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Suspended sediment input from crushed-stone ford construction on the Canadian Shield in Quebec

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ABSTRACT

Extensive and aging forest road systems, especially those that include poorly maintained stream crossings, can be significant sources of fine sediment that are detrimental to aquatic ecosystems. With limited resources available for culvert maintenance, alternative low-water crossings such as fords have been designed. Although crushed-stone fords have been used to minimize particle release during stream crossing, few studies have measured the fine sediment input that results from their construction. We used continuous turbidity monitoring paired with grab samples to obtain suspended sediment input from four construction sites with different streamflows, streambed gradients and bed and bank soil textures. Construction took place in the fall of 2018 and the summer of 2019. The results indicate that the suspended sediment load induced by the construction ranged between 72 and 831 kg. Sediment load appeared mainly sensitive to the fine particle content in the streambed and banks. We also observed that suspended sediment concentrations returned to background levels at every site within 2 h after construction. Compared with the failure of unmaintained culverts in which most road fill is washed into the stream, crushed-stone fords construction represent negligible sediment input. Our results suggest that improved fords could be an environmentally beneficial alternative to culverts on seldom-used roads where access is still required but resources for culvert maintenance are lacking.

1. Introduction

Due to limited resources, a large proportion of roads are abandoned after periods of high-intensity use for activities such as harvesting, mining and the construction of energy transmission infrastructure (Thompson, 2009). In the United States, most of the 610 000 km of classified Forest Service roads on National Forest lands were built for timber harvesting and are now being used for other purposes. However, less than 20% are maintained according to regulations (USDA Forest Service, 2002). In Quebec, Canada, there are approximately 400 000 km of roads in public forests with an estimated average of 1.2 stream crossings per kilometer, mainly culverts (Morvan and Trottier, 2011; Paradis-Lacombe and Jutras, 2016). Only 20% of forest access roads are properly maintained following high-intensity use (Paradis-Lacombe, 2018).

Without proper maintenance, culverts can fail due to blockage or deterioration (Elliot et al., 1996). In a study conducted over 400 km of roads within 13 small watersheds in the province of Quebec, Paradis-Lacombe, 2018) found that 54% of stream crossings (mostly culverts) were in mediocre condition or worse. Poorly maintained culverts can become significant barriers to fish passage (Paradis-Lacombe, 2018; Bérubé et al., 2010; Roni and Quimby, 2005; Trottier and Charrette, 2011). Culvert failure can also lead to road-fill failure, which can add up to thousands of m^3 of sediment into streams (Elliot et al., 1996). King (2017) estimated that the volume eroded after the failure of a culvert varied between 10 and 156 m^3. Best et al. (1995) reported an average eroded volume of 253 m^3 following culvert failure without channel diversion, while the average eroded volume for culvert failure causing channel diversion was 2650 m^3. Similarly, the volumes eroded measured by Weaver and Hagans (2000) ranged between 5 and 2300 m^3. Massive inputs of sediment, especially fine sediment, is known to be harmful to aquatic wildlife. The silting of spawning beds and the shift in macroinvertebrates are some of the well-documented impacts of fine sediment input on species such as brook trout (Salvelinus fontinalis) and Atlantic salmon (Salmo salar) (Brown, 1994; Kidd et al., 2014; Lilijaniemi et al., 2002). In the same way, the silting of stream beds can impact other aquatic vertebrates such as salamanders (Bérubé et al., 2010).

Many regulations, best management practices (BMPs) and water quality standards are developed to address sediment input in streams. Water quality standards are established based on scientific data, professional judgement (Ministry of the Environment and the Fight

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against Climate Change, 2019), water use and water value for public water supplies (U.S. Environmental Protection Agency, 2006). Therefore, standards vary between jurisdictions. For example, the criteria established for the province of Quebec for clear freshwater aquatic habitats require that the suspended sediment concentration (SSC) does not exceed the background level by more than 25 mg/L for short time periods (< 24 h) or 5 mg/L for longer periods (24 h to 30 days) (Ministry of the Environment and the Fight against Climate Change, 2002).

To reduce damage to aquatic ecosystems, managers may choose to remove all stream crossing structures following the intensive use of resource roads. However, most sections of these roads are left intact in order to maintain access for future forest management and infrastructure maintenance. Quebec's regulation on forest road closure requires that all stream crossings be removed, the stream bed and banks be stabilized, and that 20 m of roads be vegetated on both side of the crossing. In addition, a minimum of 250 m has to be vegetated from the starting point of closure along the road network (Government of Quebec, 2020). As observed by Gauthier et al. (2013), various users still use the remaining road sections and cross the streams at unplanned locations. Soft ground crossings without proper stabilization release sediments during streambed and bank perturbations (Chin et al., 2004; Gauthier et al., 2013). This erosion and overall deterioration of the crossing site leads to the creation of convoluted routes through adjacent areas by the passage of the user's vehicles through less disturbed pathways (Aust et al., 2005; Sample et al., 1998). In fact, in their field surveys, Hydro-Québec found that fording sites frequently used by other users (20% of surveyed sites) remained notable sources of sediments. To address this type of problems in USA, various low-water crossings and ford types have been designed and tested(Clarkin et al., 2006; Lohnes et al., 2001; Bhattarai et al., 2016). Although fording natural streams is permitted under specific conditions in most Canadian provinces (Department of Environment, 2012, Fisheries and Oceans Canada and Ministry of, 2017; Government of Newfoundland and Labrador, 2018; Hydro, 2014; Manitoba Natural Resources 1996) , Quebec regulations do not currently permit this practice. In order to address the issue of under-maintained roads, regulations for medium- and long-term road maintenance or alternatives such as fording must be developed.

