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Exploratory study of suspended sediment concentrations downstream of harvested peat bogs

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Abstract Peat bog harvesting is an important industry in many countries, including Canada. To harvest peat, bogs are drained and drainage water is evacuated towards neighboring rivers, estuaries or coastal waters. High suspended sediment concentrations (SSC) were found in the drainage water at one particular site during the 2001–2002 spring seasons in New Brunswick (Canada). The main objective of this study was to verify this observation at other sites, compare SSC levels leaving harvested peat bogs with those leaving an unharvested bog, and to determine if high SSC events happen only in Spring or all year round. Suspended sediment concentrations were monitored downstream of three harvested peat bogs and an unharvested reference bog located in New Brunswick during the ice free seasons of 2003–2004. On average, SSC at the harvested sites exceeded 25 mg/l, which is the recommended daily maximum concentration, 72% of the time, while the same concentration was exceeded 30% of the time at the unharvested sites. SSC were found to be significantly higher at harvested sites than at the reference sites for all seasons. The highest SSC medians were recorded in the Fall but SSC was elevated in all seasons. High SSC levels in receiving waters may be caused by field ditching activities and insufficient sediment controls. Findings suggest the NB Peat Harvesting 25 mg/l SSC guideline should be reviewed.

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Introduction

Peatlands ecosystems are widespread in the Northern Hemisphere. In Canada, peatlands cover 11% of the country's surface area (approximately 113 million ha) and comprise over 75% of Canada's 148 million ha of wetland area. The primary vegetation in ombrotrophic (rain-fed) peat bogs is *Sphagnum* moss, a product that is commercially extracted and sold due to its water retention capacity, desirable in the horticultural industry. Canada is the first producer of horticultural peat in the world. In 2003 and 2004, peat shipments in the province of New Brunswick (NB), which produces approximately 30% of Canadian peat, were valued at $CDN 95 million and $CDN 103 million respectively (Thibault 2006).

Modern peat harvesting is performed using industrial vacuums which require that the top layer of peat be dry. Drainage ditches are dug around and through the prospective harvesting area. As a result, the water level in the bog decreases and drainage water is evacuated via this network of ditches to a neighboring water body (stream, river or coastal area). In many instances, water is first routed through a sedimentation pond prior to its release into a nearby water course. These ponds are designed for the purpose of retaining peat and clay particles suspended in the drainage water.

Peat mining can cause changes in both the quantity and quality of runoff water (Selin and Koskinen 1988; Heikkinen 1990; Ihme et al. 1991; Kløve 2000). Direct environmental effects of peat bog harvesting may include: changes to the quality and quantity of drainage water; irreversible changes to the structure of peat, leading to diminished storage capacity and leaching of organic matter and nutrients (Gregory et al. 1984; Johansson and Olofsson 1985; Olsson 1985; Schlotzhauer and Price 1999; Kløve 2000; Bragg and Tallis 2001).

Regulations associated with peat mining vary by jurisdiction. In New Brunswick, the provincial guidelines recommend the use of sedimentation ponds and stipulate that suspended sediment concentrations downstream of the ponds should not exceed 25 mg/l (Thibault 2001). Some of the older harvesting operations retrofitted their drainage system with sedimentation ponds after the guidelines were promulgated in the early 1990s.

One such peat operation, located in the southeastern part of the province was the site of an important study initiated in 1994, after a large peat deposit was observed, in an estuarine tributary of the Richibucto River named Mill Creek. During the first 9 years of harvesting (1985–1994), drainage water from this site emptied directly into Malpec Brook, which drains into Mill Creek. The peat deposit covered a surface area of 0.9–1.0 ha and was exposed at low tide, with thickness exceeding 500 cm in many points (MGI Limited 1994; Brylinsky 1995). It was rapidly concluded that the peat originated from a peat harvesting site draining into Malpec Brook (MGI Limited 1994). Furthermore, Ouellette et al. (2006) found that the proportion of peat (in volume) in the surficial sediment layer (0–15 cm) in Mill Creek increased from 30% in 1997 to 76% in 1999. Subsequently, St-Hilaire et al. (2006) monitored turbidity during the spring season of 2001 and 2002 in Malpec Brook. They found that the 25 mg/L provincial guideline was exceeded 53.6% of the time in 2001 and 86.0% of the time in 2002 at their upstream site.

Questions remaining after these two studies include the following: Are the high SSC events found by St-Hilaire et al. (2006) specific to the Malpec location or are high suspended concentrations observed in other harvested bogs?; Is high SSC simply related to the spring flood or can we observe this problem year-round? Lastly, what SSC levels would be observed in an unperturbed system (i.e. what levels of SSC are observed downstream of unharvested bogs?).

The present study was designed to answer those questions. Its main objective was to compare SSC levels at three harvested bogs and one unharvested, reference bog. In addition, harvested sites were compared with each other to determine if operational or physical differences influence suspended sediment concentrations. The specific objectives of this study were to:

(1) Determine the magnitude and variability of suspended sediment concentration emanating from three separate harvested bogs and compare them to the SSC exiting an unharvested reference site;
(2) Determine how often and when the NB Peat Harvesting 25 mg/l SSC guideline is exceeded;
(3) Compare harvested sites and determine which variables (meteorological, hydrometric or operational) may explain the observed exceedances.

Study site and methods

Study site

To achieve these objectives, turbidity was monitored continually at five sites in the central and eastern part of the province of New Brunswick (Canada) during 2003 and 2004 (Fig. 1). The climate of New Brunswick is classified as mid-latitude continental with a yearly temperature range of 31°C (Phillips

