Particle trapping effects by dams on downstream deposits in the Saguenay River Prodelta: Textural data from an unbioturbated core sample

Charles T. Schafer

Schafer CT. Particle trapping effects by dams on downstream deposits in the Saguenay River Prodelta: Textural data from an unbioturbated core sample. J Environ Geol. 2022;6(4):15-20.

ABSTRACT

Unbioturbated sediment deposits present on the Saguenay River Prodelta (North Arm, Saguenay Fiord) indicate a statistically-significant 8.4µm decrease in average Median Diameter (Md) in a post-dams period (~1965 – 1970) compared to a pre-dams period (~1907 - 1912). The post-dams average percentage of the 2.3ø, 2.7ø, 3.0ø, 3.7ø, and 4.0ø fine and very fine sand-size classes decreases, whereas that of the 4.7ø, 5.0ø, 5.3ø, 5.7ø, 6.0ø and 6.3ø coarse, medium and fine silt-sizes increases in relation to those sediments deposited in pre-dams time. Although cumulative effects of climate change and dam construction on river hydrology and prodelta sediment texture variations remain incomplete for the Saguenay River system as a whole, it appears that, for the river's lower reaches, the post-dams period average reduction in Maximum Mean Monthly Discharge (MMMD) that is typically associated with the river's spring freshet, has shifted the deposition of relatively fine silt-size particles toward the upstream end of the river's Prodelta. This shift is associated with a 0.52 cm yr^{-1} increase in average sedimentation rate based on ^{210}Pb dating results..

Key Words: *Bioturbation, Suspended sediment flux; Sediment trapping; Texture indicators; Prodelta deposits.*

CASE PRESENTATION

Issues concerning natural and human-modulated suspended sediment flux variations to lower reach river basin environments, deltas and submerged prodelta's, and to particular offshore coastal zone areas that support coral communities, has been investigated in many parts of the world at time scales of days to centuries [1-7]. In particular, problems surrounding particle transport behind and below dams have continued to produce research on a broad range of topics such as compensation strategies for managing sediment deficits below dams through various replenishment mechanisms, improving habitat quality in impacted downstream reaches below dams, and on the role of fine-grained sediment in the hydrological, geomorphological and ecosystems services functioning of river systems and their associated downstream deltas [8-11]. These reports have been complemented by investigations of sediment yields above and below dams during floods, and by studies aimed at developing integrated management plans for controlling effective sediment sluicing operations ie., [12-15].

Human infrastructure impacts regarding the role of dams as sediment traps offers numerous research opportunities in those cases where the age-dating of suspended sediment deposits observed in cores can be determined to be within 1-2 years. The occurrence of an approximately 73 year-long period of continuously unbioturbated sediment in an offshore prodelta environmental setting has provided the requisite samples for this investigation [16].

During the early 20th Century, three dams were constructed in the lower reaches of the Saguenay River channel near the municipalities of Alma, on the eastern shore of Lac Saint and at two locations about 34 km downstream in the river's lower reaches near Kenogami which is now part of the amalgamated city of Saguenay. By the time the Shipshaw dam became operational, the minimum mean monthly discharge of the river had risen from 300-400 M3S-1 to about 1000 M3S-1 [16]. The comprehensive report of Kondolf et al. (2014) contains a detailed summary of the various designs of dam infrastructure and allied bypass channels for the movement of suspended and bedload sediments to the downstream river channel and submerged prodelta environments [8]. In addition, they describe (1) various sediment trapping mitigation strategies that involve sediment collector dams located upstream from major reservoirs; (2) dam siting criteria that facilitate cost-effective construction of sediment bypass channels and tunnels; and (3) techniques for the mechanical removal or dispersal of sediment trapped behind dams, including the use of excavators, suction dredges and "warping" techniques designed to divert sediment-laden river water onto agricultural lands. An illustrative example of how these river management approaches have been applied to the Mississippi River basin can be found in Alexander et al (2012) [17]. Nevertheless, despite the effective use of many such mitigation strategies, Vörösmarty et al. (2003) concluded that half of the world's largest reservoirs still show a sediment trapping efficiency of 80% [18]. Kondolf et al. (2014) argue that the transport characteristics, trapping potential and downstream impacts of fine and coarse sediment are distinct and that bedload versus suspended loads and should be considered separately [8]. However, that approach likely expensive and requires the deployment of expensive instrumentation such as recording nephelometers and automated seafloor sediment traps. In contrast, this paper exploits the proxy textural signal contained in prodelta sediments, an approach that remains popular among paleo-environmentalists. It is focused on both suspended loads and bed loads of fine particles with size characteristics in the 2.3ø to 6.3ø range (~0.2 mm to 0.03 mm; fine sand to fine silt) in two sections of a piston core each representing five year intervals before and after the dam construction era. The core was raised from an ~88 m depth location in the Saguenay River Prodelta at a location where pulp mill particulate and fibrous organic matter (OM) deposition has produced distinctly unbioturbated annual deposits starting at the 1912 core horizon [19,16]. The laminar-like structure of these deposits is present until at least 1982 in the piston core described in this study, notwithstanding the 1971 proclamation of Environment Canada and Climate Change (ECCC) regulations regarding restrictions on the discharge of OM by local pulp and paper mills [20].

