Characterizing and modelling the trapping efficiency of sedimentation basins downstream of harvested peat bog

Short Title: Peat sediment basin efficiency

Myriam Samson-Dô, André St-Hilaire

Myriam Samson-Dô
Institut National de la Recherche Scientifique – Centre Eau, Terre, Environnement and Canadian Rivers Institute, 490 de la Couronne, Quebec City, Qc, G1K 9A9

André St-Hilaire*
Institut National de la Recherche Scientifique – Centre Eau, Terre, Environnement and Canadian Rivers Institute, 490 de la Couronne, Quebec City, Qc, G1K 9A9
andre.st-hilaire@ete.inrs.ca
*Corresponding Author

Abstract

Peat moss harvesting is an important industry in Canada. To harvest peat, the water table of the peatland must be lowered to allow the surficial peat layer to dry and be harvested. Drainage water can contain suspended sediments, so at most harvesting sites, the water is routed through sedimentation basins. This work focuses on characterizing and modelling their trapping efficiency. Eight basins with different volume/watershed area ratios (705 to 4170 m^3/km^2) were studied in three Quebec regions. Suspended sediment concentration and discharge were monitored up- and downstream of each basin during the ice-free season. Basins with high ratios of volume/drainage area, multiple basin configurations (i.e., two basins in series or in parallel) and those equipped with a flow regulation structure were more efficient than regular basins. Moreover, the nature of sediments (size, decomposition level and organic content) influences loads, but not the trapping efficiency.

Finally, two empirical models developed to predict trapping efficiency of municipal sedimentation basins were tested/adapted for basins that capture peat sediments.

Keywords: harvested peat bog, trapping efficiency, sediment, peat

Introduction

Peat bogs are wetlands in which sphagnum is the dominant vegetation. These plants die at the end of each growing season and subsequently decompose very slowly. Over the years, this transformation leads to the accumulation of peat moss, which can be several meters deep. In fact, the annual mass of peat produced by degradation is lower than the annual living biomass produced because the water table is near the surface, thereby limiting aerobic decomposition (Eggelsmann et al. 1993). In North America, peat moss is used in horticulture as a growth substrate because of its water retention properties. Canada is the largest producer of horticultural peat moss in the world (Daigle & Gautreau-Daigle 2001). About 0.2% of the total area of Canadian peat bogs is harvested, representing around 170km^2.

In Canada, peat extraction is made with industrial vacuums. The acrotelm, which is the living vegetation layer at the surface of the bog is first withdrawn and a network of drainage ditches is dug to lower the water table in the harvested area. Then, the first layer of peat is allowed to dry and is subsequently vacuumed. Only a few millimeters are removed during each harvest, so more than twenty years are typically needed to reach the lower layers of peat that are of poorer commercial quality and often cannot be harvested. Subsequent restoration efforts include re-vegetation of transformation of the harvested site for berry culture (Rochefort et al. 2003).

The drained water can contain suspended sediments. During rain events, runoff can erode the superficial layer of the bog and the drainage channel (Kløve 1998). Thus, some sediment can flow with the drainage water to the receptor stream. High suspended sediment concentrations (i.e. > 100 mg/L) have been reported in previous studies (Clément et al. 2009; Ouellette, et al. 2006).

Every trophic level of the receptor stream may be affected by suspended sediments and by accumulation of fine sediments on the streambed. For example, light attenuation caused by the suspended peat particles in the water column can reduce the primary production of a stream (Whatley et al. 2014). The accumulation of peat on the bed of an estuary may also affect the habitat quality of some epibenthic invertebrate species, such as sand shrimp (*Crangon septemspinosa*) (Ouellette et al. 2006) or increase the mortality of trout alevins (Olsson & Persson 1986).

The size of sediments and their type (organic or mineral) affect their sedimentation rate. According to Stokes' Law, lighter and smaller sediments have a slower sedimentation rate. Typically, the density of peat particles is around $0.4 g/cm^3$ (Rydin & Jeglum 2006) and the density of clay is around $1.0 g/cm^3$. So, peat particles typically settle slower than mineral particles and they tend to re-suspend when the water discharge increases (Kløve 1998).

In order to minimize the sediment loads into surrounding streams, sedimentation basins are dug at the downstream end of the harvested peatlands drainage system. GEMTEC (1993) established a design standard based on the study of three sedimentation basins in New Brunswick. This report recommended that the minimum volume for a sedimentation basin should be $25 m^3$ per hectare of harvested peat bog. Moreover, they recommended a minimum depth of 1.5m and a length: width ratio between 6.5:1 and 12:1 to ensure a minimum retention time of two hours.

In addition, suspended sediment concentration (SSC) guidelines exist in some jurisdictions. For instance, based on GEMTEC (1993), the Canadian province of New Brunswick published the *Guidelines for Peat Mining Operations in New Brunswick* (Thibault 1998), in which a maximum SSC of 0.025g/L was promulgated for water leaving a sedimentation basin. However, many Canadian studies recently showed that some sedimentation basins do not always meet the New Brunswick SSC criterion. SSC downstream of the basin studied by Clément et al. (2009) exceeded the 0.025g/L threshold 36% of the time, whereas the basin studied by Es-Salhi et al. (2013) exceeded 0.025g/L 50% of the time. Those studied by St-Hilaire et al. (2006) exceeded it 54% and 86% of the time, while those of Pavey et al. (2007) exceeded the same threshold 71% of the time (average). Studied sites of Clément et al. (2009) and Es-Salhi et al. (2013) were in the stream in which the water from the sedimentation basin is discharged, while sites of St-Hilaire et al. (2006) and Pavey et al. (2007) were between the sedimentation basin and the stream. Thus, the SSC of the two first studies is diluted by the stream discharge, but still exceeded 0.025g/L frequently, with concentrations exceeding 100 mg/L or more during some events. Moreover, even in streams draining unperturbed peatlands, the threshold was exceeded between 3% (Clément et al. 2009) and 30% of the time (Pavey et al. 2007), indicating that a fixed threshold that does not account for natural SSC variability may not be adequate. These previous studies measured SSC, but failed to quantify suspended sediment loads and consequently trapping efficiency (*TE*), which can be useful as a basin design criterion. Moreover, the impact of peat properties on sediment delivery was not addressed in details. The present study addresses these shortcomings.

Mineral sediments behavior in sedimentation basins have been largely studied, while very few studies focused on sedimentation of organic sediments. Verstraeten & Poesen (2000) review the principal existing empirical and theoretical models developed to predict the efficiency of basins in trapping mineral sediments, but to the authors' knowledge, there has been no attempt to adapt such models to the context of peatland drainage.