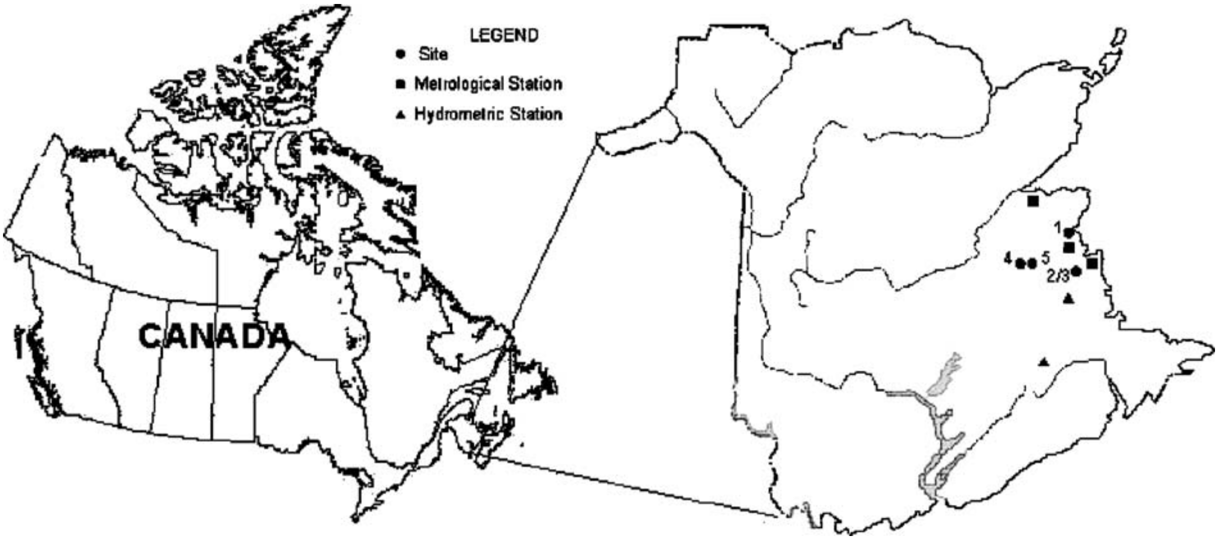


Fig. 1 Map of study locations, meteorological stations and hydrometric stations used during the study

1990). The 65-year mean total annual precipitation in the area is 817.5 mm, with nearly a third falling as snow.

Sites 1a and 1b, located in Kouchibouguac National Park, served as unharvested reference sites. Site 2 and 3 were located downstream of a harvested bog in the St. Charles Plain located a few kilometers north of Rexton and correspond to the study sites used by St-Hilaire et al. (2006). Sites 4 and 5 were located approximately 70 km west of Sites 2 and 3, near Rogersville on two separate harvested bogs.

Table 1 Summary of monitoring site characteristics

Site characteristics	Unharvested		Harvested		
	Site 1a	Site 1b	Site 2, Site 3[a]	Site 4	Site 5
GPS coordinates	46.5046N, 64.5950W	46.8139N, 64.9391W	(2): 46.63881N, 64.91888W (3): 46.63718N, 64.91891W	46.71217N, 65.58912W	46.70453N, 65.41693W
Elevation (m)	9.4	16	(2): 28 (3): 13	16	88
Total bog area (ha)	84	204	367	202	360
Harvested/cleared area (ha)	0	0	232	82	199
Total area being drained into studied sedimentation ponds (ha)	41	100	175	52	105
Sedimentation pond volume (m^3)	na	na	5,478[b]	2280	2,160[c] 6,048[d]
Ratio: drainage area to pond volume (m^2/m^3)	na	na	319	228	174[e]
Number of harvest years (in 2003)	0	0	23	2	10
Number of peat collection days (2003)	na	na	26	46	46
Number of peat collection days (2004)	na	na	43	60	60

na not applicable.

[a] Site 3 is downstream from Site 2.

[b] Combined volume of three ponds all draining into Sites 2 and 3.

[c] Size of pond in spring 2003.

[d] Size of pond for remainder of study period, Fall 2003 and 2004.

[e] Larger pond size was used in calculation.

Site 1a was located on an unnamed bog that partly drains into a forested area near Black River. In October 2003, a new reference site, Site 1b, was selected. The sensor was placed in a narrow stream exiting Rankin bog towards Black River. Site 1b was selected because it is more similar in size and drainage pattern to the harvested sites (Table 1). Data from Site 1a were used for spring 2003 and data from Site 1b were used for Fall 2003.

Sites 2 and 3 were located downstream of the harvested bog on the St. Charles Plain, a 19.3 km^2 wetland. Peat has been extracted since 1985, the longest operating period of the sites studied. More specifically, Site 2 was located in Malpec Brook at the downstream confluence of the drainage system that combines the discharge from three sedimentation ponds. Site 3 was located 500 m downstream of Site 2 in Malpec Brook. This was the only location that permitted the installation of two stations. At Site 4, a major beaver dam located near the confluence of the drainage ditch and the stream precluded accurate SSC sampling and Site 5 was located in a long drainage ditch that flowed into a roadside ditch prior to emptying into a nearby river.

Site 4 was located on a 202 ha peat bog of which 82 ha was being harvested. Site 5 was located on a second bog near Rogersville, with an area of 360 ha, of which 199 ha was being harvested. The equipment at both Site 4 and Site 5 was located 50 m downstream of the sedimentation pond. At Site 5, the sedimentation pond was enlarged from 2,160 m^3 during the Summer 2003 to its current size of 6,048 m^3. Table 1 summarizes the characteristics of each monitoring site in more detail.

Field methods

One Optical backscatterometer (OBS-3; D&A Instruments, Port Townsend, WA), also called a nephelometer, was deployed at each site to continuously monitor turbidity from early spring, just prior to snowmelt, until late Fall (late November or early December, Table 2). Turbidity is an indirect measurement of SSC that depends on the optical properties of substances that cause light to be scattered and absorbed rather than transmitted in straight lines through water (Wetzel 1975). Specifically, the OBS-3 measures the deflection of incident radiation from particles scattered between 90 and 180° angles (back scattering) from a beam axis. Each OBS-3 was mounted on a purpose-built metal cage anchored to the stream bed that positioned the OBS-3 in the middle of the water column and prevented it from moving during high flow events. The instruments and dataloggers were powered by a 12 V battery receiving power from a south facing solar panel or two 6 V batteries in series housed in a weather-resistant box. Dataloggers (Campbell Scientific CR510 or CR10) recorded a voltage proportional to turbidity. The probes were set at 15 s scanning intervals with 5 min, hourly and daily averages (in millivolts) outputted to the attached datalogger. The voltages were then converted to SSC (mgl^{-1}) using calibration curves described below. Deployment periods are summarized in Table 2.

