Development of a water quality index for watercourses downstream of harvested peatlands

Hermine Betis, André St-Hilaire, Claude Fortin and Sophie Duchesne

ABSTRACT

This study aimed to adapt the Water Quality Index of the Canadian Council of Ministers of the Environment (CCME WQI) for its application to water quality assessment of drainage water and watercourses downstream of peat harvesting operations. It integrates different parameters that potentially reflect the overall water quality condition of a stream. Thus, it is calculated using multivariate water quality data and accounts for their conformity with respect to water quality guidelines. Adaptation of the index proceeded to identify, through a literature review, the physico-chemical parameters that may change due to peat harvesting. The CCME WQI was used to compare water quality of receiving watercourses to that of streams located within a 200 km radius from the study sites in three regions of Quebec. The availability of water quality data guided the selection of parameters among those identified. They are ammonia, conductivity, pH and suspended sediment concentrations. Results indicated a significant difference between WQI values of water from harvested peatlands and those of streams in two of the three regions studied. Results have also shown that it is the pH guideline that is not respected in most cases for harvested peatlands.

Key words | CCME, drainage water quality, harvested peatlands, water quality index

Hermine Betis
André St-Hilaire (corresponding author)
Claude Fortin
Sophie Duchesne
Institut national de la recherche scientifique, Centre Eau Terre Environnement,
490 Rue de la Couronne, Québec, QC G1 K 9A9, Canada
E-mail: *andre.st-hilaire@ete.inrs.ca*

This article has been made Open Access thanks to the kind support of CAWQ/ACQE (https://www.cawq.ca).

INTRODUCTION

Peatlands are wetlands characterized by a high accumulation of partially decomposed organic matter (Moore 2001). In Canada, peatlands represent approximately 9% of the territory, i.e. 113.6 million hectares (Tarnocai *et al.* 2011) of which 29,750 hectares are being or have been harvested (Canadian Sphagnum Peat Moss Association 2016). Harvested peat in Canada is used mainly for horticulture to improve the quality of soils to which it is added. Peat is hydrophilic and has a large cation exchange capacity (Carpenter & Farmer 1981). Harvesting is usually done by vacuuming the dried peat surface, after having removed the living vegetation and drained the water contained in the upper peat layers. To this end, drainage ditches are dug in harvested areas. Drainage water is generally routed to nearby streams which will, henceforth, be named 'receiving streams' or 'receiving watercourses'.

The disturbance of the peatland by artificial drainage and peat harvesting leads to changes in hydrology and possibly in the accumulation and decomposition of organic material. Holden *et al.* (2006), in their review on the impacts of artificial drainage on peatlands, reported that changes in runoff, as well as changes in the physical and chemical properties of water and peat, are often observed. These modifications can have impacts on the water quality and fish habitat of receiving streams.

Peatlands are complex systems where different physical, chemical and biological processes occur. In order to evaluate a potential impact from their harvest on the quality of

doi: 10.2166/wqrj.2020.007

receiving watercourses, the variability in concentrations of physico-chemical parameters in drainage water from harvested peatlands must be taken into account. In fact, these parameters depend in part on the local geology in which peatlands are located. The next paragraphs summarize succinctly the information found in the literature about the variability of these parameters in the context of peat harvesting.

In North America, the peat harvesting industry mainly operates in ombrotrophic peatlands (Ferland & Rochefort 1997). This type of peatland is typically acidic with a vegetation that is not very diversified, i.e. dominated by sphagnum mosses, poor in minerals and with a low decomposition rate of organic matter (Payette 2001). Some studies conducted on the potential impact of peat harvesting on peatland drainage water chemistry are summarized in Table 1. This table, albeit not exhaustive, presents different water quality parameters and the ranges of concentrations that have been measured, mainly in Québec (Canada).

It was also mentioned in some studies that conductivity, which is a function of the amount of dissolved solids, can be higher in the drainage water of harvested sites than in natural peatlands (Morrison *et al.* 2001). Aluminium (Al), manganese (Mn) (Åström *et al.* 2001) and total organic carbon (TOC) concentrations can also differ in drainage water of natural vs. harvested peatlands (Moore 1987; Holden *et al.* 2006). Data in Table 1 suggest an increase of the concentration for most parameters in harvested peatlands, compared to undisturbed sites. However, for pH and TOC, several studies have shown an increase (Moore 1987; Wind-Mulder *et al.* 1996; Holden *et al.* 2006), while other a decrease of values (Moore 1987; Holden *et al.* 2006) in harvested vs. natural peatlands.

Potential changes in several physico-chemical parameters in receiving watercourses have also been mentioned in the literature. Several studies have shown an increase of suspended sediment (SS) concentrations (e.g. Clément *et al.* 2009) and of dissolved organic carbon (DOC) (Wallage *et al.* 2006) in watercourses downstream of harvested peatlands. An increase of conductivity and metal concentrations, such as Al and Mn (Andersen *et al.* 2011), and of nutrient concentrations near peat harvesting sites have been observed (St-Hilaire *et al.* 2004). In a study on peat harvesting, Carpenter & Farmer (1981) mentioned that peat particles contained in the drainage water can lead to an increase in the mobility of metals in receiving watercourses such as copper (Cu), nickel (Ni), lead (Pb), mercury (Hg) and uranium (U), that are adsorbed on the peat particles.

These changes in physico-chemical parameters can have negative consequences on the health of aquatic species and their habitat quality. Indeed, chemical changes in receiving watercourses, such as the increase in nutrient loads that promote eutrophication, can cause the loss of aquatic diversity (Kløve 2001). An increase in conductivity can

Table 1 | Physico-chemical parameters in water of natural and harvested peatlands

Parameters		Natural peatlands	Harvested peatlands	References
Nutrients	Ammonium (NH_4^+)	0–1.4	0–5.7	a, b
	Nitrate (NO_3^-)	0–0.1	0–0.6	a
	Phosphorus (P)	0–0.2	<0.6	a, b
Other inorganic parameters	pH	3.6–4.1	3.7–5.4	a, b, c, d
	Calcium (Ca^{2+})	0.07–4.6	0.02–8.3	a, b, c, d
	Magnesium (Mg^{2+})	0.06–3.1	0–4.4	a, b, c, d
	Sodium (Na^+)	0.1–16.5	0.2–12.3	a, b, c, d
	Potassium (K^+)	0–0.5	0.1–2.5	a, b, c, d
	Chloride (Cl^-)	0.1–14.9	0.1–7.2	a, c
	Sulfate (SO_4^{2-})	0.7–9.6	0–17.4	a, c
Metal	Iron (Fe)	0.07–0.35	0.08–0.48	b
Organic and physical parameters	Conductivity	0–115	0–143	a
	Suspended sediments (SS)	36	71	e
	Dissolved organic carbon (DOC)	23.7–43.7	26.2–46.6	a

Nutrients, ions, metals, DOC and SS concentrations are in mg/L and the specific conductivity is in μS/cm.
(a) Wind-Mulder *et al.* (1996); (b) Moore (1987); (c) Comeau & Bellamy (1986); (d) Glaser (1992); (e) Pavey *et al.* (2007).

have a negative effect on aquatic species (Morrison *et al.* 2001). The decrease of pH can lead to loss of fish habitat (Papoulias & Velasco 2013). Furthermore, a decrease in pH and an increase in nutrient loads can stimulate the methylation of mercury leading to methylmercury accumulation in the food chain (Surette *et al.* 2002). An increase in SS concentration can lead to local reduction of quality and availability of habitats, which may lead to a decrease in the density and diversity of resident populations in these streams. This also affects the survival and reproduction of some aquatic species (Bilotta & Brazier 2008).

