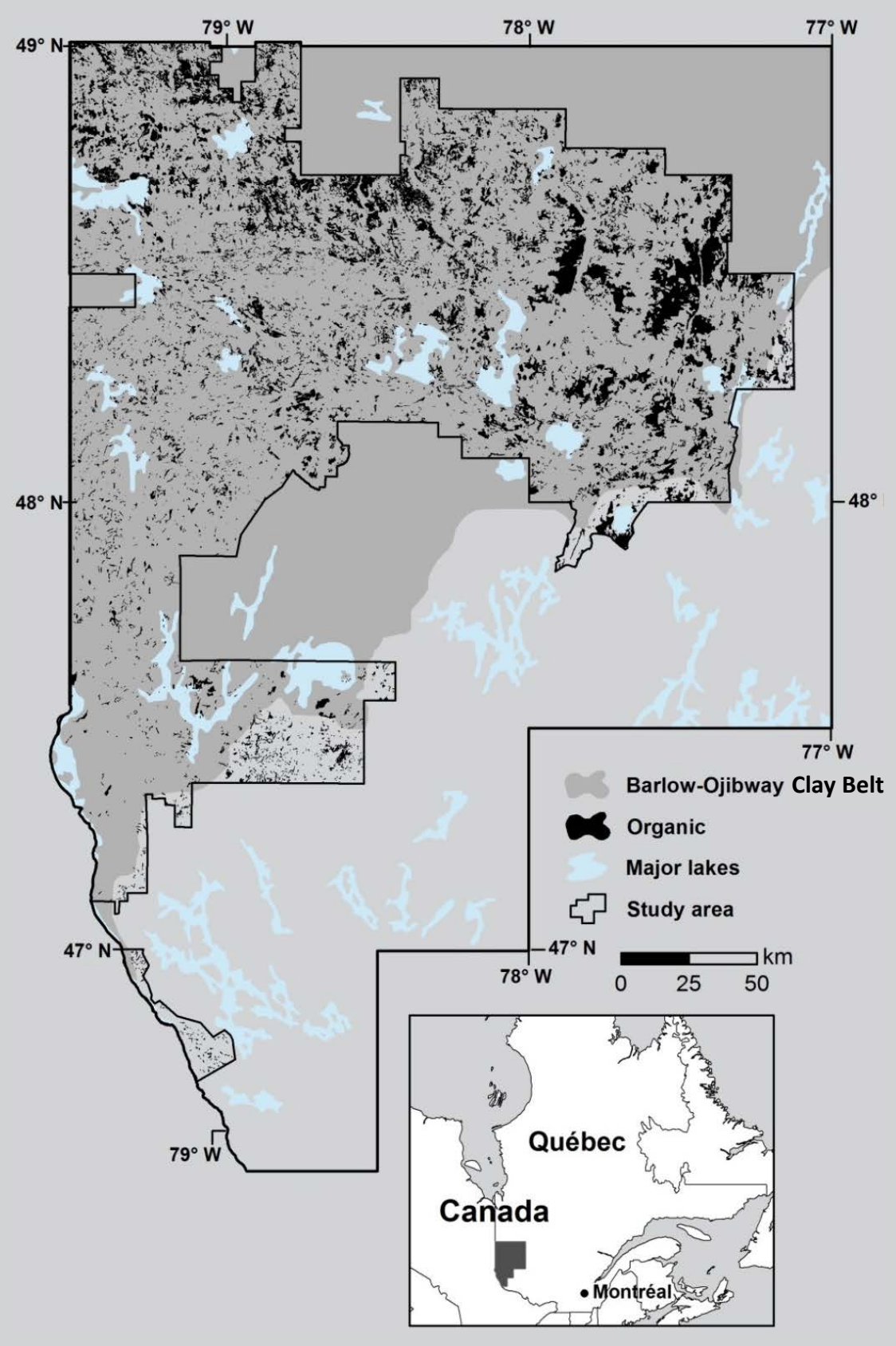

Figure 2. Study region (Organic deposits from Geological maps of the Canadian geological Survey)

