Influence of hydrological conditions and peat extraction operations on suspended sediment concentration and deposition in the East Branch Portage River, New Brunswick (Canada)

M. A. Es-Salhi, M. Clément, A. St-Hilaire, D. Caissie and S. C. Courtenay

ABSTRACT

Peat extraction activities often generate sediments that can be transported into streams and rivers. These sediments have sometimes been shown to negatively affect the natural environment. This study investigated the effects of peat production on the East Branch Portage River, New Brunswick (NB), Canada. Relationships between discharge, precipitation and suspended sediment concentration (SSC) were analysed. The effect of sedimentation pond maintenance activities on SSC was also studied. Finally, the grain size distribution and organic content of deposited sediments were quantified at five sites downstream of the pond. Three water quality stations were monitored during the ice-free period in 2007 and 2008. Results showed that SSC was not significantly correlated with precipitation and weakly correlated with discharge, although some of the high SSC events were triggered by high discharge and precipitation. Pond maintenance alone failed to ensure optimal sedimentation pond efficiency. In 2008, SSC increased a few days after pond maintenance. The NB SSC 25 mg/L guideline was exceeded at all stations in both years. Analysis of variance results showed that there were significant differences in the grain size distribution of deposited sediments at the five sampled sites. Sand was the prevailing sediment type deposited downstream of the sedimentation pond.

Key words | extraction, flow, peatland, precipitation, sedimentation basin, suspended sediment

INTRODUCTION

Peatlands cover an area of approximately 400 million ha worldwide and represent 3% of continental surfaces (Lappalainen 1996). Because of its water retention characteristics, peat is used in horticulture worldwide. In Canada, peatlands cover 111 million ha, representing 76% of 127 million ha of wetlands across the country (Zoltai 1988). Canada’s production focuses on horticultural peat, for which it has 22% of the global share (Daigle et al. 2001). In New Brunswick (NB), peatlands cover 2% (140,000 ha) of the area of the province, of which 5,500 ha are currently used for the production of peat (New Brunswick Department of Natural Resources 2009). The most common extraction method is the use of vacuum harvesters (Daigle et al. 2001; Gonzalez 2003). Prior to extraction, the surface vegetation is removed and intensive drainage is carried out to dry the underlying peat. This leads to a decrease in evapotranspiration and can result in increased flow in nearby rivers (Gottlich et al. 1995). Generally, peat extraction can have multiple and variable impacts on the local hydrology, including increases of the unsaturated soil layer due to
drainage. For instance, Holden et al. (2006) reported that peat drainage resulted in flashier storm hydrographs than those observed in unperturbed peatlands.

In 1987, a study was done at various peat extraction sites in northeastern New Brunswick to determine the impact of peat extraction operations (Environment Canada 1987). Due to the potential negative consequences to the aquatic environment, it was recommended that sedimentation ponds be used. During the early 1990s, the New Brunswick Department of Natural Resources commissioned studies to perform further analyses on water quality of runoff from extracted peatlands due to concerns about environmental impacts on aquatic habitats. Studies of exploited peatlands on Lamèque Island (NB) showed that sedimentation pond size, installation of structures within the pond (such as floating booms), pond cleaning schedules, ditching activities, discharge and the ratio of pond volume to peatland area all influenced the quantity of suspended sediment in drainage waters (Gemtec 1993). To minimize the impact of increased sediment loads within receiving waters, sedimentation ponds are now installed and a buffer zone of at least 50 m between sedimentation ponds and water courses is required. The guidelines of the province of New Brunswick stipulate that the suspended sediment concentration (SSC) in the drainage water must not exceed 25 mg/L (Thibault 1998).

Other studies have evaluated the effectiveness of sedimentation ponds to mitigate sediment loads. Klove (1997) stated that expected pond sediment removal efficiency for sedimentation ponds in Findland should be in the order of 30–40%. Klove (2000) measured sediment removal efficiencies as high as 68% in a 720 m³ Finnish pond located downstream from a harvested site. Ouellette et al. (2005, 2006) reported that, from 1997 to 1999, the volume of peat deposits in Mill Creek (NB) more than doubled despite the construction of sedimentation ponds downstream of the drainage network of the peat extraction operation. However, until 2004, the sedimentation ponds at this site did not meet the provincial guidelines (J. Thibault, NB Department of Natural Resources, personal communication). Studies showed that the presence of peat particles affected the distribution and condition of sand shrimp (Crangon septemspinosa) (Ouellette et al. 2005, 2006). Peat particles can also have a negative impact on benthic invertebrate and fish communities in receiving streams (Laine & Heikkinen 2000; Laine 2001). Other studies in New Brunswick showed that the frequency of exceedance of the 25 mg/L guideline for SSC was surpassed between 54 and 72% of the monitored period (St-Hilaire et al. 2006; Pavey et al. 2007a).