The main goal of this study is to compare the *TE* of eight sedimentation basins built to trap peat sediments in order to determine the optimal design for future basins. The *TE* of these basins has been calculated from SSC and discharge measured *in situ*. The second goal is to compare the *TE* predicted by simple empirical models typically used for the design of municipal sedimentation basins with the *TE* of sedimentation basins downstream of a drained peatland.

Methods

The sampling period lasted two ice-free seasons, from April to November 2013 and 2014. Eight basins were equipped in three Quebec (Canada) regions (Fig. 1). However, their specific locations cannot be divulgated due to privacy of the data. All basins are located in watersheds smaller than 4000 km^2. Basins 2, 3, 4 and 5 are located on the same drainage basin in the lower portion of the St. Lawrence River valley, but empty in different tributaries. Climate is similar in all regions with spring snowmelt being the main generator of flow. Rain events are typically more frequent in the fall than in the summer. The average seasonal rainfall over ten years (April to October) for region R1 is 569 mm. Total seasonal rainfall was 489 mm in 2013 (-14%) and 552 mm (-3%) for the 2014 season. 2014 was thus a normal season in terms of rain while 2013 was below average. Region R2 received 714 mm (-11%) of rain in 2014 while the average for ten years is 798mm. Finally, region R3 received 634 mm (-18%) of rain in 2014 while the average for ten years is 774 mm. Only one basin (B2) has been studied in 2013 while the others were studied in 2014.

Field measurements

Discharge

A water level gauge (HOBO U20 (±0.05%), *Onset* or KPSI720 (±0.25%), *Measurement Specialities* or Levelogger, *Solinst*) was installed in each inflow and outflow channel at the bottom of a perforated PVC pipe covered by a thin nylon mesh to prevent clogging by sediments. Between four and eleven water discharge measurements (velocity-area technique with a *Marsh McBirney,* FlowMate 2000 model) were performed in each channel, at different stages. A non-linear stage-discharge curve was fitted for each upstream and downstream site (curve fitting tool, MathWorks) and the parameters are presented in Table 1. The equations in Table 1 allow converting levels to discharge at each site for the entire sampling period.

SSC estimation

The suspended sediment concentration (SSC) of the water entering and leaving a basin was continuously monitored with an optical turbidity sensor (NEP 390 from *Analite* (0-3000 NTU; accuracy of 1NTU) and OBS-3+ from *Campbell scientific* (0-2000/0-4000 NTU and 0-1000/0-2000 NTU; accuracy of 0.5 NTU).

Turbidity is measured in Nephelometric Turbidity Unit (NTU), which needs to be converted to SSC (g/L). As shown by Davies-Colley & Smith (2001), the variation of turbidity and SSC are closely related. Moreover, the size, the density, the composition, the shape of suspended sediments and the water colour influence the response of the turbidity sensors. Thus, every turbidity sensor must be calibrated with the water and the sediments of their own basin. Due to the technical challenge that represent a complete *in situ* calibration, the protocol of Pavey et al. (2007), which involves creating calibration samples using *in situ* water and sediments of different concentrations, was implemented in the present study. Each turbidity sensor was connected to a datalogger (CR-1000, *Campbell Scientific*), charged by a solar panel. A tipping bucket rain gauge was also deployed in each region, which was also connected to a data logger.

Trapping Efficiency

Many authors agree that Trapping Efficiency (*TE*) is an essential characteristic to consider when designing a basin (Henemann 1981; Verstraeten and Posen 2000). The velocity of the water entering a basin decreases due to the enlargement of the wetted area. Sediments with a sedimentation rate higher than the water velocity are thus allowed to settle. To estimate the proportion of sediments retained in the basin, its *TE* is measured. The sediment mass accumulated in the basin and the total sediment load entering the basin for a period of time are often used to measure *TE*:

$$TE = \frac{Accumulated\ Load}{Total\ Load} \qquad [1]$$

For this work, the *TE* of eight basins were compared. A *TE* of 75% was considered as a threshold for basin to be adequate. This threshold, albeit suggestive, provides a basis of comparison for all basins in the present study. The threshold could be adjusted if regulators and industrial partners find it too restrictive or inadequate for certain regions or configurations. *TE* was calculated using the load entering the basin (upstream) and the load leaving the basin (downstream):

$$TE(\%) = 100 \times \frac{Load_{up}Load_{down}}{Load_{up}} \qquad [2]$$

Sediment load is an indirect measure estimated by suspended sediment concentration (SSC) and water discharge (Q) as in Equation 3. Sediment load was measured at a 15 minutes time step:

$$Load(tons) = Q(m^3s^{-1}) \times SSC(gL^{-1}) \times \frac{1000L}{m^3} \times \frac{ton}{10^6g} \times \frac{60\,s}{min} \times 15min \qquad [3]$$

Factors that influence the TE of a basin

The *TE* of a basin is affected by its retention time and by the properties of the sediments that flow through the basin (Verstraeten and Poesen, 2000). For each basin, sediment properties (origin of sediments, grain size distribution), basins characteristics (measured lengths, widths and depths, inflow and outflow configurations), calibrations curves and stage-discharge curves are shown in Table 1. For most basins, data were recorded without interruption, but as shown in Table 1, there were some exceptions. Many reasons explain missing data: construction of dams by beavers that flooded the basin, instruments failure and unforeseen delays in the deployment of some sensors.

Sediments properties

After a few years, harvested peat originates from the deeper layers, where the peat is more decomposed. Moreover, drainage accelerates the decomposition rate because the upper peat layer becomes aerobic (Heathwaite et al. 1993) and tractors break peat particle. Thus, peat particles lose their stable fibric structure, become smaller and granular and hence, they are more easily eroded by wind and water (Eggelsmann et al. 1993; Payette & Rochefort 2001). The Von Post scale allows to easily determine the decomposition degree of an organic soil. This scale ranges from H1 to H10, H1 is unperturbed peat and H10 is completely decomposed peat (Stanek & Silc 1977). Samples from the superficial layer of peat were used to determine the Von Post degree of the suspended sediments at each site. In addition to determining the Von Post degree, between two and six samples per site were used to determine mean grain size diameter of suspended sediments by sieving and analysis in a Coulter counter.

In situ water samples were collected during rain events in order to determine the grain size distribution of suspended sediments, using a laser diffraction particle size analyser (Beckman Coulter LS13 320). Most of the time, multiple water samples from the same site needed to be combined in order to satisfy the minimum concentration required by the particle size analyser. Thus, up to three samples of each site were analysed by the device.

A loss by ignition (LBI) was also measured on those *in situ* water samples to determine the fraction of organic matter (O.M.) contained by the suspended sediments at each site. In some cases, drainage ditches were sufficiently deep that they reached the mineral layer, so the erosion generated by runoff could also mobilize mineral sediments that could be routed to the basin. In order to achieve this LBI, water samples were filtered on a glass fiber filter (pore 1μm), dried 24h at 70°C, weighted, burned at 500°C and weighted again.