Facing possible changes, there is a need to monitor watercourses downstream of harvested peatlands to assess their physical and chemical characteristics against water quality guidelines for the protection of aquatic life. Presently, no predefined index adapted to the assessment of water quality in these watercourses exists (Andersen *et al.* 2011). Therefore, the purpose of this study was to adapt the Water Quality Index of the Canadian Council of Ministers of the Environment (CCME WQI; CCME 2016) to watercourses receiving drainage water from peat harvesting operations, in order to assess and monitor their potential effects on receiving streams.

The CCME WQI is a mathematical tool developed in 2001 by the Canadian Council of Ministers of the Environment that combines multivariate water quality data and provides a single score for describing the state of water quality (CCME 2016). It is a flexible index which can be applied to a variety of situations. Its calculation involves water quality data and their associated guidelines, which have been defined depending on water use (CCME 2016). This index is based on three factors: (1) the number of variables not in compliance with recommended guideline threshold values, (2) the number of times that recommended values are not met and (3) the difference between the measured and recommended values. These factors are combined in a formula (described in the Methods section) that gives a score between 0 and 100, categorized in five classes of water quality, with a CCME WQI of 100 indicating water of excellent quality.

The CCME WQI has been used in numerous applications and is recognized as a helpful tool for communicating the status of water quality to the public, policymakers and managers (Khan *et al.* 2004; Khan *et al.* 2005; Lumb *et al.* 2006). In Canada, the water component of the Canadian Environmental Sustainability Indicators (CESI) uses the CCME WQI to report on water quality at the national level (Lumb *et al.* 2011). This index has also been used for other purposes. For instance, it allowed a water quality assessment in three rivers of Atlantic Canada for various water usages (Khan *et al.* 2003). Khan *et al.* (2004) have adapted the CCME WQI for drinking water quality assessment in Newfoundland and Labrador. In New Brunswick, it was applied in water quality assessments of Mackenzie Lake (Lumb *et al.* 2006), and Rosemond *et al.* (2009) adapted it for a comparative study of water quality sites exposed to metal mining and reference sites in Canada. In addition, the CCME WQI has been used to assess the spatial and temporal variability of water quality for small water distribution systems in Newfoundland and Labrador to monitor some contaminants, and thus to identify seasons/locations for which water quality did not meet guidelines (Scheili *et al.* 2015). It has also been used as an indicator of the freshwater quality for a monitoring network in watercourses of southern Canada (Environnement & Climate Change Canada 2017).

The CCME User Manual mentions parameters that may be relevant when the guideline objectives are related to the protection of aquatic life (CCME 2016). These parameters include pH, TOC, DOC, SS, turbidity, ammonia (NH_3), NO_3^-, NO_2^-, P, Al, Cadmium (Cd), Cu, Pb and Zn. NH_3 is mentioned instead of NH_4^+ because, along with NO_3^-/NO_2^-, they are the forms of nitrogen (N) that are the most toxic for aquatic species (Ministère de l'environnement et de la lutte contre les changements climatiques (MELCC) 2018).

Table 2 summarizes parameters that have been taken into account for the evaluation of water quality downstream of harvested peatland in previous studies. Parameters are divided into four categories: (1) organic and physical parameters, (2) nutrients, (3) metals and (4) inorganic parameters.

The first objective of this study was to adapt the CCME WQI to evaluate the variability of physico-chemical parameters of streams downstream of harvested peatlands. This was done by selecting a short list of parameters among those collated in Table 2 and their associated guidelines. A second objective was to apply this index to water quality data from drained water, effluents of sedimentation ponds and receiving streams to see how they compare to

Table 2 | Relevant parameters for assessment of water quality for the protection of aquatic life in watercourses downstream of harvested peatlands

Categories	(1) Organic and physical parameters	(2) Nutrients	(3) Metals	(4) Other inorganic parameters
Parameters	TOC	NH_3	Fe	pH
	DOC	NO_3^-/NO_2^-	Al	Ca
	SS	P total	Mn	Mg
	Turbidity	N total	Cu	Na
	Conductivity	Total dissolved phosphorus (TDP)	Ni	K
			Pb	Cl
			Hg	SO_4^{2-}
			U	
			Cd	
			Zn	

other streams in the study regions. Data used were measured physical and chemical variables from harvested peatlands and a set of streams in three regions of Quebec (Canada) where there is commercial peat harvesting.

METHODOLOGY

Calculation of the CCME WQI (CCME 2016)

The CCME WQI value is obtained by the comparison of physico-chemical parameters against their guidelines. In this calculation, three factors are considered:

- The scope (F_1) to determine the percentage of parameters for which at least one measure does not meet the prescribed guideline ('failed parameters')

$$F_1 = \frac{\text{Number of failed parameters}}{\text{Total number of parameters}} \times 100$$

- The frequency (F_2) that gives for all parameters the percentage of measurements that do not meet their guidelines ('failed tests')

$$F_2 = \frac{\text{Number of failed tests}}{\text{Total number of tests}} \times 100$$

- The amplitude (F_3) that gives for all parameters and each failed test the amount by which a guideline value ('Objective') is not met. This calculation is based on the determination of the coefficient of deviation against guidelines ('excursion' (CCME 2016)).

