Mactaquac Aquatic Ecosystem Study
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Observed Suspended Sediment Characteristics of the Saint John River (2018)

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DISCLAIMER

Intended use and technical limitations of the report, "Observed Suspended Sediment Characteristics of the Saint John River (2018)". This report presents suspended sediment data collected in support of the Mactaquac Aquatic Ecosystem Study and is not intended as a stand-alone interpretation of existing conditions. The data contained herein were intended as input into the hydrodynamic model scenarios considered for Options 1-3 and were collected over a three-year period under high flow conditions to provide a general understanding of the range of maximum suspended sediment characteristics at discrete locations. The historical review was limited to publicly available sources. No attempt has been made to statistically link these observations with other physical or climatological parameters or processes of influence. The CRI does not assume liability for any use of the included data or analyses outside the stated scope.

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1 Introduction

All reservoirs formed by dams experience some degree of sediment deposition and accumulation. Sedimentation occurs when the velocity of the water no longer supports the transport of the sediment particles and they drop out of suspension due to gravity. Deposition of coarser sediment occurs in the upper reaches of the reservoir and where tributaries enter, while finer sediments may reach the dam (Kondolf, 1997; Abraham et al., 1999). Sedimentation of a reservoir can reduce its storage capacity, affect its ability generate hydroelectricity, and negatively impact aquatic life. As water storage volume is lost, water supply and flood control will decline. Trapping sediment behind a dam also leads to degradation of the downstream channel bed through the release of clear water, stream bank erosion, and alteration of riparian habitat.

The purpose of this report is to: (1) determine if turbidity could be used to produce an estimate of TSS; (2) determine background limits of both parameters so that Canadian Council of Ministers of the Environment (CCME) guidelines can be adhered to in the event that work is done on the Mactaquac Dam and sediment must be discharged from the headpond; and (3) use available data to make a link between total suspended sediment levels in the water and the volume of sediment that has accumulated behind the dam over its lifetime. We also aim to comment on the geological and geomorphological process governing the supply of sediment to the Saint John River. Sediment management is often the most challenging aspect of a dam removal. In the Mactaquac Headpond (MH) the nature of sediment in the reservoir plays an important role in decision-making about the future of the Mactaquac Dam.

2 Geology and geomorphology – Factors influencing sediment delivery to the Mactaquac Headpond

Sediment is fragmented rock material that has been broken down by the processes of weathering or erosion. Sediment is transported through a watershed by the forces of wind, water, ice, and/or gravity on the particles. In a river, erosion and shear stress continually remove material from the river bottom and banks. In a fluvial system, sediment can be transported either as dissolved load, in suspension (entrained in the water) or as bed load (rolling or bouncing along the bottom). Important factors influencing the sediment yield of the Saint John River watershed include but are not limited to: amount and intensity of rainfall; topography and relief; land use; geology and soil type(s); type of ground cover (impervious versus pervious); and the nature of the watershed including slope and channel size.

Sedimentation of a reservoir occurs when the velocity of the water slows to a point that it can no longer transport the sediment particles and they drop out of suspension and become trapped behind the dam. Coarser materials drop out first, while finer materials are carried further, with the distance being dependent on the water velocity (Strand and Pemberton, 1982). Over time, sand and gravel deposition forms a delta at the upstream end of the reservoir while finer sediments and silt may reach the dam. Sedimentation of a reservoir is affected by many factors including: slope of the stream; daily fluctuations in water and sediment inflow; length and shape of the reservoir; particle size variation; and the inflow pattern.

The landscape we observe today in New Brunswick was formed during the Cretaceous (145-66 Ma) and Tertiary (65-~2 Ma) eras by tectonic and erosional forces. Glaciers and water modified the area during the Quaternary (~2 Ma-present). New Brunswick is located in the Canadian Appalachians and consists of a complex belt of folded mountains comprising highlands, flat topped rolling uplands and gently rolling lowlands (e.g., Fahmy et al. 1986). The surficial geology of the Saint John River Valley comprises Late Wisconsinan (50,000 YBP) morainal sediments whose constituents are lodgement till, ablation till and associated sand and gravel deposits with minor reworking by water (e.g., Rampton et al. 1984). The morainal deposits vary from hummocky, ribbed and rolling ablation moraines (generally ≥ 1.5m thick), to blanket (between 0.5-3m thick) and discontinuous veneer (generally ≤ 0.5m thick) deposits of loamy lodgement till, minor ablation till, silt, sand, gravel, and rubble (e.g., Rampton et al. 1984).

Relief, or slope, is a major factor influencing sediment delivery. The MH sits in an area of low relief (0-10° slope) and low energy. Considering the low relief and surrounding surficial geology, it could be predicted that that soil erosion is minimal and therefore, sediment supply to the MH is also relatively low (O'Sullivan et al., 2016). However, anthropogenic related erosion, particularly from agriculture within and upstream of the MH, is occurring. In addition, there are fluxes in erosion due to the freeze-thaw cycle and spring snowmelt. Though, these are seasonal events and given the gently sloping relief of the catchment, it is highly likely that sediment supply through soil erosion is significantly less than that in other dam removal projects, e.g., Elwha and Glines Canyon, where high magnitude landslide events occurred with high frequency. Therefore, O'Sullivan et al. (2016) concluded that the MH lies in a low energy environment and the sediment yield supplied to the reservoir is likely to be relatively low even when erosion from weathering and anthropogenic forcing is considered.