Hydraulic properties

The size of a basin affects its retention time and large basin volumes typically lead to greater sediment deposition (Verstraeten & Poesen 2000). However, the length-width ratio of a basin may impact its retention time. WSUD (2006) recommends a minimum ratio of 3:1 to keep the retention time optimal. Every basin studied was dug directly into the peat bog. Basin B8 was the only one to be lined with rocks. All the basins were rectangular, but at two of the eight sites, multiple basins were used: basin B4 included two ponds in parallel and basin B6 had three ponds in series (Fig. 1). Basins B1, B2 and B4 were equipped with a geotextile hanging from the surface, in the middle section of the basin, to reduce the water velocity and stop some of the sediments. All basins were aligned to be parallel to the main slope and flow direction. Typical depth was of the order of 1.5 m and never exceeded 2 m when the basin was empty of sediments.

The water contained by the basin mainly comes from the excess water running off to the channel and finally to the basin. The runoff originating from layers of highly decomposed peatbog is increased when compared to that of a more recently harvested site, because the soil is less permeable (Eggelsmann et al. 1993). This would typically lead to smaller retention time in the older harvested sites than in more recent ones.

To measure the impact of the size of a basin on its *TE*, the basin Capacity (C, in m^3)-Watershed area (D, in km^2) ratio (C/D) of each basin was compared. However, no matter the size of a basin, its effective volume decreases as sediments settle to the bottom. Maintenance frequency may thus affect the *TE* of a basin as it ensures that the basin effective volume remains at its maximum and sediments are less likely to re-suspend during rain events.

Another way to measure the impact of the size of a basin on its *TE* is by the Capacity (C in m^3)-Inflow (I, in m^3) ratio (C/I). Here, *I* is defined as the total volume of water entering a basin during the ice free season. It was estimated for each basin with the fraction of rain that actually flows toward the basin (*R* in Equation 4)

$$R = 1 - \frac{(P_{common} \times w) - \int discharge}{(P_{common} \times w)} \qquad [4]$$

$$I = P_{season} \times w \times R \qquad [5]$$

Where:

R= fraction of total rain that flows as runoff toward the basin between 08/06 and 11/05;
$\int discharge$ = the water volume going through the basin between 06/08 and 05/11 (m^3);
P_{common} = precipitation between 06/08 and 05/11 (common period, in m)
P_{season} = precipitation for the entire ice-free season (April to October, in m);
w = harvested (drained) area in m^2.

The first empirical model was developed by Brown (1943), who found that *TE* for mineral sediments (TE_{mineral}) of a basin was linked to its Capacity-Watershed ratio (*C*/*W*):

$$TE_{\text{mineral}} = 100 \times \left(1 - \frac{1}{1+0.0021 \times \varepsilon \times \frac{C}{W}}\right) \qquad [6]$$

Where ε is a parameter to be adjusted. It typically ranges between 0.046 and 1, depending on basin characteristics. In the present study, the ε that yielded the lowest RMSE when fitted by a least squares approach to field measurements of *TE* against *C*/*W* ratio was selected, without prior log transformation.

However, Brune (1953) criticized Brown's equation for not being well adapted for basins with a *C*/*W* ratio smaller than 5000 m^3/km^2. In fact, small basins from different regions can have a different *TE*, while their *C*/*W* ratio is the same. However, in this study, the hydrology of all the basins is considered similar, so the Brown equation was tested. Basins used by Brown (1943) had a *C*/*W* ratio that ranged between 500 m^3/km^2 and 140 000 m^3/km^2, whereas the *C*/*W* ratios of the basins in the present study ranged between 705 m^3/km^2 and 4 170 m^3/km^2, which correspond to the lower range of those used by Brown (1943).

The second empirical model tested was developed by Brune (1953), who used 40 basins to determine the factors that may predict their *TE*. He established that the Capacity-Inflow ratio (*C*/*I* ratio) is a good predictor of the *TE* of a basin. The Inflow represents the volume of water entering the basin during the season. Later, Moris (1963) elaborated an equation from the 40 basins studied by Brune (1953). However, Morris's equation is only valid for basins with a high C/I ratio. Heinemann (1981) thus modified Morris's equation for 20 basins with a drained area smaller than 40 km^2 Basins used by Heinnemann (1981) had a C/I ratio that ranged between $3x10^{-3}$ and $2280x10^{-3}$, whereas the C/I ratio of the eight basins in our study ranged between $2x10^{-3}$ and $78x10^{-3}$, representing again the lower range of basins used in previous studies.

$$\boldsymbol{TE_{mineral} = \alpha + \frac{\beta\, C/I}{\gamma + \delta\, C/I}} \qquad [7]$$

Where the parameters of the empirical models were reported by the two aforementioned authors as shown in Table 2. In the present study, new parameters values were estimated by least squares fit of *TE* vs C/I values of the monitored basin.

Results

Time series

Prior to calculating loads and *TE* from measured SSC time series of the daily averaged data were screened for outlier. High value can be created artificially by obstruction caused by floating debris. All excessive high values that occurred suddenly, without being associated to a measured hydrometeorological event or mechanical operations on the harvesting site (pond maintenance, ditching, etc.) were removed. Daily *TE* are shown in Figure 2 (grey bars). The vertical line represents the basin maintenance (cleaning) date. The cumulative load of sediments entering (solid line) and leaving (dotted line) the basins are also shown. Total loads varied greatly from site to site. The lowest loads were measured for B3 and B8, with less than 30 ha of drained/harvested peatlands. The highest total loads were found for B2 with a drained and harvested area of 63 ha, which is the highest of all basins.

From Figure 2, it is clear that, except for basins B2 and B3, the bulk of the sediment load occurs in the latter part of the season, more than a month after basin maintenance occurred and often after a rainy period. Basin B2 showed constant negative efficiencies (i.e., higher sediment outflow than inflow), while B6 (composed of three basins in series) showed constant positive *TE*. Basin B4 (composed of two basins in parallel) and B8 (riprap structure) were characterized by positive *TE* during the high sediment load period, when it is most crucial to retain sediments. Daily precipitation in excess of 20 mm was systematically associated with subsequent negative efficiency at basins B1, B2, B3, B4 and B7. Basin B6 (33.7 m^3/ha, highest C: w ratio) is the only basin system with systematic positive trapping efficiency during rain events with daily precipitation in excess of 20 mm (Figure 2). B6 is also the only one equipped with culverts at both the inlet and outlet. The period following basin maintenance (emptying) is characterized by positive efficiency at B1, B2, B4, B6 B7 and B8. This period is variable in length, from a few days (e.g. B4) to more than one month (B6).