Crushed-stone fords were selected for this study because they are simple and economical to construct, and require minimal maintenance compared to culverts and bridges (Clarkin et al., 2006; Lohnes et al., 2001). They also represent little environmental risk because there is no road fill to washout and because plugging by debris is unlikely. Warren and Pardew (1998) also found that fords showed little difference from natural reaches in overall movement of fishes. Although numerous studies have evaluated the effects of stream crossing structures such as fords on water quality in the United States (Warren and Pardew, 1998; Aust et al., 2011; Holmquist et al., 2015), there is a paucity of scientific data on sediment inputs generated during crushed-stone ford construction, particularly within the Canadian Shield.

The objective of this study was to measure the suspended sediment input generated by the construction of crushed-stone fords and to identify the relative importance of key phases of construction to the total sediment load. A second objective was to compare regulatory suspended sediment concentration (SSC) guidelines to the observations made during construction.

2. Material and methods

2.1. Study sites and ford construction

The four study sites were located within right-of-ways of Hydro-Québec energy transmission lines in Quebec, Canada (Fig. 1). The sites represented a range of initial conditions as well as varying flows, streambed gradients and soil textures (Table 1). The succession of ford construction phases are linked to the initial conditions at each site. To avoid repetition, a detailed description of these conditions at each site is reported in the results section.

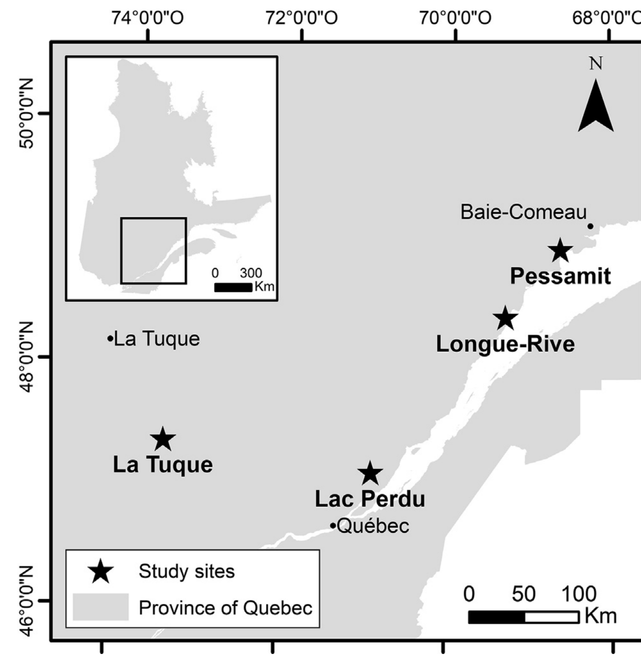

Fig. 1. Location of study sites.

Constructions took place during the fall of 2018 and the summer of 2019 during low flows and rainless days. Crushed-stone fords were constructed in straight sections of the streams by excavating the roadway area (4 m width) of the streambed 20 to 30 cm deep and then backfilling the excavation with 100 to 200 mm crushed stone. The natural gradient of each stream was maintained. At the end of construction, the streambed was 5 to 10 cm below the previous level to ensure water and fish passage during low-flow periods and to support the reestablishment of a natural streambed. Larger rocks found on-site were placed downstream to keep the crushed stone in place during periods of high flow. The banks were shaped to obtain a maximum slope of 20% as illustrated by the ford at the Lac Perdu site (Fig. 2). The first 5 m on each side of the stream were stabilized using 100- to 200 mm crushed stone without a geotextile membrane. The 15 m stretch beyond those first 5 m were stabilized using 50- to 100 mm crushed stone placed on top of a geotextile membrane. Water bars were also built at the ends of these stabilized roadbeds to divert water to undisturbed forest floor according to the provincial regulations for road embankments (Government of Quebec, 2020). At every site, all of the bare soil was covered with straw and grass seed at the end of construction.

A locally available excavator was used at each site so the makes and models differed between them (all were 10–90 mt). Bucket capacity ranged from 0.5 to 1.6 m^3. In Pessamit, the excavator was equipped with a thumb and a dozer blade. Construction was carried out during low-flow periods without flow diversion, allowing the excavator to be in contact with live water at each site.

2.2. Field measurements

The methods presented here are adapted from Lewis and Eads (2001) and Steffy and Shank (2018). Streamflow was estimated by multiplying the cross-sectional area of the stream determined using a high precision altimeter (Zip level pro-2000, ± 0.5 cm, Technidea Corporation, Escondido, USA) by water velocity measured with a velocity flow meter (Hach FH950, ± 0.015 m/s, Hach, Loveland, USA). Because the maximum water depth ranged from 20 to 50 cm, the velocity was only measured in the thalweg at 40% of the water depth relative to the bed. Hence, the

Table 1
Physical characteristics of the four study sites.

Site	Drainage area (ha)	Streambed width (m)	Streambed gradient[a] (%)	Particles < 2 mm[b] (%)		Q_{10}[d] (m^3/s)	Coordinates (DD)
				Bed	Banks		
Longue-Rive	483.7	3	0.4	99	99	4.24	48.513901° −69.308137°
Pessamit	216.3	2	3.4	21	58	1.51	49.075611° −68.628513°
La Tuque	113.7	3	4.0	-[c]	64	1.64	47.405237° −73.447487°
Lac Perdu	117.0	3	3.7	<10	51	4.07	47.211270° −70.91918 °

[a] Streambed gradient was measured over a distance of 30 m upstream and downstream of the crossing site.
[b] Bed and bank compositions were determined by pebble count (Wolman, 1954) and sieving of soil samples, respectively.
[c] We were unable to characterize the natural bed composition at this site because a culvert was in place at the beginning of construction.
[d] The 10-year recurrence discharge was calculated using the rational method (Ministry of Forests, Wildlife and Parks, 2021).