This paper explores sediment trapping by three Saguenay River dams by comparing total precipitation data from before and after dam construction (1907-1925 vs. 1965-1975) with respect to: (1) fine sand and silt size particle abundance characteristics for the ~1898 – ~1903 and ~1956 - ~1961 core intervals of core 82008-72; (2) five year averages of total OM percentages and ^{210}Pb composite sedimentation rates derived from cores D-1 and 72; (3) 11-year averages of maximum mean monthly discharge (MMMD); and (4) 6-year averages of mean annual discharge (MAD) extracted from Canadian government reports.

Geological Survey of Canada – Atlantic (GSCA); Bedford Institute of Oceanography (BIO); P.O. Box 1006, Dartmouth, Nova Scotia B2Y4A2

Correspondence: Charels T Schafer, Geological Survey of Canada – Atlantic (GSCA); Bedford Institute of Oceanography (BIO); P.O. Box 1006, Dartmouth, Nova Scotia B2Y4A2; E-mail: charlestschafer@gmail.com

Received: 07-July-2022, Manuscript No. PULJEG-22-5318; Editor assigned: 10-July-2022, PreQC No. PULJEG-22-5318(PQ); Reviewed: 19-July-2022, QC No. PULJEG-22-5318(Q); Revised: 23-July-2022, Manuscript No. PULJEG-22-5318(R); Published: 30-August-2022, DOI: 10.37532/puljeg.22.6(4).15-20

DEPOSITIONAL SETTING

The Saguenay River valley incises crystalline rocks of the Canadian Shield overlain by deposits of raised marine clays and littoral quartz sands [21]. The marine clays ("Leda" clays) were deposited in an arm of the late glacial Champlain Sea called the Mer de Laflamme during a high relative sea level stand about 8000 - 11000 years Before Present (BP) at the time of the melting and retreat of the Late Wisconsinan ice sheet [21]. Littoral sands prograde over the clays as relative sea level fell during the subsequent interval of postglacial crustal rebound.

During the Saguenay River's annual spring freshet (typically May and June), meltwater from snow and ice that accumulates within its ~78000 km2 drainage basin tributary network transports relatively easily eroded unconsolidated sediment (especially fine sands and coarse silts) along with finer grains and OM originating from the watershed's tributaries to the main Saguenay River channel; this process is generally consistent with descriptive models of fluvial particle erosion and transport [22]. Eroded and transported particles are likely stored temporarily in the lower reaches of the main river channel below the dams. They are subsequently washed out into the deeper prodelta environment of the Fiord's North Arm Basin during the annual spring freshet and by occasional floods as both suspended load and bedload [23]. During much of the 20th Century, the detrital particle flux to the submerged prodelta situated in the North Arm basin of the Saguenay Fiord was accompanied by a significant amount of fibrous OM discharged into the main river channel by local pulp and paper mills. Upon reaching the North Arm, the river's flow undergoes a pronounced decrease in speed as the channel widens and water depth increases rapidly from about 5 m to more than 200 m thereby promoting particle deposition of river-transported sediment on the prodelta's seafloor especially in the southeastern part of the Arm's basin. Seafloor slopes near the two coring sites sampled for this investigation are about 2.5o parallel to the shoreline and about 4.00 perpendicular to the channel. Piston and gravity cores from this area have been collected from time-to-time to study textural proxy signals of river discharge magnitudes and local landslide deposits that are preserved within unbioturbated annual layers in this unique depositional setting [19,24] (Figure 1).