Sediment properties

To test if sediment properties have an impact on *TE*, the Von Post degree of surficial peat, the average grain size of suspended sediments, the fraction of organic matter contained in the suspended sediments and the peat bog area drained by each basin have been plotted has a function of *TE* (Fig. (a) to (d)). No significant correlation was found with *TE* (i.e., p-values > 0.10). However, the Von Post degree, the average sediment size, the fraction of organic matter in suspended sediments and the drained area all show relatively high correlation with the total load entering the basin ($0.4<r^2<0.72$; Figure 3 (e) to (h)). However, the significant correlation between drained area and *TE* seems to be driven mostly by one basin, with a total load of 100 tons. Taking this into account, two of these relationships, i.e. inflow load vs sediments size and percentage of organic matter, are statistically significant (p-value $\leq$ 0.05).

Gray dots in Figure 3 represent basins excluded of the correlation analysis. Basin B5 has not been cleaned often enough so its *TE* is considered biased and basin B7 only has 43 days of record, which is deemed too short for proper statistical analysis. Only basin B7 is excluded from correlations with total upstream sediment load for the same reason (Figure 3, (e) to (h)). Finally, basin B8 is excluded of the correlation analysis for sediment size (Figure 3, (b) and (f)) because the water sample collected was not concentrated enough to meet the minimum criterion of the particle size analyser.

TE modelling

As mentioned earlier, in the present study, a basin is considered efficient if its *TE* is above 75%. Based on this criterion, basins B4, B6 and B8 are considered efficient (Table 3). Those three basins also have the highest C/I ratio and C/W ratio.

Two of those three efficient basins are composed of multiple units (B4 in parallel and B6 in series). Due to the unique season sampled (2014, except for basin B2), there is no way to test if there is a statistically significant difference between the overall seasonal *TE* of simple and multiple basins configurations.

Brune-Heinemann model

The Brune-Heinemann model (Equation 7) links the *TE* of sedimentation basins to their C/I ratio. This model has been tested with six of the eight basins that receive peat sediments. Basins B5 and B7 have not been used to fit the empirical model for reasons mentioned earlier. When adjusted for basins with peat sediments, model parameters that yielded the lowest RMSE are:

	α	β	γ	δ
TE_{peat}	-1738	119.6	$1.74\ 10^{-5}$	0.0652

Thus, based on this modified Brune-Heinemann model, an efficient peat sedimentation basin (*TE* > 75%) should have a C/I ratio minimum of 0.024 m^3m3. The solid curve of Figure 4(a) shows Equation 7 developed by Brune-Heinemann for basins with mineral sediments, for comparaison. The dotted curve is the empirical model fitted for peat sediments. The root mean square error (RMSE) of the observed vs predicted *TE* is 22% and a partial model validation (by jackknife or leave-one-out resampling) is presented in Figure 4(b). All points shown on this figure lie close to the bisectrix, which would represent perfect agreement between predicted and observed *TE*.

Brown model

The Brown model links the *TE* of sedimentation basins with their C/W ratio. This model has been tested with four of the eight basins that receive peat sediments. When adjusted for the basins monitored in the present study, the ε parameter of the model is equal to 0.48. Thus, based on the modified Brown model, an efficient basin (*TE* > 75%) should have a C/W ratio minimum of 3000m^3/km^2. The dotted curves of Figure 5 (a) show the original model developed by Brown for basins with mineral sediments. The solid curve represents the model modified for peat sediments. The root mean square error (RMSE) of the observed *TE* is 10% and the partial jackknife resampling validation is presented in Figure 5 (b). This RMSE is lower than that of the Brune-Heinemann model. However, as shown in Figure 5, the Brown model is not able to predict the negative *TE* observed in some basins. The lowest possible *TE* value, for this model being 0.Basins in grey were excluded from the model for different reasons: B5 and B7 have not been used for reasons mentioned earlier and basins B1 and B3 were impossible to include because their C/W ratio was too low. This is coherent with the Brune's criticism of the model, who said that Brown's equation is not well suited for basins with C/W ratio under 5000m^3/km^2. However, those results show that *TE*s of basins with peat sediments are in the same range as those with mineral sediments studied by Brown.

Discussion

Biases and uncertainties

The stage-discharge curves developed in the present study have a certain uncertainty due to the technical challenges incurred by data acquisition. Water velocities were sometimes difficult to measure in the channels because of their relatively small wetted areas (especially during low flow periods) and their soft bottom. During low flow events, some of the velocity measurements were close to zero stability of the instrument (i.e. 0.05 m/s). However, it is difficult to quantify the impact of this uncertainty on the stage-discharge curves. All sites were subjected to the same level of uncertainty associated with flow measurements. The installation of a V notch weir upstream and downstream of each basin would have perhaps facilitated discharge measurements, but it was not realistic due to the large number of basins sampled and the risk of peat accumulation upstream of the weirs.

Another potential source of uncertainty stems from the calibration of nephelometers. The protocol of Pavey et al. (2007) can lead to differences between the size of the *in situ* suspended sediments and those used for the calibration. Those results are not presented here, but a fraction of the sediments used for the calibration, albeit originating from the bottom of the basin, are suspected to be larger than those present in the water column. Thus, there is a risk that calibration curves overestimate the higher end of the SSC values (see Samson-Dô, 2016 and Alberto et al., 2017 for details). However, this probable overestimation occurs both upstream and downstream of each basin and thus, the estimated *TE* should not be affected. However, the total load value may be positively biased because the high SSC values are likely overestimated.

The variability in meteorological conditions between sites may hinder the comparative analysis to a certain extent. Even the comparison of similar rain events from one region to the other is difficult, because antecedent conditions were not the same. However, the rain amounts encountered during the sampling seasons were not extreme. If extreme conditions have been encountered in certain regions and not in others, the comparison of efficiencies would not be as relevant.

Inter-site variability also includes the type and timing of operations during the harvesting period. Basin cleaning and ditching can affect sediment loads and trapping efficiency. In the present study, most basins showed improved trapping efficiency after maintenance. This is contrary to the finding of Es-Sahli et al. (2013) who found an increase in turbidity at the outlet of a sedimentation basin after maintenance. Es-Sahli et al. (2013) hypothesized that the stirring of sediments associated to basin cleaning mobilized the surface of basin bed and banks and that a significant portion of excavated sediments that were disposed of in the vicinity drained back into the basin rapidly. However, for many operators, the cleaning method has changed since 2013. In many cases, a pump is now used to empty the basin and sediments are disposed of at a longer distance from the basin than when an excavator is used.

Finally, the sediment grain size results contain a certain uncertainty due to the small number of water samples tested for each basin.