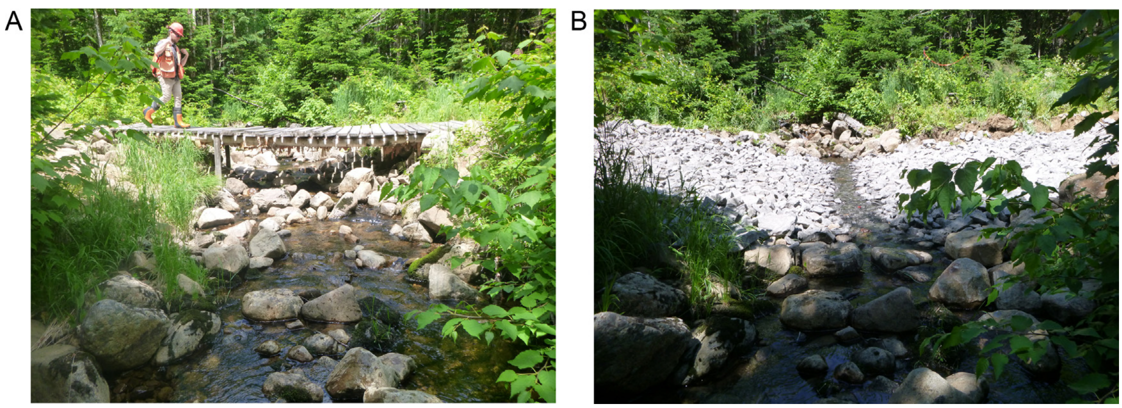

Fig. 2. Before (4 July 2019) and after photos (18 July 2019) of the Lac Perdu site.

average velocity and therefore the streamflow and sediment loads were overestimated. Streamflow measurements nearby the Pessamit site in a U shape stream indicated a 23% overestimation of the flow when using the velocity at a single point in the thalweg (unpublished data). This value is similar to the 18% overestimation calculated from a U shape stream data in Table 6.3 of Viessman and Lewis (1996). The estimated streamflow from the velocity measurement at the thalweg was not corrected since the overestimation was not evaluated at any study reach. Five velocity readings were recorded at the beginning and end of each construction day. We used a water level sensor (KPSI 710, ± 0.5%; Measurement Specialities Inc., Hampton, USA) connected to a data logger (H21-USB, Onset, Bourne, USA) to continuously record the water level in order to take new velocity measurements for any change in level of 0.5 cm.

At each site, low-range (0–1000 NTU) nephelometric turbidimeters (Analite, NEP9510GPI, ± 1%, McVan Instruments, Mulgrave, Australia and WQ730, ± 1%, Global Water, College Station, USA) were used to monitor upstream and downstream turbidity. A high-range (0–5000 NTU) nephelometric turbidimeter (Analite NEP9510GPI, ± 1%, McVan Instruments, Mulgrave, Australia) was also installed alongside the low-range sensor downstream from the ford. Turbidity sensors were mounted on metal rods that were inserted in the streambed. The upstream rods were installed in the nearest pool above the ford (5–15 m above ford depending on the site). The downstream rods were installed below a zone of turbulence to ensure adequate mixing of water and sediments. The downstream sensors were located 20 m, 7 m, 13 m, and 12 m below the ford for Longue-Rive, Pessamit, La Tuque and Lac Perdu, respectively. The sensors were fixed at 40% of the total water depth relative to the bed. We used a H21-USB data logger to record the mean of five turbidity readings for each 5 s period.

In order to transform turbidity values in concentration of suspended sediments, 500 mL water samples were collected using an autosampler (ISCO-6712, ± 5 mL, Teledyne ISCO, Lincoln, USA) at 20 min intervals throughout the construction period. Manual samples were also collected, mainly during visible plumes of particles, in order to capture the maximum concentrations. Although we acknowledge that it is possible to have underestimated the maximum, our results still provide an adequate means of comparison with other stream crossing structures by providing an order of magnitude of the suspended sediment being generated. At each site, both automatic and manual samples were collected at approximately 15 cm downstream from and at the same depth as the turbidity sensors. Water was sampled using pre-acidified bottles and stored at 4 °C until processed. Samples were later vacuum-filtered through 0.7 μm filters, oven-dried and weighed (0.0001 g) to measure suspended sediment concentration. During construction, detailed field notes and videos with timestamps were taken to precisely document every construction phase and help keep track of noticeable changes in turbidity.

2.3. Analysis

All turbidity data were carefully inspected to omit erroneous or uncertain values. Images captured during construction were a great tool to validate suspected fouling or malfunctioning of sensors when water samples were unavailable for specific periods. The mean values from the 5 s intervals were used to compute a median turbidity for every 30 s time period to reduce the influence of outlier values (Lewis and Eads, 2001). When the 30 s turbidity exceeded the calibrated range of the high-range sensor, a value of 5000.01 NTU was substituted.

