From pristine to present state: hydrology evolution of Lake Saint-François, St. Lawrence River

Jean Morin and Michel Leclerc

Abstract: Lake Saint-François is a relatively shallow fluvial lake of the St. Lawrence River with numerous deep channels. This complex system has been considerably altered from its pristine state 150 years ago. Currently, the water level is stabilized and the flow is regulated; important areas have been dredged and the major part of its outflow is diverted through the Beauharnois canal. The evolution of water levels shows a trend towards stabilization as required for ship traffic in the St. Lawrence Seaway and for hydropower production. With the construction of the Moses-Saunders dam in 1960, the flow of the river could be regulated; changes occur in the seasonal pattern of the flow. Ancient stage–discharge relationships were recreated to describe the impact of the 1849 damming and of the present level stabilization. Stabilization of the water level has favored the growth of submerged plants. Manning's friction coefficient was used to show that plant biomass has doubled since 1920; the onset of biomass increases corresponds to a water level stabilization event. The distribution of wetlands in the Lake Saint-François area was drastically modified by the water level rise caused by the 1849 damming. New wetlands were created and pre-1849 wetlands, located on what are currently shoals in the central part of the lake, have totally disappeared.

Key words: Lake Saint-François, St. Lawrence River, impact of civil works, flow discharge regulation, water level regulation, wetland flooding cycle, submerged macrophyte, ecosystem reaction, civil work history.

Résumé : Le lac Saint-François est un lac fluvial du fleuve Saint-Laurent, peu profond et entrecoupé d'un réseau de chenaux. Ce système complexe a été considérablement modifié par les interventions humaines depuis 150 ans. Présentement, les niveaux d'eau y sont stabilisés, le débit du fleuve y est régularisé, des superficies importantes ont été draguées et la majeure partie des eaux du fleuve est détournée dans le canal de Beauharnois. L'évolution des niveaux d'eau montre une tendance marquée vers la stabilisation, exigée par la navigation fluviale et par la production hydro-électrique. Les débits du fleuve sont régularisés depuis la construction du barrage de Moses-Saunders en 1960; des changements significatifs apparaissent dans la distribution saisonnière du débit. Les anciennes relations niveau-débit ont été recréées et nous ont permis de décrire l'effet du barrage de 1849 ainsi que l'impact de la stabilisation des niveaux. La stabilisation des niveaux d'eau a probablement favorisé la croissance des plantes submergées. Le coefficient de frottement de Manning calculé pour chaque année montre que depuis 1920, la biomasse de plante submergée a doublé et les augmentations soudaines de biomasse correspondent à des périodes de stabilisation des niveaux. Les milieux humides actuels du lac Saint-François ont été modifiés en 1849.

Mots clés : Lac Saint-François, fleuve Saint-Laurent, impacts des ouvrages de génie, régularisation du débit, régularisation des niveaux d'eau, cycle d'inondation des milieux humides, macrophytes submergées, réaction de l'écosystème, histoire du génie civil.

Context

Lake Saint-François is the first fluvial lake of the St. Lawrence River (Fig. 1). It is an important expansion of the river, nearly 50 km long, with a maximum width of 8 km (Allan 1986; Lorrain et al. 1993), covering a total area of 254 km^2. The mean discharge at Cornwall is 7500 m^3/s, consisting essentially of Lake Ontario waters. Currents are strong, between 0.2 and 1.5 m/s in the main channels, accounting for the absence of stratification observed in the lake. The flow pattern varies greatly with seasonal factors such as ice and plant friction (Morin et al. 1996).

The bottom of Lake Saint-François is covered by submerged plants, and the surrounding land supports extensive and diversified wetlands. Some of these areas benefit from a protected status, e.g., Lake Saint-François National Wildlife Reserve and Cooper Marsh. These areas are crucial for bird reproduction, especially the National Wildlife Reserve where 134 species have been known to nest (Gauthier and Aubry 1995). Fifty-seven species of fish have also been reported in the lake (Environment Canada 1994).

The study area is in the centre of a small industrial zone directly linked to the presence of the river. Upstream of the

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J. Morin and M. Leclerc. Institut national de la recherche scientifique (INRS-Eau), Sainte-Foy, QC G1V 4C7, Canada.