Sediments properties

It is known that the size and the density of suspended particles influence their sedimentation speed (Stokes law), so denser peat sediments should settle quicker that smaller/lighter sediments. Moreover, draining a peat bog accelerates the decomposition rate of the peat. More decomposed peat particles are typically smaller and more friable than less decomposed peat particles (Heathwaite et al. 1993). Thus, more decomposed peat particles are smaller and should reduce the *TE* of a basin. However, this theory could not be confirmed (Fig. (a) and (b)), in part because of the small number of basins and harvesting sites considered in this study. However, our results indicate that as harvesting progress and mean grain size decreases over the years, suspended sediments loads are likely to become larger for similar hydrometeorological conditions. Hence, basins design should account for the temporal evolution of mean grain size over the entire harvesting period, which typically lasts decades. This could be done by core-sampling the lower peat horizons of the harvesting site, determining the Von post scale and/or mean diameter of the peat in these lower horizons, and increasing the basin volume when harvesting the more decomposed peat found in these deeper regions.

Our analyses have confirmed that sediment properties seem to affect the total sediment load entering a basin (Fig. (e), (f) and (g)). As mentioned, more decomposed peat particles are typically more friable. When rain occurs, decomposed peat particles are easily drained to the basin, so the total amount of peat is increased.

While loads are impacted by sediment properties, our results further confirm that it is principally the size of a basin (via C/I ratio or C/W ratio) that affect its *TE* (Table 3), irrespective of the size and origin (organic vs. mineral) of sediments entering the basin. Proper pond design must also be associated with a maintenance frequency that guarantees sufficient volume at all times.

Those results should help the industry to know which factor must be included when designing a new basin. For instance, a peat with a higher Von Post degree should produce more peat sediment and the main design criteria should be a sufficient C/I or C/W ratio. In fact, the present study suggests that a C/W ratio of 3000

m^3/km^2 (30 m^3/ha) is the lower threshold for maintaining *TE* above 75%. This is somewhat higher than the 25m^3/ha guideline currently proposed by some Canadian jurisdictions, such as the province of New Brunswick (Canada). A number of confounding factors will need to be investigated to complete the present study. For instance, results of Table 3 show that basins with a high C/I ratio and C/W ratio are more efficient. Basins B4, B6 and B8 are the most efficient (*TE* > 75%), but they are also the only three with a flow regulation device (culvert or weir) at the upstream end, the downstream end or at both ends. Thus, basins B4 and B6 are composed of multiple sub-basins, so it is difficult to attribute the high *TE* of those three basins only to their high C/I or C/W ratio.

The C/W ratio seems to be a good tool to predict the *TE* of a basin. Results of the studied basins were in the same range as those studied by Brown (1943). Moreover, although Brune (1953) recommended to not generalize the C/W ratio relation out of the region where it was developed, a C/W ratio higher than 3000m^3/km^2 seems to be adequate, at least for the three regions included in the present study.

The C/I ratio may also be a good predictor of the *TE* of a basin. This ratio takes into account the volume of water entering the basin during a season (*Inflow*). The *TE*s observed are in the same range as those studied by Brune (1953) and Heinemann (1981). A basin with a C/I ratio higher than 0.024 m^3/m^3 seems to be adequate. A determinist numerical modelling exercise, including estimates of the sediment loads and runoff entering a basin under different rainfall scenarios could be an interesting way to confirm this recommendation.

In our study, the Brown (1943) and Brune-Heinemann (1981) empirical models have been tested with respectively only four and six sedimentation basins. Ideally, different C/I and C/W ratios should be added in order to refine those adapted models. The models would also benefit from validation using an independent sample. Validation in the present study was limited to a leave-one-out resampling scheme. However, adding sedimentation basins to the study represent an important logistic challenge. In spite of these shortcomings, the RMSE values of *TE* estimates using both models were relatively low (≤ 25%), which is an indication of the potential adaptability of these empirical formulas to the context or peat sediment basins. The Brune-Heinemann model has a RMSE of 22%, which is higher than that of the Brown (1943) model, but is more efficient at predicting the full range of *TE*, whereas the Brown (1943) model was less efficient for low *TE* values. Therefore, the Brune-Heinemann model is recommended for further studies and applications.

Until now, *TE* and SSC have been used to evaluate the influence of sedimentation basins on the water quality (Es-Salhi et al. 2013; GEMTEC 1993; St-Hilaire et al. 2006; Pavey et al. 2007b). For some jurisdictions, a fixed SSC threshold (e.g. 0.025g/L in the province of New Brunswick) is used to assess water quality downstream of a sedimentation basin. An interesting alternative would be to consider the sediment load instead of SSC, i.e. the amount of sediments leaving a sedimentation basin. For example, a basin with a *TE* of 80% that receives 30 tons of peat/year would release six tons of peat in the receptor stream. On the other side, a basin with a *TE* of 40% that receive only five tons/year would only release three tons of peat in the receptor stream. In the same manner, a basin that releases an average SSC of 0.01g/L and an average discharge of $0.02m^3/s$ is compared to a basin that releases an average SSC of 0.1g/L and an average discharge of $0.002m^3/s$. Both basins would release the same amount of peat sediments, but the second would have been suspected to pollute more than the first one if only SSC measured from a water sample would have been considered. A combination of maximum load and concentration may be a more useful guideline for peat producers.

Conclusion

This study is the first in North America, since GEMTEC (1993), to measure and compare the *TE* of numerous (eight) sedimentation basins downstream of harvested peatbogs. Moreover, basins on peat harvesting sites located in the province of Quebec, which has a somewhat drier climate than New Brunswick where the GEMTEC study was completed, had never been studied before. *TE* of sedimentation basins was measured using sediment loads instead of limiting the analysis to SSC, which allowed for a more thorough analysis. Moreover, sediment load appears to be more relevant for water quality analysis than SSC, in many respects even though it is more complicated to measure.

This work also showed for the first time a significant correlation between sediments properties (Von Post degree, average sediment size and organic matter content) and the sediment load entering a basin. No significant correlation has been found between those sediment properties and the *TE* of a basin. The latter reinforces the fact that the size of a basin compared to the harvested area and total water inflow are key factors that influence the *TE* of a basin.

Finally, two empirical models developed for sedimentation basins with mineral sediments have been adapted for peat sediments. The Brown (1943) model has been tested with four basins and the Brune-Heinemann (1981) model has been tested with six basins. Despite the small number of tested basins, those with a high C/I ratio and C/W ratio seem to be more efficient. However, there are two configurations with multiple sub-basins among them, so it is delicate to attribute their high *TE* solely to the high ratios. More research effort is required to compare multiple to single basin designs. Given the number of confounding factors (climate, flow control, structures, etc.), the numerical modelling effort currently underway is a promising avenue.