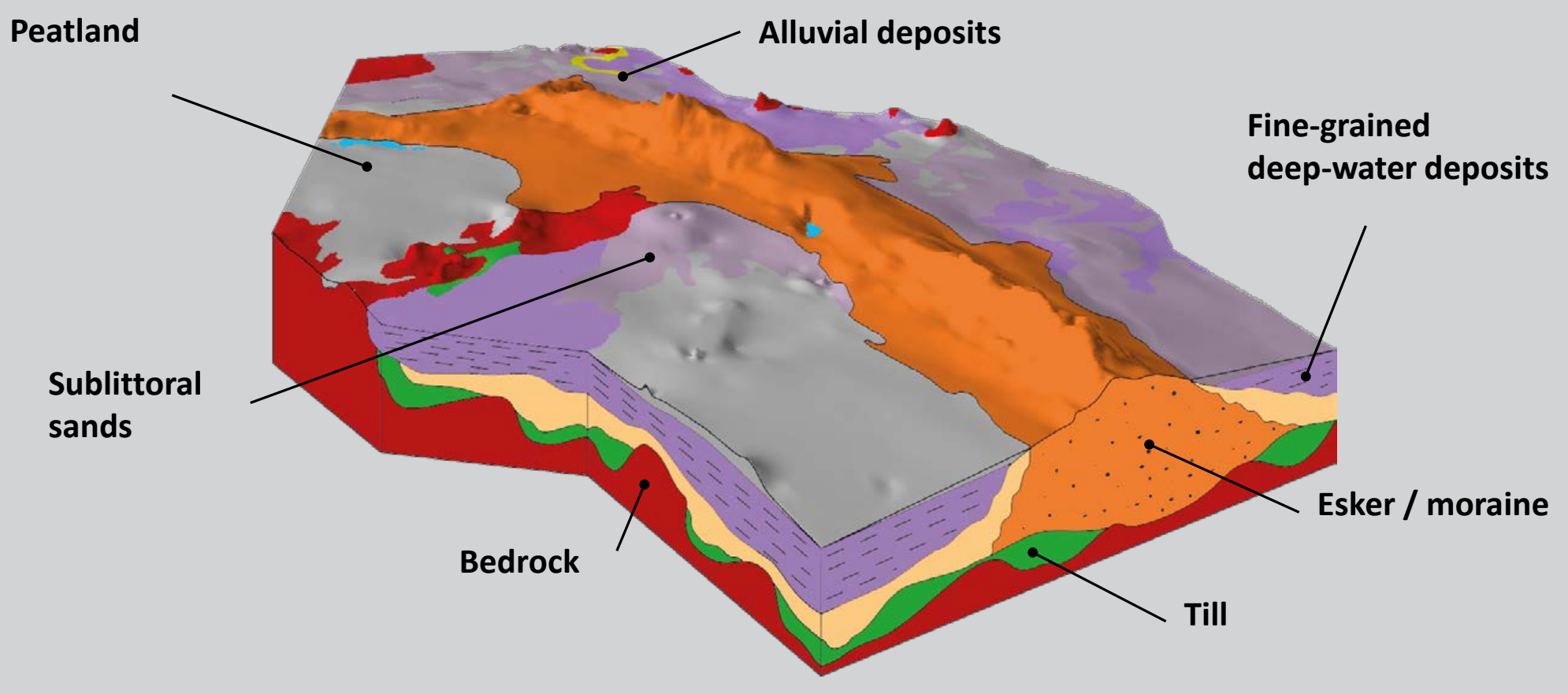

Figure 3. Schematic representation of the regional hydrogeological framework

3. Methods

3.1. Geographic Information System (GIS) approach

The cartographic approach proposed by **Ménard et al., (2006)** was adapted for mapping peatlands within the study area. This technical report, produced by Ducks Unlimited Canada, identifies the different requests needed to recognize areas of wetlands (including peatlands, ponds, marshes and swamps) from forest inventory data (**SIEF 2009; 2011**) with the use of *ArcMap (version 10.2)*. Polygons defining peatlands were subsequently characterized as a function of their geological framework based on the identification of the neighboring inorganic units (**see Figure 3**). This allowed categorizing peatlands set (1) in bedrock cavities, (2) on eskers / moraines margins and (3) in clayey depressions. The originating points of watercourses were evaluated from hydrographic network data provided by **MDDEP (2011)**.

3.1. Geophysical approach

Ground penetrating radar (GPR) data were collected during the ice-on period (March 2014) using a *Pulse EKKO Pro* device from *Sensors & Software* equipped with 100 Mhz antenna fixed to a sleigh (**Figure 4**). A common offset survey design was applied using a 640 ns time window. The data were edited using the *Reflex-Win* (version 5.0.8) software. A mean electromagnetic wave propagation velocity of 0,046 m ns^{-1} was assumed, consistent with values reported for data acquired under similar conditions (**van Bellen et al., 2011**). Position data (x, y, z) were collected using a *Trimble R8 Global Navigation Satellite System* (GNSS). Manual peat depth measurements were performed at each site using an *Oakfield* soil sampler during summer 2014. These measurements were systematically duplicated.