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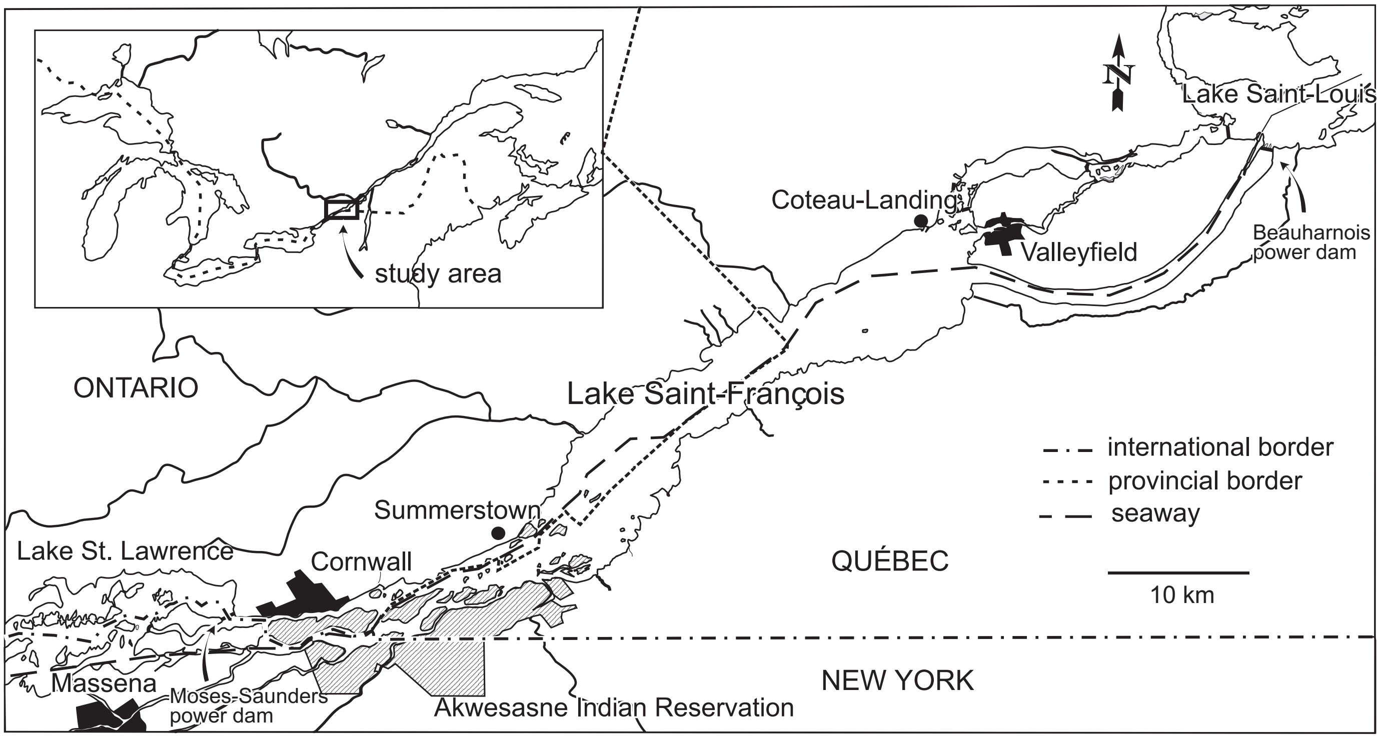
Fig. 1. Location of Lake Saint-François, limited upstream by the Moses-Saunders power dam and downstream by the Beauharnois power dam.



lake, hydroelectric power is produced at the Moses-Saunders dam, operated jointly by the New York Power Authority (928 MW) and Ontario Hydro (876 MW). Downstream, the Beauharnois dam is operated by Hydro-Québec with 1582 MW of installed capacity. Several industries have settled in the area, mainly in the Cornwall–Massena sector. Flow discharge regulation and especially the change in water level are sensitive issues in the Lake Saint-François area. Conflicting interests are numerous with the presence of hydroelectric power plants upstream and downstream: navigation in the St. Lawrence Seaway, recreational boating, lakeshore residents, and the "natural" ecosystem conditions.