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Tables

Table 1 For each basin, monitoring period for the 2014 season (2013 for basin B2), the maintenance date, the number of days included in the TE estimation, the drained area, the basin volume, the average size of suspended sediments entering a basin, the Von Post degree of the peat, nephelometer calibration equations, stage discharge curves of each basins and basins specification are reproduced.

#	First day	Last day	Maintenance day	nb days	W (ha)	C (m^3)	Grain size (µm)	Von Post		Calibration curves	r^2	Stage-discharge rating curves	r^2	Notes
1	14-May	13-Nov	21-Oct	182	43	318	10	8	upstream	$SSC = 0.0001535NTU^{1.593}$	0.99	$Q=0.2239x-0.045$	0.89	
									downstream	$SSC = 0.0000009246NTU^{2.287}$	0.87	$Q=0.2576x-0.0501$	0.91	
2	13-May	08-Nov	31-May	95	63	827	44	8	upstream	$SSC = 0.0002218NTU^{1.556}$	0.96	$Q=0.08291x^{3.425}$	1.00	Beaver dams: from 17/07 and 06/08 and from 23/09 to the end
									downstream	$SSC = 0.004536NTU^{1.254}$	0.97	$Q=0.07509x^{1.261}$	1.00	
3	08-Jul	13-Nov	-	120	23	161	351	4.5	upstream	$SSC = 0.005041NTU$	0.98	$Q=3898x^{5.514}$	0.96	New basin
									downstream	$SSC = 0.001805NTU$	1.00	$Q=6873x^{8.257}$	0.65	
4	01-Jul	13-Nov	18-Aug	158	47	1400	64	2	upstream	$SSC = 0.002115NTU$	0.99	$Q=0.7726x^{2.393}$	0.94	Multiple basins (in parallel). Culvert at the downstream end
									downstream	$SSC = 0.001552NTU$	0.99	$Q=0.9252x^{4.846}$	0.90	
5	28-May	29-oct	19-Aug	112	54	381	256	3.5	upstream	$SSC = 0.008091NTU^{1.273}$	0.99	$Q=0.1192x-0.02401$	0.97	Upstream calibration curve: Equation 1 for turbidity<20NTU. Equation 2 for turbidity>550NTU and linear regression for intermediate turbidity values. Basin was filled with sediments prior to maintenance
										$SSC = 0.0009152NTU+0.0991$				
										$SSC = 0.00003707NTU^{1.513}$	0.95			
									downstream	$SSC = 0.00002447NTU^{1.771}$	0.92	$Q=1.001x^{3.548}$	0.95	
6	30-Apr	24-Nov	21-Aug	85	42	1415	110	6.5	upstream	$SSC = 0.00001569NTU^{1.908}$	0.98	$Q=0.8x^2-0.4139x+0.05367$	0.87	Beaver dams from 25/05 to 03/08. Multiple basins (in series). Culverts at the upstream end of basins
									downstream	$SSC = 0.00000499NTU^{1.755}$	0.98	$Q=0.8436x^2-0.6615x+0.1292$	1.00	

7	24-Aug	05-Nov	03-Oct	33	66	1658	180	4	upstream	$SSC = 0.0006155 NTU^{1.35}$	0.99	$Q = 1.6x^2 - 0.2784x - 0.004359$	0.98	Technical problems until 24/09
									downstream	$SSC = 0.00003409 NTU^{1.877}$	0.98	$Q = 8.2x^2 - 1.571x + 0.0777$	0.91	
8	25-Aug	05-Nov	30-Sept	72	23	938		5	upstream	$SSC = 0.005603 NTU - 0.05$	0.83	$Q = 0.0000000009468 exp 43.12x$	0.86	Downstream weir is rip-rapped
									downstream	$SSC = 0.0044 NTU - 0.045$	0,81	$Q = 0{,}0000000007019 exp 35{,}16x$	0,97	

Table 2. Parameters values of the Brune (1953) model for trapping efficiency.

	α	β	γ	δ
Morris (1963)	0	1	0.012	1.02
Heinemann (1981)	22	119.6	0.012	1.92

Table 3 Seasonal trapping efficiency (TE), Capacity/Inflow ratio and Capacity/Watershed ratio of each basin. TEs in bold (B4, B6, B8) are near or above 75%.

# Basin	TE (%)	C/I ratio 10^{-3} m^3/m^3	C/W ratio m^3/km^2
1	-116	2	740
2	49	22	1319
3	-39	3	706
4	**85**	**14**	**2985**
5	-379	3	706
6	**84**	**18**	**3369**
7	30	7	2512
8	**73**	**78**	**4169**

Figures Captions

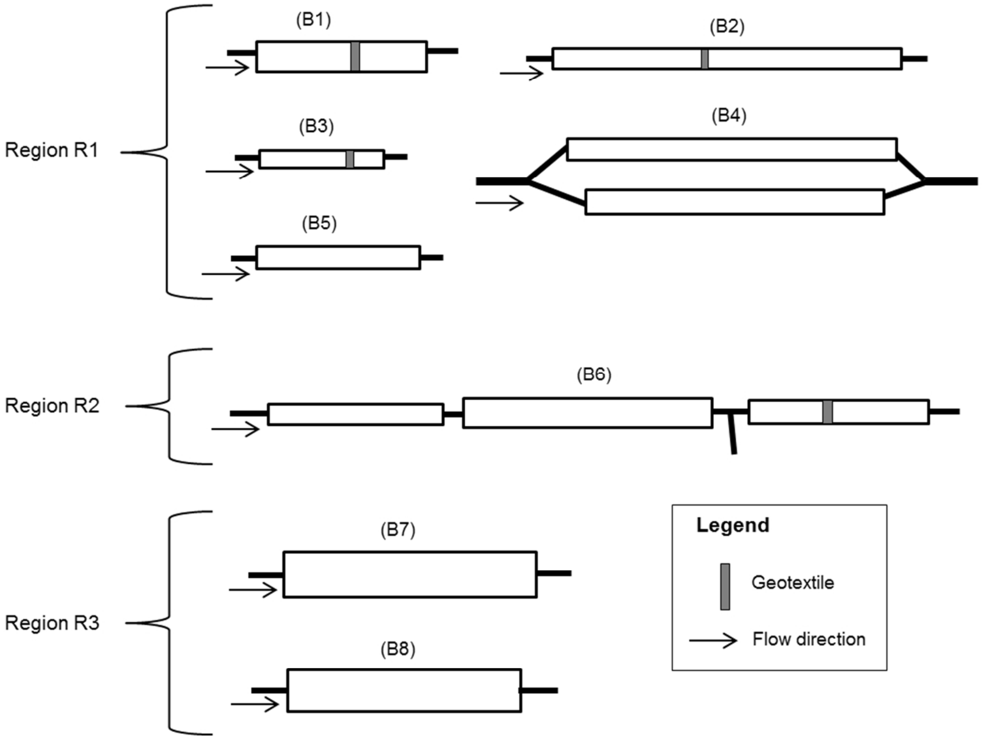
Fig. 1 Scale diagram (1:100) of the eight basins studied (aerial view).