METHODS

Core 82008-72 was raised in from a water depth of approximately 88 m (~48 fathoms) in April, 1982 near the southern shore of the Saguenay Fiord's North Arm (Lat. 48°25'00"; Long. 70°51'30") [25]). The 558 cm-long core was split, described and X-rayed with a Phillips 150 KV water-cooled industrial unit. The working half of the core was cut into one cm thick slices (about 50 cm^3 wet volume per slice) and freeze dried. Dried samples were subsampled for ^{210}Pb analysis. The remaining fractions were weighed and then heated for 8 hours at 550°C to remove the OM component. After cooling, they were re-weighed to estimate the OM percentage and then completely disaggregated by a 5-hour immersion in a 5% solution of sodium hexametaphosphate followed by a 20-minute sonification. Next, the residues were washed through a 420 µm sieve to remove very coarse particles. The <420 µm finer component was analyzed to determine the relative abundances of particles within the 2.3ø - 6.3ø size fractions using a Coulter Counter Model TA II fitted with a 560 µm aperture.

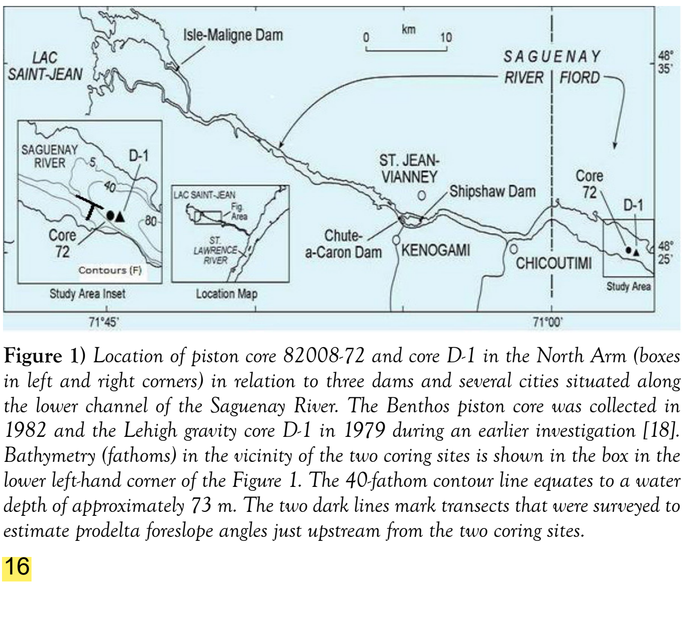


Figure 1) *Location of piston core 82008-72 and core D-1 in the North Arm (boxes in left and right corners) in relation to three dams and several cities situated along the lower channel of the Saguenay River. The Benthos piston core was collected in 1982 and the Lehigh gravity core D-1 in 1979 during an earlier investigation [18]. Bathymetry (fathoms) in the vicinity of the two coring sites is shown in the box in the lower left-hand corner of the Figure 1. The 40-fathom contour line equates to a water depth of approximately 73 m. The two dark lines mark transects that were surveyed to estimate prodelta foreslope angles just upstream from the two coring sites.*

The ^{210}Pb chronology of core 72 was determined according to the methods given in Smith and Walton (1980) and Smith and Schafer (1987) [26,27] . Results were used, along with ^{210}Pb data from core D-1 (see section 4.1 below), to estimate year-to-year variability and long-term (post-18th Century) average annual ^{210}Pb sedimentation rate in this part of the North Arm Basin. An independent measure of average annual sedimentation rate was obtained from annual layer thicknesses measured on core 72 X-radiographs. The Standard Error index (SE) was used to estimate statistical significance of difference between averaged data sets representing times before and after dam construction [28]. The index classifies SE's of less than two as probably not significant, those between 2 and 3 as possibly significant, and those greater than three as definitely significant. According to Moroney (1964) [28], the probability of a difference between two means of three SE's or higher arising by chance in random sampling is considered to be less than one half of one percent (i.e., P = 0.005).

RESULTS

^{210}Pb versus annual layer thickness sedimentation rates

^{210}Pb geochronology results for core 72 suggest that the annual deposits at the coring site accumulated at an average sedimentation rate of about 2.80 cm yr-1. Conversely, yearly layer thicknesses measured on X-radiographs yielded an average rate of 2.66 cm yr^{-1}. Thus, based on an average composite sedimentation rate of 2.73 cm yr-1 derived from both methods, the 558 cm-long section of core 72 is estimated to represent approximately 190-years (i.e., 1982 - ~ 1792). However, after accounting for the rapid deposition of two possible late-19th Century turbidity current deposits, the extrapolated age of the bottom of the core was re-estimated to be ~ 1816, or about 24 years younger [29]. The core 72 composite sedimentation rate of 2.73 cm yr-1 is generally comparable to the average ^{210}Pb sedimentation rate of 2.85 cm yr-1 determined for core D-1 that was age-dated using ^{210}Pb analytical methods similar to those used for core 72 [19].