Site visits were made weekly during which data were downloaded, probes were checked and cleaned. Biological fouling and occlusion of the OBS optical plate were recorded. Site visits were charted with SSC measurements and if SSC dropped shortly after the field visit (during which the OBS was cleaned), the preceding high SSC days were considered erroneous. Data affected by this type of fouling were eliminated from the data set. In 2004, 18 of 227 days at Site 5 were eliminated as a result of fouling.

In other cases, data were not included in the analysis due to equipment failure or dry conditions which lowered the water level below that of the OBS.

Table 2 Dates equipment was deployed and collected

	Season	Site 1	Site 2	Site 3	Site 4	Site 5
Date deployed	Spring 2003	22-Apr-03	17-Apr-03	17-Apr-03	No data	17-Apr-03
Date collected	Spring 2003	20-Jun-03	20-Jun-03	20-Jun-03	No data	26-Jun-03
Date deployed	Fall 2003	3-Oct-03	01-Oct-03	07-Nov-03	07-Oct-03	04-Oct-03
Date collected	Fall 2003	26-Nov-03	26-Nov-03	26-Nov-03	01-Dec-03	18-Dec-03
Date deployed	2004	21-Apr-04	14-Apr-04	15-Apr-04	16-Apr-04	16-Apr-04
Date collected	2004	29-Sep-04	29-Nov-04	29-Nov-04	15-Nov-04	01-Dec-04

Table 3 Number of days with recorded SSC at each site in 2003 and 2004

	Site 1 (ref)	Site 2	Site 3	Site 4	Site 5
Spring 2003	60	0[b]	65	0	71
Fall 2003	49	0[b]	20	56	76
Spring 2004	36	69	49[c]	67	67
Summer 2004	23[a]	58	80	93	93
Fall 2004	0[b]	63	67	54	67

[a] Only 16 days were concomitant with all harvested sites thus this season was not included in the comparative analysis.

[b] Erratic outputs, equipment failure.

[c] Only 21 concomitant with the reference site thus this site was not included in the comparative analysis.

Equipment failure and fouling resulted in a limited (59 days) quantity of useful data at Site 1b in 2004 (Table 3).

OBS sensor response depends on grain size, sediment type, water colour, light source and optical geometry (Lewis 1996). In situ calibration was necessary due to the unique sediment and water characteristics found at each site. To obtain SSC from the voltage readings, each OBS was calibrated by mixing a volume of ditch or brook water with a quantity of stream-bottom sediment (composed mostly of peat and clay particles) in a 20 l bucket. For a given concentration, a voltage reading was obtained from the OBS and five 1 l grab samples were collected for each reading. The amount of sediment in the bucket was increased incrementally to cover the observed range of voltage readings. Overall 128 samples were used to establish the calibration curves (n=18, 32, 24, 31, 23 points for Sites 1,2,3,4 and 5 respectively).

In the laboratory, each 1 l sample was filtered through a Whatman GF/C 100 mm filter paper (1.2 μm pore size). The filtrate was oven-dried at 70°C for 24 h and then weighed. The net weight was divided by the filtered volume (usually 1 l, except for very high concentrations where a smaller volume >200 ml was used) to obtain SSC in milligrams per litre.

Daily precipitation and air temperature data for the study period were obtained from Environment Canada meteorological stations (http://www.climate.weather-office.ec.gc.ca/prods_servs/cdcd_iso_e.html, see Fig. 1 for locations). Stations used were: Kouchibouguac CS (station 8102328, 46°46′N, 65°9′W) for Site 1; Rexton (station 8104400, lat 45°49′N, long 64°52′W) for Sites 2 and 3; and Miramichi A (station 8101000, 47°9′N, 65°28′W) for Site 4 and 5.

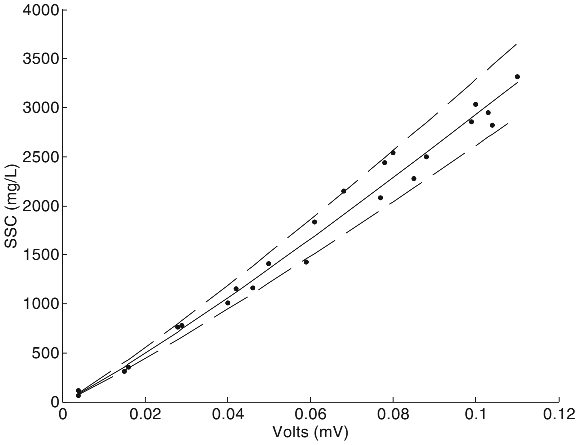


Fig. 2 Example of a calibration curve relating SSC to voltage recorded by the nephelometer at Site 5. The *dotted lines* indicate the 95% confidence intervals. The equation for this example is: SSC=$e^{10.538}(V+0)^{1.1098}$. The n and R^2 are listed in Table 4

Instantaneous discharge measurements were taken during each visit except when prohibited by shallow water conditions (less than 3 cm) using a Marsh McBirney electromagnetic flow meter (Flo-Mate model 2000).

Statistical analysis

Calibration

DC voltage output from each OBS-3 were related to measured SSC from the associated samples using a geometric power function of the form:

$$\mathrm{SSC} = e^{a}(V+b)^{c} \tag{1}$$

Where, a, b and c are the estimated coefficients and V is the recorded Voltage signal (mV). An

Table 4 Table of calibration curve coefficients for each study site

Site	n	R^2	a	b	c
1	19	0.937	10.9447	0	1.051
2	33	0.965	10.0962	0.038	1.057
3	24	0.988	11.6592	0	1.517
4	32	0.882	7.3607	0	0.901
5	24	0.988	10.538	0	1.1098

R^2 and sample size (n) are also listed.

example of Eq. 1 fitted to the samples taken at Site 5 is given in Fig. 2. Table 4 lists the coefficients used for each site. Calibration uncertainty is quantified using 95% confidence intervals. For instance, a 0.041 V OBS reading located at Site 5 would correspond to a SSC of 1089.1±127.6 mg/l.