Fig. 2 Time series of the upstream and downstream sediment load of basins B1 to B8 and the daily TE (gray bars). The vertical line shows the basin maintenance date.

Fig. 3 TE of basins related to (a) the Von Post degree of the peat bog drained, (b) the average suspended particles size (μm), (c) the percentage of organic matter contained in suspended particles, and (d) the size of the watershed area. The total sediment load entering the basin is related to the same features ((e) to (h)). Gray dots represent excluded basins.

Fig. 4 (a) Adapted Brune-Heinemann model (solid curve), Brune-Heinemann curve (dotted curve) and field observation (black dots). (b) Partial validation of the adapted Brune-Heinemann model. Gray dots represent excluded basins.

Fig. 5 (a) Adapted Brown model (solid curve), Brown curves for different ε values (dotted curves) and field observation (black dots). (b) Partial validation of the adapted Brown model.



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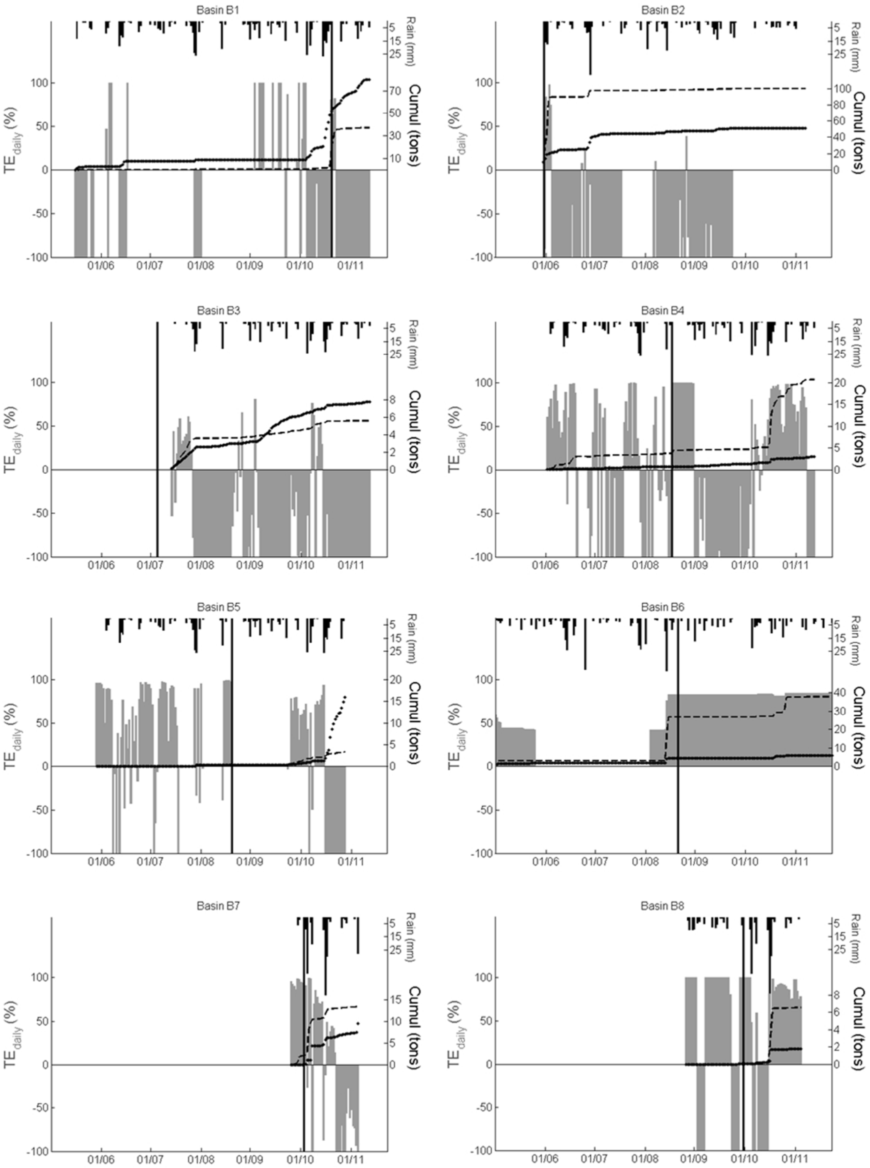