Pavey et al. (2007b) also studied the type and quantity of sediments that were deposited 50 m downstream of the sedimentation ponds in the spring and fall of 2003 and during the ice-free (spring to fall) period of 2004. The rate of sediment deposition downstream of peat extraction areas was significantly higher than that of the reference site (undisturbed peatland). At the peat extraction sites, the majority of sediments was composed of sand and contained low (pooled median = 4%) organic content (including peat particles). These findings do not necessarily indicate that a small amount of organic matter is coming from the peat production area. It was suggested that, because of its low density, the majority of organic matter remained in the water column for a longer period than coarser inorganic material and was settling farther downstream than where the sediment traps were placed. This hypothesis is supported in a study by Madej (2005) in four streams in northern California. It is also supported in part by the study of Marttila & Klove (2008), who measured the settling velocity of peat particles. Albeit variable, some settling velocities were as low as 0.06 m/h in a static column.

Clément et al. (2009) monitored the SSC in the East Branch Portage River (NB) during the opening extraction activities of a peatland in 2007. They concluded that an insufficient quantity of sediment was being trapped in the sedimentation pond, perhaps as a consequence of insufficient pond cleaning. The 250 m buffer zone downstream of the pond was also not efficient in trapping sediments as a channel formed by the outflow transported sediments directly into the river. Elevated SSC (>200 mg/L) was observed and the New Brunswick SSC guideline was exceeded 25% of the time at a site located immediately downstream of the exploited peatland.

As a whole, these studies have shown that current practices for the retention of suspended sediment from peatland extraction do not meet the New Brunswick guidelines with respect to SSC. Moreover, studies indicate that high SSC is often related to important hydrological events (e.g., St-Hilaire et al. 2006; Pavey et al. 2007a; Marttila & Klove
Previous studies have tried to establish a relationship between SSC, discharge and precipitation (e.g., St-Hilaire et al. 2006; Pavey et al. 2007a). Other studies have found weak correlations between SSC and flow in peatland drainage basins (Marttila & Klove 2010). Marttila & Klove (2009) found a significant relationship between SSC and discharge at the Luisansua peat extraction site, near Oulu, Finland. St-Hilaire et al. (2006) found a statistically significant relationship between SSC exceedance of a 500 mg/L threshold and precipitation and discharge (estimated using nearby gauging stations) with a lag of 3 days, which resulted in increased SSC levels 82% of the time. Another study found that important increases in SSC occurred with small changes in discharge (Benyahya et al. 2003). In most of these cases, however, discharge was not monitored at the site and/or on a continuous basis. In addition, previous studies did not focus on confounding factors such as maintenance operations of sediment ponds. Therefore, the goals of this research project were to: (1) determine if SSC is correlated to water discharge and precipitation; (2) compare SSC at two stations located downstream and one station located upstream of the peat operations; and (3) investigate sediment deposition and organic content of sediments upstream and downstream of the peat production area.

METHODOLOGY

Description of the sites and stations

The study area was located on the East Branch Portage River (Northumberland County, New Brunswick; Figure 1). The Hardwood Peatland is located in the headwater of the

![Figure 1](https://iwaponline.com/wqrj/article-pdf/48/4/305/379978/305.pdf)

Figure 1 | Study area with station and site locations in the East Branch Portage River in New Brunswick. The dotted line indicates the channel that was created through the buffer zone from the drainage water exiting the sedimentation pond (see Clément et al. (2009) for channel description). Source: Premier Horticulture, modified in 2010.
drainage basin and has a total area of 125 ha. In 2007, 19 ha were cleared of vegetation and drained. A network of ditches having a depth of 1 m and a width of 2–3 m was dug to drain the area. Drainage water was diverted towards a sedimentation pond and then flowed through a 250 m buffer zone, prior to emptying in the river. Three water quality monitoring stations were established in the East Branch Portage River in 2007 (Clément et al. 2009) and 2008. Station C1 was located downstream of a low gradient wetland located 2 km downstream of the exploited peatland (Figure 1). This is a site with known suitable fish habitat (Clément et al. 2009). Station C2 was located approximately 10 m downstream of the confluence of the East Branch Portage River with a channel (depression) formed by the drainage water flowing into the buffer zone. Station C3 was located upstream of all operational activities in the peatland and outside the influence of extraction activities at the time of the study.

Field measurements

At each station, one optical back scatterometer (OBS3, D&A Instruments Ltd) was attached at mid-depth in the channel to a metal frame to protect the equipment from large debris accumulation. A wiper brush (Hydro-Wiper, Zebra-Tech Ltd) operated by batteries was attached to the OBS to remove debris and biofouling on the sensors. The wiper was set to clean the OBS every 2 h. The OBS sensor measured water turbidity using infrared light emitting from the sensor and incidental light entering the sensor. Turbidity was recorded every 15 s and hourly averages were recorded in a datalogger (Campbell Scientific CR510 or CR10). At each station, a calibration curve was developed to convert turbidity measurements (in mV) to SSC (in mg/L) as described in the ‘Calibration’ section.

A pressure transducer (Keller model 173-L, Pressure System Inc.) was installed at C1 to measure hourly water levels. During site visits, instantaneous discharge was estimated using water velocity measured at 20 points along a transect using a Marsh McBirney electromagnetic flow meter (Flo-Mate model 2000). These discharge measurements were then used to obtain a flow rating curve that converted water level measurements into water discharge.