Because continuous discharge time series were unavailable for the study sites, discharges were estimated from the relationships of the instantaneous discharges measured during site visits to daily discharges at the closest hydrometric stations. For Sites 2 and 3, discharge data were transferred from the only hydrometric station located within the Richibucto drainage basin (station 01BS001, Coal Branch at Beersville, Environment Canada) using a linear regression between instantaneous discharge measurements taken at Site 3 and daily discharge at station 01BS002. Based on 43 points, a statistically significant ($F=127.28$, $p<0.0001$) regression with a coefficient of determination (R^2) of 0.80 was obtained and the standard error of the estimates (also called root mean square error or RMSE) was 0.03 m^3/s (Fig. 3a).

Site 1 did not correlate to any nearby hydrometric station thus discharge data were not used. The lack of correlation may be related to natural drainage from unaltered ombrotrophic bogs that are not synchronized with flood events that occur in watersheds with little wetland cover (Holden and Burt 2002).

For Sites 4 and 5, discharge was transferred from station 01AP002 (Canaan River, Environment Canada). Twenty instantaneous flow measurements were used to establish the regression at Site 4 ($R^2=0.69$ and RMSE=0.005 m^3/s; Fig. 3b). Site 5 regression was based on 31 points with a resulting R^2 of 0.83 and a RMSE of 0.061 m^3/s (Fig. 3c). Despite the relatively low number of instantaneous discharge measurements at sites 4 and 5, the regressions were found to be statistically significant ($F=40.737$ and $F=96.264$, $p<0.0001$ respectively). As always when applying a linear regression, extrapolation of Fig. 3 should be done with caution, as there is no guarantee that the relationships remain linear for higher flows.

Examining threshold exceedences

As mentioned, the NB SSC harvesting guideline of 25 mg/l was used as a threshold and the numbers of days for which this threshold was exceeded were compared for harvested and reference sites. Higher thresholds (50, 100, 150, 200, 300, 500, 1,000 and 2,000 mg/l) were also of interest because these concentrations are known to harm or stress local fish such as brook trout (*Salvelinus fontinalis*), white perch (*Morone americana*) and striped bass (*Morone saxatilis*) (St-Hilaire et al. 2006). The number of exceedances of each threshold was calculated using daily means. Only days during which data were collected at all sites were used. Percent exceedance was calculated using Eq. 2:

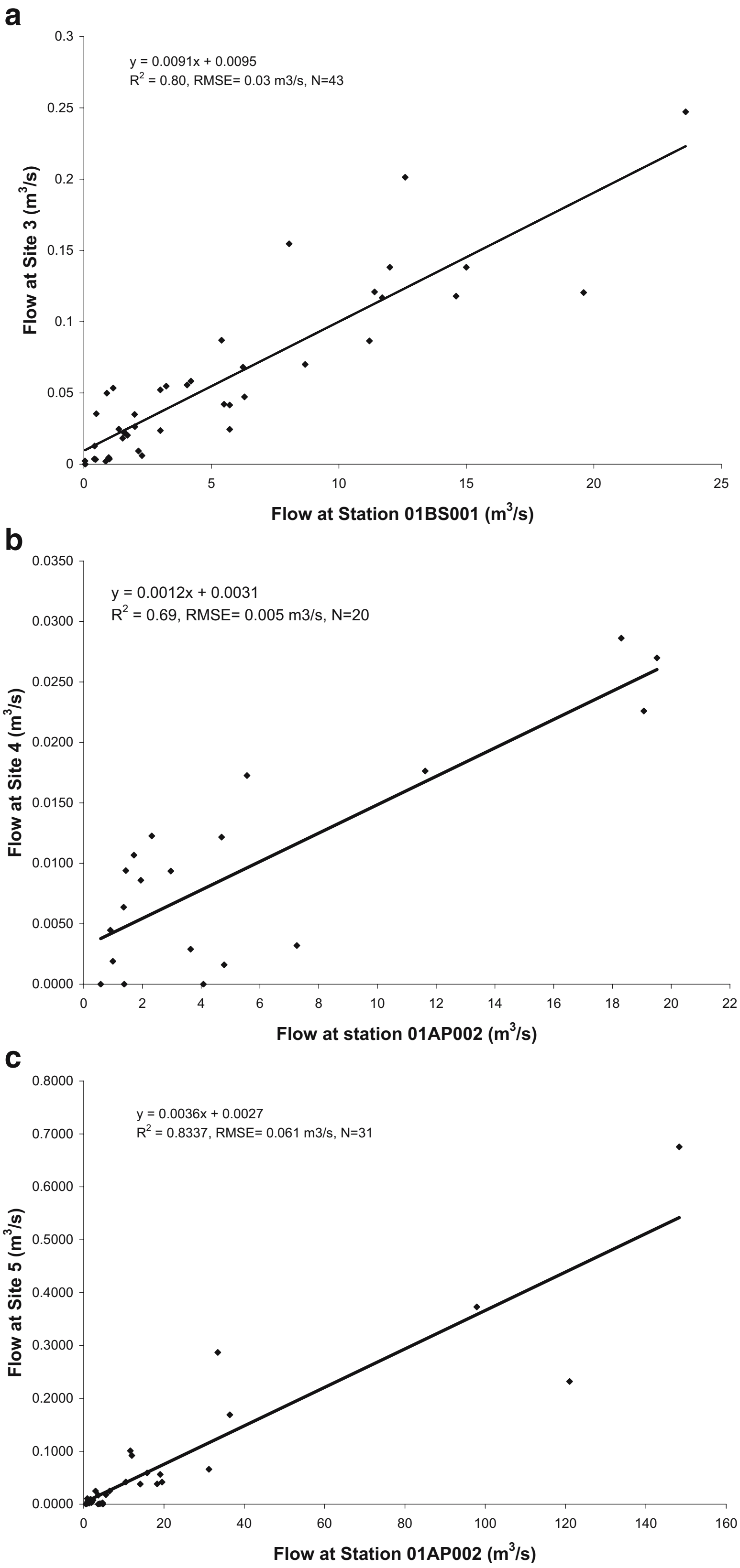
$$\%\,\text{Exceedance} = \frac{\#\text{days threshold exceeded} \times 100}{n} \tag{2}$$

Where n is the total number of days during which data were collected at all five sites in the 2003–2004 period. To determine whether the level of exceedance at the reference site was significantly different from those at the harvested sites, a 95% confidence interval was calculated for the mean percent exceedance of all harvested sites. This confidence interval was calculated using a bootstrap resampling method with 1,000 pseudo-samples (Efron 1979).