In contrast, the headwaters of the SJR have significantly more energy to transport sediment due to the topography and steeper gradient. There are two other large hydroelectric dams on the SJR above Mactaquac: The Beechwood Generating Station built in 1955 and the Grand Falls Generating Station built in 1931. Additionally, there are a number of dams on tributaries, including the Tobique and the Aroostook. O'Sullivan et al. (2016) concluded that the sediment supplied by the headwater erosion is likely to be held behind the Beechwood Dam in its reservoir. The gradient of the river is much steeper above the Grand Falls Dam (Figure 1). The Beechwood headpond has a higher gradient in its upper half but becomes very flat in the lower half, which would allow sediment to drop out of suspension.

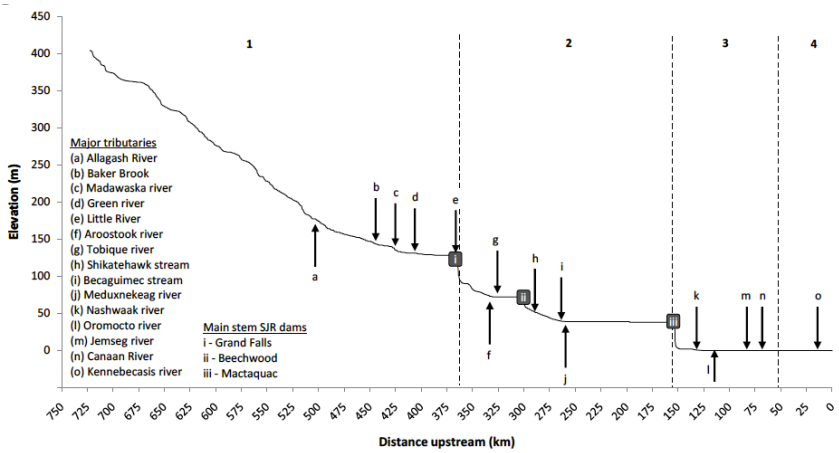


Figure 1. Elevation profile of the Saint John River from the headwaters to the river mouth. Arrows represent major tributaries, squares represent major hydroelectric dams (Kidd el al., 2011)

3 Total suspended sediment and turbidity

Total suspended sediment (TSS) is defined as particles of sediment >2 μm that are suspended in the water column. From an aquatic ecosystem perspective, suspended sediment is of interest because it can absorb heat, increasing the water temperature. It can lead to respiratory distress in fish, or it may be transported and deposited in areas of fish habitat causing degradation of the habitat in a process known as 'sedimentation' (Yamazaki et al., 2017).

Turbidity is a measure of the optical clarity of the water or how the light scatters off the particles in the water. The clarity or transparency of the water is affected by the presence of biotic or abiotic suspended or dissolved matter but turbidity is not a measure of the particles themselves. High turbidity is associated with elevated stress in fish, predatory efficiency, and suffocation of incubating salmonid embryos. It also affects primary production by blocking sunlight.

3.1 Historical Conditions

3.1.1 1994 – 2014

The analysis of historical data, collected by the New Brunswick Department of Environment (now NBDELG) between 1994-1998 and 2003-2014, showed that the amount of suspended sediment in the Saint John River system is very low. TSS concentrations were routinely below lab detection level (15 mg L^{-1} pre-2005 and 10 mg L^{-1} 2005 and later) in the summer and fall. Peak values of 70 to 110 mg L^{-1} occurred during the spring freshet and after fall storms. This suggests that the bulk of sediment available to be moved from overland flow occurs during the snowmelt. Directly following some major rain events the TSS levels were observed peaking between 30 to 80 mg L^{-1} and rapidly lowering back to pre-event conditions within a matter of days (Yamazaki et al., 2017). Historical fall storms resulted in peak levels of 12 to 77.5 mg L^{-1}, depending on location. The historical record clearly shows that TSS levels never exceed 20 mg L^{-1} during prolonged low flow conditions (i.e., the summer average). Levels only exceed 20 mg L^{-1} during the spring freshet and large precipitation events; a more in-depth analysis of historical TSS values can be found in Yamazaki et al. (2017).

Based on the analysis of historical DELG data, spring freshet peaks for turbidity range from 2 to 15 NTU while summer averages are in the range of 0.6 to 3.9 NTU. Similar to TSS, turbidity also shows a peak during fall storms in the range of 4 to 52.8 NTU. The limit of quantitation for turbidity was consistently 0.200 NTUs (Yamazaki et al., 2017).

3.1.2 2015-2017

Field sampling was conducted in 2015, 2016, and 2017 and focused on establishing a range of TSS values. Data collection was attempted during periods of high flow. Correlating suspended sediment load to precipitation events proved challenging due to the large size of the catchment area versus the limited distribution of rain events and variable snow-pack melt rates (Yamazaki et al. 2017). The 2015 sampling program was unsuccessful in capturing the freshet but some data were obtained during peak and post-peak periods. TSS levels between 23 and 25 April 2015 were 30 mg L^{-1} at Fredericton and Mactaquac but dropped quickly by 29 April. The rapid reduction between 25 and 29 April despite relatively similar water levels suggest that the majority of available sediment is moved early in the event as the result of overland flow introduction of fine sediments (Yamazaki et al., 2017). Turbidity was also measured, with a maximum of 35 NTUs observed.