The equipment was installed in the spring (April or May of 2007 and 2008) and removed in late fall (November). However, the datalogger at C1 malfunctioned from October 1, 2008 to the end of the sampling season, so discharge and SSC data were not collected during the latter part of 2008. Daily precipitation from the Environment Canada meteorological station at Miramichi Station RCS (station ID: 8100989, 46 0.600’N, 65 28.200’W) was obtained from May to October for both 2007 and 2008. We analysed data from June to September, in order to have information for complete concomitant periods in 2007 and 2008. The average daily precipitation for the months of June to September during 2007 and 2008 were compared to the 30 year averages for the same months. The precipitation station is approximately 60 km southwest of the Hardwood Peatland study site.

In addition to SSC and water discharge, sediment traps (Sedibacs™, Bio Innove Inc.) were installed at various sites on June 26 and 27, 2007 and on July 3, 2008. The sediment traps were composed of 1 L plastic cylinders measuring 12 cm in diameter and 13.5 cm in height and perforated on the sides with holes measuring 1.3 cm in diameter. Before placing the sediment traps in the streambed, a 10 mm mesh bag filled with gravel measuring between 2 and 4 cm in diameter was placed inside the cylinders. Sediment traps were buried in the stream with their opening leveled with the streambed surface. The sediment traps remained open at the top and on the sides, thereby allowing sediment to be trapped within the gravel but also to be laterally transported by hyporheic flow. This enabled the measurement of net deposition of fine sediment.

Four sets, each composed of four sediment traps, were installed downstream of C1, in a stream reach known to support a number of fish species, including brook trout (Salvelinus fontinalis) (Clément et al. 2009). Sites with sediment traps were identified as S1–S5 in order to differentiate them from SSC monitoring stations C1, C2 and C3. More specifically, sets of sedimentation traps were installed in slow moving areas (sedimentation areas) at 353 m (Site S1), 113 m (Site S2), 73 m (Site S3) and 3 m (Site S4) downstream of C1 (Figure 1). A fifth set of sediment traps (Site S5) was installed in the channel formed in the buffer zone, 5 m upstream of the confluence between the channel and East Branch Portage River (Figure 1) to quantify sedimentation near the extraction activities. No sedimentation trap was installed in the East Branch Portage River near C2 and C3 because of the deep water (>1 m) and the low probability of retrieving the sediment traps in this stream reach.
Upon retrieval of the sedimentation traps from the streams (November 22, 2007 and November 5, 2008), sediments were dried in an oven at 70 °C for 24 h. Grain size distribution was obtained by sieving (64 µm–16 mm). The sediments were shaken for 15 min using a portable sieve shaker (model RX-24; W/S Tyler Co.). If the sediments remained attached to the large pieces of gravel, they were removed carefully with a brush and then put into the shaker again for 10 min. The sediment fractions were weighed using an APX-200 Denver Instrument scale (precision of 0.1 mg) and a percentage by weight of each fraction was calculated. The organic content was determined by burning in a muffle oven at 500 °C for 3 h and reweighing the remaining sediments. Sediments were subsequently grouped into three size classes: fine gravel (2 ≤ d < 4 mm), sand (0.0625 ≤ d < 2 mm) and clay and silt (<0.0625 mm) (Gordon et al. 2004).

Survey of peat volume in the sedimentation pond

Measurements of peat accumulation in the sedimentation pond were taken on June 7, 2007, July 23, 2008 and August 19, 2008. The length and the width of the pond were measured using a measuring tape. The pond was divided into six equidistant transects. Five measurement points were used for each transect, based on the wetted width of the sedimentation pond.

At each transect point and at the outflow of the pond, two measurements were taken: total water depth (bottom of the pond to the top of the water) and water depth to the peat. The total water depth at the outflow was then subtracted from the average of the depth measurements taken at each transect to calculate the effective volume of the pond and peat accumulation. The pond was trapezoidal in shape and had an initial volume of 700 m³ (length = 87 m, width = 7–10 m at the top and 2–5 m at the base, with 45° sloping banks). As required, a volume of 25 m³ was allowed for each hectare of drained peatland. The average depth of the sedimentation pond was 1.1 m, which is less than the required minimum depth of 1.5 m.

Calibration

Turbidity measurements were recorded by the OBS in mV. A calibration curve was constructed for each station to convert the mV values to mg/L. The calibration was done with in situ water and sediments, and was performed in the shade in order to prevent light from affecting the measurements. Water turbidity was increased by mixing stream sediments into a rectangular container (50 cm × 75 cm × 28 cm) filled with water. The turbidity was measured (while the sediments were kept in suspension by stirring continuously) and a water sample was immediately collected and transferred to a 2 L bottle for subsequent filtration in the laboratory. An interval of desired turbidity was set and subsequent samples were collected by adding sediments to the water and then stirring the water. Turbidity and water samples were obtained for at least 20 different turbidity levels (ranging from 10 to 680 mV) at each station.