Site comparisons

SSC time series were tested for normality using the Shapiro–Wilks test. The variable SSC was non-normally distributed ($W=0.446$–0.857, $p<0.001$) at all sites even when log-transformed. Kruskal–Wallis analyses of variance were therefore used to conduct inter-site comparisons for each year and per season. Post hoc comparisons with the reference site were made with the Mann–Whitney U test. Kruskal–Wallis and Mann–Whitney U are standard tests described in many texts such as Zar (1999). A significance level of 0.05 was used. The same approach was used to compare SSC values between the harvested sites. It was also used to compare seasonal differences between combined SSC at the harvested sites. Seasons were defined as follows: spring, March 20–June 20; Summer, June 21–September 22; Fall, September 23–December 21.

Fig. 3 Linear regression between spot discharge measurements at sampling sites and daily flow from nearby hydrometric stations: **a** Site 3 and Station 1BS001 (representative of both Sites 2 and 3); **b** Site 4 and Station 01AP002; **c** Site 4 and Station 01AP002



Results

Threshold exceedance

Figure 4 shows the percentage of days that the environmentally-relevant SSC thresholds were exceeded. The data presented were calculated using 56 concomitant days between each site in 2003 and 2004. The percentage of exceedance at the unharvested site (1) was less than 30% for the lowest threshold (25 mg/l), while the average exceedance for three harvested sites (2, 4, 5) was 71%. The dotted lines indicate the upper and lower 95% confidence intervals of the SSC mean of the four harvested sites. The percentage of time that each threshold was exceeded at the reference site was below the lower confidence interval for the harvested sites in all cases. Threshold exceedances were also plotted for each site individually with similar results. Figure 4 illustrates only the combined threshold exceedances for the harvested sites.

Comparison between harvested sites and the reference site

In spring 2003, only three sites were successfully monitored: the unharvested site (1) and harvested sites 3 and 5 (Table 3). SSC medians were significantly different among sites (Table 5). Median SSC in waters leaving harvested bog Site 5, but not Site 3 (located in Malpec Brook), was significantly greater than the reference site (Table 5, Fig. 5).

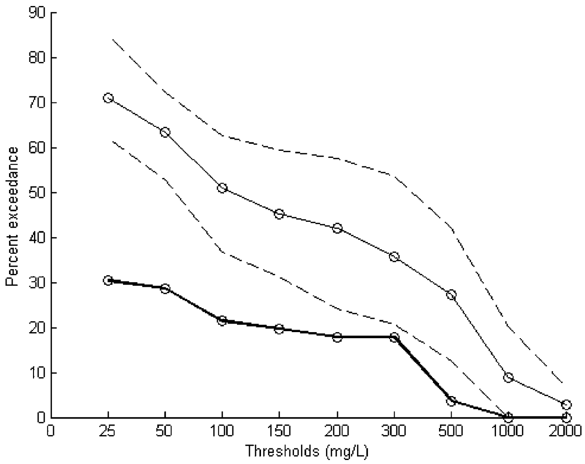


Fig. 4 Percent exceedence of various SSC thresholds. The *thick bottom line* shows the percentage of days of threshold exceedance at reference site. The *upper solid line* shows the mean percentage of threshold exceedance at harvested sites. *Dotted lines* are the 95% confidence intervals on the harvested sites mean percent exceedance

In Fall 2003, Sites 1, 4 and 5 were monitored. Both harvested sites had significantly higher SSC medians than the reference site (Table 5 and Fig. 6). It should be noted however that, although the Site 4 SSC median was significantly greater than the reference site (Table 5), Fall 2003 was the only season during which a harvested site had a median below 25 mg/l (Table 5).

In spring 2004, all harvested sites (Sites 2, 4, 5) had significantly higher SSC medians than the reference site (Table 5 and Fig. 7).The sample size at the reference site (*n*=16) was not large enough in Summer 2004 to compare SSC medians with the harvested sites. In Fall 2004, no data were collected at the reference site (Table 3) (Fig. 8).

Comparison between harvested sites

In 2004, it was possible to compare all harvested sites, as they shared more than 20 concomitant sampling days. Site 2 had the highest SSC median in all seasons of 2004 (Table 6). All sites were set up in drainage ditches except for Site 3. Removing Site 3 from the analysis, the order of SSC medians at the harvested sites is always as follows from highest to lowest: Site 2>Site 4>Site 5 (Table 6, Figs. 8, 9 and 10).

At no time during the ice-free sampling period in 2004 did the seasonal median at any of the harvested sites measure below the NB peat harvesting SSC guideline of 25 mg/l. The 95th percentile, taken as a measure of an extreme event exceeded 1200 mg/l at two of four harvested sites during every season in 2004.

Comparison of SSC at harvested sites (2–5) across seasons in 2004

Suspended sediment concentration data collected in 2004 were pooled across sites and compared between seasons (Fig. 11). The average median of all four harvested sites combined was highest in the Fall (421.18 mg/L) compared to 172.90 mg/l in the spring and 254.80 mg/l in the Summer (Table 7).

Table 5 Precipitation, specific mean discharge, specific max discharge, median SSC, Mann–Whitney U results and Kruskal–Wallis results for all sites

Site	Precipitation[a] (mm)	Specific mean Q[a] (l/s/ha)	Specific max Q[a] (l/s/ha)	Median SSC (mg/l)	MWU vs. Site 1	p
Spring 2003				χ^2=75.17, p<0.001, n=35		
1	156.1	nd	nd	0	na	na
2	138.7	0.554	2.098	nd	nd	nd
3	138.7	0.554	2.098	0	6,040.00	0.894
4	137.2	0.728	2.613	nd	nd	nd
5	137.2	1.03	2.299	213.19	0.00	p<0.001
Fall 2003				χ^2=97.27, p<0.001, n=46		
1	193.8	nd	nd	0	na	na
2	177.9	0.227	1.495	nd	nd	nd
3	177.9	0.227	1.495	nd	nd	nd
4	202.3	0.316	1.811	2.91	539.00	p<0.001
5	202.3	0.419	2.626	81.53	9.00	p<0.001
Spring 2004				χ^2=59.66, p<0.001, n=36		
1	42.1	nd	nd	73.78	na	na
2	86.6	0.104	0.132	763.68	43.00	p<0.001
3	86.6	0.104	0.132	nd	nd	nd
4	55.5	0.114	0.177	523.97	220.00	p<0.001
5	55.5	0.057	0.074	228.02	260.00	p<0.001

Data used to conduct comparisons between the reference site (1) and the harvested sites (2–5).