The 2016 sampling run began earlier (8 April in Fredericton, 14 April in Nackawic and Perth Andover, and 19 April for Clair to Fredericton). The peak of the freshet was 14 April. Results show TSS values ranging from 8.6 – 75.9 mg L^{-1} during the spring freshet with the highest values near Florenceville (Yamazaki et al., 2017).

In 2017, sampling was only conducted during the freshet from the Bill Thorpe Walking Bridge in Fredericton. Observed TSS values peaked on 17 April at 30 mg L^{-1}. Sampling was conducted from Clair to Jemseg after the freshet following a large precipitation event (7-11 May) and observed TSS values averaged 11.8 mg L^{-1}. Again, though water levels were similar to April, TSS values had dropped off indicating that the bulk of sediment available to be moved from overland flow occurs during the snowmelt (i.e., early in the freshet).

3.2 2018 data collection

3.2.1 Methods

As many of the historical values were below the lab detection levels, they could not be used for analytical purposes. Therefore, more robust sampling was completed for TSS and turbidity in the summer of 2018. Data were collected between 8 May and 14 August 2018 at two transects in the headpond (Meductic and Long's Creek) and at the Mactaquac Generating Station (MGS) to determine background levels and to further explore the relationship between the two parameters in the Saint John River. Although it is technically within the Mactaquac Headpond, the river reach near the Meductic area was considered as representative of fluvial conditions based on: 1) the evidence of fluvial processes affecting the river bathymetry (Figure 2) as seen in the presence of sandy features and boulders; and 2) the lack of thermal stratification occurring during summer conditions (Figure 3) as measured on July 30, 2015. The Long's Creek site was considered to be within a depositional zone. The MGS samples were collected from the turbulent water in the tailrace because it was the most accessible location.

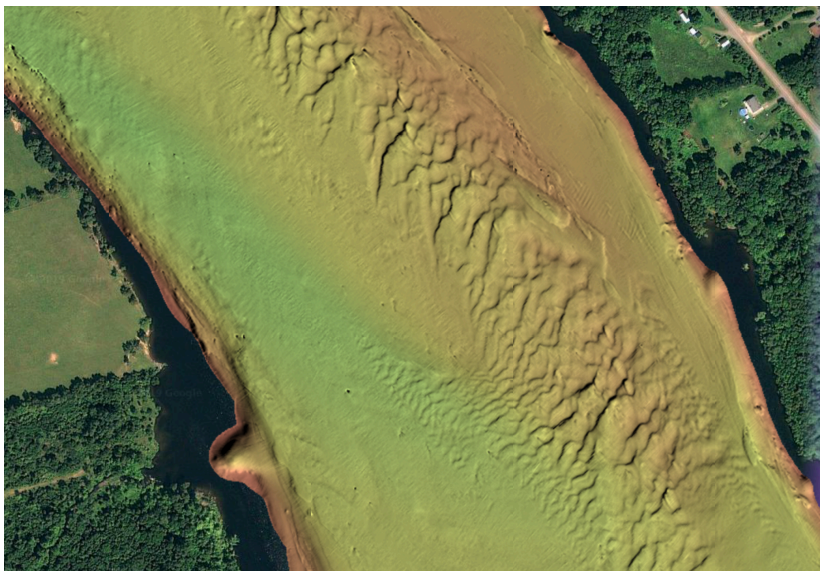


Figure 2: Typical Bathymetry of River Reach Near Meductic, Saint John River, New Brunswick (Image derived from bathymetric data obtained in 2014 (Bremner et al, 2016))