In the laboratory, ProWeighTM 11 cm filters (1.2 µm pore size) were used to filter water samples. The resulting particles were dried in an oven at 70 °C for 24 h and weighed. Calibration curves of mV to mg/L were constructed for each station. Data collected during previous years (2005–2007) and in 2009 were included in the calculation to improve the calibration curves. Note that sediments used to construct the curves originated from the stream and ditch beds, which may include sediments coarser than those that would usually get resuspended.

Statistical analyses

Percentages of SSC exceedances were calculated as the percentage of hourly mean SSC values exceeding the defined SSC threshold. Based on the results of the Lilliefors test, it was determined that the grain size and organic content data measured from sediment traps were normally distributed in both 2007 and 2008, except for one combination of grain size and site (sand at Site 2). Hence sand data were log-transformed for subsequent analysis. Given the high risk of within-site correlation, a repeat measure Analysis of variance (ANOVA) was performed to test for inter-site differences. ANOVAs were followed by the multiple comparison test using the pgirmess package in R (Siegel & Castellan 1988). Given the non-normality of SSC and flow time series, the rank-based Kendall’s tau was used to determine if any significant correlation existed between SSC and discharge. Lagged correlations were also tested.
RESULTS

Hydroclimatic conditions

Between June and September, totals of 351 and 459 mm of rain fell in 2007 and 2008, respectively (Table 1; 30 year average is 370 mm). Total precipitations in June, July and August 2007 were similar to 30 year averages, while precipitations in September 2007 were 30% lower than the monthly normal average. In 2008, precipitations in July and September were similar to the 30 year average, while June (25%) and August (63%) were wetter than normal (Table 1).

Mean discharges in the East Branch Portage River were calculated for the same time period of June to September in 2007 and 2008. The average discharge was 0.047 m$^3$/s in 2007 compared to 0.068 m$^3$/s in 2008. August 2008 had a discharge of 0.114 m$^3$/s, five times higher than in 2007 (Table 1).

Suspended sediment concentrations

Correlation of precipitation and discharge with SSC levels

Although some increases in SSC were synchronized with precipitation events, this was not systematic. For instance, in 2007, 46 mm of rain fell on October 12 and an increase of SSC was subsequently observed at each station; C1–33 mg/L on October 13, C2–268 mg/L on October 12 and C3–27 mg/L on October 15 (Figure 2). However, on August 24, 21 mm of rain were recorded and no corresponding increase in SSC was observed in the following days at any of the stations. Similarly, 45 mm of rain fell on July 19 in 2008 and no corresponding increases in SSC were recorded at the three stations (Figure 3). In contrast, on August 3, a similar amount of rain (54 mm) resulted in an SSC level of 121 mg/L 3 days later at C2. Stations C1 and C3 showed no increase in SSC after this particular rainfall event. The SSC was not significantly correlated with precipitation at C1, C2 or C3 in 2007 or 2008 ($p$-value > 0.05).

As with precipitation, there was no systematic synchronicity between discharge and SSC events (Figures 2 and 3). In 2007, events of elevated SSC at C2 occurred mainly during the low discharge period (July 7–25; 0.072–0.050 m$^3$/s), which coincided with a period of high intensity ditching activities at the peatland. Missing data in 2007 (at C1) from July 10 to August 22 made it difficult to determine if the elevated SSC recorded at C2 persisted over a distance of 2 km downstream from the peatland (Station C1). In 2008, some SSC peaks were associated with higher discharge. For instance, Station C2 showed a series of four SSC peaks (varying from 542 to 742 mg/L; June 19 to July 7). Only the third peak (July 1) was associated with an increase in discharge. On August 5, the highest discharge recorded during the summer resulted in only a small increase (121 mg/L) in SSC at C2 1 day after the discharge event.

<table>
<thead>
<tr>
<th>Precipitation (mm)*</th>
<th>Average precipitation 1971 to 2000b (mm)</th>
<th>Average discharge and standard deviation (m$^3$/s)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Months</td>
<td>2007</td>
<td>2008</td>
</tr>
<tr>
<td></td>
<td>Q</td>
<td>SD</td>
</tr>
<tr>
<td>June</td>
<td>80.6</td>
<td>111.2</td>
</tr>
<tr>
<td>July</td>
<td>115.1</td>
<td>109.2</td>
</tr>
<tr>
<td>August</td>
<td>95.9</td>
<td>145.5</td>
</tr>
<tr>
<td>September</td>
<td>59.9</td>
<td>93.0</td>
</tr>
<tr>
<td>Total</td>
<td>351.5</td>
<td>458.9</td>
</tr>
</tbody>
</table>

*Miramichi Station RCS (station ID: 8100989, 46°0.600’N, 65°28.200’W).
1Miramichi Station A (station ID: 8101000, 47°0.600’N, 65°28.200’W).
Non-parametric correlations between SSC and discharge were calculated using hourly data at both sites. When all available SSC data were used, the correlation coefficients were non-significant in 2007 and were higher (in absolute value) at C1 than C2 and C3 in 2008 (Table 2). In fact, correlations were close to 0 at Station C2 for both years. The fact that some correlations are significant in 2008 and not in 2007 may be associated with higher flows during the summer period of 2008 than 2007. These higher flows may have produced a dilution of SSC in

Figure 2 | Time series of suspended sediment in 2007 from days of the year 131 to 313. (a) Station C1, (b) Station C2, (c) Station C3, (d) discharge, and (e) daily precipitation (Environment Canada Miramichi Station). The horizontal dark line on the SSC plots represents the NB 25 mg/L guideline (Clément et al. 2009). The dotted lines represent the period of pond maintenance (days 205 to 213).