Q discharge, *MWU* Mann–Whitney U, *na* not applicable, *nd* no data.

[a] Based on concomitant days used for the Kruskal–Wallis and Mann–Whitney U analyses.

Precipitation and flow data

Since heavy rain events and high discharge periods were hypothesized to cause increased SSC, we compared hydro-meteorological conditions between sites. Total seasonal precipitation was quite similar between sites with a few exceptions (see Tables 5 and 6). Tables 5 and 6 show that median SSC does not correlate with total precipitation at the harvested sites. For instance, in the Fall of 2004, Sites 4 and 5, which are located less than 20 km apart, received the same amount of rain. Yet, the SSC median at Site 4 (431 mg/l) is more than five times greater than the median at Site 5 (84 mg/l) (Table 6).

Mean and maximum seasonal specific discharge (i.e. discharge value divided by drained area) is also reported in Tables 5 and 6. The same value is reported for Sites 2 and 3 since they are separated by a relatively short distance and there is less than 10% difference in drained area between the two sites. The highest mean discharge values are those reported for the spring season during which discharge is dominated by snowmelt whereas flow events during Summer and Fall are triggered by rain events. Again, it can be seen that the highest median SSC do not necessarily correspond to the highest mean or maximum specific discharge. For instance, during Spring 2004, the

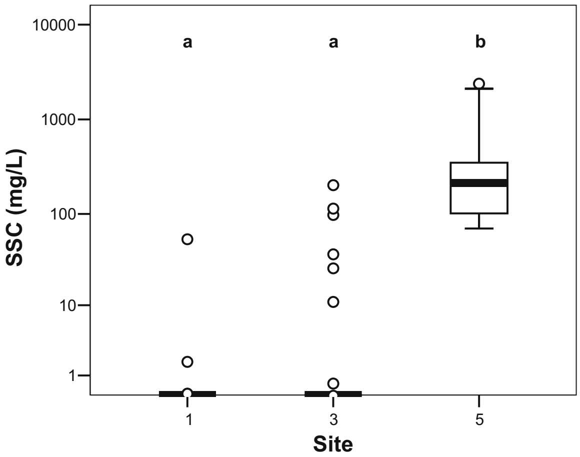


Fig. 5 Spring 2003 Boxplot. The figure shows the median, quartiles and 95th percentile for each site. The *circles* indicate outliers. *Letters* indicate which medians are significantly different based on the Mann–Whitney U statistic reported in Table 5

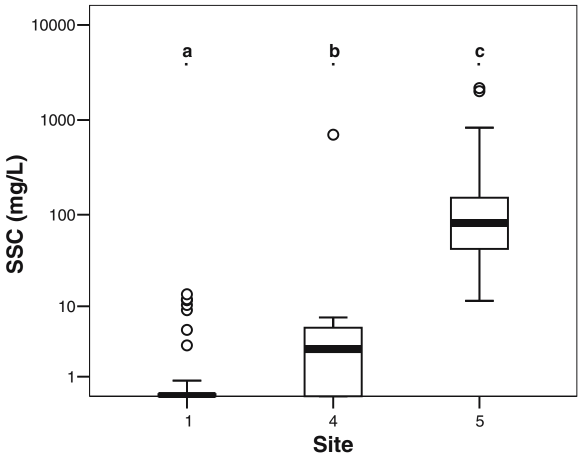


Fig. 6 Fall 2003 Boxplot. The figure shows the median, quartiles and 95th percentile for each site. The *circles* indicate outliers. *Letters* indicate which medians are significantly different based on the Mann–Whitney U statistic reported in Table 5

highest mean (0.436 l/s/ha) and maximum (3.483 l/s/ha) specific discharge were found at Site 4, which had a median SSC of 172.9 mg/l (Table 6). Site 2 had a higher SSC median (775.63 mg/l) with a mean specific discharge of only 0.282 l/s/ha.

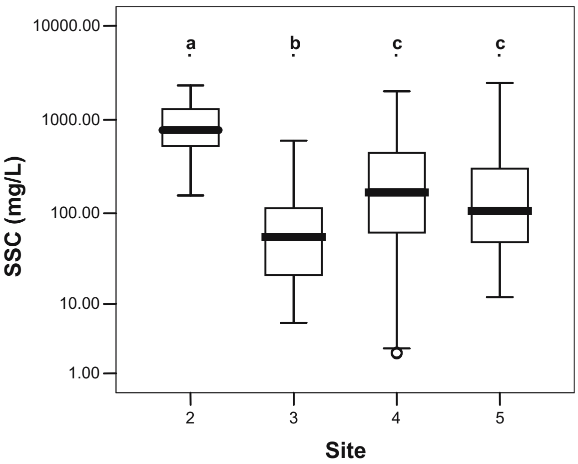


Fig. 8 Spring 2004 Boxplot, Harvested Sites Only. The figure shows the median, quartiles and 95th percentile for each site. The *circle* indicates an outlier. *Letters* indicate which medians are significantly different based on the Mann–Whitney U statistic reported in Table 6

Discussion

Suspended sediments can have significant negative effects on aquatic biota including damaging salmonid spawning sites, abrasion and damage to fish gills, scouring of periphyton from the stream bottom, reduced light penetration and adverse impacts on aquatic insects (Schuler 2000). This study found that harvested peat moss bogs regularly exceed the 25 mg/l guideline for SSC in drainage water. Figure 4 illustrates two important points: (1) The NB provincial guideline for SSC in waters draining peat bogs (25 mg/l) is exceeded 30% of the time at the unharvested reference sites which may indicate that the current guideline is unrealistically low; and (2) Overall, harvested bogs