Events of known age

The 1912 (231 cm), 1924 (200 cm) and 1971 (55 cm) horizons of core 72 are readily evident from direct visual observations of split core surfaces, median diameter (Md) results and visual X-radiograph data. A distinctive layer of grey-coloured postglacial Leda clay was deposited throughout much of the North Arm Basin due to a major landslide that occurred upstream at St. Jean Vianney in May 1971. A portion of the slide sediment discharged into the Saguenay River's lower channel was transported downstream to the prodelta by the river's spring freshet of that year [16,19,24,26]. The bottom of the 1971 clayey landslide layer is clearly visible in the split halves of core 72 at a depth of 52 cm – 54 cm. A minor landslide in 1924 is also evident from its percent clay content as reflected in Md grain-size data at the 200 cm core depth horizon. The 1912 OM-enriched horizon is easily distinguished in X-radiographs at a core depth of 230 cm. It is marked by a change to distinctly sharp (unbioturbated) annual layer boundaries that reflect the sudden increase of pulp and paper mill-derived OM concentrations from a new large mill located near Kenogami that reached >8% values in that year [16]. X-radiograph negatives of the post-1912 core section show that each annually-deposited unit consists of a lighter and relatively thicker layer of fine sand and coarse silt spring freshet bedload sediment overlain by a darker and thinner late summer, fall and winter OM-enriched layer suspended sediment deposit (26, 19] (Figure 2). The present study relies on subsampled textural data derived from two core 72 sections that represent ~6- years-long time interval just above the 1912 OM horizon and just below the 1971 landslide horizon. Supporting data relate to OM, composite sedimentation rate, and mean monthly and mean annual river discharge information collected at the Isle Maligne gauging station 062901 (Service l'Hydrométrie, Ministère Richesses Naturelles, Quebec,1983.)

Hydrology

6 year averages of Annual Mean Monthly Discharge (MAD) data for the Saguenay River measured at the Isle Maligne gauging station are shown in Table 1. The between-interval MAD averages are statistically similar although their year-to-year variation as measured by the Coefficient of Variation (CV) is more than 5% higher for the 1915-1925 interval. Eleven-year averages of annual maximum mean monthly discharge (MMMD) data show a value for the 1915-1925 interval that is 1525.5 M3S-1 higher than its 1965-1975 counterpart (definitely significant). However, although the average MAD comparison CV pattern is generally consistent with MMMD CV results, the averaged MMMD CV percent for the 1965-1975 interval is almost two times higher than its 1915 to 1925 counterpart and opposite to the MAD CV pattern. These results generally reflect relatively higher but less variable

MMMD conditions during pre-dams times that would be expected to transport suspended sediment to more distal parts of the prodelta.

Sediment deposition variation

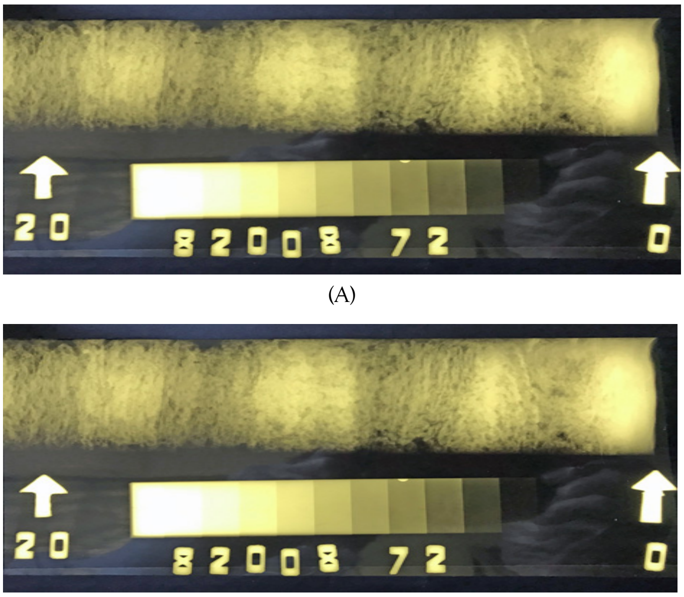
Core 72 composite sedimentation rate data for the 1965-1970 and the 1907-1912 intervals derived from ^{210}Pb measurements indicate that the average rate and its corresponding CV were respectively about 0.52 cm yr-1 and 5.2% lower during the 1907-1912 core interval than is observed for the 1965-1970 interval (Table 1).