Figure 3 | Time series of suspended sediment in 2008 from days of the year 149 to 275. (a) Station C1, (b) Station C2, (c) Station C3, (d) discharge, and (e) daily precipitation (Environment Canada Miramichi Station). The horizontal dark line on the SSC plots represents the NB 25 mg/L guideline. The dotted line represents the day of pond maintenance (day 168).
2008, a phenomenon that may not have occurred in the summer of 2007 because of lower discharge.

The frequent low values may have prevented the detection of a stronger correlation between SCC and discharge when only important events are considered. In order to investigate this possibility, correlation coefficients were also calculated for each data set when SCC lower than a certain threshold was excluded. Table 2 shows the correlation coefficients for SCC higher than 25 and 50 mg/L. Eliminating values lower than 25 mg/L marginally improved the correlations at Sites C1 and C3. Increasing the threshold to 50 mg/L only improved the correlation coefficients at C3, but the sample size became very small (n = 12).

Lagged correlations (3, 6, 12 and 24h) were also investigated. Marginal improvements were observed in 2008 when SCC time series lagged discharge by 3 h at Site C1. Kendall’s tau increased from −0.247 to −0.250 in 2008. At Sites C2 and C3, marginal improvement in correlations were observed with lags up to 24 h (e.g., from −0.030 at lag 0 to −0.041 in 2007 for a 24 h lag at Site C2).

**Percentage of exceedance of thresholds during the sampling period**

Table 3 outlines the percentage of SCC exceedance of 25 mg/L (New Brunswick guideline), 50 mg/L, 100 mg/L and 500 mg/L for each station in both 2007 and 2008. All three stations exceeded 25 mg/L in both years, with the highest exceedance being at C2 in 2007 (47%) and 2008 (52%) and the lowest at Site C3 (3% in 2007 and 2% in 2008). At C1 and C3, SSC levels never exceeded 100 mg/L in 2007. At C2, SSC exceeded 100 mg/L 20% of the time and 500 mg/L, 6% of the time in 2007. In 2008, C1 exceeded 100 mg/L 7% of the time but C3 never exceeded 100 mg/L. At C2, SSC exceeded 100 and 500 mg/L, 28 and 8% of the time, respectively. SSC distributions at each station are shown in Figure 4. Median SSC levels were highest at C2, followed by C1 and C3 (Figure 4).

**Peat accumulation in sedimentation pond**

Peat accumulation in the pond was measured once in 2007, on June 7 (Figure 2). A total of 172 m³ of peat had accumulated, representing 25% of total pond volume. Pond maintenance occurred 47 to 55 days later (exact date of

<table>
<thead>
<tr>
<th>Table 2</th>
<th>Sample sizes (n), rank correlation (Kendall’s tau) and significance levels (p-value) between hourly SSC and discharge for 2007 and 2008</th>
</tr>
</thead>
<tbody>
<tr>
<td>2007</td>
<td>2008</td>
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<tr>
<td></td>
<td>n</td>
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<tr>
<td>All data</td>
<td>C1</td>
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<td></td>
<td>C2</td>
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<td></td>
<td>C3</td>
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<td>&gt; 25 mg/L</td>
<td>C1</td>
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<td>C2</td>
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<td>C3</td>
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<td>&gt; 50 mg/L</td>
<td>C1</td>
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<td></td>
<td>C2</td>
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<td>C3</td>
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Correlations are significant for p-value < 0.05.

<table>
<thead>
<tr>
<th>Table 3</th>
<th>SSC percentage exceedance at the three stations (C1, C2 and C3) in 2007 and 2008 during the monitored days</th>
</tr>
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<tbody>
<tr>
<td>2007</td>
<td>2008</td>
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<tr>
<td>SSC (mg/L)</td>
<td>C1</td>
</tr>
<tr>
<td>25</td>
<td>10.6%</td>
</tr>
<tr>
<td>50</td>
<td>4.0%</td>
</tr>
<tr>
<td>100</td>
<td>0%</td>
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<tr>
<td>500</td>
<td>0%</td>
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cleaning not recorded in 2007). In 2008, pond maintenance was carried out earlier (Figure 3), and was completed in 1 day. In both years, pond maintenance was accomplished using a backhoe. Peat accumulation was measured 37 days after pond maintenance in 2008. At that time, 418 m$^3$ of peat had accumulated in the pond. This accumulation represented 60% of total pond volume. A second measurement was taken 27 days after the first measurement and 64 days after pond maintenance. Peat volume in the pond was estimated at 406 m$^3$ (58% of total pond volume).