The 'excursion' is computed in two different ways, depending on the type of guideline. When the guideline must not be exceeded, it is computed using:

$$\text{Excursion}_i = \left(\frac{\text{Failed test value}_j}{\text{Objective}_j}\right) - 1$$

And when the actual value must not be less than the guideline:

$$\text{Excursion}_i = \left(\frac{\text{Objective}_j}{\text{Failed test value}_j}\right) - 1$$

Then, excursions are normalized to obtain an F_3 value in percentage:

$$F_3 = \frac{\left(\sum_{i=1}^{n} \text{Excursion }_i\right)/(\text{Number of tests})}{\left(0.01\left(\sum_{i=1}^{n} \text{Excursion}_i\right)/(\text{Number of tests})\right) + 0.01}$$

- Subsequently, these three factors are combined in a calculated index in which the denominator value of 1.732 is used to normalize the end result to a value between 0 and 100.

$$\text{CCME WQI} = 100 - \left(\frac{\sqrt{F_1^2 + F_2^2 + F_3^2}}{1.732}\right)$$

WQI values were classified into five categories that are as follows (Canadian Council of Ministers of the Environment 2016): Excellent: between 95 and 100; Good: between 80 and 94; Fair: between 65 and 79; Marginal: between 45 and 64; Poor: between 0 and 44.

In this work, the CCME WQI values were computed by means of the WQI Calculator, Version 1.2, developed by the CCME (CCME 2014a). This version of the calculator is constructed in Microsoft Excel and contains a large selection of potential parameters (note that Version 2.0 is constructed in Visual Studio.NET 2013; CCME 2014b). For each selected parameter, water quality data can be imported in the Calculator, along with associated guidelines (CCME 2016).

Monitoring sites, sampling period and final selection of parameters

Monitoring sites

The choice of monitoring sites was guided by the requirements of the CCME WQI application, that a minimum of four variables be sampled at least four times per year, during three consecutive years (CCME 2016). The emphasis was on sites located in or near harvested areas, immediately downstream of sedimentation ponds and in receiving watercourses for three distinct hydroclimatic regions (R1, R2 and R3) of Quebec (as delineated by the provincial Department of Environment and Fight Against Climate Change using major drainage basins) where peat harvesting operations are concentrated. Subsequently, the index has been applied to streams in these regions ('reference watercourses') in order to use them as control sites to compare water quality. Ideally, local control sites should include a sampling station in the receiving waters upstream of the input of drainage water from peatlands. However, in most cases, these upstream sites are currently not sampled by the peat producers. R1 covers an area of approximately 22,000 km^2 with 10% of agricultural land and 6% of wetlands and its average (±standard deviation) total annual precipitation ($n = 16$) is 1041 ± 62 mm/year. R2 covers an area of more than 230,000 km^2 with 0.02% of agricultural land and 1.72% of wetlands and its average total annual precipitation ($n = 7$) is 978 ± 120 mm/year. And finally, R3 covers an area of 95,000 km^2 with 2% of agricultural land and 9% of wetland and its average total annual precipitation ($n = 8$) is 1031 ± 102 mm/year. Therefore, most rivers used as reference sites can be considered as being pristine or moderately impacted by agriculture (especially in region R1).

Reference watercourses. To calculate the CCME WQI of reference watercourses in the three regions, data were accessed from the Quebec Aquatic Environmental Quality database (the BQMA), which collates surface water physico-chemical data from existing sampling stations (MELCC 2017). Generally, stations were sampled monthly throughout the years. This database contains 22 parameters, of which the physico-chemical parameters include cations (Ca^{2+}, K^+, Mg^{2+} and Na^+), determined during the years 2006–2007, total dissolved phosphorus (TDP), from 2006 to 2009, as well as pH, SS, COD, conductivity, ammonia-nitrogen (N-NH_3), N total, NO_3^- and NO_2^-, all measured between 2006 and 2016 (MELCC 2017).

In R1, data from 19 selected stations were used. The chosen watercourses are located at a distance of 5–200 km of the studied peatland. For R2, data from 12 stations were used. A distance between 4 and 172 km separates the streams from the peatlands. In R3, 18 reference river stations were used, with a distance between the streams and peatland of approximately 12–80 km.

Although these rivers are sometimes far from the peatland sites, comparing them with harvested sites offers the first benchmark for broad characterization of the variability of water quality in regions that were predefined by local (provincial) authorities.

Harvested peatlands. The CCME WQI values were calculated from water quality data obtained from peat moss producers participating in this study. In this paper, actual locations are not mentioned to preserve confidentiality. The period was selected to include years during which sampling has been done concomitantly in harvested peatlands and in reference rivers. In accordance with CCME methodology, the WQIs were calculated over a period of three consecutive years. The chosen period was from 2014 to 2016 during the ice-free months (April–October). The location of sampling points is shown in Figure 1. In R1, peatland A, sampling points at sedimentation ponds exit (PE) are named R1-PE-1 and R1-PE-2. In R2, sampling points in the PE are named R2_B-PE-1 and R2_B-PE-2 for peatland B; and R2_C-PE-1, R2_C-PE-2 and R2_C-PE-3 for peatland C. In R3, peatland D, sampling points in the PE are named R3-PE-1, R3-PE-2, R3-PE-3 and R3-PE-4. In this last region, a receiving watercourse was also sampled