Organic matter

On average, particulate OM percentage is 4.2 % lower and its CV is 4.6% higher during the older 1907-1912 interval than during the 1965-1970 interval (Table 1). These results appear to be consistent with the significant 1912 increase in OM discharge by local pulp mills [16]

Sediment grain size shift

In order to obtain a robust measure of the textural signature difference of prodelta fine sediments, two 15 subsample data sets were utilized (Table 2). They represent periods of deposition over several decades before the completion of the oldest dam at Isle Maligne in 1929 and about 20 years after construction of the youngest (Shipshaw Dam) near St. Jean Vianney. The chosen grain size intervals cover phi size classes ranging from fine sands to fine silts that would be expected to be present in suspended and bedload particle populations carried to the Prodelta during the annual spring freshet, or by floods. The median grain size (Md) average for the post- dam's suite of subsamples is 8.44 um smaller with a CV that is only 2% lower compared to its pre-dams counterpart. Several size fractions within the relatively coarser



(A)

(B)

Figure 2) *Annual layer sediment features in core 72 before and after 1971. Upper X-radiograph of the 0 cm– 20 cm core depth interval (1982 -˜1976) showing diffuse partially bioturbated but still recognizable boundary between dark (OM-enriched) and relatively light (sand and silt-enriched) yearly – deposited layers. Lower X-radiograph of the 80 – 100 cm core depth interval (˜1950's) showing distinct layering of sand (light) and OM-enriched (dark) layers.*

TABLE 1

Averaged pre- and post-dam comparison data for MAD, MMMD, composite sedimentation rate and OM percentage for pre-dams and post-dams intervals. Interval differences between average MMMD's and average OM yield SE values that are considered to be definitely significant (Source for MAD and MMMD data is: Service l'Hydrométrie, Ministère Richesses Naturelles, Quebec, 1983, STN.062901).

INTERVAL (6 years)	**1965-1970**	**1915-1920**
Average MAD (M^3S^{-1})	1493.3	1500
Standard Deviation	137.2	218.3
Coefficient of Variation (%)	9.2	14.6
Number of data points	6	6
SE = 0.06 (not significant)		
INTERVAL (11 years)	**1965-1975**	**1915-1925**
Average MMMD (M^3S^{-1})	2492.7	4018.2
Standard Deviation	739.4	627.1
Coefficient of Variation (%)	29.7	15.6
Number of data points	11	11
SE = 5.2 (definitely significant)		
INTERVAL (5 years)	**1965-1970**	**1907-1912**
Average Comp. Sed. Rate (cm yr^{-1})	2.35	1.83
Standard Deviation	0.6	0.4
Coefficient of Variation (%)	25.3	20.1
Number of data points	16	15
SE = 2.9 (probably significant)		
INTERVAL (5 years)	**1965-1970**	**1907-1912**
Average Organic Matter (%)	13.5	9.3
Standard Deviation	3.1	2.5
Coefficient of variation (%)	22.9	27.5
Number of data points	15	15
SE = 4.1 (definitely significant)		

TABLE 2

Summary of 2.3ø – 6.3ø grain size class percentages and of Md grain size in µm before and after construction of the three dams. The post-dams % difference for each phi size class (Av.Af.), the post-dams Standard Deviation difference for each size class (SD.dif.), and differences in between-interval % CV's (CV.dif.) are shown in the lowermost section of the Table. The post-dams core interval begins just below the 1971 St. Jean Vianney landslide layer. The pre-dams core interval starts just below the 1912 change from slightly bioturbated older deposits to unbioturbated younger annual deposits that resulted from an increase in pulp mill waste OM deposition starting in 1912.

Pre-dams Interval (~1907-1912) (230 cm-216 cm core depth) – 15 samples

Phi Grain Size Fractions (%)

Phi	2.3	2.7	3	3.3	3.7	4	4.3	4.7	5	5.3	5.7	6	6.3	Md (µm)
Av.%	0.72	1.18	2.6	6.9	13.9	15	12.7	10.1	8.96	7.77	7.14	6.3	5.35	54.96
SD	0.27	0.72	1.5	5.8	4.05	2.5	1.28	1.43	1.74	1.92	1.97	1.77	1.47	8.57
CV.%	38	61	59	84	29	17	10	14	19	25	28	28	28	16