Data recorded at C2 (in the vicinity of the peatland) were analysed to determine the effect of pond maintenance on SSC (Figure 2(b)). In 2007, periods of high precipitation occurred during and after the period of pond maintenance (Figure 2(e)). The 20-day average SSC levels at C2 before and after maintenance in 2007 were 704 mg/L (total precipitation ($P = 66$ mm) and 130 mg/L ($P = 51$ mm) in 2007. Maintenance reduced the SSC by 82%. Nonetheless, the New Brunswick guideline of 25 mg/L was exceeded 90% of the time during the 20-day period after maintenance. The SSC increased to values exceeding 400 mg/L 3 days after pond maintenance (Figure 2(b)) which coincided with a precipitation event (Figure 2(e)). Elevated SSC was observed periodically after pond maintenance.

The 20-day average SSC levels at C2 before maintenance and after maintenance in 2008 were 17 mg/L ($P = 40$ mm and average $Q = 0.056$ m$^3$/s) and 187 mg/L ($P = 97$ mm and average $Q = 0.063$ m$^3$/s) (Figure 3). Hence, C2 did not experience a decrease in SSC after pond maintenance in 2008, perhaps because of the important rainfall amounts during this period. In fact, SSC increased by more than ten times after maintenance (Figure 3(b)). The New Brunswick guideline of 25 mg/L was exceeded 21% of the time during the 20-day period prior to the pond maintenance and 75% afterwards. Five days after maintenance, there was a series of four peaks from June 19 to July 7, ranging from 504 to 742 mg/L. These elevated SSC were observed over a period of 30 days after pond maintenance and three of the four SSC peaks were not associated with precipitation (Figures 3(b) and 3(e)). High SSC values were again noted between August 15 and September 29, with maximum SSC levels ranging from 913 to 1,938 mg/L (Figure 3(b)).
Sediment deposition

Clay and silt

In both 2007 and 2008, the mean percentages of clay and silt deposited from S1 to S4 (sites located downstream of C1) were generally small, with less than 8%, except for S4 in 2008 (Figure 5). Site S5 systematically had more than 19% of clay and silt.

The ANOVA showed that means were significantly different between sites in 2007 and 2008. The multiple comparison test indicated that the following sites were significantly different from each other in 2007: S2 and S5, and S4 and S5 and in 2008: S2 and S4, and S2 and S5 (Figure 6).

Sand

In general, sand had the largest proportion of deposited sediments in both 2007 and 2008. The highest mean percentage was measured at S3 (86% in 2008), while the lowest accumulation was observed at S5 (20% in 2008) (Figure 5). At the downstream sites (S1–S4), the mean percentage remained fairly constant and ranged between 69 and 86%.

The ANOVA results confirmed that means by site were significantly different in 2007 and 2008. The multiple comparison test indicated that no sites were significantly different from each other in 2007; however, when reviewing Figure 6, there visually appears to be a difference between S1 and S5. In 2008, S5 was significantly different than S2 and S3 (Figure 6).

Fine gravel

In general, fine gravel comprised a relatively small percentage (<26%) of the deposits collected in 2007 and 2008 with the notable exception of S5 in 2008. The highest mean percentage for both years was found at S5, with 50% in 2007 and 60% in 2008 (Figure 5). The ANOVA showed significant inter-site differences in mean percentage of fine gravel in 2007 and 2008. The multiple comparison test indicated that S5 was significantly different than S2 and S3 in 2008 (Figure 6).

Organic content

In 2007, the median percentage of organic content for sediment less than 2 mm in size (fine sediment) was
similar from S1 to S4, with 3–4% of organic matter (Figure 7(a)). The ANOVA results confirmed that organic content at S5 was markedly different (25%) than at the other four sites ($F = 37.89$; $p$-value < 0.001). In 2008, the mean percentage of organic content for sediment less than 2 mm in size demonstrated a slightly different spatial pattern than in 2007. The percentage of organic content (<2 mm) increased from S2 to S5 and S5 remained the site with the highest mean percentage organic content at 22% (Figure 7(b)). Significant differences between sites were found ($F = 87.56$; $p$-value < 0.001), with S2 being significantly different than S5 (Figure 7(b)).

The percentage of organic sediment greater than 2 mm in size was very small (<1%) in 2007. The inter-site comparison indicated that no sites were significantly different from each other (Figure 7(c)). The percentage of organic content for sediment greater than 2 mm was higher in 2008 than 2007 (Figures 7(c) and 7(d)). In 2008, the minimum percentage was 3% at S1 and the maximum reached 13% at S5, with S1 significantly different from S5 (Figure 7(d)).

**DISCUSSION AND CONCLUSION**

One of the objectives of the present study was to test if a statistical relationship existed between SSC and hydrological conditions. Our results, using on-site flow measurements, did not confirm the results of St-Hilaire et al. (2006), who...
used transferred flow data. Although there was some temporal concordance between some SSC increases and discharge, correlation coefficients were weak (albeit significant in many cases) between these two variables. Site C2 was not highly correlated with flow data, compared with Sites C1 and C3. This was expected, as this is the site that is most impacted by water released from the sedimentation pond and peat extraction activities. The storage capacity of the pond was sufficient to withhold large volumes of water after a rain event, thereby affecting the flow pattern at C2.