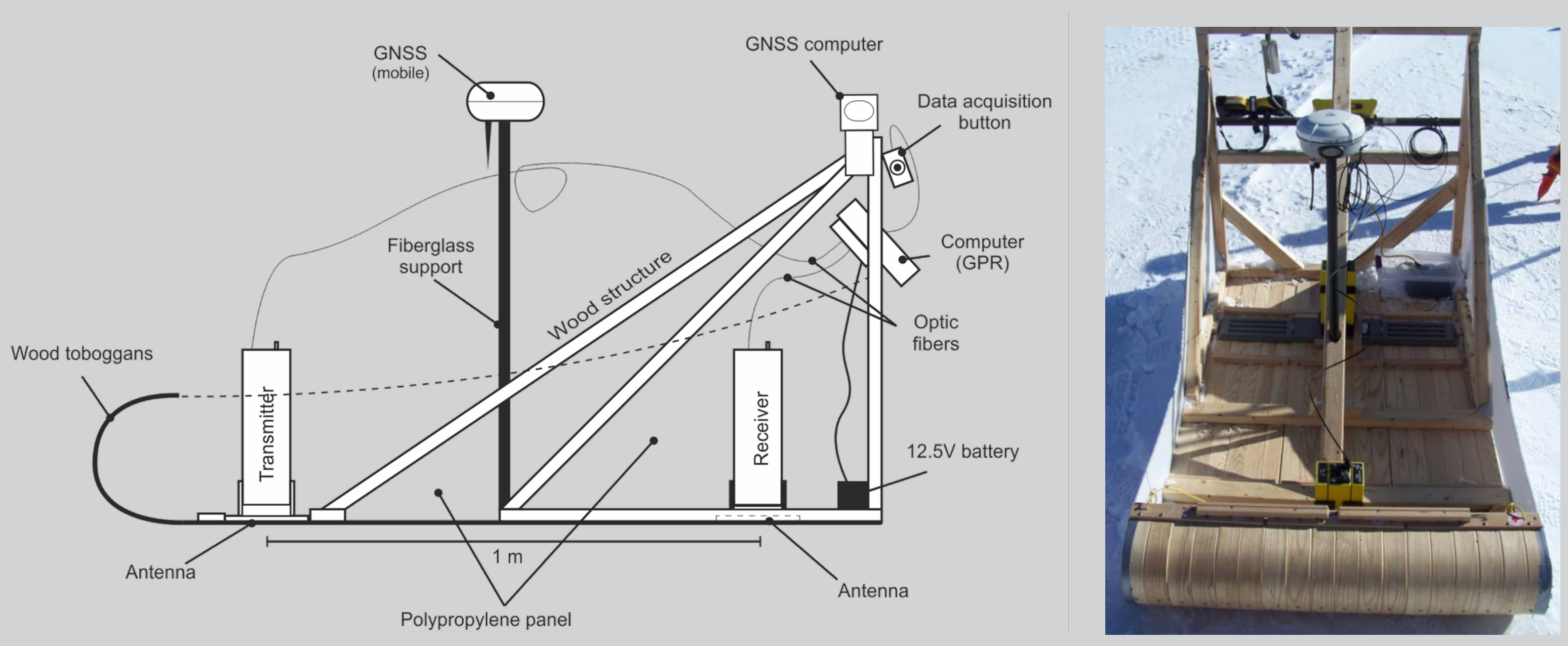

Figure 4. Details of components related to the acquisition of GPR data

4. Results

Figure 5 illustrates the spatial distribution of peatlands (within the study area). The spatial attributes calculated for peatlands set in bedrock cavities, clayey depressions and on eskers margins are reported in **table 1**.

	Context	Clayey depressions	Eskers margins	Bedrock cavities	Total
Peatlands	n	3 090 (36%)	2 235 (26%)	3 084 (36%)	8 549
	Avg. area (km²)	398 (26%)	614.2 (40%)	509.8 (34%)	1 524
	Mean area (km²)	0.13	0.27	0.17	0.18
Watercourses	SO 1	605	430	676	7 390
	SO 2	93	72	135	1 093
	SO 3	24	13	15	255
	SO 4	2	1	4	48
	Total	724 (8%)	516 (6%)	830 (9%)	8 786

Table 1. Spatial attributes of peatlands by category and quantification of watercourses taking their source within peatlands. SO: Strahler order, n: number, avg.: average

Manual peat thickness measurements (n=484) were performed in order to validate the interpretations based on GPR data. **Figure 6** illustrates the relationship obtained by comparing measured two way travel times (GPR data) and manual peat thickness measurements. Overall, 41 GPR profiles were acquired, altogether accounting for a total investigation distance of 19.7 km. **Figure 5** illustrates the location of the 6 sites that were selected for data acquisition. **Table 2** summarizes the data collected at each site.