The present ecosystem is quite different from that of the pristine state, encountered 150 years ago. Upstream and downstream dams have almost completely cut off fish migration routes. Animal and plant species have disappeared and been replaced by others; some species are currently endangered or threatened. A protracted sequence of damming, diversions and dredging has slowly modified the hydrology of the river. Several myths persist in the literature concerning the evolution of these works and their effects on the hydrology of Lake Saint-François. It is likely that their effect on the stabilization of water levels has important consequences on the productivity and biodiversity of the ecosystem (Environment Canada 1994). However, the actual impacts of discharge and water level management on wetland vegetation, submerged macrophytes, and habitats have not been fully assessed.

Considering that any decision related to hydrological management could have important economical and ecosystemic repercussions, it is our opinion that hard facts have to be separated from mere opinions. A synthesis of the hydrological conditions of present, past, and pristine states was prepared. This paper should be viewed as a reference tool for anyone interested and involved in decision making for future modifications of flow discharge and water level management in the Lake Saint-François area.

The objective of this paper is to present an overview of the hydrology of this complex system. It focuses on the evolution of the St. Lawrence River hydrology in the Lake Saint-François area, and its direct impacts on the ecosytem. Historical transformation of the environment by civil works is described. The cumulative impacts of these works on flow and water level evolution are described and analyzed, along with the natural fluctuations and the current management practices. The pristine hydrological conditions of Lake Saint-François are reconstructed with historical stage–discharge relationships. Also, the direct impacts of these physical alterations on aquatic plant abundance and wetland flooding cycles have been analyzed.

Methodology

Description and analysis of civil works evolution require inputs from several sources. The historical evolution of civil works is described based on a literature review and on the rich collection of maps of the area. Old maps are kept in the Map Library of the National Library of Canada. Various documents were used, such as Bouchette's map of 1831 (Bouchette 1831), several maps produced at the end of the 19th century, maps drawn by the Department of National Defense, and other cartographic documents prepared for the planning of various projects. A list of the maps consulted is given at the end of the paper.

An analysis of dredging and deposition of dredged material was performed by comparing two bathymetry data sets of Lake Saint-François. An old data set of water depth soundings from 1900 to 1907, surveyed by the Canadian Hydrographic Service (see CHS 1900–1907 in the List of maps), containing 66 500 measurement points has been digitized. After digitization and georeference rectification, these field sheets were compared with a recent data set (CHS 1987–1989, see List of maps) comprising 300 012 soundings. A subtraction of the two data sets gave us an indication of dredging depths and material deposit thickness, natural erosion and sedimentation processes, and their spatial distributions. Uncertainties associated with this subtraction technique are estimated to be ±1.5 m vertically, mostly related to the lack of precision from the 1900–1907 soundings. Sedimentation rates are very low (Lorrain and Carignan 1992), and areas associated with important bathymetric changes are assumed to be mainly related to dredging activities.

Flow discharge and water level data were extracted from the HYDAT database (Environment Canada 1996). The annual flow pattern of the St. Lawrence River was analyzed using interannual daily average flow from data between 1960 and 1990. Data were collected at Cornwall, upstream of Lake Saint-François, and downstream at Coteau-Landing and at the Beauharnois power dam. Long-term evolution of discharge was analyzed with a monthly average series from Cornwall and Iroquois. Daily average flow data from Cornwall are available from 1958 onward. Prior to 1958, data were measured at Iroquois and daily averages are available from 1919 to 1958, with monthly averages only from 1860 to 1919. Data from Cornwall and Iroquois can be used as one series, since only a negligible basin of about 360 km^2 contributes to the flow of the St. Lawrence River between these two stations.

Water levels were analyzed using monthly averages calculated from daily average measurements available from Coteau-Landing since 1920. Summerstown, 35 km upstream from Coteau-Landing, has the same database; it was used for free surface slope analysis. All the water level data presented herein are based on the International Great Lake Datum of 1985 (IGLD85).

Methodologies used to analyze impacts of hydrology management on aquatic plants and on wetlands are described in this paper. The term aquatic plants is used here to refer to macroscopic forms of aquatic vegetation, whereas the term submerged plants refers to certain aquatic plants, mainly angiosperms, pteridophytes, and macroalgae, whose biomass is mostly underwater.