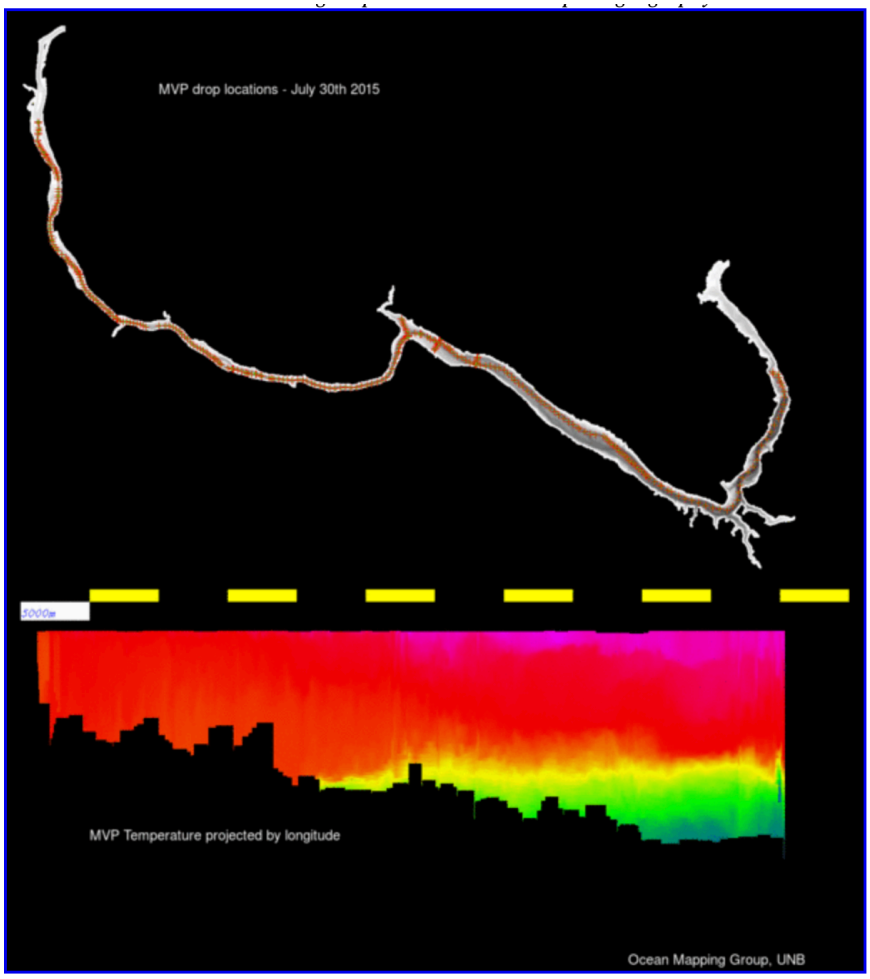


Figure 3: Thermal Imagery Cross-Section of the Mactaquac Headpond, Saint John River, NB on July 30, 2015 (Image generated using 303 thermal profiles obtained from towing a Moving Vessel Profiler over an 8-hour period from Woodstock, NB to Mactaquac, NB)

One-litre water samples were collected from the Saint John River immediately following the peak of the 2018 spring freshet and throughout the summer using a 2.2 L Van Dorn Beta horizontal water sampler. Surficial (upper 1 m) samples, as well as additional ones taken throughout the depth of the water column were taken from a boat in the headpond at the Meductic and Long's Creek sites. Only surficial samples were taken using the sampler from the deck of the MGS.

A separate set of samples were taken from the Bill Thorpe Walking Bridge from 30 April to 14 August 2018 since they were easy to obtain, even during inclement weather and flood conditions. It was recognized that there are complex hydraulic and hydrologic differences between the headpond sites and the Walking Bridge site that is downstream of the dam and Fredericton, but we felt that they were worth collecting anyway.

Samples were kept refrigerated until analyzed. Turbidity, Total Suspended Solids (TSS) and Volatile Suspended Solids (VSS) analyses were conducted in the Environmental Lab, Department of Civil Engineering, University of New Brunswick, Fredericton. Turbidity analysis of each sample was measured with a nephelometer (Hach 2100Q Turbidimeter) in the lab. TSS and VSS analyses were conducted using the methods outlined by APHA (1998), 2540D Total Suspended Solids Dried at 103-105°C and 2540E Fixed and Volatile Solids Ignited at 550°C, respectively.

3.2.2 2018 Results and Discussion

Figure 4 shows that water levels began rising around 16 April 2018 and hit their peak on 28 April 2018. Rapidly rising temperatures (leading to a high rate of snowmelt), coupled with several rain events at the end of April, led to a rapid rise in water level in the Saint John River.

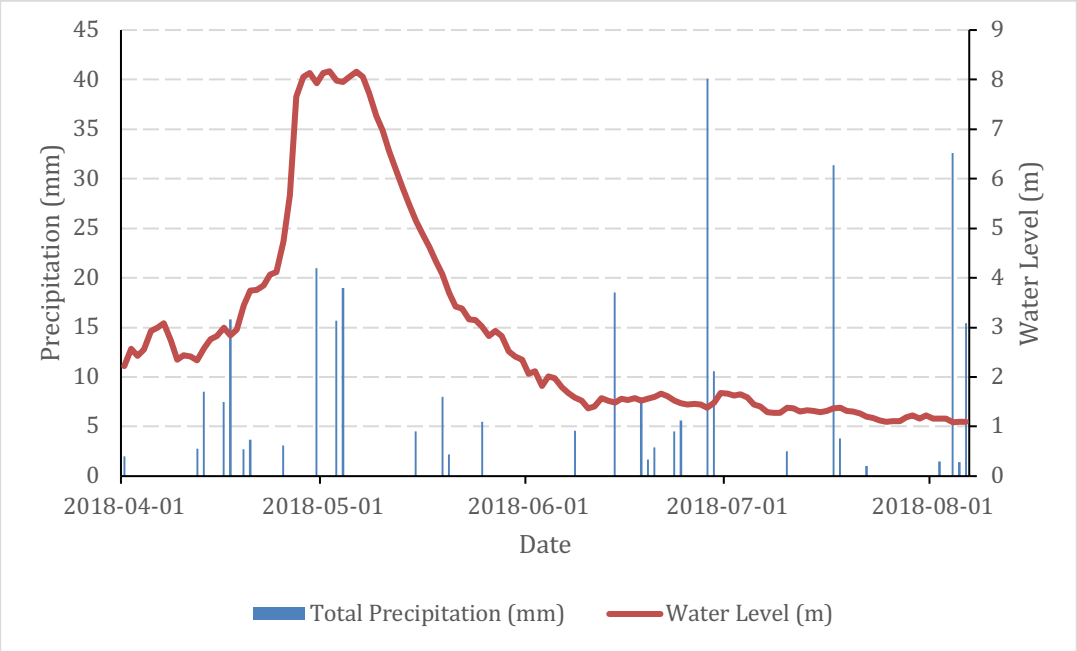
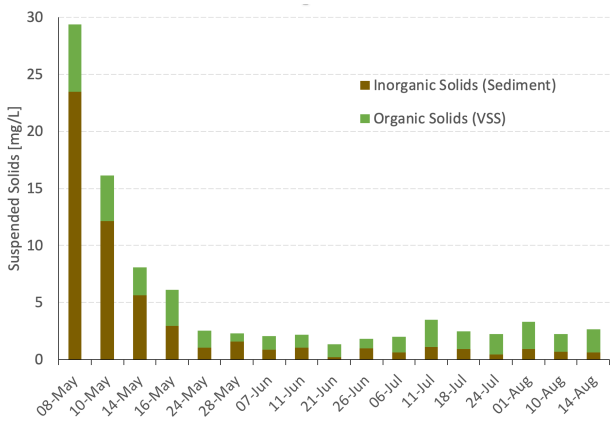
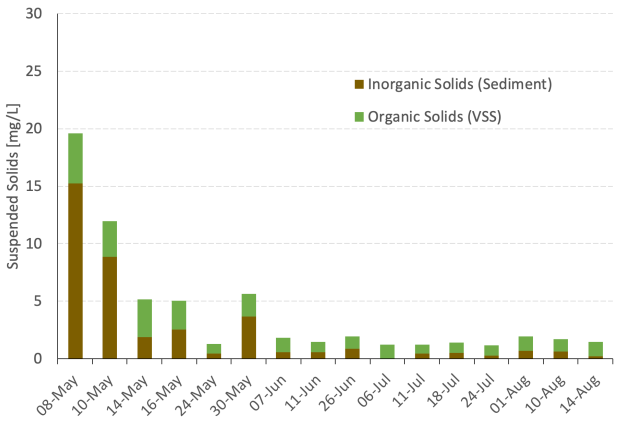