Sector	Contexts	GPR profiles		Peat thickness	
		n	Lenght (km)	Avg. (m)	Max (m)
1	Clayey depressions	4	1.4	4.0	5.0
6	Eskers margins	8	5.1	2.3	3.7
4		3	1	2.6	4.6
2		14	6.7	1.5	6.7
3	Bedrock cavities	4	2.2	2.4	3.0
5		5	2.5	2.9	5.0
4		3	0.8	1.3	2.3
Total		41	19.7	2.4	6.7

Table 2. Summary of available GPR data (also refer to figure 5)

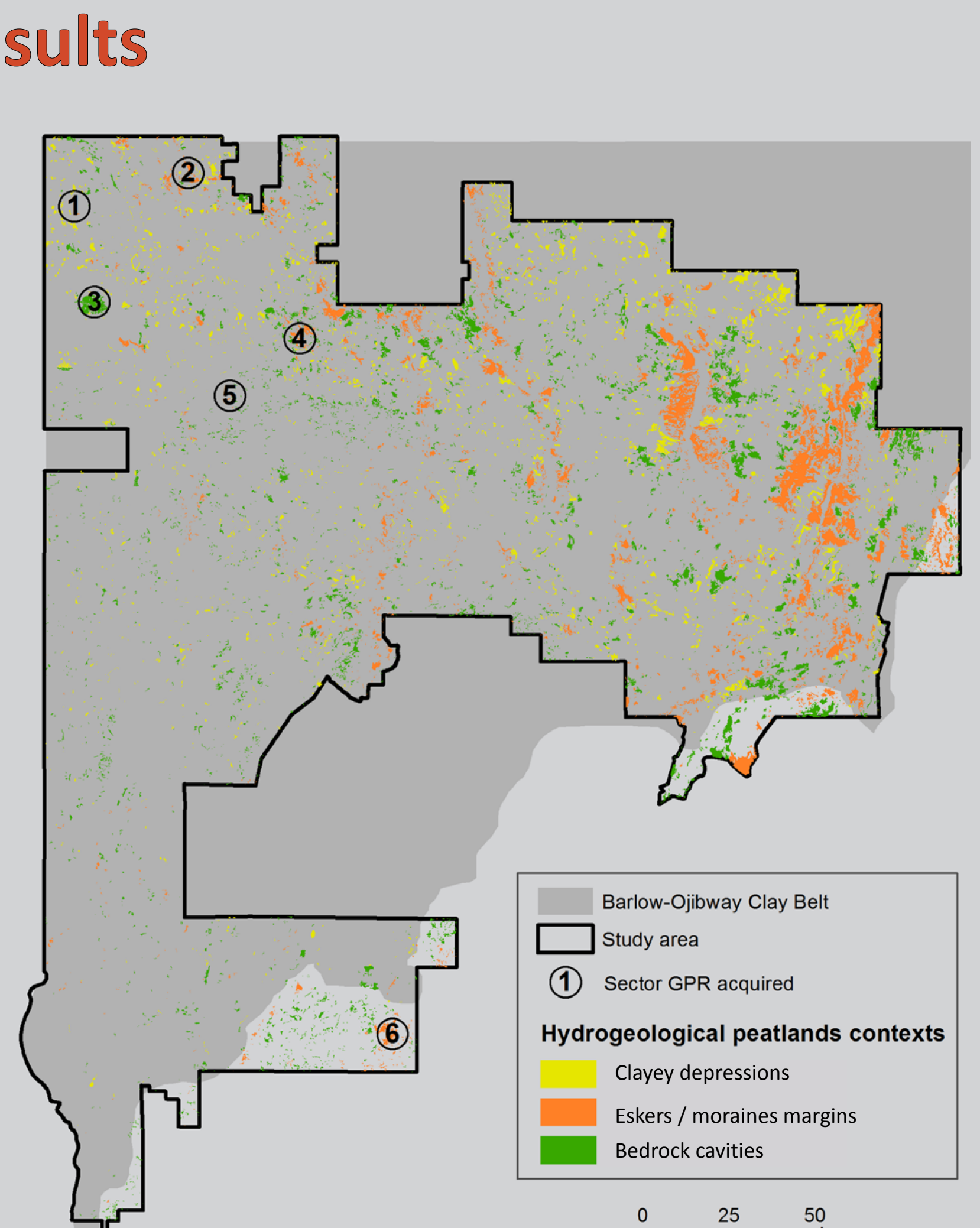

Figure 5. Spatial distribution of peatlands at the regional scale. 1-6: selected sectors for field data acquisition. Refer to tables 1 and 2 for further details