Historical evolution of civil works

Rapids downstream and upstream from Lake Saint-François were exploited for hydroelectric power generation and modified for commercial shipping, and channels in the lake itself have been dredged for navigation.

Downstream portion of Lake Saint-François

The Soulanges Rapids is a 29 km reach located between Lake Saint-François and Lake Saint-Louis and composed of four sections (Fig. 2*a*): Coteau, Des Cèdres, Rocher Fendu, and Cascades, representing a total drop of 25 m.

The Beauharnois canal, now known as the old Beauharnois canal, was built on the south side of the St. Lawrence River between 1842 and 1845 (Fig. 2*b*). This canal, 18.5 km long and 2.7 m deep, had nine locks through which ships bypassed the Soulanges Rapids. This old canal was replaced in 1899 by the Soulanges canal, 4.3 m deep, built on the north side of the St. Lawrence River and used until 1959. The Soulanges power station used about 85 m^3/s of water from the canal for electric power generation from 1906 to 1915. From 1911 to 1951, water was channeled to the Saint-Timothée power station through the old Beauharnois canal; the flow was approximately 110 m^3/s.

The southern branch of the St. Lawrence River has been successively known as “chenal de Beauharnois,” Lost Channel, and Saint-Charles River (Fig. 2). This branch was dammed at Salaberry-de-Valleyfield in 1849 to reduce the currents around the entrance to the old Beauharnois canal. Originally, the discharge was about 1100 m^3/s (Chevrier 1955) but it was reduced by damming to 280 m^3/s (McNaughton 1962). In 1853, a paper mill was erected close to the dam, using the 3 m head to produce energy. A cotton mill replaced it in 1900 and the flow was increased to 370 m^3/s in 1901. This branch of the St. Lawrence was almost completely filled around 1930; less than 5 m^3/s of water still flows through it.

The main channel of the St. Lawrence was modified at the Des Cèdres Rapids in 1914 for power production; this plant is still in operation. The Ile Juillet dams were added in 1932, forcing the flow through the power station. Finally, several works were erected between 1959 and 1963 for water level control (Hydro-Québec 1970).

The construction of the present Beauharnois canal began in 1929 and was completed in 1932. The 26 km long by 1 km wide canal diverts the major part of the St. Lawrence flow to the Beauharnois power station. This plant was built in three phases: the first phase was completed in 1932 and used 2350 m^3/s of the flow, the second phase was completed in 1952 and used 4500 m^3/s, and the third phase was completed in 1961 and used more than 6500 m^3/s.

Water level control dams were erected at the outlet of Lake Saint-François in order to force the flow into the Beauharnois canal. The Coteau works are composed of four distinct dams: Coteau dam numbers I, II, III, and IV. Three of the dams are equipped with gates to control the flow (dam number II is never used) and the fourth is a jetty with an underwater gate (Fig. 2*c*). The first dam was finished in 1933 and the others in 1942 (Hydro-Québec 1970).

The St. Lawrence Seaway was built in 1959, using the Beauharnois canal for navigation. A 3 km long shipping channel was then dredged in the lake, and a lock was built beside the power dam (Fig. 2*c*).

Upstream portion of Lake Saint-François

The civil works upstream of Lake Saint-François are related to another zone of former rapids, known as the International Rapids. This zone was composed of three sections: the former Galop, Plat, and Long Sault rapids, representing a drop of more than 25 m over 60 km of river.

The first major intervention in the area was the construction of the Cornwall canal between 1834 and 1842 (Chevrier 1955). This work, 18 km long and 3 m deep, was built on the north shore of the St. Lawrence. It allowed ships to get

Fig. 2. Evolution of civil works in the Soulanges Rapids section: (*a*) pre-1800, (*b*) 1900, and (*c*) 1960.