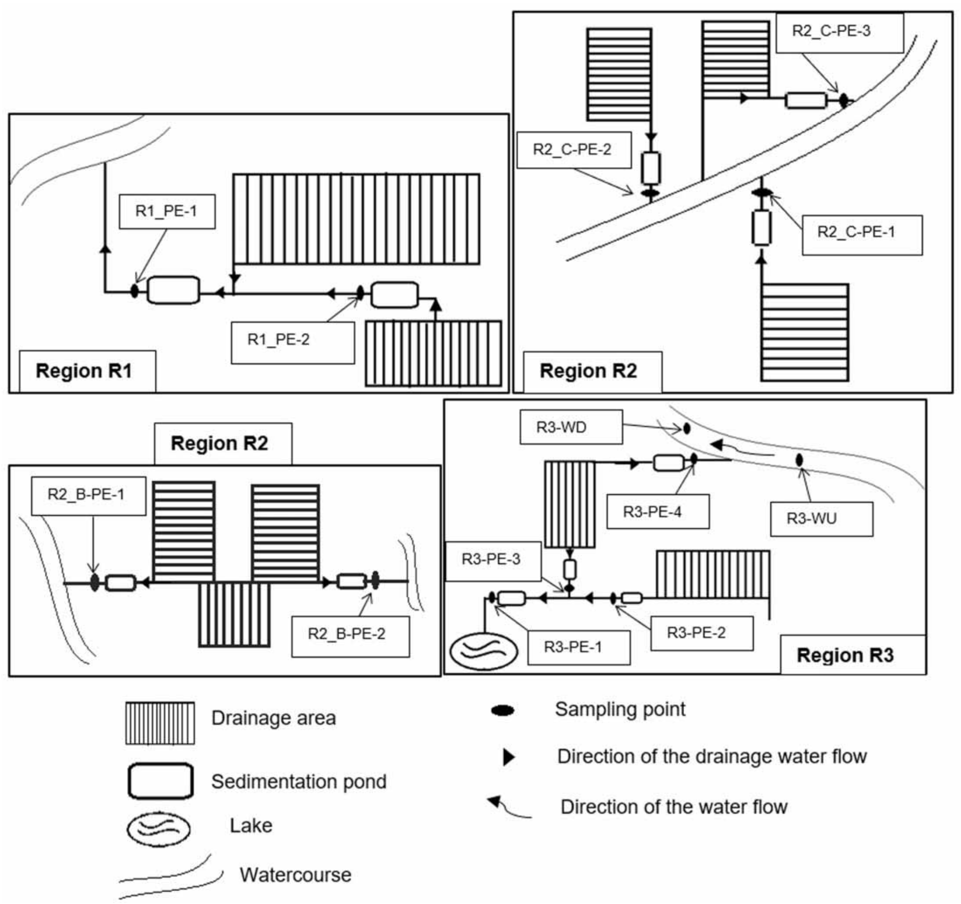

Figure 1 | Location of sampling points in harvested peatlands. R1: Region 1, R2_B: Region R2 peatland A, R2_C: Region R2 peatland C, R3: Region R3, PE: Sedimentation pond exit, WD: Watercourse downstream, WU: Watercourse upstream.

downstream (R3-WD) and upstream (R3-WU) of the point of discharge of the drained water from site R3-PE-4.

- In R1, the CCME WQI was tested on physico-chemical data from two sites located in one harvested peatland (A). In this peatland, available parameters were SS, pH, conductivity, N-NH_3, Fe and Na. Data were obtained from sampling that was conducted from 2014 to 2016.
- In R2, WQIs were calculated using physico-chemical data from two peatlands (B and C). Available parameters were Ca, Cu, Fe, Mg, Mn, K, Na, Zn, N-NH_3, conductivity, SS, NO_3^-, NO_2^-, pH and P total from 2011 to 2016.
- In R3, the CCME WQI was tested on physico-chemical data from peatland D. Available parameters were Ca, Cu, Fe, Mg, Mn, K, Na, Zn, N-NH_3, conductivity, SS, NO_3^-, NO_2^-, pH and P total from 2011 to 2016.

The period was selected to include years during which sampling has been done concomitantly in harvested peatlands and in reference rivers. In accordance with CCME methodology, the WQIs were calculated over a period of three consecutive years. The chosen period was from 2014 to 2016 during the ice-free months (April–October).

Choice of physico-chemical parameters

Taking into account the limited number of parameters sampled at site R1_A, a maximum of six parameters could be used for the calculations, i.e. pH, SS, conductivity, N-NH_3, Fe and Na. However, few data are available for Fe and Na in reference streams (MELCC 2017), so these two parameters were excluded. Conductivity data were used because this measure provides global information about ions present in water. Ultimately, four parameters were used in the calculation of the WQIs; these are pH, SS, conductivity and N-NH_3.

Water quality guidelines for selected parameters

The Canadian Water Quality Guidelines (CWQGs) developed by the CCME (CCME 2007) were used as threshold values. Among these, guidelines for N-NH_3, pH and SS were used (CCME 2014c). For the protection of aquatic life, the concentration of SS should not exceed 25 mg/L; the guideline for N-NH_3 is calculated according to pH and temperature, and pH should be between 6.5 and 9.0 (CCME 2014c). In natural peatlands, pH of water is naturally low (e.g. St-Hilaire *et al.* 2004) and this could cause a decrease of pH in receiving watercourses compared to other rivers for which peatlands do not occupy a large percentage of the drainage basin. Hence, CWQGs for pH were deemed potentially inadequate for this study. Finally, there is no stated guideline for conductivity.

Thus, for pH and conductivity, local conditions have been considered to define a guideline. Specific objectives for the region (RSO) have therefore been calculated by the determination of the upper and lower limit of the background concentrations using descriptive statistics like the mean ± two standard deviations (sd) on water quality reference river data (CCME 2003; Rosemond *et al.* 2009). The use of the RSO approach was completed using water quality data collected over several years (CCME 2003) (knowing that the RSO approach can be used only if the database contains at least 10 values (Rosemond *et al.* 2009)). The mean plus two standard deviations (2sd) was used to determine the upper limit and the mean minus 2sd must be used to determine the lower limit of the RSO values (Khan *et al.* 2005). In this study, monitored data (MELCC 2017) were used to calculate the upper limit of the RSO for the conductivity. For pH, the RSO for the lower limit was calculated using data collected by Andersen *et al.* (2011), and the existing guideline regarding the upper limit was retained (pH of 9.0 (CCME 2014c)). For pH and conductivity, RSOs were calculated from datasets having sample sizes greater than 10. Table 3 presents the values of RSOs and CCME CWQGs corresponding to the parameters that were used in the WQI calculations.

Table 3 | Specific objectives for the region and CWQGs of the CCME of the parameters selected for the calculations of WQIs

		RSO		
Parameters	**CCME guidelines**	**R1**	**R2**	**R3**
N-NH_3 (mg/L)	Calculated according to pH and temperature	–	–	–
SS (mg/L)	25	–	–	–
pH	6.5 to 9	5.1	3.7	2.7
Conductivity (μS/cm)	–	422.7	105.5	380.1

Calculation of CCME WQIs

For the application of CCME WQI to drainage waters, sedimentation pond outlets, receiving streams and reference streams of each region, the WQIs were calculated firstly by using CWQG of the CCME and the RSO values for conductivity (for which there is no CCME CWQG) (*Method 1*). Then, the second set of WQIs was calculated using the RSO values for the lower limit of pH instead of the guideline given by the CCME (*Method 2*). This was done to consider the fact that pH can be naturally acidic in the water downstream of undisturbed natural peatlands.

Statistical tests

Results of WQI values are presented by boxplots for each region. Each boxplot describes the entire distribution of the WQIs; the 25th percentile (Q1) is represented by the lower edge of the box, the median (50th percentile) is represented by the bar in the box, and the 75th percentile (Q3) is represented by the upper edge of the box; the interquartile method was used to identify outliers (data points outside of the 25th and 75th percentile; see Figure 2). The Shapiro–Wilks test was used to determine if the WQI values were normally distributed (Ghasemi & Zahediasl 2012). The Shapiro–Wilks test revealed that in most sites, WQI values are not normally distributed (p-value <0.05). For this reason, a non-parametric method, the

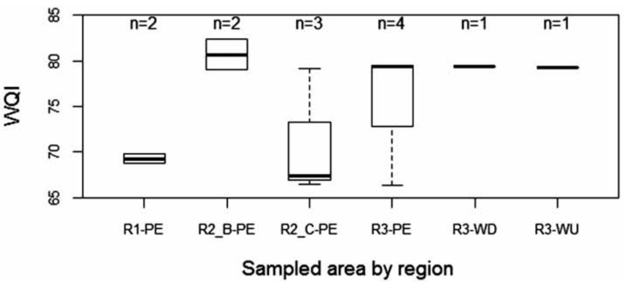

Figure 2 | Boxplots of WQI values for each type of site sampled in R1, R2 and R3. R1: Region R1, R2: Region R2, R3: Region R3, PE: Pond Exit, WD: Watercourse Downstream, WU: Watercourse Upstream.