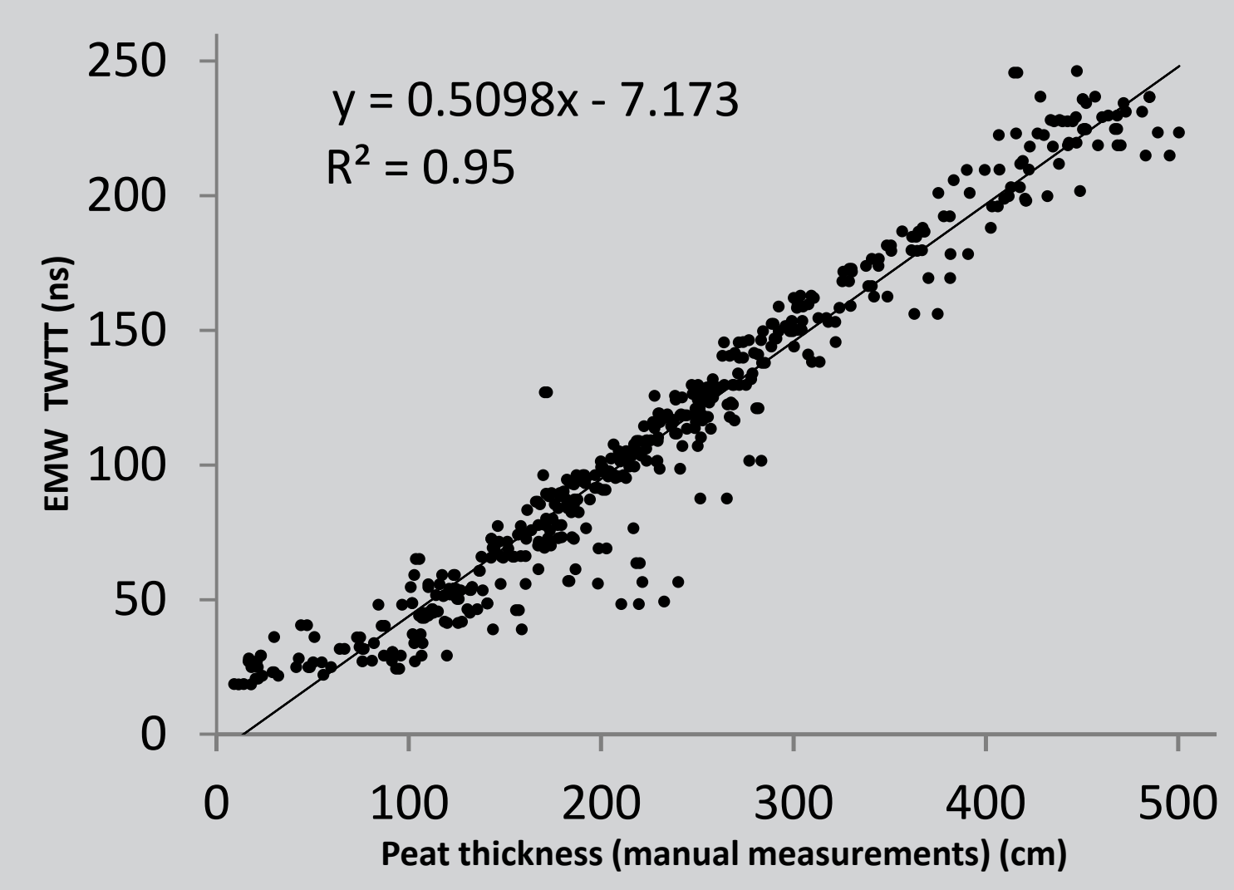

Figure 6. Comparison of electromagnetic wave two way travel time (EMW TWTT) with manual peat thickness measurements

5. Discussion

Based on the available cartographic and GPR data, two study cases were selected in order to discuss the potential hydrogeological functions of peatlands. Both cases (**Figures 7 and 8**) are discussed on the basis of schematic cross sections that illustrate the geomorphological attributes of the peatlands and surrounding geological units.