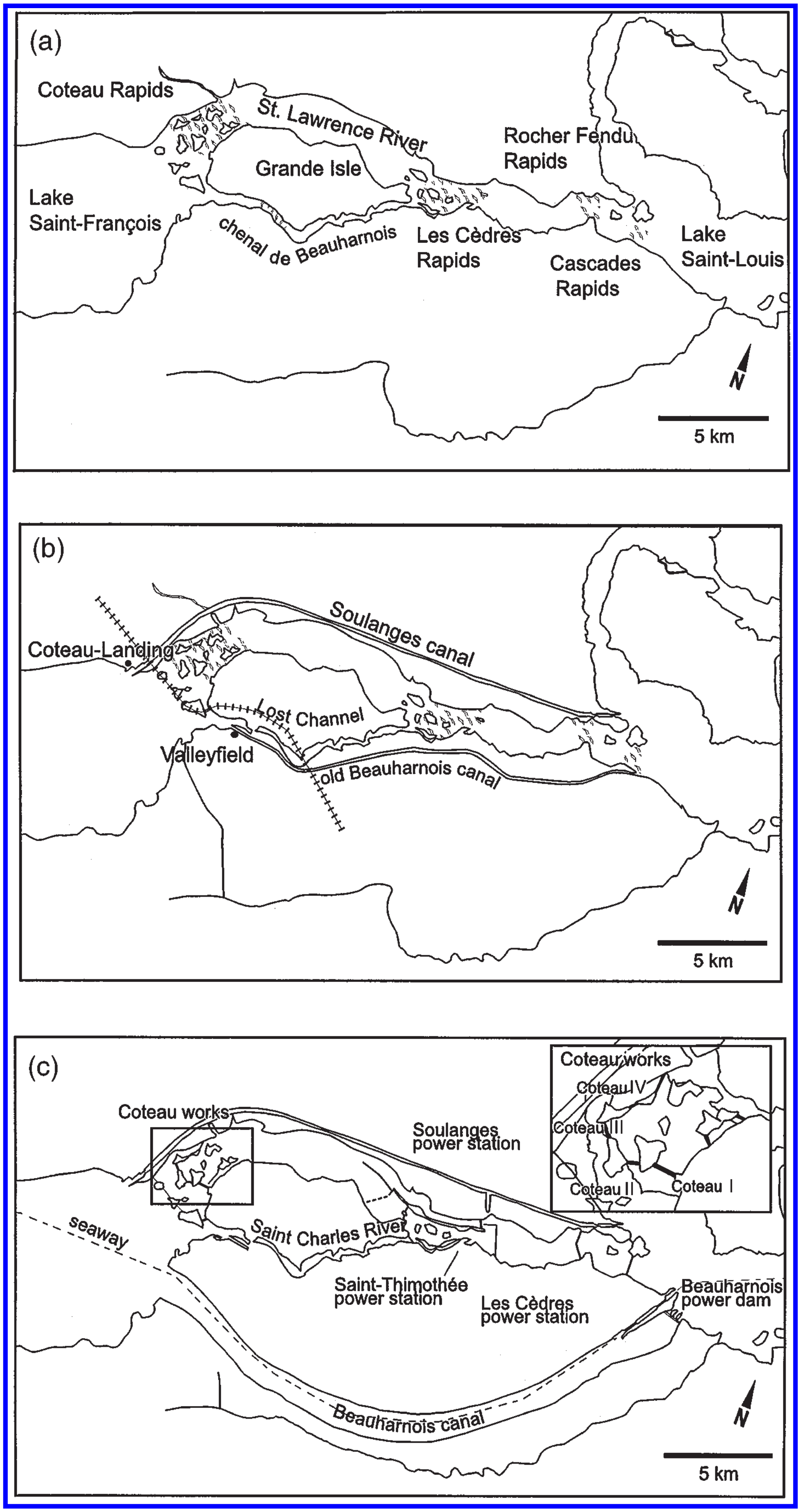