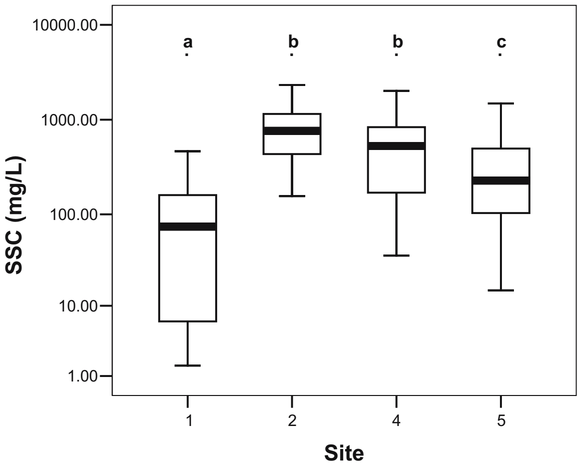


Fig. 7 Spring 2004 Boxplot. The figure shows the median, quartiles and 95th percentile for each site. The *circles* indicate outliers. *Letters* indicate which medians are significantly different based on the Mann–Whitney U statistic reported in Table 5

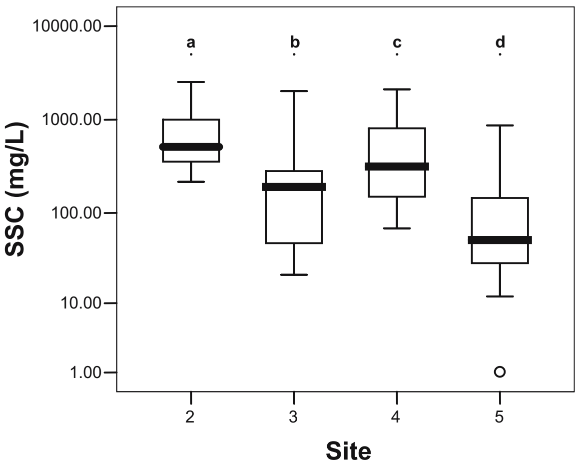


Fig. 9 Summer 2004 Boxplot, Harvested Sites Only. The figure shows the median, quartiles and 95th percentile for each site. The *circle* indicates an outlier. *Letters* indicate which medians are significantly different based on the Mann-Whitney U statistic reported in Table 6

Table 6 Precipitation, specific mean discharge, specific max discharge, median SSC, Mann–Whitney U results and Kruskal–Wallis results based on 2004 harvested sites (2–5) data only

Site	Precipitation[a] (mm)	Specific mean Q^a (l/s/ha)	Specific max Q^a (l/s/ha)	Median SSC (mg/l)	MWU vs. 2	*p*	MWU vs. 3	*p*	MWU vs. 4	*p*
Spring 2004					$X^2=85.10$, $p<0.001$, $n=50$					
2	98	0.282	1.833	775.63	na	na				
3	98	0.282	1.833	56.09	48.00	$p<0.001$				
4	112.1	0.436	3.482	172.9	383.00	$p<0.001$	729.00	$p<0.001$		
5	112.1	0.174	1.198	102.71	303.00	$p<0.001$	799.00	0.002	1129.00	0.40
Summer 2004					$X^2=73.10$, $p<0.001$, $n=45$					
2	108	0.113	0.352	511.66	na	na				
3	108	0.113	0.352	190.6	257.00	$p<0.001$				
4	104.6	0.181	1.041	314.85	637.00	0.002	609.00	0.001		
5	104.6	0.065	0.222	51.00	161.00	$p<0.001$	634.00	0.002	287.00	$p<0.001$
Fall 2004					$X^2=77.34$, $p<0.001$, $n=43$					
2	182.3	0.153	0.649	1219.14	na	na				
3	182.3	0.153	0.649	38.76	270.00	$p<0.001$				
4	97.5	0.206	1.041	431.13	174.00	$p<0.001$	465.00	$p<0.001$		
5	97.5	0.094	0.418	83.69	45.00	$p<0.001$	688.00	0.041	481.00	$p<0.001$

Q discharge, *MWU* Mann–Whitney U, *na* not applicable.

[a] Based on concomitant days used for the Kruskal–Wallis and Mann–Whitney U analyses.

produce significantly higher SSC than the reference site and this holds true for any SSC threshold below 1 g/l.

Intersite comparisons carried out by season showed that harvested sites had significantly higher medians than the reference site. The only exception occurred during Spring 2003 when Site 1 and Site 3 were not significantly different. Site 3 was located in a stream 500 m downstream from the outflow ditch and 1,000 m downstream from the sedimentation pond. Possibly, sediment settled somewhere in the 1 km upstream of Site 3. Figure 5 shows, however, that the number of SSC values >25 mg/l was still greater at Site 3 than at Site 1.

When comparing between harvested sites in 2004, the results can be explained, in part, by the ratio of drainage area to sedimentation pond size (Table 1). In all cases, a higher ratio of drainage area to pond size was associated with a higher SSC median (i.e., Site 2&3>4>5). A larger pond may increase the retention time thus allow particles more time to settle out. Further study of sediment retention basins and structures within the Canadian context is needed.

Other factors that may explain SSC differences between sites include the number of years of harvest. On older harvested sites, the surface soil has been compacted and lowered. Older peat operations such as Site 2 (>20 years of operation) will be cultivating deeper, more highly decomposed peat layers that are more friable (Paivanen 1973). This could lead to easier dislodgement of particles when hit by precipitation or moved by the wind. This logic, however, would predict that Site 4, harvested for 2 years at the time of sampling, would have lower SSC levels than

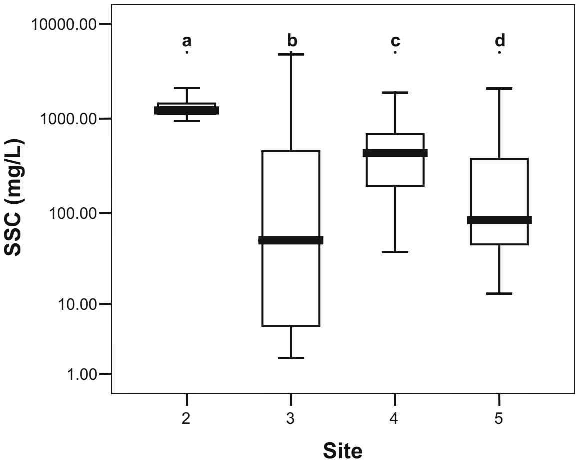


Fig. 10 Fall 2004, Boxplot, Harvested Sites Only. The figure shows the median, quartiles and 95th percentile for each site. *Letters* indicate which medians are significantly different based on the Mann–Whitney U statistic reported in Table 6