Post-dams Interval (1970-~1965) (57-72 cm core depth) – 15 samples

Phi	2.3	2.7	3	3.3	3.7	4	4.3	4.7	5	5.3	5.7	6	6.3	Md (µm)
Av. %	0.56%	0.67%	1.69%	5.38%	11.21	13.27	12.27	11.26	10.57	9.81	9.19	7.87	6.21	46.25
SD	0.17	0.21	0.86	2.7	2.93	1.91	1.61	1.4	1.54	1.33	1.54	1.85	1.69	6.35
CV. %	30	31	51	50	26	14	13	12	15	14	17	23	27	14
		D	I	F	F	E	R	E	N	C	E			
Av.dif.	-0.16	-0.51	-0.91	-1.49	-2.66	-2.1	-0.43	1.13	1.61	2.04	2.05	1.57	0.86	-8.44
SD.dif.	-0.1	-0.51	-0.67	-3.05	-1.12	-0.63	0.33	-0.03	-0.2	-0.59	-0.43	0.08	0.22	-2.22
CV.dif.	-8	-30	-8	-34	-3	-3	3	-2	-4	-11	-11	-5	-1	-2

TABLE 3.

Comparison of average 3-month springtime temperatures and total precipitation for post-dams versus pre-dams times in the Isle Maligne Dam area of the Saguenay River watershed

(Data sourced from: Service l'Hydrométrie, Ministère Richesses Naturelles, Quebec, 1983).

Apr.+My.+Jn Average	1965-1970	1925-1930	Standard Error (SE)
Mean Temp. (°C)	8.47	8.81	
SD. Mean Temp.	5.81	6.03	
CV. Mean Temp. (%)	69	68	
Standard Error (SE)			0.17
Mean Total Precip. (mm)	59.13	84.81	
SD. Mean Total Precip.	33.27	40.13	
Standard Error (SE)			2.09
Total Months (3 x 6 years)	18	18	

particle size classes (fine sand to coarse silt) show statistically significant post-dams decreases for the 2.3ø, 2.7ø, 3.0ø, 3.3ø,3.7ø, 4.0ø, and 4.3ø fractions that are coeval with higher post-dams values for the relatively finer 4.7ø, 5.0ø, 5.3ø, 5.7ø, 6.0ø, and 6.3ø particle size classes (coarse to fine silt). Higher percentages of the 4.7ø - 6.3ø silt fractions are coeval with the higher post-dams average composite sedimentation rate in the prodelta setting and relatively lower average MMMD levels.

Local temperature and total precipitation

Concerning climate condition differences, a cursory examination of average temperature and average total precipitation (TP) in the area of the Isle Maligne Dam during the spring freshet months (April, May and June) appears to have contributed to higher MMMD's observed during pre-dam times (Table 3). Although spring temperatures show no statistically significant difference between intervals, the TP average for the pre-dams interval was 25.68 mm larger than its post-dams counterpart and produced an SE value just over 2.0 which is considered to be "probably significant" according to Moroney (1973).

DISCUSSION

An increase in sediment-transport efficiency in river channels upstream from reservoirs can have negative economic and ecosystems services impacts, such as shortening of dam lifetimes and reservoir capacity [9,30-33]. Schwind et al. (2010) have shown that the construction of reservoirs in freshwater systems modulates the concentration of inorganic particulates which [34], in turn, can have either positive or negative impacts on the population growth of testate amoebae. Their study found that higher concentrations of suspended inorganic particulates reduced the population growth of some testate amoebae species inhabiting Neotropical flood plain lakes downstream from dams. In contrast, for the coring area of the Saguenay Prodelta, seafloor OM concentrations effectively reduced near bottom oxygen concentrations to a level that essentially prevented colonization by bioturbating species until after the mid -1970's.

High-resolution sedimentary records of natural and anthropogenic processes and events that are manifested as textural, geochemical and micropaleontological "signals" are often preserved in sub-aqueous delta deposits of specific estuarine environments [35]. In addition, sedimentation rate variations often serve as recorders of annual impacts of climate, land use, storms, floods, and relative sea level changes [10]. The prodelta seafloor of the Saguenay Fiord's North Arm Basin is one such environment. Post-1912 increases in industrial OM discharges to this location have transformed part of the Prodelta seabed into what has been referred to elsewhere as a seasonal "dead zone" in the northern part of the Gulf of Mexico near the mouth of the Mississippi River [36,37]. At that location, the seasonal nature of hypoxia has been linked to the local ocean circulation and to high spring-summer productivity. However, in the Prodelta study area's seafloor setting, hypoxic and anoxic seabed conditions apparently prevailed continuously throughout the entire year from 1912 until shortly after 1971 (e.g., 80 cm-100 cm, Figure 2). Bioturbation – free conditions are evidenced by the exceptionally sharp boundaries between annual sediment layers (e.g., [38,16]).