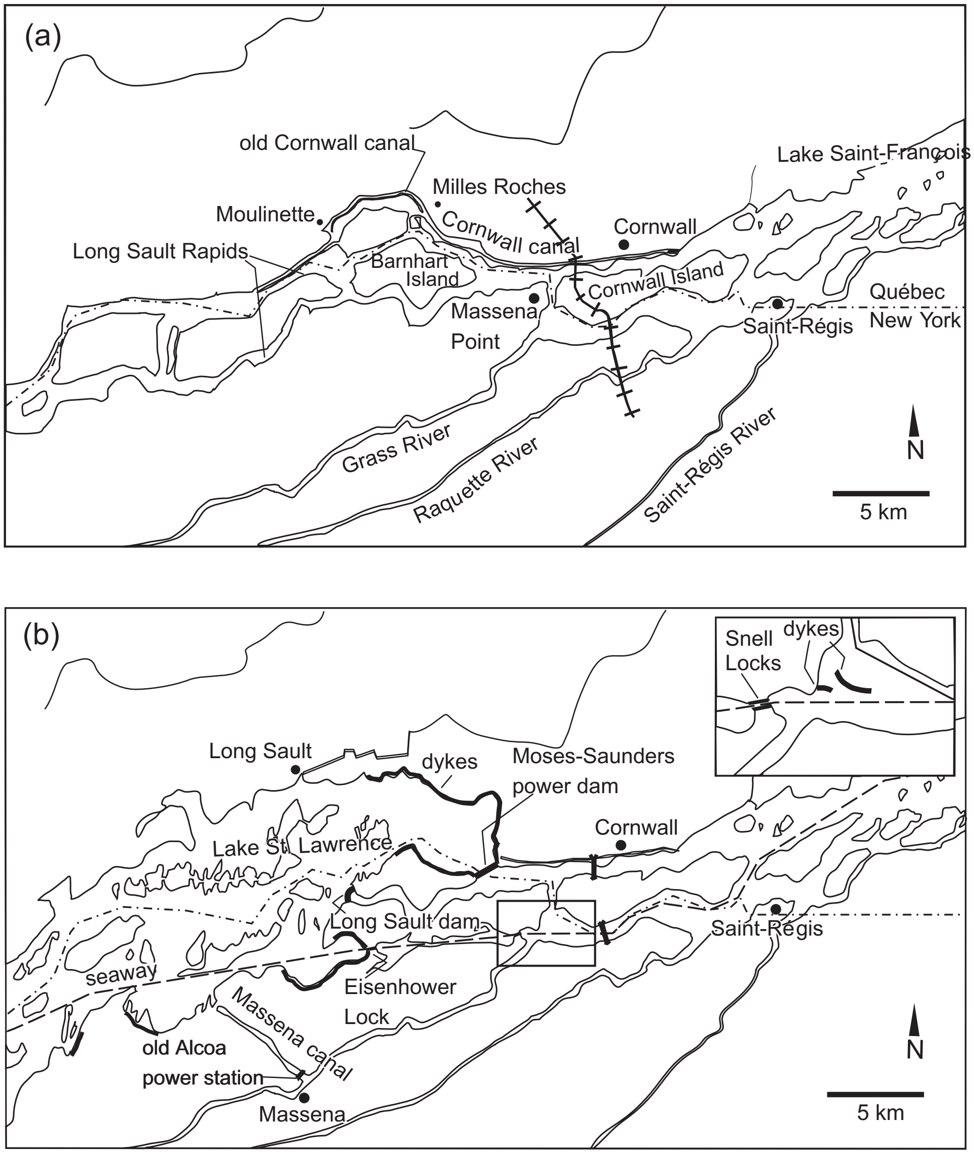