Previous studies have showed that turbidity-SSC regression models are site specific (Lewis and Eads, 2001; Grayson et al., 1996;

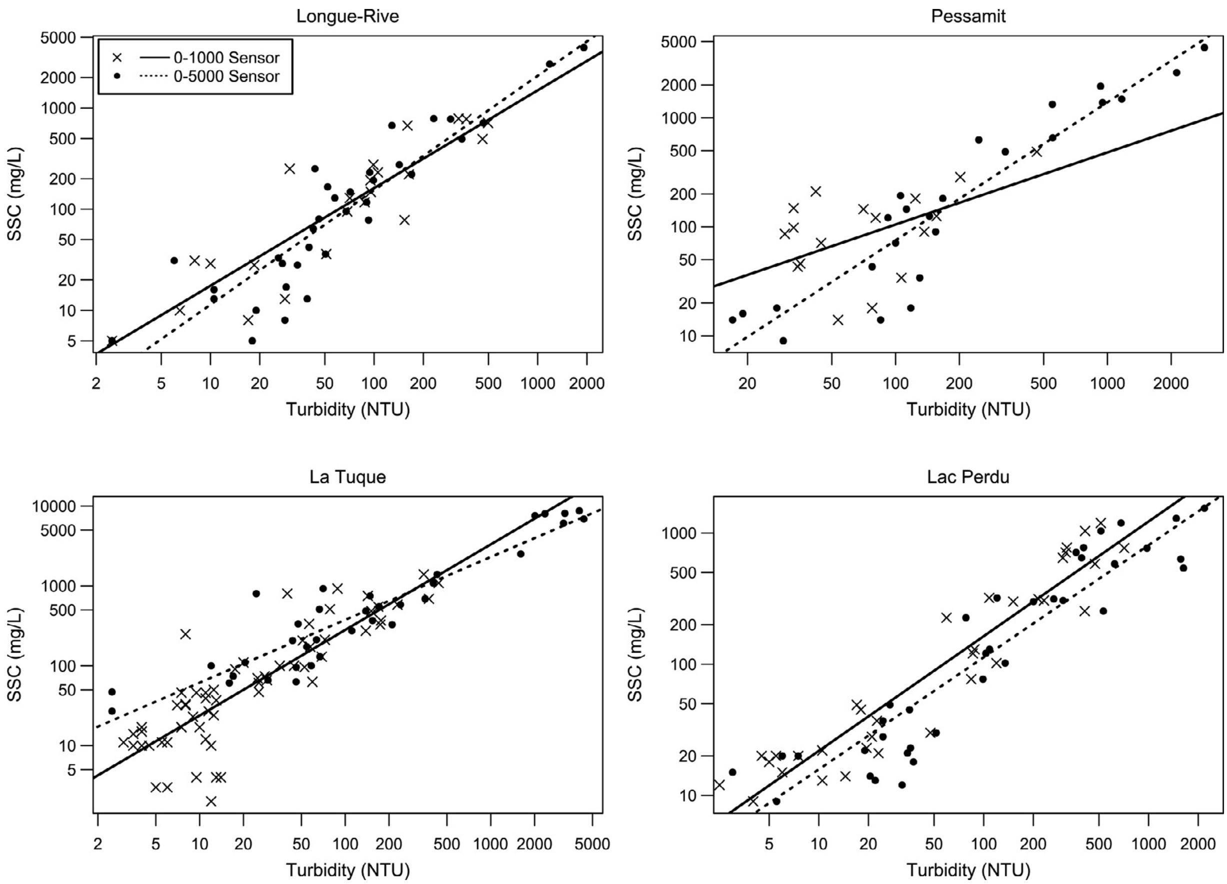

Fig. 3. Linear regressions between turbidity and suspended sediment concentration (SSC) for each sensor on each site. Regression equations are presented in Table 2.

Table 2
Regression equations parameters for low-range (top) and high-range (bottom) turbidity sensors and range of SSC measured in water samples.

Site	Sensors	n	Intercept ± SE	Slope ± SE	R^2_{adj}	Peak turbidity (NTU)	Min. SSC (mg/L)	Max. SSC (mg/L)
Longue-Rive	NEP9510GPI	23	0.64 ± 0.46	0.97 ± 0.11	0.79	1915	5	3955
	NEP9510GPI	34	−0.17 ± 0.04	1.13 ± 0.09	0.81			
Pessamit	WQ730	21	1.61 ± 0.60	0.66 ± 0.15	0.48	2870	3	4402
	NEP9510GPI	24	−1.51 ± 0.55	1.27 ± 0.10	0.87			
La Tuque	NEP9510GPI	62	0.70 ± 0.29	1.07 ± 0.09	0.72	>5000	1	9394
	NEP9510GPI	71	2.31 ± 0.28	0.79 ± 0.05	0.86			
Lac Perdu	NEP9510GPI	34	1.07 ± 0.22	0.87 ± 0.05	0.90	>5000	9	1545
	NEP9510GPI	39	0.79 ± 0.28	0.85 ± 0.06	0.86			

Rasmussen et al., 2009) and that turbidity readings vary considerably between sensors, but can still lead to reliable turbidity-SSC ratings (Rymszewicz et al., 2017). Therefore, for each sensor at each site, a linear regression of SSC values (obtained from both automatic and manual water samples) against median turbidity for the corresponding 30 s interval was produced (Fig. 3, Table 2). A natural log (ln) transformation of both variables was used to ensure that the regression assumptions of normality and homoscedasticity were met. The "predict" function in R was used to estimate SSC and the upper and lower 95% confidence intervals using site-specific model outputs (Steffy and Shank, 2018; Grayson et al., 1996; Core Team). Because the range of turbidity from the upstream (background) samples were deemed insufficient to build an adequate regression, the regression from the downstream low-range sensor at the site was used.