Wilcoxon–Mann–Whitney (WMW) test, was used to compare WQI values. This test indicates if data of two populations have the same distribution with a null hypothesis that the populations are identical. The null hypothesis is rejected when the *p*-value is lower than the significance level (Rosenthal 2011); a significance level of 0.05 was used in this study. The WMW test allowed us to determine if there is a difference between WQI values of different harvested sites and to compare WQI values of reference streams and those of water located in harvested peatlands.

The Mann–Whitney pairwise test was used to compare WQI calculated from harvested peatlands and in reference streams using Method 1 with those obtained from the calculations using Method 2. This test allows multiple comparisons, that is, pair by pair comparisons of two datasets, with the null hypothesis that members of a pair are identical. The *p*-value was obtained for each pair compared. The null hypothesis was rejected when p-value <0.05. Statistical tests were carried out in the RStudio interface.

RESULTS

Method 1

Water quality in harvested sites

Boxplots of WQIs distribution by site type in harvested peatlands of each region are presented in Figure 2. It can be seen that most of the sampling effort and WQI variability occur at the pond outlets (PE).

Taking into account the physico-chemical parameters used in the calculation of the CCME WQI (pH, conductivity, SS and $N\text{-}NH_3$), we can see in Figure 2 that, for R1, the quality of the water sampled at the sedimentation pond exit (PE) was fair (median WQI = 69.2) for the study period of 2014–2016. Both pH and $N\text{-}NH_3$ caused the relatively low WQI values, with a failure to comply with the guideline in 45% of the cases for pH and 18% of the cases for $N\text{-}NH_3$.

In R2, the water quality had been assessed for two peatlands (B and C). In peatland B, for water sampled at the PE, the boxplot in Figure 2 shows that the WQI values varied from fair to good with a median WQI of 80.7. However, in peatland C, the water sampled at the PE was of fair quality (median WQI = 67.3).

In peatland B, pH did not meet the guideline for 78% of data. In peatland C, pH and conductivity are the variables that negatively affect the WQI value, with 96% of pH measurements and 7% of conductivity measurements which did not respect the guideline.

In R3, water samples taken at the PE had median WQI of 79.3. The receiving stream also had a good quality (WQI >79), whether the samples were taken downstream (R3-WD) or upstream (R3-WU) of the point of discharge of the drained water (sampling point R3-PE-4). In all sampled sites, the pH guideline of Method 1 is never respected. For the PE sites, 2% of SS measurements exceed its corresponding guideline.

Comparison between water quality of harvested peatlands and of reference watercourses

Figure 3 presents the boxplots of WQI values in reference streams and in harvested peatlands for each region with Method 1. For the sites in the harvested peatland in the region R3, like regions R1 and R2, only results of WQI for water sampled at sedimentation pond outlets are presented.

In R1, water sampled in the harvested peatland was of fair quality (median WQI = 69.2) compared to streams which had a water quality that varied from fair to excellent, with a median WQI of 85.5. The WMW test shows that there is a significant difference in the distribution of WQI values between harvested peatland and streams with a *p*-value of 0.031, on the assumption that WQI values obtained with the small sample size for the harvested peatland in R1 are representative of the quality of the water coming out of the

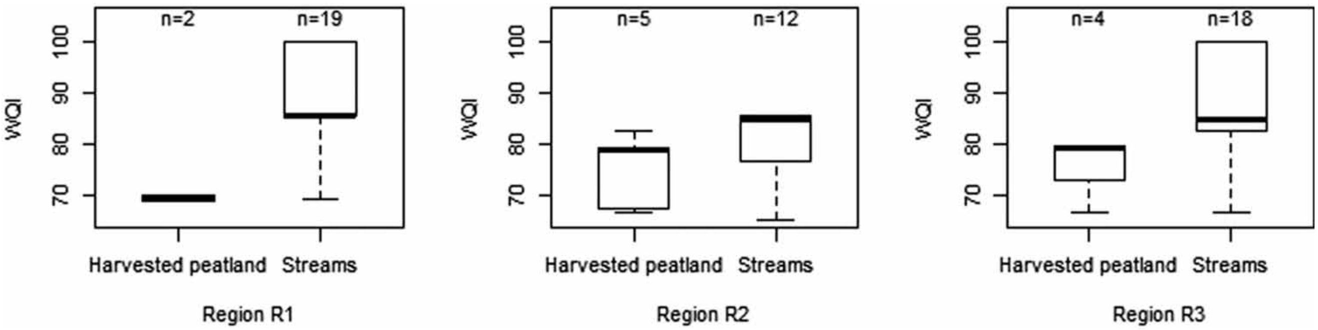

Figure 3 | Variation of WQI values obtained with Method 1 in harvested peatlands and in reference streams for R1, R2 and R3.

sedimentation pond. In streams, conductivity and SS are the variables that negatively affect the WQI (7% and 4% of measurements, respectively) compared to water sampled in the harvested peatland, in which pH (45% measurements) and N-NH_3 (18% of measurements) are responsible for the fair water quality.

In R2, the WQI median in harvested peatlands is 79.0 with a quality varying from fair to good. The same observation was made in the streams, which had a median WQI of 84.9. The WMW test shows a non-significant difference between the distribution of WQI values in harvested peatlands and streams ($p = 0.064$). In harvested peatlands, pH and conductivity negatively affect the WQI (respectively, 90% and 7% of measurements failed to meet the guideline). In streams, pH, SS and conductivity, with respectively 19%, 7% and 7% of measurements not meeting the guidelines, are the variables that lowered the WQI values.

In R3, the median WQI in peatlands is 79.3 and the water quality is generally fair, while in streams, the water quality varies from fair to excellent with a median WQI of 84.8. The WMW test shows a significant difference between the distribution of WQI values in harvested peatland and streams with a p-value of 0.023. The physico-chemical parameters that affect the WQI in the harvested peatlands are pH and SS. In streams, pH, SS and conductivity negatively impact the WQI. In harvested peatlands, 100% of pH measurements and 2% of SS measurements do not respect their corresponding guidelines. In the streams, 2% of pH measurements, 16% of SS measurements and 5% of conductivity measurements exceed their corresponding guidelines.