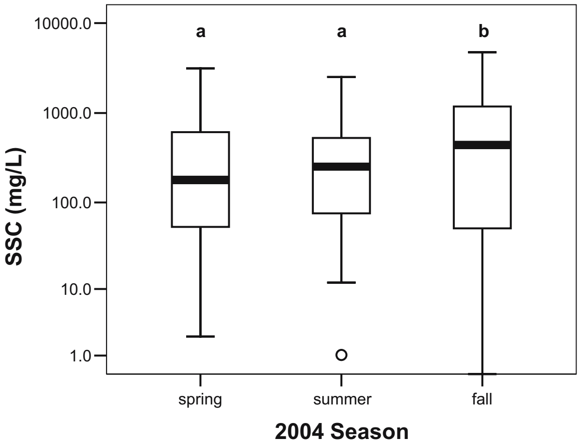


Fig. 11 2004 Seasonal Differences Boxplot, Harvested Sites Only. The figure shows the median, quartiles and 95th percentile for each site. The *circle* indicates an outlier. *Letters* indicate which medians are significantly different based on the Mann–Whitney U statistic reported in Table 7

Site 5 which had been harvested for 10 years and this was not the case.

In New Brunswick, peat is harvested using industrial vacuums that compact surficial peat and likely modifies its cohesive structure (Kløve and Bengtsson 1999). Our results showed that differences in SSC medians in the Summer do not seem to be related to the number of peat collection days. In both 2003 and 2004, Sites 4 and 5 had a higher number of harvesting days when compared to Site 2 (Table 1). However, Site 2 systematically had higher SSC medians than Sites 4 and 5 (Tables 5 and 6).

Another operational factor that may influence SSC is pond cleaning. New Brunswick guidelines stipulate that sedimentation ponds must be emptied of deposited sediments periodically so that peat accumulation does not exceed 50% and preferably 25% of the total basin volume (Thibault 2001). In Summer 2004, ponds at Sites 4 and 5 were cleaned on June 29th whereas at Site 2, the ponds were cleaned in Spring on May 20th. Temporal proximity to pond cleaning, in this case, may partly explain Summer SSC results (i.e. the ponds at Site 2 were fuller when the Summer (June 21–September 22) SSC readings were taken). Conversely, Ihme et al. (1991) found that dredging of sedimentation ponds actually increased the leaching of SSC as the bottom is disrupted during the cleaning process. Variations in hydrological, meteorological, pond and site characteristics evidently complicate analysis. Once again, further study of pond efficiency and cleaning techniques in a Canadian context is warranted.

Interseasonal comparisons are also of interest. The combined median for all four harvested sites was highest in the Fall (421.18 mg/l) suggesting that it is the worst season for suspended sediment flushing (Table 7 and Fig. 11). This is contrary to St-Hilaire et al. (2006) who focused solely on the spring season because they hypothesized that the spring flood would cause the highest suspended sediment concentrations. Other studies surveyed did find that the highest SSC do occured in Spring (Clausen 1981; Kolesin and Yanushevskiy 1985; GEMTEC Limited 1993).

The present study confirmed, however, that the highest specific mean discharges and specific maximum discharges did occur in the Spring (Table 5) as expected. There may be several reasons why SSC values were higher in the Fall: (1) Fall is the usual season of ditch maintenance, an operation known to produce elevated SSC (Ihme et al. 1991; GEMTEC Limited 1993; Joensuu 2002); (2) a dry and desiccated upper peat layer following the Summer dry season; and (3) increased precipitation leading to larger runoffs: Tables 5 and 6 show that total precipitation was generally higher in Fall 2003 and Fall 2004 than in other seasons, except for Sites 4 and 5 in 2004.

Recalling that median SSC instead of mean SSC were used throughout our comparative study because SSC data were not normally distributed, it is difficult

Table 7 2004 Comparison of SSC at harvested sites (2–5) across seasons in 2004

Site 2, 3, 4 and 5 Kruskal–Wallis	$X^2=8.634$, $p=0.013$, $n=556$					
2004 Season	*n*	Combined median SSC (mg/l)	MWU vs. Spring	*p*	MWU vs. Summer	*p*
Spring	204	172.90	na			
Summer	180	254.80	16,875.50	0.171		
Fall	172	421.18	14,721.00	0.007	13,559.50	0.044

MWU Mann–Whitney U, *na* not applicable.

to assess our results against other studies that have used mean values. In order to do so, a mean SSC value for the harvested sites was calculated and was found to be 485.70 mg/l for the period surveyed (2003–2004). Using grab samples (n=1,185), Joensuu et al. (1999) found that SSC in drainage waters exiting sedimentation ponds had monthly averages between 204.6 mg/l in April and 51.3 mg/l in September during the first year of harvest. The grab samples were collected at exit of the sedimentation ponds, approximately the same location as the OBS in our study, in 37 catchments with peat mining areas in Finland. Conversely, the 31 control areas (unharvested) had monthly averages that varied from a high of 9.63 mg/l in July to a low of 2.11 mg/l in October (n=1,626). We found the mean SSC at our control sites to be 10.74 mg/l, within range of previously reported values (Clausen 1981; Clausen and Brooks 1983; Panu 1989; Joensuu et al. 1999).

Conclusion

A study of SSC downstream of harvested and unharvested peat bogs has revealed significantly higher amounts of suspended sediment are leaving harvested peat bogs. We found that SSC levels at the harvested sites were high all year round with the highest overall SSC occurring in Fall. It appears that field ditching and insufficient sediment controls contribute to the elevated SSC levels. The 25 mg/l NB guideline was exceeded 30% of the time at the unharvested site and 72% of the time at the harvested sites. This guideline may require review in light of these new findings. As stated in the introduction, peat harvesting is a multi-million dollar industry in Canada. Once currently harvested bogs are depleted, new bogs will be drained and harvested. Hence, opportunities for future studies exist and should include alternate pond designs, other mitigation techniques such as buffer strips and monitoring of unharvested bogs to provide a more comprehensive understanding of natural peat bog dynamics and potential impacts of harvesting on aquatic habitat.

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