A total of 174 paired samples of turbidity and SSC were collected downstream. Measured SSC ranged from 1 to 9394 mg/L (Table 2). All site-specific turbidity vs. SSC regression models were statistically significant (*p*value < 0.001). The coefficients of determination (R^2_{adj}) ranging from 0.48 to 0.90 largely differed between sites as observed by Steffy and Shank (2018) and Arismendi et al. (2017) (Fig. 3, Table 2).

The regressions were used to produce a continuous record of SSC based on every 30 s turbidity measurement. We used the high-range sensor readings to complete datasets when turbidity exceeded the calibrated range of the low-range sensor or when the low-range sensor readings were unavailable. Because of the poor model fit with the low-range sensor at the Pessamit site, which can be attributed to the sensor employed, we used the high range sensor to estimate SSC. The low-range sensor was only used to complete datasets when the high-range sensor readings were unavailable. The peak SSCs that were estimated with the regression were 4335 mg/L (11:00) in Longue-Rive, 5268 mg/L (10:38) in Pessamit, 8164 mgL^{-1} in La Tuque and 3199 mg/L in Lac Perdu. We then estimated the total load for the construction by summing the product of discharge and predicted SSC at 30 s intervals.

Finally, we documented the relative contribution of targeted key phases of construction, such as bank shaping, bed excavation, bed and bank stabilization, and excavator crossings. We also included other spe-

Table 3
Duration, suspended sediment (SS) load and mean suspended sediment concentration (SSC) induced by targeted construction phases. Letters in the first column refer to the letters in Fig. 4.

	Phase	Duration (min)	SS load[a] (kg)	Mean SSC[a] (mg/L)
Longue-Rive (Streamflow= 0.260 m^3/s; Thalweg water depth=0.50 m)				
	Background	300	23.4	5
A	Installation and removal of cofferdams	61.5	115.9	121
B	Bed excavation	12	109.1	583
C	Excavator crossing	8	124.9	1001
D	Excavator crossing	9.5	124.8	842
E	Bed stabilization	18	156.0	555
F, G	Access bank stabilization	14.5	82.6	365
	Total	300	830.6	177
Pessamit (Streamflow= 0.114 m^3/s; Thalweg water depth= 0.52 m)				
	Background	480	6.4	2
A	Access bank stabilization	35	10.4	43
B	Bed excavation and stabilization	34	16.8	72
C	Removal of culvert	8	20.7	378
D	Removal of beaver dam	22	84.2	559
E	Excavator crossing and filling of the diversion channel	10	29.5	432
F	Excavator crossing	6	5.9	145
G, H	Opposite bank stabilization	33.5	10.8	95
I	Excavator crossing	10.5	7.2	100
J	Opposite bank stabilization	19	7.1	55
K	Excavator crossing	15	6.5	63
	Total	480	228.5	70
La Tuque (Streamflow= 0.018 m^3/s to 0.013 m^3/s[b]; Thalweg water depth=0.27 m to 0.24 m[b])				
	Background	1140	5.9	5
A	Removal of downstream rock wall above the culvert	11.5	7.9	634
B	Silt fence installation	26.5	13.5	471
C	Removal of upstream rock wall above the culvert	21	2.4	106
D	Culvert removal	67	116.4	1609
E	Opposite bank stabilization	21	14.7	649
F	Temporary bridge removal	17	22.0	1196
G	Bed excavation	19	69.0	3365
H, I	Bed stabilization	42	118.3	2607
J	Silt fence removal	73	42.9	754
	Total	1140	450.3	395
Lac Perdu (Streamflow= 0.014 m^3/s; Thalweg water depth=0.22 m)				
	Background	420	2.4	7
A	Excavator crossing	8	0.9	137
B	Excavator crossing	6	0.4	89
C, D	Bed excavation	58	12.4	261
E	Excavator crossing	8.5	1.3	184
F	Opposite bank stabilization (+26 crossings)	45.5	33.2	887
G, H	Bed stabilization	38.5	20.4	645
	Total	420	71.8	208

[a] Suspended sediment loads and SSC are the ones measured downstream and thus, include upstream contributio.
[b] Streamflow and water depth at the thalweg for the third day of construction.

cific activities (e.g. culvert removal) when the sediment input was significant. The beginning and end of a phase was defined as the moment when the downstream SSC surpassed the background level or when the minimum SSC value was reached between two phases. All analyses were conducted in Core Team.

3. Results

3.1. Sediment input from key phases of construction

For every rainless construction period, the water level and, therefore the streamflow, remained constant and are presented in Table 3. The concentrations of suspended sediment obtained from the continuous turbidity measurements at the four sites are illustrated in Fig. 4. The construction phases are indicated by capital letters in Fig. 4 and are defined in Table 3. The initial conditions varied between sites, and therefore the construction phases were adjusted accordingly.

The Longue-Rive site was the only site that did not have proper road infrastructure leading to the stream crossing. Fording by locals and vegetation management teams using all-terrain vehicles and without any stabilization measures caused major stream bed and bank erosion. At the beginning of construction, there was an attempt at drying the site (phase A) using cofferdams and pumps. However, the pumps were insufficient to control the seepage. Cofferdams and pumps were removed (phase A) before bed excavation (phase B). The operator moved the excavator across the stream twice during construction (during phases C and D). This occurred before bed stabilization (phase E) and was necessary to properly shape the opposite bank. Only the first 5 m of the opposite bank were stabilized using crushed stone (phase G). There were no crossings over the stabilized bed.