Comparison between WQI values of Methods 1 and 2

It should be recalled that Method 2 differs from Method 1 by the pH guideline. In Method 1, the guideline used was that of the CCME, while in Method 2, a specific objective was calculated for each region (RSO) using water chemistry data from natural peatlands. Figure 4 shows boxplots of WQI values obtained with Method 2 in the harvested peatlands and in the reference streams. For the region R3, only results of WQI for water sampled at sedimentation pond exit are also presented.

In R1 (Figures 3 and 4), for the harvested peatland, the Mann–Whitney pairwise test shows that the difference is not

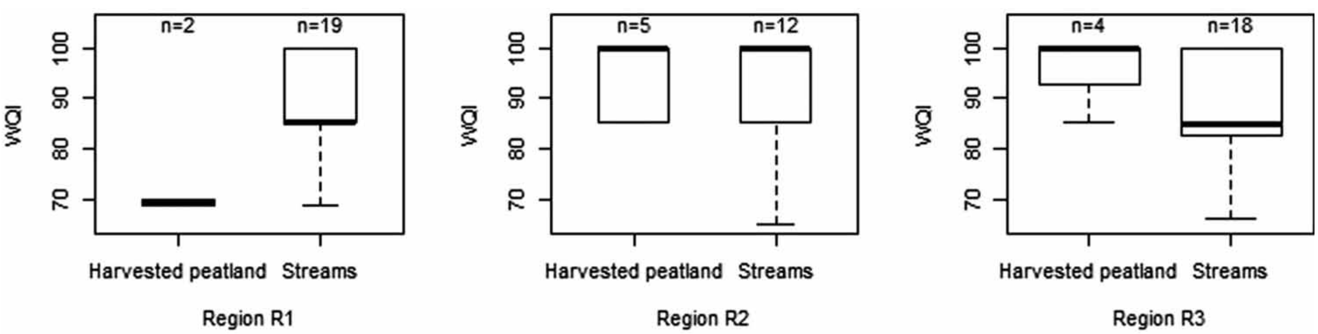

Figure 4 | Variation of WQI values obtained with Method 2 in harvested peatlands and in reference streams for R1, R2 and R3.

significant between results of WQI obtained from the two methods (p-value = 0.667). With Method 2, the water quality remains fair with a median WQI of 69.4. Furthermore, the pH is still negatively affecting the WQI in addition to N-NH_3. For the streams, pH did not have a notable impact on the WQI value, and there are no significant differences between results of both methods (p-value = 1.000). The variation of the WQI values in R1 remains the same with a median WQI of 85.5.

In R2 (Figures 3 and 4), for the harvested peatlands, the Mann–Whitney pairwise test shows a significant difference between WQI calculated using Methods 1 and 2 (p-value = 0.003). With Method 2, the water quality varied from good to excellent with a median WQI of 100 (3 values out of 5 are of 100); the conductivity is the only parameter that affects the WQI. For the streams, the WQIs obtained with Method 1 are significantly different from those obtained with Method 2 (p-value = 0.005). With Method 2, the water quality varies from good to excellent in the majority with a median WQI of 100 (7 values out of 12 are 100), and the parameters that affect the WQI are SS and conductivity.

In R3 (Figures 3 and 4), for the harvested peatlands, the difference is significant between the two methods (p-value = 0.003). With Method 2, the water quality varies from good to excellent with a median WQI of 100 (3 values out of 4 are 100). The SS parameter is the only one that has measurements not respecting the guideline. For the streams, results of WQI obtained with Method 1 are not significantly different from results obtained with Method 2 (p-value = 0.641). With Method 2, pH is not a parameter that affected the WQI value (median = 85.1) and water quality varies from fair to good.

For Method 2, the comparison of WQI values obtained for the water sampled in the harvested peatlands and in the streams shows a significant difference in R1 (p-value = 0.031) and no significant difference in R2 (p-value = 0.906) and R3 (p-value = 0.103). For R1, the water quality of streams is better than that of the harvested peatland.

DISCUSSION AND CONCLUSIONS

We adapted the CCME WQI to apply it to streams receiving water from harvested peatlands. This was made by selecting relevant physico-chemical parameters based on information obtained from the literature. We then applied this adapted CCME WQI to water samples taken from harvested peatlands and reference streams in three regions of Quebec, Canada. Based on data availability in this study, parameters selected for their relevance in the calculation of the WQI are pH, conductivity, SS and N-NH_3.

The use of this adapted CCME WQI shows that the quality of water in harvested peatlands is less than in reference streams in two of the studied regions (R1 and R3), whereas in the other (R2), no significant difference has been observed. Differences in water quality are mostly caused by pH that failed to meet guidelines and with the additional effect of conductivity, SS and N-NH_3. For the harvested peatlands in the study regions, we can see that the CCME guideline of pH (6.5–9.0) is not respected for most measurements because of the lower pH naturally occurring in peat environments. Considering this characteristic, the use of the pH of threshold values that are specific to peat environments (RSO) resulted in a more environmentally realistic guideline and improved WQI values for R2 and R3. However, care should be taken in the choice of data used for the calculation of the RSO. Here, only data from sampled water in natural peatlands were available. The use of these data have resulted in RSO values that are more lenient in R2 and R3 (pH of 3.7 and 2.7, respectively), leading to a water quality in peatlands ranked as excellent, whereas at pH values less than 5, fish cannot survive (Faurie *et al.* 2011). Considering that the CCME WQI is used here for the protection of aquatic life, the calculated RSO value should be consistent with necessary biological and physico-chemical conditions needed for the survival of aquatic life. Ideally, data from sampled water downstream of natural peatlands could have been used to compute the RSO, but no such data have been found in the literature. The range of values defining the guidelines was calculated using the standard deviation approach based on the limited data available in the literature. In future work, with an augmented database, it will be possible to test for normality and decide whether the parametric standard deviation approach should be replaced by the non-parametric percentile method.

Results obtained for R2 showed the importance of the number of parameters used in the CCME WQI calculation. Having only four parameters makes the index sensitive to changes in a single parameter. Indeed, in the harvested peatland B, pH is the variable that affected the WQI value (WQI = 80.7; 78% of pH data do not meet the guideline), while for the samples in the harvested peatland C, both pH (96% of pH data) and conductivity (7% of conductivity data) lowered the WQI value (WQI = 67.3). This difference of 13.4 points between the two peatlands shows that the WQI value is strongly affected by the number of parameters that do not respect their guidelines when only a few parameters are included in the calculation. As mentioned by the CCME (2016), including only a few parameters gives more importance to each of these parameters. For a better use of the WQI CCME, the CCME recommends to include at least eight parameters in the calculations, which would potentially require an increase in the sampling effort by peat producers. The choice of sampled sites must also be considered; in this study, because of data availability, WQI values of water sampled in harvested peatlands were compared with those of reference streams. It could also be interesting, in future work, to compare the quality of water downstream of harvested peatlands and of water from sedimentation pond with the quality of receiving streams as it was done in R3. In this region, we could see that there is no significant difference between the WQI of water from a sedimentation pond and those from the receiving stream. It, therefore, appears from this analysis that this harvested peatland does not impact the receiving stream quality. However, it must be taken into account that the receiving watercourse is in a wetland area, so the upstream (R3-WU) and downstream (R3-WD) sites may receive water drained from these wetlands, which could explain a lower quality of the water in the upstream site.