Study case A

The first study case corresponds to a peatland set within a cavity of the bedrock in sector 5 (**Figure 5**). The peatland is set above a structural discontinuity that appears to coincide with an E-W depression within the bedrock **(Figure 7a)**. The available topographic data indicates that the peatland reaches a maximum altitude of approximately 333 m in its northern section and shares a boundary with a 0.3 km² lake located eastwards. The lake reaches an altitude of 327.45 m and has an outlet in its western portion. The stream originating from this outlet flows westwards through the peatland and quickly reaches altitudes below 326 m. The GPR data collected on a NW-SE axis (**Figure 7b**) reveals that the bedrock surface elevation decreases irregularly towards the southeastern part of the peatland, where peat thickness reaches 6 m, suggesting that in the absence of peat deposits, the stream would restrict free waters to a maximum altitude of approximately 326 m, significantly below the actual lake and peatland levels. The data also indicate that the bedrock surface altitude is above 326 m (and above the actual lake level) within the entire northern section of the peatland (**Figure 7a, sector highlighted in green**) suggesting that the peatland contributes to maintain water saturation conditions well above the altitude imposed by the stream. The previously described geomorphological features were used to propose a schematic cross section of the peatland (**Figure 7c**) used as a conceptual hydrogeological model. The surface elevation pattern indicates that precipitation reaching the outcropping bedrock are likely to generate runoff towards the peatland before reaching the small stream. Under such conditions, water has to migrate through the upper peat layer (acrotelm) where transient state storage effects are likely to occur given partial saturation conditions (especially following drought periods). This will most likely result in a buffering of hydrological variations within the stream. It is also proposed that the low hydraulic conductivity bottom layer of the peatland (catotelm) is likely to limit shallow subsurface flows from the bedrock towards the stream, hence favoring groundwater recharge within the bedrock unit. Given the spatial attributes reported in **table 1** for peatlands set in bedrock cavities, it seems realistic to propose that similar conditions are likely to prevail elsewhere within the study region.

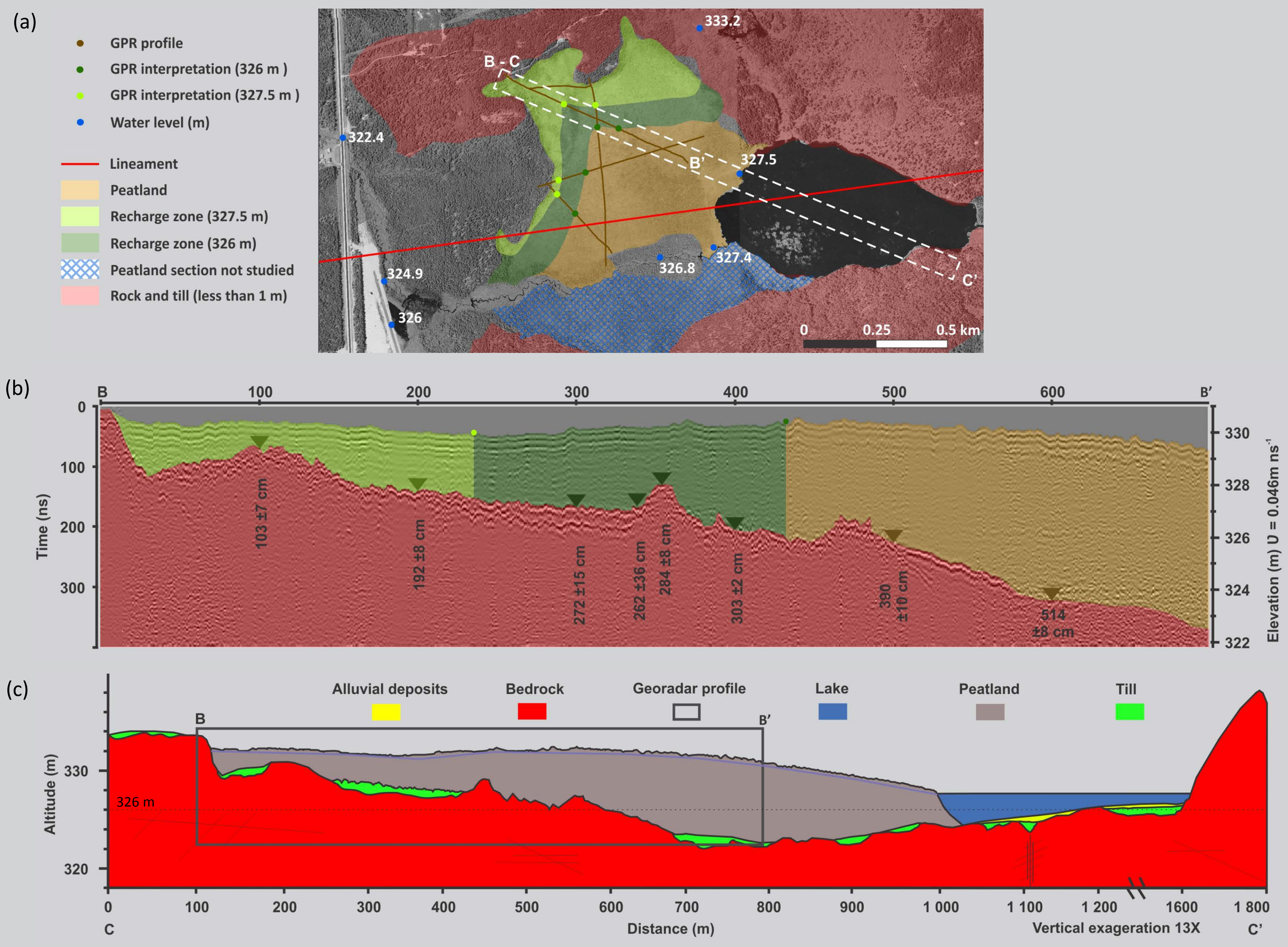

Figure 7. Conceptual hydrogeological model proposed for a peatland set in a cavity of the bedrock