At the Pessamit site, an old beaver dam and several broken culverts were present, suggesting that culvert failure may have occurred more than once, causing substantial road-fill erosion and a stream channel diversion. First, the operator shaped the access bank (phase A). The original streambed was then excavated and stabilized using crushed stone (phase B). The plugged culvert (phase C) was removed in nearly dry conditions because the water was still flowing through the diversion channel. The beaver dam (phase D) located upstream of the ford was then removed and the stream regained its original streambed position. The operator moved the excavator across the stream on the stabilized bed and filled the diversion channel near the opposite bank while the excavator tracks were still in contact with water (phase E). To shape and stabilize the opposite bank (phases G, H, J), the operator made three more crossings on the stabilized streambed (phases I, F, K).

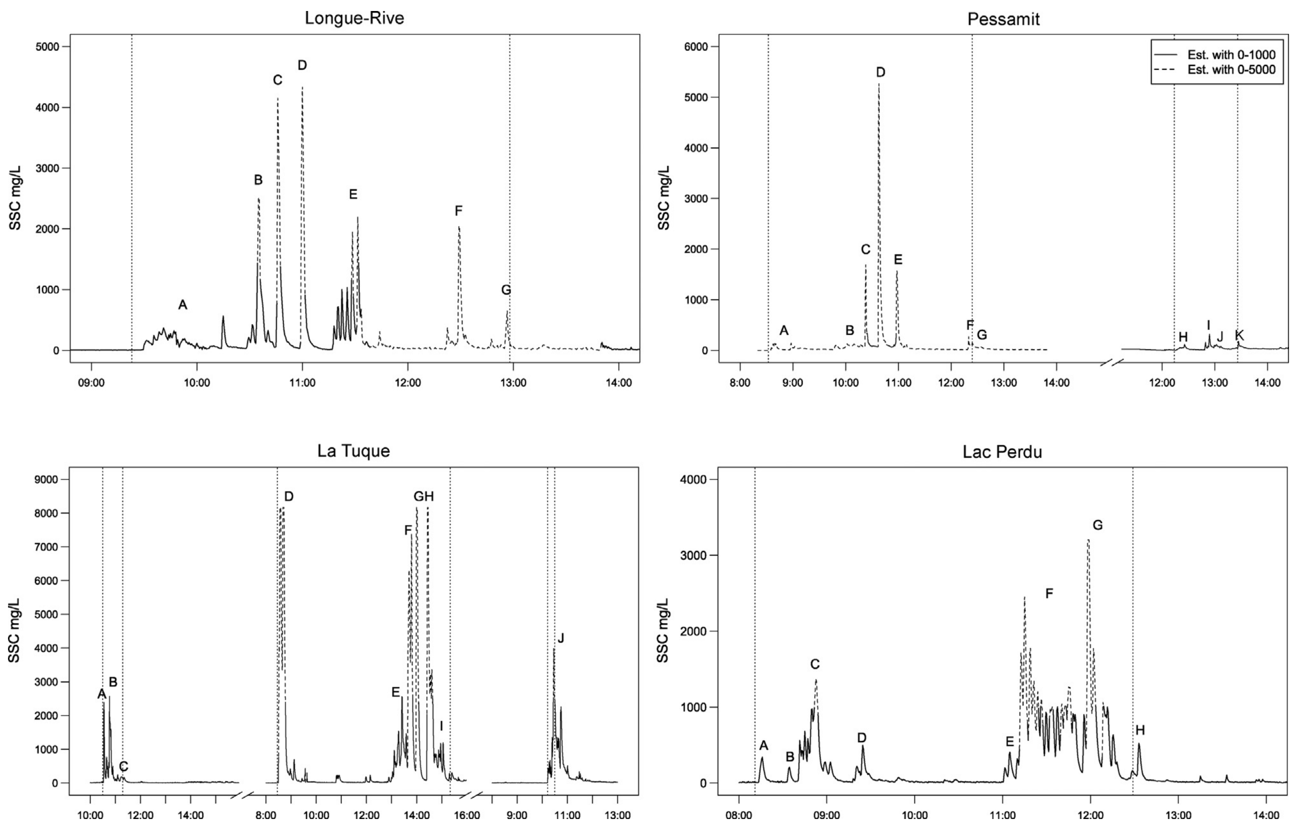

Fig. 4. Downstream suspended sediment concentration (SSC) during construction using the low-range (solid line) and high-range (dashed line) turbidity sensors. First and last excavator contact with water are represented by vertical dashed lines. Letters on the graph refer to construction phases presented in Table 3.

The La Tuque site was part of a road closure project and a culvert (1.4 m X 12 m corrugated steel pipe) was in place before this study. On the first day of construction, the operator removed the road-fill material and the stones that retained the road fill downstream of the culvert (phase A). Then a geotextile silt fence was installed downstream of the crossing (phase B). The silt fence was installed upstream of the turbidity sensors. On the second day of construction, the stones that were retaining the road fill upstream of the culvert (phase C) and the culvert itself (phase D) were removed. A temporary bridge was set across the stream (at 8:50:00) to serve as a crossing structure for the excavator during the stabilization of the opposite bank (phase E). The bridge was then removed (phase F) to allow streambed excavation (phase G) and stabilization (phase H). The access bank was stabilized with no attributable sediment input. The upstream and downstream areas of the banks left bare by the removal of the culvert were stabilized using large rocks and vegetation strips found on site (phase I). Finally, on the third day of construction, the silt fence was removed (phase J). However, due to poor design, the geotextile laid upstream was too short to remove the accumulated silt, and sediment was released into the stream. The turbidity exceeded the upper limit (5000 NTU) of the sensor during 9 min ([8:33:00–8:35:00], [8:40:30–8:43:30], [13:59:30–14:01:30], and [14:26:00–14:28:00]) throughout the second day of construction (Fig. 4).