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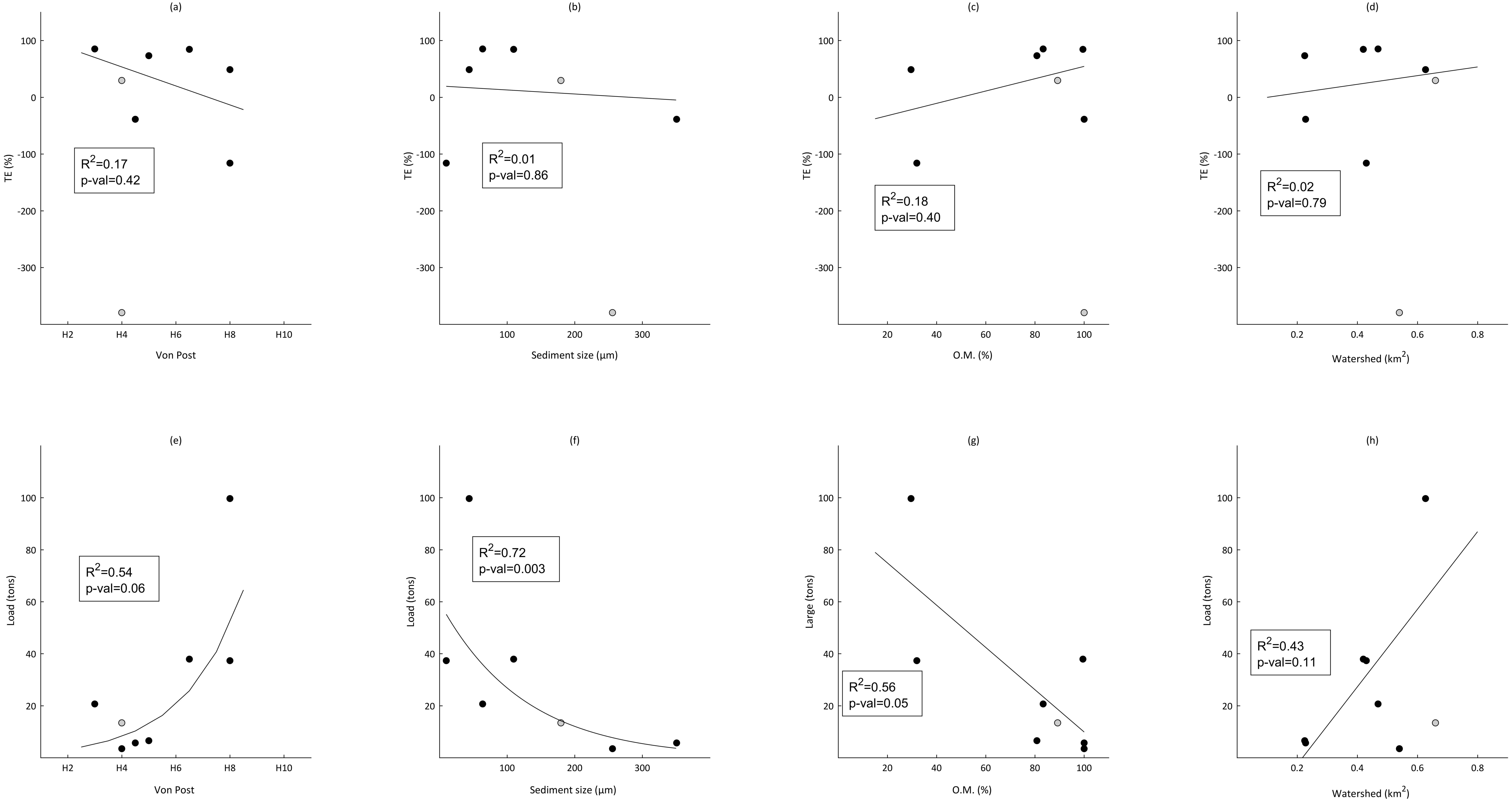
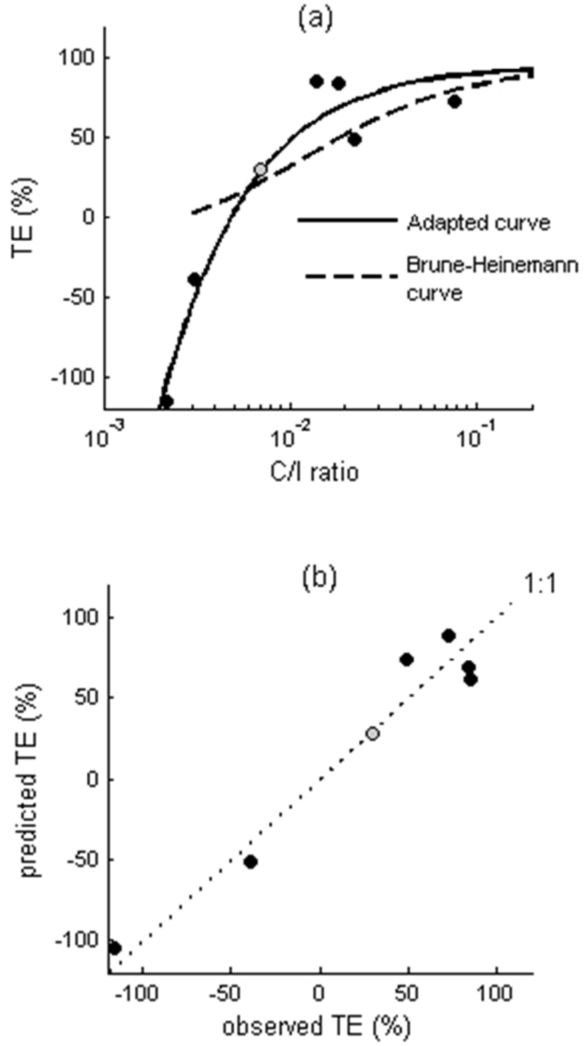

(a)
TE (%)
Von Post
R²=0.17
p-val=0.42
(b)
TE (%)
Sediment size (μm)
R²=0.01
p-val=0.86
(c)
TE (%)
O.M. (%)
R²=0.18
p-val=0.40
(d)
TE (%)
Watershed (km²)
R²=0.02
p-val=0.79
(e)
Load (tons)
Von Post
R²=0.54
p-val=0.06
(f)
Load (tons)
Sediment size (μm)
R²=0.72
p-val=0.003
(g)
Large (tons)
O.M. (%)
R²=0.56
p-val=0.05
(h)
Load (tons)
Watershed (km²)
R²=0.43
p-val=0.11
100
0
-100
-200
-300
80
60
40
20
H2
H4
H6
H8
H10
200
300
0.2
0.4
0.6
0.8



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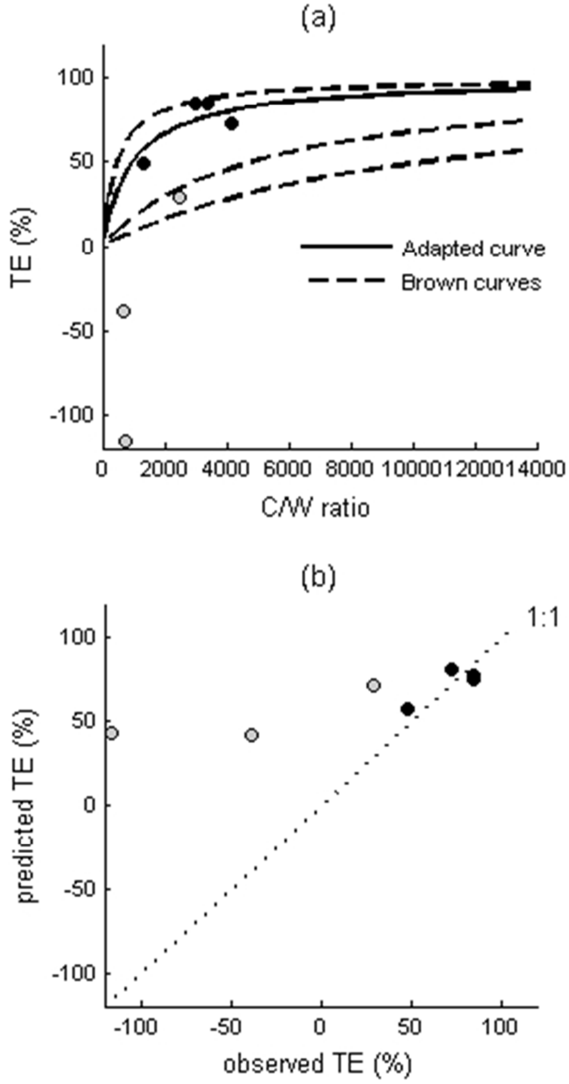

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