Following the 1971 St. Jean Vianney Landslide, recognizable (although somewhat irregular and diffuse) annual deposits continued to occur from 1971 to 1982 despite evidence of a slight (0.8%) reduction in average OM percentage compared to that observed for the 1907-1912 interval 0 cm-20 cm, Figure 2). Apparently, 1971 Environment and Climate Change Canada (ECCC) legislated OM reduction appears to have promoted seasonal colonization by a microfaunal community of small bioturbating species such as benthic Foraminifera [39,40]. Mean Annual Discharge (MAD) averages show a difference between pre- and post-dam intervals that is statistically insignificant (Table 1). The relatively higher MAD Coefficient of Variation (CV) of the 1915-1925 pre-dams interval may partly be a reflection of the absence of dam-related management of much of the river's natural annual discharge pattern [41]. In contrast, the statistically significant relatively higher average MMMD for the pre-dams 1915-1925 interval suggests post-dam river management of high discharges during spring freshet months. However, MMMD CV results are opposite to MAD CV results, indicating that the post-dams interval of relatively lower average MMMD conditions was more significant in regard to variability than witnessed during pre-dams higher average MMMD conditions. Possible explanations for these contrasting results are provisionally attributed to river discharge management practices that appear to have more significant effect during relatively low average MMMD discharges, seasonal changes in local climate, land use factors such as watershed forest management and agricultural development that may have modulated meltwater and rainfall transport of sediment to tributary channels. For example, the completion of two reservoirs in the upper reaches of the Yellow River in 1968 and 1985 resulted in a step-wise decrease in sediment load that has been attributed a 30% decrease in rainfall, a 40% decrease in soil conservation practices and to a 30% decrease caused by sediment retention in reservoirs [42]. They also report that soil conservation practices, in concert with the operation of the two reservoirs they studied, have lowered the content of relatively coarse (bedload?) sediment which has reduced deposition in the river's lower reaches. Similarly, a study of the Columbia River system found that the spring freshet magnitude decrease due to climate change was 11% and that water withdrawal and river flow regulation accounted, respectively, for about 12% and 26% [43]. In contrast, construction of the Three Gorges dam (TGD) on the Yangtze River in 2003 was characterized by a 70% reduction of sediment load reaching the river's submerged delta. However, between 1958 and 2009, sediment accumulation at that delta's depocentre showed a rate of 10 cm/yr [44]. They concluded that, in general, the dam had little effect on sediment accumulation except at short-term scales when episodic extreme floods and storm surges increased both the magnitude of deposition and erosion events. In their study of the New Zealand's Waipaoa River system, Kettner et al. (2007) concluded that water discharge tracks precipitation and that annual average discharge may have been up to 20% higher and 6% lower over the past 3000 years [45]. For example, they note that during the Anthropocene (1950 to the present), suspended sediment discharge of the Waipaoa River system changed from 2.3 +/- 4.5 to 14.9 +/- 8.7 MT yr-1, increasing by 140% after the Polynesian arrival, by 350% after European colonization and by 660% after catchment headwaters deforestation. Similar results are reported at a global scale by Syvitski et al. (2005) [46].

There is a pronounced and statistically significant difference between composite sedimentation rate averages and respective CVs for the two prodelta core 72 intervals (Table 1). Higher sedimentation rates with higher variability prevailed during the post-dams interval suggesting that river discharge management is a crucial factor controlling the increase in sediment deposition at the prodelta core 72 site of particles in relatively finer 4.7ø to 6.0ø size classes. In pre-dam time, these finer sediments constitute suspended load that likely would have been carried to deeper and more distal parts of the North Arm Basin prodelta by the larger MMMD's. Both the higher average post-dams sedimentation rate and its associated higher CV might therefore also be indicative of the management of seasonal MMMD amplitudes in post-dams time. As such, the observed post-dams average MMMD decrease could perhaps be singularly responsible for a shift of the depocentre of the suspended sediment load of relatively finer silt-size particles to upstream prodelta locations that encompasses the core 72 sampling site and, as well, to upstream prodelta seafloor settings that are located closer to the mouth of the Saguenay River just downstream from the city of Chicoutimi. The relatively finer 4.7ø to 6.0ø post–dams silt fractions percentage increases are also reflected by the statistically significant reduction of the pre-dams interval average median particle diameter (Md) from 54.5 µm to a post-dams average value of 46.3 µm that appears to record an overall decrease in the river's sediment transport energy at the core 72 location. This Md decrease likely impacted seafloor sediment textures for some unknown distance from the Saguenay River mouth especially on the south side of the North Arm Basin Prodelta due to the Coriolis Effect. Changes in grain size fraction percentages from pre-dams to post-dams times show several other features that appear to be linked to river discharge management activities. The 2.7ø, 3.0ø and 3.7ø size fraction percentages (fine and very fine sand) all show significant post-dams reductions that imply a decrease in sediment transport energy of river currents that carry fine sandy bedload to the core 72 location of the prodelta. Obreja (2012) observed that sediment trapping efficiency is directly proportional to reservoir capacity for reservoirs in Romania's Siret Basin [47]. As such, that relationship implies that the greatest influence on changing sediment textures on the modern Saguenay Prodelta is associated with the Isle Maligne Dam and its exceptionally large Lac St. Jean reservoir, as opposed to the smaller secondary 44 km-long Saguenay River channel reservoir that lies between Lac St. Jean and the Shipshaw and Chute-a-Caron dams.