Finally, the Lac Perdu site was located on a closed road where a temporary bridge had been removed before ford construction (Fig. 2). Construction took place during a low-flow period but no additional mitigation methods were used. Bed excavation and four excavator crossings were carried out (phases A to E) before crushed stone was placed in the streambed under the excavator tracks to limit rutting. The crossings occurred while the compacted road surface was still undisturbed. The banks were then shaped and the opposite bank was stabilized (phase F) before completing the stabilization of the bed (phases G and H). The upper limit of the turbidity sensor was exceeded for a duration of 1.5 min [11:58:00–11:59:30] (Fig. 4).

3.2. Total sediment loads

The estimated cumulative suspended sediment load for the construction period was 831 kg for Longue-Rive , 228 kg for Pessamit, 450 kg for La Tuque and 72 kg for Lac Perdu (Table 4). Averaged over the total construction duration, this represents maximum downstream SSCs of 177 mg/L, 70 mg/L, 395 mg/L and 208 mg/L, respectively. The average background SSC calculated over the same period at each site varied between 2 and 7 mg/L (Table 3).

3.3. Compliance with regulatory SSC guidelines

Construction lasted 5 h in Longue-Rive, 8 h over 2 days in Pessamit, 19 h over 3 days in La Tuque, and 7 h in Lac Perdu (Table 4). Downstream SSC exceeded the regulatory limit of 25 mg/L above the background for less than 5 h at every site except the La Tuque one, where the limit was exceeded during 10.8 h (Table 5). The SSC returned to regulatory compliance levels within 1 h after the last time the excavator made contact with water except for the last day of construction at the La Tuque site. It took 2 h after the removal of the silt fence (Phase J, Fig. 4) for SSC values to return to compliance levels (Table 5).

4. Discussion

4.1. Sediment input from key phases of construction

4.1.1. Major contributors

Most of the sediments were generated by key phases of construction during a relatively short period. More than 80% of the sediment load was

Table 4
Duration of construction days, suspended sediment (SS) loads and associated confidence intervals for each site.

Site	Construction date/s	Start time	End time	SS load estimate (kg)	SS load estimate 95% interval (kg)
Longue-Rive	18 Oct 18	9:00	14:00	830	507 – 1390
Pessamit	22 Oct 18	8:00	14:00	228	145 – 367
	23 Oct 18	12:00	14:00		
La Tuque	26 June 19	10:00	16:00	450	293 – 687
	27 June 19	8:00	16:00		
	2 July 19	8:00	13:00		
Lac Perdu	18 July 19	8:00	15:00	72	52 – 101

Table 5
Time exceeding regulatory limit of 25 mg/L higher than background for suspended sediment concentration (SSC) and time required to get back to regulatory levels after last excavator contact with water.

Site	Time exceeding regulatory limit (h)	Time required to reach SSC regulatory limit (h)		
		Day 1	Day 2	Day 3
Longue-Rive	2.8–4.1	0.4	–	–
Pessamit	3.0–4.8	0.3	0.5	–
La Tuque	8.2–10.8	0.2	1.0	2.1
Lac Perdu	3.4–4.0	0.4	–	–

generated in less than 40% of the total construction time at every site (Table 3). The construction phase that represented the largest sediment input was bed stabilization in Longue-Rive (19% of total), beaver dam removal in Pessamit (37% of total), fill and culvert removal in La Tuque (28% of total), and opposite bank stabilization in Lac Perdu (46% of total) (Table 3). As expected, the major sediment inputs originated from the shuffling of streambed material. At every study site, more than 30% of the sediment input was caused by bed excavation and stabilization except for the Pessamit site (7%) where this phase was carried out in dry conditions outside the natural diversion channel. Streambed material shuffling is inevitable during the construction of most stream-crossing structures, except maybe for some types of bridges, but sediment input is minimized when working in low flow or dry conditions.

4.1.2. Culvert removal

The load input from culvert removal in dry conditions in Pessamit was only 20.7 kg whereas culvert removal in wet conditions produced the highest load in La Tuque with 126.7 kg. The effect of culvert removal is highly variable, as indicated by Foltz et al. (2008), who found that sediment loads generated by the removal of three culverts with flow diversion ranged from 0.2 to 3.1 kg, whereas the removal of eight culverts without mitigation measures generated sediment loads that ranged from 2.6 to 170 kg. This emphasizes the importance of working in low flow conditions, as recommended in most BMPs (Lohnes et al., 2001; Hydro, 2014; Department of Environment, 2012; Fisheries and Oceans Canada and Ministry of, 2017; Government of Newfoundland and Labrador, 2018).

4.1.3. Excavator crossings

We do not have a comparison of sediment loads between crossings before and after bed stabilization at the same site. However, excavator crossings before streambed stabilization produced a very small sediment load in Lac Perdu (<1 kg) whereas the load was very high in Longue-Rive (125 kg). As presented in Table 1, the bed and bank of the latter were composed of much finer particles. This is consistent with the results obtained by Sample et al. (1998) who found that the sedimentation produced by a four-wheel-drive vehicle crossing at a natural ford was nearly 15 times greater than the sedimentation produced at a ford that had been improved using crushed stone. However, the much higher streamflow at Longue-Rive has probably contributed to the larger load due to excavator crossings at this site.