Figure 4: Daily total precipitation and water level between 1 April and 6 August 2018 at Fredericton (Environment and Natural Resources, 2018a, b)

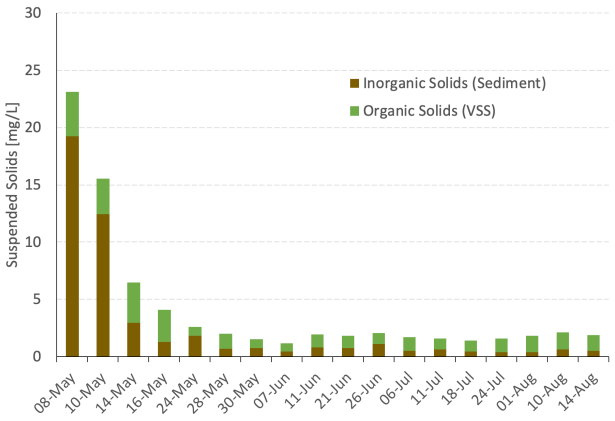
Due to logistics and ice presence, no samples were taken above the Mactaquac Dam prior to 8 May 2018. The TSS and turbidity samples taken in 2018 should be considered as representative of post-freshet and low-flow conditions. The highest observed TSS value in the headpond (29.4 mg L^{-1}) was at the farthest upstream site Meductic on 8 May 2018, dropping rapidly over the following week (Figure 5a). Mean TSS values did not exceed 5 mg L^{-1} after 16 May. Summer levels (i.e., background levels for low flow), ranged between 1.0 and 3.5 mg L^{-1}, averaging 1.90 mg L^{-1} over all sites after 1 June 2018 (Figures 5a-c). Based on the results from 2015-2017, it is expected that the majority of available sediment would have been moved early in the event (i.e., prior to 30 April). Therefore, the bulk of the sediment likely moved through the system before sampling began. Unlike in the historical dataset, summer precipitation events did not seem to have an effect on TSS concentrations, as they remained below 10 mg L^{-1} even after >70 mm of precipitation. The organic portion (VSS) of the total suspended solids (TSS) concentrations increased proportionally with time through the summer, following a similar trend in previous years.