Thus, the use of the WQI CCME with our proposed parameters allowed comparing the water quality from harvested peatlands to that of reference streams. This study led to the following recommendations for the use of the WQI CCME for the assessment of water quality from harvested peatlands: (i) the sampling of receiving streams and water from the sedimentation pond which flows into these streams; (ii) the analysis of physico-chemical parameters for the protection of aquatic life such as those listed in Table 2, from which at least eight parameters, weakly correlated, and sampled at least four times per year during three consecutive years should be selected (CCME 2016); (iii) the building of a database of water quality of receiving streams, downstream of natural peatlands and (iv) using Version 2.0 of the WQI calculator will allow to better quantify uncertainty and variability by using confidence intervals calculated in this later version.

ACKNOWLEDGEMENTS

The authors wish to acknowledge the *Fonds de recherche du Québec – Nature et technologies* and the Quebec Horticultural Sphagnum Peat Moss Association for their financial support. They also wish to thank the peat producers who participated in the study by providing access to their site, as well as sharing their water quality data and for their availability to provide information throughout this study.

REFERENCES

Andersen, R., Rochefort, L. & Landry, J. 2011 La chimie des tourbières du Québec: une synthèse de 30 années de données. *Le Naturaliste Canadien* **135** (1), 5–14.

Åström, M., Aaltonen, E.-K. & Koivusaari, J. 2001 Effect of ditching operations on stream-water chemistry in a boreal forested catchment. *Science of The Total Environment* **279** (1–3), 117–129. doi:10.1016/s0048-9697(01)00757-4.

Bilotta, G. S. & Brazier, R. E. 2008 Understanding the influence of suspended solids on water quality and aquatic biota. *Water Research* **42** (12), 2849–2861. doi:10.1016/j.watres.2008.03.018.

Canadian Council of Ministers of the Environment 2003 Canadian Water Quality Guidelines for the protection of aquatic life: guidance on the site-specific application of water quality guidelines in Canada: procedures for deriving numerical water quality objectives. In: Canadian *Environmental Quality Guidelines*, 1999. Canadian Council of Ministers of the Environment, Winnipeg. Available from: http://ceqg-rcqe.ccme.ca/download/en/221 (accessed 15 septembre 2018).

Canadian Council of Ministers of the Environment 2007 A protocol for the derivation of water quality guidelines for the protection of aquatic life 2007. In: Canadian *Environmental Quality Guide*lines, 1999. Canadian Council of Ministers of the Environment, Winnipeg. Available from: http://ceqg-rcqe.ccme.ca/download/en/220 (accessed 15 septembre 2018).

Canadian Council of Ministers of the Environment 2014a *Canadian Environmental Quality Guidelines. Canadian Water Quality Guidelines for the Protection of Aquatic Life.*

Water Quality Index, WQI Calculator 1.2. Available from: http://ceqg-rcqe.ccme.ca/en/index.html#void (accessed 05 juin 2017).

Canadian Council of Ministers of the Environment 2014b *Resources, Canadian Environmental Quality Guidelines*. Available from: https://www.ccme.ca/en/resources/canadian_environmental_quality_guidelines/calculators.html (accessed 17 janvier 2019).

Canadian Council of Ministers of the Environment 2014c *Summary table*. Available from: http://st-ts.ccme.ca/fr/index.html (accessed 20 novembre 2017).

Canadian Council of Ministers of the Environment 2016 Canadian Water Quality Guidelines for the protection of aquatic life: CCME water quality index, user's manual – 2017 update. In: *Canadian Environmental Quality Guidelines, 1999*. Canadian Council of Ministers of the Environment, Winnipeg. Available from: https://www.ccme.ca/files/Resources/water/water_quality/WQI%20Manual%20EN.pdf (accessed 02 avril 2018).

Canadian Sphagnum Peat Moss Association 2016 *2015 Statistics about Peatland Areas Managed for Horticultural Peat Harvesting in Canada*. CSPMA. Available from: http://tourbehorticole.com/la-tourbe-en-chiffres/ (accessed 20 septembre 2018).

Carpenter, J. & Farmer, G. 1981 *Peat Mining: An Initial Assessment of Wetland Impacts and Measures to Mitigate Adverse Effects, PB82-130766*. U.S. Environmental Protection Agency, McLean, Virginia, pp. 20–26.

Clément, M., St-Hilaire, A., Caissie, D., Chiasson, A., Courtenay, S. & Hardie, P. 2009 An evaluation of mitigation measures to reduce impacts of peat harvesting on the aquatic habitat of the East Branch Portage River, New Brunswick, Canada. *Canadian Water Resources Journal* **34** (4), 441–452. doi:10.4296/cwrj3404441.

Comeau, P. L. & Bellamy, D. J. 1986 An ecological interpretation of the chemistry of mire waters from selected sites in eastern Canada. *Canadian Journal of Botany* **64** (11), 2576–2581. doi:10.1139/b86-340.

Environnement et Changement climatique Canada 2017 *Indicateurs canadiens de durabilité de l'environnement: Qualité de l'eau des cours d'eau canadiens (Canadian Environmental Sustainability Indicators: Canadian Watercourse Water Quality)*. Available from: http://www.ec.gc.ca/indicateurs-indicators/default.asp?lang=Fr&n=68DE8F72-1

Faurie, C., Ferra, C., Médori, P., Dévaux, J. & Hemptinne, J.-L. 2011 *Ecologie: Approche Scientifique et Pratique (Ecology: Scientific and Practical Approach)*, 6ème edn. Tec & Doc, Paris, France.

Ferland, C. & Rochefort, L. 1997 Restoration techniques for sphagnum-dominated peatlands. *Canadian Journal of Botany* **75** (7), 1110–1118. doi:10.1139/b97-122.

Ghasemi, A. & Zahediasl, S. 2012 Normality tests for statistical analysis: a guide for non-statisticians. *International Journal of Endocrinology and Metabolism* **10** (2), 486–489. doi:10.5812/ijem.3505.

Glaser, P. H. 1992 Raised bogs in Eastern North America – regional controls for species richness and floristic assemblages. *Journal of Ecology* **80** (3), 535–554. doi:10.2307/2260697.