The number of excavator crossings needed for the excavation of the opposite bank can have a significant impact on the relative contribution of this phase to the total sediment input. In Longue-Rive, the ATV trail on the opposite bank was already well stabilized by the vegetation present at the site and only the first 5 m needed to be accessed. Therefore, the stabilization of the opposite bank could be achieved by the excavator arm reaching across the stream and did not require crossing. It was done with no attributable sediment input. In Pessamit, the stabilization of the opposite bank required 4 excavator crossings on a stabilized bed and produced 8% of the total sediment input. The excavator mainly circulated on stabilized banks. In La Tuque, the stabilization of the opposite bank was done using a temporary bridge laid across the stream. It required 6 crossings and produced 8% of the total sediment input. Meanwhile, in Lac Perdu, the opposite bank stabilization was done with 26 excavator crossings and produced 46% of the total load. The majority of the sediment originated from bank material being washed from the tracks of the excavator. Excavator operators in Longue-Rive and Pessamit chose to move the crushed stone closer to the stream to limit the number of excavator crossings required to shape and stabilize the opposite bank, while the operator in Lac Perdu chose to travel back and forth across the stream for each new bucket of crushed stone. If he had used the same method as the operators in the previous sites, the relative contribution of this phase to the total sediment input would probably have been a lot less in Lac Perdu. Thus, it is recommended that the number of excavator crossings during construction be limited. During a road closure, the stream crossing and the road that is in place should be used to deliver crushed stone to each side of the stream, or close enough to the opposite side so that the excavator arm can reach across the stream to place them. This can also significantly reduce the construction time (Ferland et al., unpublished data).

4.2. Sediment input from construction

The sediment load generated by the construction of the four crushed-stone fords ranged from 72 to 831 kg. Overall, construction at fine-textured sites produced higher sediment loads, as indicated by the Longue-Rive site producing a load 10 times greater than the one at the Lac Perdu site. Furthermore, over the years, without stabilization using crushed stone, fine-textured sites are more likely to yield significant amount of sediment from vehicle crossings and bank erosion during snowmelt and rainfall than coarser-textured sites. A study done in a military training area of New Brunswick, Canada estimated that eroded unimproved approaches produced 330 kg/km^2/year. The same study estimated that the improvement of ford approaches reduces erosion rates by 98% (Burdett et al., 2014). Hence, managed fords appear to be a good way to protect streams on aging forest roads. The average and peak streamflows also influence sediment input. It may exacerbate or reduce the sediment input differences between sites, as Foltz et al. (2008) observed a positive correlation between stream flow and sediment input.

In comparison, culvert plugging and failure can represent up to thousands of tons of sediment input into streams (see 1.Introduction) (Elliot et al., 1996; Best et al., 1995; Weaver and Hagans, 2000). Compared to the greatest volume of sediment generated by a ford construction in this study, the volumes of sediment eroded from culvert failure cited in other studies are 10 to 4800 times greater (Best et al., 1995; Weaver and Hagans, 2000). More concretely, at the Pessamit site, we measured the void left in the road caused by the culvert failure and found that the amount of material lost represented 350 tons. Based on the 58% fine sediment content of the remaining road fill, this represents an input of 203 tons of fine sediments, which is 890 times more than the suspended sediment generated by the construction of the ford at that site. Given that many broken culverts were found, it is also possible that this site experienced more than one washout.

4.3. Compliance with regulatory SSC guidelines

Lastly, our results show that the regulatory suspended sediment concentration limit is exceeded during the construction of crushed-stone fords. However, these perturbations are short-lived as SSC values return to regulatory compliance quickly after the end of construction.

At the La Tuque site, the silt fence did not reduce the load from ford construction because its removal released the accumulated sediments into the stream, and therefore delayed the return to the regulatory compliance level. In contrast, Foltz et al. (2008) showed that two straw bales placed in the stream caused a significant reduction in SSC and total sediment load but still failed to maintain SSCs lower than 25 mg/L at a location 100 m downstream from the construction site.

5. Conclusions

Crushed-stone ford construction has produced relatively small sediment loads and minor short-term perturbations to water quality. Sediment input can be further reduced by assuring that the stabilization of the access bank and streambed occurs before crossing the stream to shape and stabilize the opposite bank. With forest road systems aging worldwide, our results confirm that crushed-stone fords could be an environmentally beneficial alternative to road abandonment which can lead to culvert plugging and failure. In addition to these potential washouts, uncontrolled crossings can add significant sediment loads from years of vehicle crossings and bank erosion from rain events. Crushed-stone fords are suited for roads where minimal access is required and resources for maintenance are lacking. These roads may include those used for forest harvesting, silviculture, mining, power line and pipeline maintenance, and recreation.

In this study, we focused on the construction period only. Long-term monitoring of crushed stone fords is necessary to assess their impact on aquatic ecosystems in the context of road system management. Crushed-stone fords stability and sediment input must be assessed in relation to vehicle size and crossing frequency over a sufficiently long period. The small suspended sediment loads generated by ford construction supports the need for long-term monitoring studies. The method described in this paper could also be used to measure sediment input from other types of stream crossings. Calculating sediment input from various types of stream crossings in a life-cycle analysis is also necessary to provide better insight for managers in charge of planning road systems.

Ongoing companion studies are focusing on the operational cost of constructing crushed-stone fords and the impacts that all-wheel-drive vehicles crossing unimproved fords have on fish behavior. In the future, aquatic habitat and fish behavior studies should be combined with the analysis of sediment inputs related to alternative stream crossing structures.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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