Another factor which could result in variable correlation between SSC and discharge is the antecedent soil moisture in the area. During similar rainfall events, it was observed that discharge responded differently, presumably due to the level of saturation within the basin. No correlation between discharge and SSC was found during a study on an exploited peatland at Lamèque Island (NB) (GEMTEC 1993). Gemtec (1995) found that SSC levels were lowest in the spring and highest in the fall, but the rises in SSC levels were not related to discharge. Instead, they showed that high SSC levels were a result of ditching activities which loosened peat fibres and mineral substrate that were subsequently transported by water. The 2007 data also showed that ditching and drainage activities resulted in numerous SSC increases in July and August 2007 (Clément et al. 2009). Information on daily extraction operations at the peatland was not available for 2008. However, peak SSC events were recorded during known periods of ditching and peat extraction activities. Nonetheless, it is possible that precipitation and discharge may intensify sediment transport during specific rain events.

The relatively large distance between the rain gauge and the study site (60 km) means that rainfall measurements may differ in some cases from the actual on-site precipitation. There may be important differences in convective events intensity and total precipitation for distant stations (Zhang et al. 2001). This may be one of the reasons for a somewhat inconclusive correlation analysis between rainfall and SSC in the present study. Precipitation can have two distinct and opposite effects on SSC. When sediment supply is not limited, SSC loads will increase as precipitation increases. When precipitation is less intense, it is possible that the energy is insufficient to dislodge peat particles (Tramblay et al. 2010; Marttila 2011). If sediment delivery is not sustained during precipitation events, a dilution effect will occur. Our data suggest that both these mechanisms may have been present during the monitoring periods. The different signs of correlation coefficients between 2007 and 2008 may be indicative of a dilution process in 2008 that did not occur in 2007.

SSC levels were significantly higher at C2 than at the other stations, with some very high SSC values (>2,000 mg/L). Clément et al. (2009) reported an exceedance rate of 25% at C2 in 2007, but this rate only considered data for a concomitant period at the three sites. When considering the entire sampling period, the New Brunswick threshold was exceeded approximately 50% of the time at C2 in 2007 and 2008. These results indicated that C2 was the most affected site by extraction operations. At C1 in 2008, most of the exceedances of the New Brunswick guideline occurred from July 14 to 20, which did not coincide with a period of elevated SSC at C2. These elevated SSC values at C1 may have originated from the low gradient wetland located between C1 and C2. SSC values in excess of 25 mg/L were very scant at C3, which was not influenced by the extraction activities during the course of the present study. SSC values greater than the New Brunswick guideline at C3 are much lower than those observed by Pavey et al. (2007b) (around 30%) in a natural peatland located near our study site and by Clément et al. (2009) at C1 (a natural site) in 2006 (prior to the extraction activities at the peatland). Reasons for this difference may be related to site location.

Pond maintenance was found to affect levels of SSC. It did not reduce the percentage of exceedance of the New Brunswick guideline compared to pre-maintenance exceedance frequency. Pond maintenance in 2008 was followed by a ten-fold increase in SSC compared with the levels recorded prior to maintenance. Precipitation following pond maintenance in 2007 may have increased sediment transport but in 2008 many of the elevated SSC events observed after pond maintenance were not associated with precipitation. Most importantly, these high SSC events persisted over a period of up to 30 days in some cases. These results showed that even if some decreases in SSC can be achieved following pond maintenance (e.g., 2007), pond maintenance may not be sufficient to meet the New Brunswick guidelines in some instances.
The period of high SSC following pond maintenance in 2007 and 2008 may be associated with an increase in sediment mobility from the bottom and the sides of the pond after maintenance. Marttila & Klove (2008), during flume experiments using sediment samples from four peat sedimentation basins in Finland and field experiments from those same basins, showed that critical shear stress from a loose layer of peat sediments was six times lower than that of a consolidated peaty sediment layer. It can be hypothesized that maintenance activity associated with cumulative precipitation and higher discharge, may have produced higher SSC because of changes in critical shear stress. Excavation exposes easily mobilized sediment that can subsequently be flushed away with increased current velocity.

Another source of SSC may be the result of high winds during extraction activities which can blow peat fibres into the pond, as suggested by Gemtec (1993). Flow should be prevented from exiting the pond during maintenance and regulated over a period of 1 month, to allow for armouring of the resident sediments in the pond.

Gemtec (1993) recommended that sedimentation ponds be cleaned, at a minimum, after ditching activities and once in the spring of each year. Ditching activities may increase the deposited sediment by 30 to 50 m³/ha/year in the sedimentation pond. Sediment should not exceed 25% of the total volume of the sedimentation pond (Gemtec 1993). The sedimentation pond was built during the spring of 2007 and the 25% peat accumulation was measured soon after the construction of the pond (June 7, 2007). However, results from 2008 suggest that pond efficiency is likely reduced soon after maintenance because infilling of over half of the available volume happened within the first month following pond cleaning. These results suggest that the pond may reach a saturation point, beyond which the peat retention is no longer efficient. In agreement with Gemtec (1993), our study showed that pond maintenance should be conducted more frequently, i.e., before the accumulated sediment volume exceeds 40% of basin capacity. However, more research is needed to determine pond saturation level. It may be that retention efficiency drops markedly after 25% infilling or even less. Other techniques may help to reduce sediment loads, such as artificial wetland construction (Shamsudin et al. 2009) or deployment of submerged suspended flexible curtain (SFC) to trap sediment (Li et al. 2009).