Holden, J., Chapman, P., Lane, S., Brookes, C. 2006 Impacts of artificial drainage of peatlands on runoff production and water quality. In: *Peatlands: Evolution and Records of Environmental and Climate Changes* (Processes, Developments in Earth Surface eds), Elsevier Science, Amsterdam, pp. 501–528.

Khan, F., Husain, T. & Lumb, A. 2003 Water quality evaluation and trend analysis in selected watersheds of the Atlantic region of Canada. *Environmental Monitoring and Assessment* **88** (1/3), 221–248. doi:10.1023/a:1025573108513.

Khan, A. A., Paterson, R. & Khan, H. 2004 Modification and application of the Canadian Council of Ministers of the Environment Water Quality Index (CCME WQI) for the communication of drinking water quality data in Newfoundland and Labrador. *Water Quality Research Journal* **39** (3), 285–293. doi:10.2166/wqrj.2004.039.

Khan, A. A., Tobin, A., Paterson, R., Khan, H. & Warren, R. 2005 Application of CCME procedures for deriving site-specific water quality guidelines for the CCME water quality index. *Water Quality Research Journal* **40** (4), 448–456. doi:10.2166/wqrj.2005.047.

Kløve, B. 2001 Characteristics of nitrogen and phosphorus loads in peat mining wastewater. *Water Research* **35** (10), 2353–2362. doi:10.1016/s0043-1354(00)00531-5.

Lumb, A., Halliwell, D. & Sharma, T. 2006 Application of CCME water quality index to monitor water quality: a case study of the Mackenzie River Basin, Canada. *Environmental Monitoring and Assessment* **113** (1–3), 411–429. doi:10.1007/s10661-005-9092-6.

Lumb, A., Sharma, T., Bibeault, J.-F. & Klawunn, P. 2011 A comparative study of USA and Canadian water quality index models. *Water Quality, Exposure and Health* **3** (3–4), 203–216.

Ministère de l'environnement et de la lutte contre les changements climatiques (MELCC) 2017 *Banque de données sur la qualité du milieu aquatique (BQMA) (Aquatic Quality Database)*. Available from: http://www.mddelcc.gouv.qc.ca/eau/Atlas_interactif/stations/stations_rivieres.asp (accessed 01 novembre 2018).

Ministère de l'environnement et de la lutte contre les changements climatiques 2018 *Suivi de la qualité des rivières et petits cours d'eau (Monitoring of the Quality of Streams and Small Watercourses)*. Available from: http://www.environnement.gouv.qc.ca/eau/eco_aqua/rivieres/annexes.htm (accessed 05 novembre 2018).

Moore, T. R. 1987 A preliminary study of the effects of drainage and harvesting on water quality in ombrotrophic bogs near Sept-Iles, Quebec. *Journal of the American Water Resources Association* **23** (5), 785–791. doi:10.1111/j.1752-1688.1987.tb02953.x.

Moore, T. R. 2001 *Les processus biogéochimiques liés au carbone, Écologie des tourbières du Québec-Labrador (Carbon-Related*

Biogeochemical Processes, Quebec-Labrador Peatland Ecology). Les presses de l'Université Laval, Ste-Foy, Québec, pp. 183–196.

Morrison, G., Fatoki, O. S., Persson, L. & Ekberg, A. 2001 Assessment of the impact of point source pollution from the Keiskammahoek Sewage Treatment Plant on the Keiskamma River – pH, electrical conductivity, oxygen-demanding substance (COD) and nutrients. *Water SA* **27** (4). doi:10.4314/wsa.v27i4.4960.

Papoulias, D. M. & Velasco, A. L. 2013 Histopathological analysis of fish from Acorn Fork Creek, Kentucky, exposed to hydraulic fracturing fluid releases. *Southeastern Naturalist* **12** (sp4). doi:10.1656/058.012.s413.

Pavey, B., Saint-Hilaire, A., Courtenay, S., Ouarda, T. & Bobée, B. 2007 Exploratory study of suspended sediment concentrations downstream of harvested peat bogs. *Environmental Monitoring and Assessment* **135** (1–3), 369–382. doi:10.1007/s10661-007-9656-8.

Payette, S. 2001 *Les principaux types de tourbières, Écologie des tourbières du Québec-Labrador (The Main Types of Peatlands, Peatland Ecology of Quebec-Labrador)*. Les Presses de l'Université Laval, Ste-Foy, Québec, pp. 39–90.

Rosemond, S., Duro, D. C. & Dube, M. 2009 Comparative analysis of regional water quality in Canada using the water quality index. *Environmental Monitoring and Assessment* **156** (1–4), 223–240. doi:10.1007/s10661-008-0480-6.

Rosenthal, J. A. 2011 *Statistics and Data Interpretation for Social Work*, 1st edn. Springer Publishing Company, New York, NY.

Scheili, A., Rodriguez, M. J. & Sadiq, R. 2015 Development, application, and sensitivity analysis of a water quality index for drinking water management in small systems. *Environmental Monitoring and Assessment* **187** (11), 685. doi:10.1007/s10661-015-4908-5.

St-Hilaire, A., Brun, G., Courtenay, S. C., Ouarda, T. B. M. J., Boghen, A. D. & Bobée, B. 2004 Multivariate analysis of water quality in the Richibucto drainage basin (New Brunswick, Canada). *Journal of the American Water Resources Association* **40** (3), 691–703. doi:10.1111/j.1752-1688.2004.tb04453.x.

Surette, C., Brun, G. L. & Mallet, V. N. 2002 Impact of a commercial peat moss operation on water quality and biota in a small tributary of the Richibucto River, Kent County, New Brunswick, Canada. *Archives of Environmental Contamination and Toxicology* **42** (4), 423–430. doi:10.1007/s00244-001-0043-0.

Tarnocai, C., Kettles, I. M. & Lacelle, B. 2011 *Peatlands of Canada*. Geological Survey of Canada, Open File 6561, (map, scale 1:6 500 000). Available from: http://www.hww.ca/assets/images/where-they-live/peatlands/peatlands-of-canada.pdf (accessed 10 octobre 2018).

Wallage, Z. E., Holden, J. & McDonald, A. T. 2006 Drain blocking: an effective treatment for reducing dissolved organic carbon loss and water discolouration in a drained peatland. *Science of The Total Environment* **367** (2–3), 811–821. doi:10.1016/j.scitotenv.2006.02.010.

Wind-Mulder, H. L., Rochefort, L. & Vitt, D. H. 1996 Water and peat chemistry comparisons of natural and post-harvested peatlands across Canada and their relevance to peatland restoration. *Ecological Engineering* **7** (3), 161–181. doi:10.1016/0925-8574(96)00004-3.

First received 30 April 2019; accepted in revised form 4 February 2020. Available online 9 March 2020