In contrast to observed temporal texture and sedimentation rate changes, the post-dams increase in average OM between 1907-1912 from 9.3% to 13.5% for the 1965-1970 interval has been shown to be due to an increase in OM sourced from local pulp mill discharges as opposed to dam-related river discharge management activities [16,48]. River disposal of pulp mill waste that increased dramatically in 1912 appears, according to core 72 OM measurements, to have reached its maximum just before 1971. As such, the effect of the 1971 Environment Canada and Climate Change (ECCC) pulp and paper mill effluent regulations (PPER's) appears to be evidenced by the reduction in averaged 1972-1982 OM to 8.1%, or 1.2% to 5.4% less than that observed for the pre-dams core interval (**Table 1**). The positive side of this OM pollution condition is that it produced an approximately 70 year-long core section of unbioturbated annual sediment layers that has been a rich source of textural proxy data of annual river discharge variation before the initiation of monthly record keeping in 1914.

The explanation of the TP difference between the two 6-year intervals reported in Table 3 is likely climate related despite the similarity of average spring temperatures. For example, a graph produced by the US National Oceanographic and Atmospheric Administration (NOAA) shows that the Earth's average temperature was about 0.35oC lower between 1905 and 1912 compared to the 1901 – 2000 temperature average and could, therefore, have been manifested in the Isle Maligne Dam area of the Lac Saint-Jean watershed by higher amounts of snowfall [49].

CONCLUSIONS

Compared to pre-dam times, post-dams prodelta sediments at the core 72 location feature decreased percentages in the 2.7ø, 3.0ø, 3.3ø, 3.7ø, 4.0ø, and 4.3ø fine sand-size and coarse silt-size fractions and increases in in the 4.7ø, 5.0ø, 5.3ø, 5.7ø, and 6.0ø silt-size fractions. This difference can be explained by an overall reduction in sediment transport energy in the lower reaches of the Saguenay River channel during post-dams time. The imposition of ECCC pulp mill effluent regulations in 1971 that mandated a reduction pulp mill OM waste inputs apparently caused environmental changes to the prodelta's seafloor environment that eventually allowed its initial recolonization by relatively small bioturbating species that were insensitive to the observed prodelta seafloor textural changes in the core-72 area of the Saguenay River Prodelta.

The River's three dams have had their greatest trapping effect on bedload grain sizes. They created sediment transport conditions that favor relatively finer suspended-load grain-sizes. The decrease in transport energy manifested by the dams has caused an upstream shift in finer particle sizes that were formerly transported to distal and deeper prodelta depositional settings of the North Arm Basin. The upstream shift of relatively finer particles toward the river mouth changed substrate characteristics in that area of the Prodelta that has the potential to alter the species composition of benthic communities due to likely alterations of their natural ecosystems services requirements over the past 79-years.

ACKNOWLEDGMENTS

The author wishes to acknowledge the many helpful corrections and comments received from internal GSCA reviewers P. Potter, B. MacLean and external Louisiana State University reviewer Dr. B. Sen Gupta. F. Cole provided critical assistance with the organization and post-processing of textural and OM data. Special thanks are extended to D. Clattenburg and assistants for their meticulous grain size analysis of more than 500 core 72 subsamples and to my BIO colleague Dr. J. Smith for providing ^{210}Pb results for core 72. The author also wishes to offer his gratitude for changes suggested by the Journal of Environmental Research reviewer that improved the overall presentation profile of the Results and References sections of the paper. Funding for this investigation was provided by the Geological Survey of Canada Atlantic Division of Natural Resources Canada.

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