The results of our study indicate that pond maintenance did not reduce the SSC below the New Brunswick guideline threshold of 25 mg/L after cleaning. Furthermore, pond maintenance may result in episodic or even sustained increase of SSC if water is allowed to flow out of the pond during these cleaning operations. Results suggest that the current sedimentation pond design and/or maintenance practices are not sufficiently efficient. Furthermore, the buffer zone between the sedimentation pond and the receiving stream did not appear to be efficient in reducing SSC. According to Clément et al. (2009), the sediments exiting the pond were being transported directly downstream by a channel which had formed within the buffer zone. In this particular case, there was no diffusion of sediment-laden water in the buffer zone.

Ouellette et al. (1997, 2006) showed that the peat can stay suspended in the water column for nearly 1 km, prior to settling in low gradient. Madej (2005) studied forested streams in northern California and found that organic particles are able to remain suspended longer because of their structure. This was also suggested by Marttila & Klove (2008) who observed peat particles under stereomicroscope and confirmed the high variability of shape and grain size, resulting in variable settling velocities. Because of these findings and as suggested by Williams et al. (2008), studies of the relationship between the size and porosity of composite particles (flocs and aggregates), as well as settling velocities of particles, would be helpful in furthering understanding the behaviour of suspended peat sediments. In our study, it is possible that peat settled in the wetland located between C1 and C2 or conceivably, the organic portion of SSC may have deposited even further downstream in low gradient areas. Clément et al. (2009) found SSC levels at C1 that were similar to those measured in the present study (i.e., 4% exceedance of the 25 mg/L threshold in 2005 and 25% in 2006). They hypothesized that the higher levels of SSC in 2006 (prior to the exploitation at the peatland) may be a result of a decreased dilution effect caused by a 25-day low flow event during the summer.

No impact has yet been recorded on fish habitats (C1). Nonetheless, if sediment load being discharged into the river increases in future years, impacts on fish habitats...
may occur. It should be noted that even C3, upstream of the sedimentation pond discharge, exceeded the 25 mg/L guideline 2-3% of the time, supporting previous research (St-Hilaire et al. 2006; Pavey et al. 2007a) showing that the New Brunswick guideline may be unrealistically low.

Sand was the predominant sediment deposited at all sites in both years except for S5 in 2008 where fine gravel was found to have the highest levels. The presence of fine gravel may be due to higher discharge during the summer of 2008 and most likely eroded from the bottom of the ditches and sedimentation pond that are dug at a depth below the organic layer. S5 was located at the outlet of the channel formed in the buffer zone, closest to the sedimentation pond and extraction activities. Generally, coarser suspended sediments settle quickly, which is confirmed by higher percentages of deposited sediment found at S5. The percentages of organic content were also higher at S5 compared to the downstream sites (S1–S4). S5 was located close to extraction activities in an area with low discharge so higher percentages of organic content were expected to be found because more peat was naturally present. However, depending on rain and flow, some peat particles continue to float downstream, probably until reaching a very low gradient area. It should be noted that spatial correlation may exist between sites and may affect the conclusions reached using a repeat measures ANOVA. Some significant intersite correlations were found in our initial analysis, but they were inconsistent and varied greatly between grain size categories. A larger sample size would be required to confirm or refute independence between samples taken at the different sites.

This study could not adequately investigate correlations between precipitation and SSC and found very weak correlation between discharge and SSC. There may be a more complex, non-linear interaction between hydrological conditions, pond infilling and SSC levels. Future studies may consider deterministic modelling as a tool for combining hydrology and hydraulics that may provide useful information about how the variables work together to potentially affect SSC levels. Deterministic hydrological models are useful tools to estimate sediment loads under different conditions.

Current pond maintenance methodology, such as the maintenance conducted at Hardwood Peatland (i.e., with an excavator), does not sufficiently retain sediments to continuously meet the New Brunswick SSC guidelines. Exceedance frequency was nearly identical in both years, despite the fact that 2007 was drier than 2008. Peat accumulation in the sedimentation pond and pond maintenance appear to be major factors in determining the amplitude of SSC. The elevated SSC events recorded over a period of 1 month following pond maintenance (in 2008) is of concern. Further studies should include the assessment of other mitigation techniques, such as regulating the outflow of the sedimentation pond during maintenance activities and over a period of 1 month afterwards, to determine how SSC levels are affected. Monitoring SSC during a period when the sedimentation pond, as well as any other structures installed in the pond (such as floating booms or submerged SFC) (Li et al. 2009) are scheduled to be maintained is important. Maintenance should occur more frequently than once or twice during the summer, taking into consideration extraction activities and actual peat accumulation measurements. Other mitigation techniques, such as overflow wetlands have been recommended in Finland (Marttila 2011) but may not be suitable for a number of peatland operations in Canada.

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