(a) Meductic Site



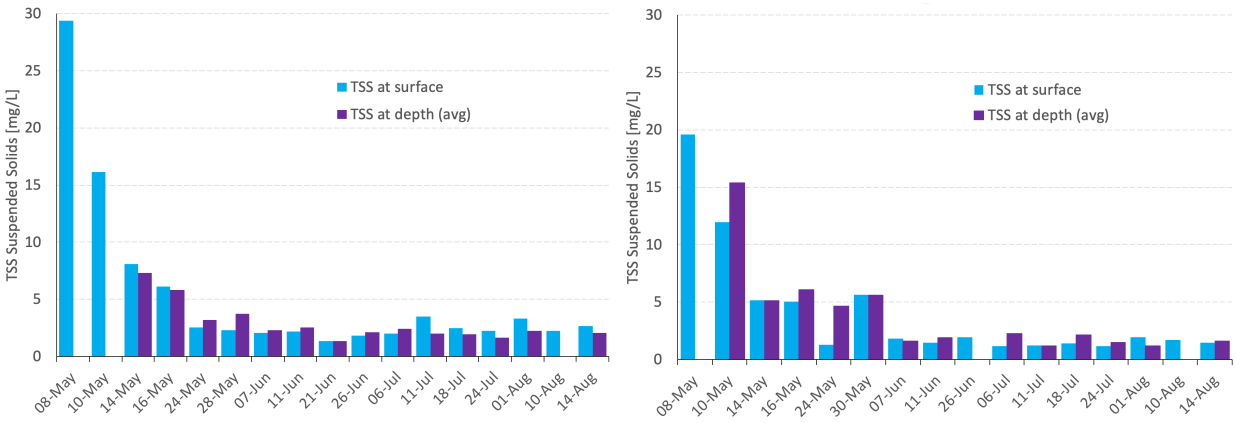
(b) Long's Creek Site



(c) Mactaquac Generating Station Site

Figure 5a-c: Total suspended solids, illustrated as separate components of Inorganic Solids (sediment) and Volatile Organic Solids (VSS) measured from 08 May – 14 August 2018 in the Headpond

Samples were also taken at various depths at Meductic and Long's Creek after mid-May. For the period that we sampled, the TSS values were similar throughout the water column. The values shown in purple in Figure 6 are the average values for samples taken at various depths. Typically, replicates were taken at Meductic (Figure 6a) at approximately 5.5 and 11m, and at Long's Creek (Figure 6b) at 5.5, 11, 23, and 27m, all with very similar readings at both sites.



(a) Meductic **(b) Long's Creek**

Figure 6: Surficial and depth-averaged total suspended solids (TSS) measured from 08 May – 14 August 2018 in the Mactaquac Headpond

Additional samples were collected downstream in Fredericton from the Bill Thorpe Walking Bridge starting on 30 April 2018. Recognizing that these samples are taken from hydraulically and hydrologically different conditions than the upstream sites in the headpond, they were still considered useful and interesting. Because we were able to start collecting samples slightly earlier than upstream, the initial observed values of TSS were higher. The highest TSS value of 73.1 mg L^{-1} was observed on 30 April and dropped off quickly afterwards (Figure 7). TSS levels may have been even higher prior to the start of the 2018 sampling program, though.

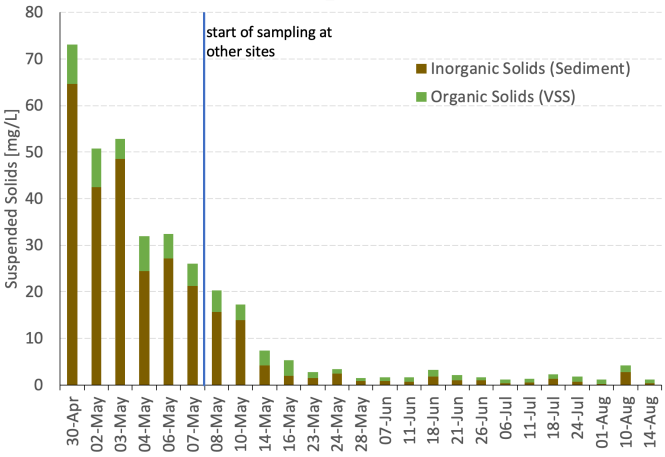


Figure 7: Total suspended solids, illustrated as separate components of Inorganic Solids (sediment) and Volatile Organic Solids (VSS) measured from 30 April – 14 August 2018 from Walking Bridge

TSS values varied slightly from upstream to downstream sampling sites. Summer averages (after 1 June) were highest at Meductic 2.24 mg L^{-1} dropping to a low of 1.46 mg L^{-1} at Long's Creek, then climbing slightly to 1.7 mg L^{-1} at the MGS and 2.0 mg L^{-1} at the walking bridge. Discounting the extra days of data at the walking bridge (earlier in the spring when TSS was higher), the mean post-freshest values and overall mean values show the same pattern: highest at Meductic and lowest at Long's Creek (Figure 8). This pattern indicates that sediment may be settling out of suspension in the reservoir below Meductic, decreasing TSS levels.

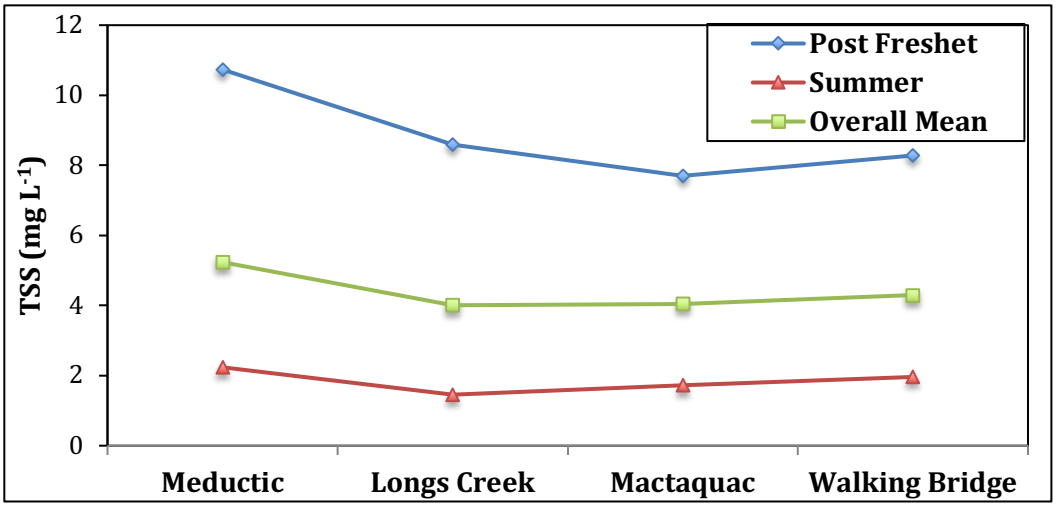


Figure 8: Mean TSS values for samples taken at four transects between 8 May and 14 August