Study case B

The second study case corresponds to a peatland set on an esker margin in **sector 3** (**Figure 5**). The peatland complex is set on the eastern flank of an esker (**Figure 8a**). On an E-W axis, the available topographic data indicate altitudes reaching 326 m on the esker crest and decreasing smoothly eastwards where small streams develop at an altitude of approximately 300 m. The GPR data collected along the same axis (**Figure 8b**) reveal peat thicknesses reaching 1.9 m in the western portion of the peatland and tapering eastwards in a sector where the hydrographic network develops. The previously described geomorphological features were used to propose a schematic cross section of the peatland (**Figure 8c**) used as a conceptual hydrogeological model. Within the study region, it is generally assumed that the maximum elevations of fine-grained deep-water sediments (**see Figure 2**) dictate the maximum water levels within eskers. Simply said, groundwater is expected to emerge from eskers above the altitude of the low hydraulic conductivity units set on their margins. In the context conceptualized in **Figure 8c**, it is proposed that the catotelm (characterized by a low hydraulic conductivity), which reaches higher altitudes than the underlying fine-grained deep-water unit imposes higher potentiometric levels within the esker.

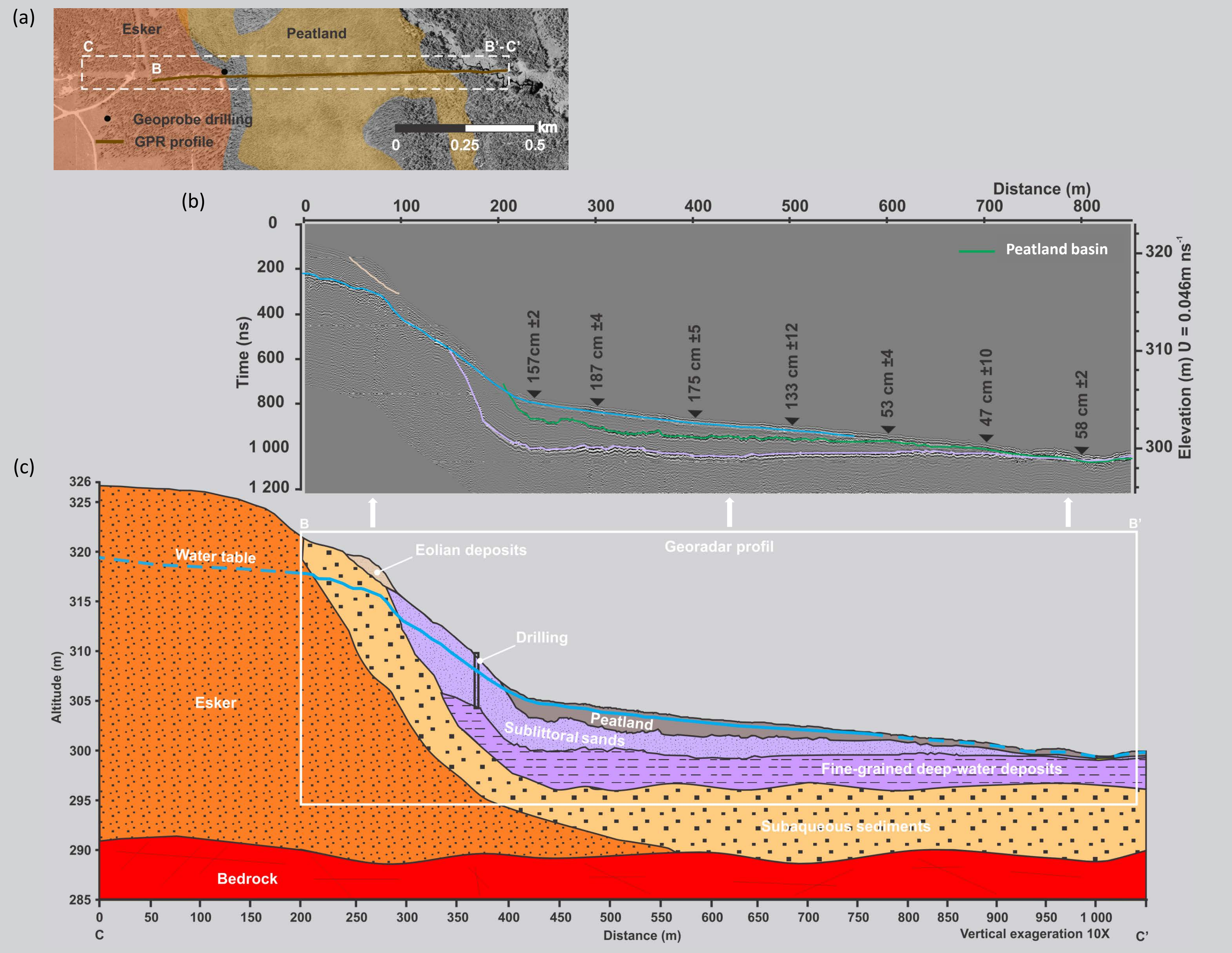

Figure 8. Conceptual hydrogeological model proposed for a peatland set on an esker margin

6. Concluding remarks

This study aimed at documenting the hydrogeological functions of peatlands on the basis of geographic information system (GIS) and ground penetrating radar (GPR) data. A cartographic approach relying on the use of forest inventories data was applied in order to delineate the polygons corresponding to peatlands. The latter were subsequently characterized as a function of their geological framework based on the identification of the neighboring inorganic geological units. This allowed categorizing peatlands set (1) in bedrock cavities, (2) on eskers margins and (3) in clayey depressions. The acquisition of GPR and topographic data within six sectors allowed a first assessment of the geomorphological features of the three categories of peatlands. Two study cases were selected for proposing conceptual hydrogeological models that are consistent with the geomorphological attributes of the landscape. These conceptual models were used to discuss the potential hydrogeological functions of peatlands. The data allowed proposing that within the study region, peatlands are likely to (1) favor groundwater recharge over rock units, (2) influence groundwater levels in eskers, and (3) buffer hydrological variations within small streams.