Turbidity values were measured after 7 May 2018. Levels peaked at 41.2 NTU on 7 May and dropped below 10 NTU for all sites after 16 May. The summer average (after 1 June) was 1.53 NTU. Analyses of historical and new data showed that during late spring and summer levels of sediment and turbidity in the Saint John River are extremely low, with summer background levels for TSS in the Saint John River approximately 1.0 – 3.5 mg L^{-1} and typical summer background levels for turbidity in the range of 0.6 – 3.9 NTU.

3.2.3 Turbidity-TSS relationship and CCME limits

The relationship between turbidity and TSS is site-specific and depends on geology and landscape features. At sites where the relationship between the two parameters is known, turbidity can be used as a surrogate to predict TSS concentrations. Turbidity can be measured in the field, thereby avoiding the greater time and expense of testing for TSS. Though a review of historical turbidity and TSS data as well as field data from 2015 – 2018 were used to determine the background levels for each parameter, the relationship equation was determined only using the 2018 data.

The turbidity/TSS relationship can be interpreted by a linear regression analysis. The equation for the regression line for the 2018 data was determined to be $y = 1.2498x - 0.4084$, where y = turbidity and x = TSS, and the R^2 value was 0.94 (Figure 9). This R^2 is very similar to others reported in the literature (summarized in Rügner et al., 2013). 1 NTU correlates roughly to 1.127 mg L^{-1} TSS, which is comparable to the literature where factors between 1 and 2 have been reported (Rügner et al., 2013). The relationship between the two parameters is strongest at levels <12 mg L^{-1} TSS. The residual plot shows a random distribution around the horizontal line at values <30 mg L^{-1}, which indicates that the choice of the linear regression model was appropriate. Data show a stronger correlation than those presented in Yamazaki et al. (2017), where there were limited data points plotted (n=21).

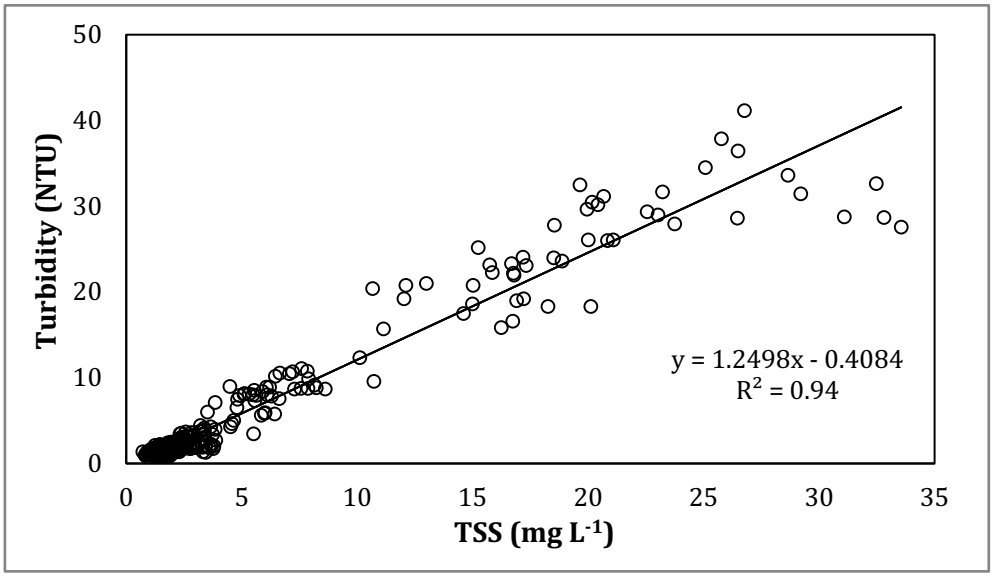


Figure 9: A linear regression model of TSS and turbidity. A strong relationship is evident at low concentrations.

The results of this study indicate that turbidity can be used as a viable surrogate for determining TSS in the Saint John River. According to the CCME guidelines, during clear flow TSS should not increase from the background level (BL) by more than 25 mg L^{-1} for short-time exposure (<24 hrs). For 1-30 day exposure, the maximum average increase should be no more than 5 mg L^{-1} above the BL. In high flow, the maximum increase of TSS should be no more than 25 mg L^{-1} from the BL (when the BL is between 25 and 250 mg L^{-1}), or no more than 10% increase when the BL is >250 mg L^{-1}.

Analysis of historical data and 2018 field data collection show that during summer and late fall, levels of sediment and turbidity in the Saint John River are extremely low. The BLs for TSS in the Saint John River are 1.0 – 3.5 mg L^{-1} while normal BLs for turbidity are within the range of 0.6 – 3.9 NTU. If work on the Mactaquac Dam was to be done during clear/low flow conditions then TSS should remain below 8.5 mg L^{-1} to comply with CCME guidelines. This would correlate with a turbidity value of ~10.2 NTU. If work was done during the post-freshet, TSS concentrations could range up to ~100 mg L^{-1}, corresponding with a turbidity value of ~124 NTU.

3.2.4 Using Total Suspended Solids to Determine Trapping Efficiency of the Mactaquac Dam

One of the goals of the sampling program is to further the understanding of the movement and fate of the sediment in the Saint John River, specifically using the data to provide an additional means of estimating the post-inundation sediment thickness in the Mactaquac Headpond. It was assumed that the reservoir is large enough and deep enough that it acts as a sediment trap. Trap efficiency (TE) is defined as the ratio of deposited sediment to the total sediment inflow for a given period, or the percentage of total incoming sediment that is retained or "trapped" in the reservoir. The best way to determine trap efficiency is to use incoming and outgoing sediment concentrations in a long-term dataset, which we are currently developing by collecting TSS samples in the upper and lower reaches of the Mactaquac Headpond. For an accurate estimate of sediment inflow, values of TSS and correlated river discharge are needed throughout the year, including during the freshet, low flows, fall storms, and winter conditions. Site-specific values of sediment density are also needed to estimate the thickness of inundated material once the suspended sediment has deposited.

The amount of sediment trapped by a dam depends on a complicated set of variables, not just the capacity and flow, such as geometry of the reservoir, management of water levels, incoming sediment concentration, and grain-size distribution (Snyder et al., 2004). Lewis et al. (2013) commented that the highest efficiency occurs when the water is still and sediment sinks uniformly, while the lowest TE occurs during turbulent conditions, such as during the freshet. Brown (1943) developed a curve that relates TE to a capacity/watershed ratio based on data from 15 reservoirs (Equation 1, Brown (1943)):

$$TE = 100\left(1 - \frac{1}{\left[1 + 0.0021D\frac{C}{W}\right]}\right) \quad \langle 1 \rangle$$

Where *TE* is the trap efficiency of a reservoir in percentage of sediment trapped; *C* is the capacity of the reservoir in m^3 and *W* is the catchment area in km^2. Values of *D* range from 0.046 to 1, with a mean value of 0.1 and they are dependant on the characteristics of the reservoir. Brown (1943) suggests using a value of *D* closer to 1 for reservoirs in regions with smaller and more variable runoff and for those that hold back and store flood flows (i.e., not a run-of-the-river dam like Mactaquac). D = 0.1 is recommended for average conditions. Trap efficiency is not static; it changes as the reservoir fills with sediment and with hydrologic conditions (Verstraeten and Poesen, 2000). Trap efficiency would likely decrease if the water surface elevation in the reservoir is drawn down often, providing the opportunity for re-suspension and transport of stored sediments (Verstraeten and Poesen, 2000).

The total capacity [*C*] of the Mactaquac reservoir is 1,307,491,000 m^3 with a surface area of 83.85 km^2. Catchment area (*W*) is 39,898 km^2. *C/W* is 32,771 m^3 km^{-2}. Due to high precipitation and run-off in the region, residency time is fairly short, around three weeks on average (Chateauvert et al., 2015). However, distribution is not even, as evidenced by the Seistec and coring surveys (Grace and Butler, 2015; 2016), which showed that sediments were thickest near the submerged islands and thinner (below Seistec resolution detail) above Bear Island. Coarser sediments would settle out at the top of the reservoir with a gradation to the finest sediment located near the dam. Further research is needed to estimate appropriate parameter values for use in Equation ⟨1⟩ and for estimating the sediment load and deposit thickness.

4 Future Work

To determine the total amount of sediment being delivered to the reservoir annually and to ultimately determine how much sediment has been trapped behind the MGS over its 51 years lifespan, we require TSS or turbidity measurements during the freshet and during fall storms, as well as during summer and winter conditions. Currently, much of these data are lacking. Since most of the annual flow moves through the reservoir over about a period of one to two weeks during the freshet, we can assume that the bulk of the annual sediment load would also be delivered during this time, with minor amounts being delivered during fall storms. Future sampling efforts will focus on capturing TSS and/or turbidity levels above the MGS prior to the freshet, during the peak of the freshet, and during fall storms.

This study shows that turbidity can be used as a surrogate for TSS using a regression equation developed from the 2018 data presented here. Sampling for TSS is more time consuming then sampling for turbidity, which can be measured in the field. In addition, weather and access conditions can be dangerous during the freshet. An alternative solution would be to install turbidity loggers that could measure turbidity multiple times per day during high-flow conditions. The regression equation could be used to calculate TSS concentrations.

Considering the shallow gradient, surrounding surficial geology, and established vegetation of the SJR watershed, erosion is minimal even when taking anthropogenic factors into account (O'Sullivan et al., 2016). Though the MH lies in a naturally sediment starved system, the potential impacts from the erosion, re-suspension, transportation, and deposition of reservoir sediments should be considered if the Mactaquac Dam is to be decommissioned. With an appropriate sediment management plan, downstream impacts could be minimized or avoided.

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