7. References and acknowledgements

Cloutier V., Blanchette D., Dallaire P.-L., Nadeau S., Rosa E. and Roy M. 2013a. Projet d'acquisition de connaissances sur les eaux souterraines de l'Abitibi-Témiscamingue (partie 1). Rapport final. 135 p.
Cloutier V., Dallaire P.-L., Nadeau S., Roy M. and Rosa E. 2013b. Projet d'acquisition de connaissances sur les eaux souterraines de l'Abitibi-Témiscamingue (partie 2). Rapport de phase 1. 74 pages.
Gorham, E. 1991. Northern peatlands: role in the carbon cycle and probable responses to climatic warning. Ecological Applications. vol. 2, p. 182-195.
Gouvernement du Québec, Ministère du Développement durable, de l'Environnement et des Parcs (MDDEP), Direction du patrimoine écologique et des parcs (DPEP). 2011. Cadre de référence hydrologique du Québec (CRHQ) [Données numériques vectorielles]. MDDEP-DPEP, 1 :20 000, Québec, Québec.
Ménard, S., M. Darveau, L. Imbeau and L.-V. Lemelin. 2006. Méthode de classification des milieux humides du Québec boréal à partir de la carte écoforestière du 3e inventaire décennal. Rapport technique N° Q2006-3, Canards Illimités Canada-Québec. 19 p
Mitsch W.J. and Gosselink J.G. 2000. Wetlands, 3rd edn. Wiley: New York, 920 p.
Payette, Serge and Line Rochefort (Eds). 2001. Écologie des tourbières du Québec-Labrador. Saint-Nicolas: Les Presses de l'Université Laval, 644 p.
Système d'information écoforestière (SIEF). 2009. 3e inventaire écoforestier; Gouvernement du Québec Ministère des Ressources naturelles et de la Faune, Direction des inventaires forestiers.
Système d'information écoforestière (SIEF). 2011. 4e inventaire écoforestier; Gouvernement du Québec Ministère des Ressources naturelles et de la Faune, Direction des inventaires forestiers.
Van Bellen S., Dallaire P.-L., Garneau M. and Bergeron Y. 2011. Quantifying spatial and temporal Holocene carbon accumulation in ombrotrophic peatlands of the Eastmain region, Quebec, Canada. Global Biogeochemical Cycles 25 (2).

The authors would like to acknowledge the financial contribution of the Ministry of Sustainable Development, Environment and the Fight against Climate Change (Québec) through the Groundwater Knowledge Acquisition Program (PACES). We also acknowledge the financial contribution of regional partners involved in the PACES program, including the Regional County Municipalities (Abitibi, Vallée-de-l'Or, Abitibi-Ouest, Ville de Rouyn-Noranda, Témiscamingue) and the Regional Conference of Elected Officials of Abitibi-Témiscamingue (CRÉ-AT). A special thanks goes to the field assistants A. Deschênes-Denomme and A. Paré.