Fig. 3. Evolution of civil works in the Cornwall area (International Rapids section): (*a*) circa 1900 and (*b*) 1960.



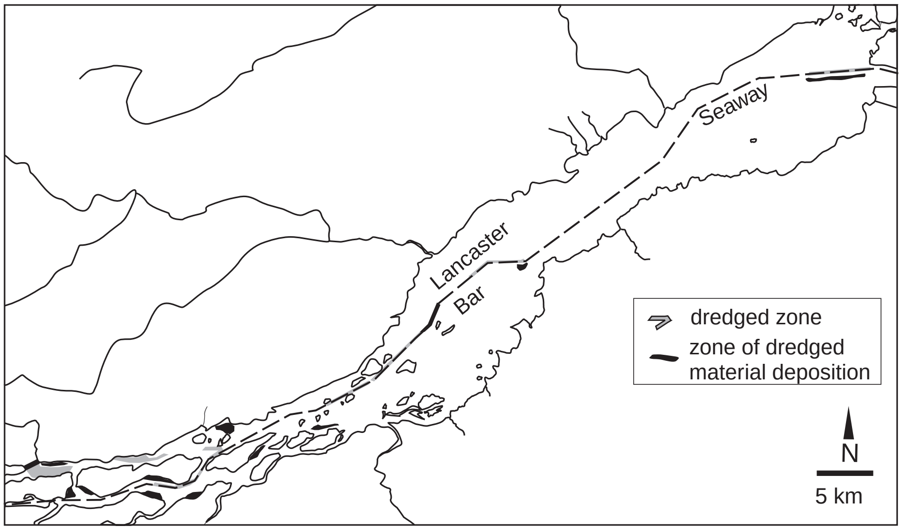
upstream from the Long Sault Rapids and other swift-current zones around Barnhart Island (Fig. 3*a*). The canal was deepened to 14 ft (1 ft = 0.3048 m) between 1897 and 1901. From 1900 to 1959, the Massena canal was used on the American side to bring water to the Grass River where the Alcoa power plant is located. This canal is still used by Alcoa, but less than 1 m^3/s is diverted.

The flow pattern has been considerably modified in the area after transformations occurred at the end of the 1950s, including three dams, several navigation channels, two locks, important dredging, several kilometres of dikes, creation of an artificial lake, and two bridges linking Cornwall Island to the mainland (Fig. 3*b*). The Moses-Saunders power dam and Long Sault control dam were constructed between Barnhart Island and the mainland, creating the artificial Lake St. Lawrence. The Iroquois dam is a control structure located at the outlet of Lake Ontario, 70 km upstream from Cornwall. The St. Lawrence Seaway is located on the south side of the river and passes through Snell and Eisenhower locks downstream and upstream, respectively.

Lake Saint-François

In Lake Saint-François, modifications to natural flow patterns were caused by changes in the main flow output and by dredging for the St. Lawrence Seaway. Extensive dredging was undertaken for the construction of the seaway and the Moses-Saunders power dam at the end of the 1950s (Fig. 4). As mentioned previously, a 3 km long by 100 m wide channel was dredged at the entrance to the Beauharnois canal. From this channel to approximately Lancaster Bar, there is no evidence of any modification of the lake bottom. However, in the upper part of the lake, from Lancaster Bar to Snell Lock, almost the entire navigation channel had to be dug. Interventions varied from thin grading to major trench digging. Around Cornwall Island, the river was straightened, points were removed, and the material was used to fill small

Fig. 4. Transformation of the main part of Lake Saint-François.



bays. The area close to the Moses-Saunders dam was dredged to facilitate the evacuation of water from the power station tailrace. Dredged materials were deposited in several areas, mainly in secondary channels. The thickness of these deposits reaches 12 m in several areas.

Evolution of flow discharge

The flow of the St. Lawrence River has been regulated since the construction of the Moses-Saunders and Long Sault dams in 1958. Before that period, the Galop Rapids acted as a control section for the outflow of the Lake Ontario waters (Yee 1995). With the construction of the dams, Lake St. Lawrence has flooded shores and control sections from Cornwall to Iroquois, over more than 70 km. Since 1958, the power plant is the main structure controlling Lake Ontario outflow. The Long Sault dam is open only when the flow exceeds 9500 m^3/s. The Iroquois control dam, upstream of Lake St. Lawrence, can also be used to control the flow. Its main function is to favor the formation of a stable ice cover in winter and to reduce high water levels in Lake St. Lawrence (Yee et al. 1990). The regulation has slightly modified the annual variation of the natural flow.

Seasonal variations

The flow of the St. Lawrence River has small seasonal variations due to the natural regulatory effect of the Great Lakes. Under natural conditions, prior to 1958, the average maximum flood occurred during June, whereas drought appeared in February. The lowest flow corresponds to the period of thickest ice. The flow clearly increases during the spring thaw, and a slight increase is observable during fall (Fig. 5). These characteristics appear clearly in natural flow simulations for Cornwall (1959–1989) as well as in the actual flow measurements at Iroquois (1919–1949). Artificial regulation of the flow since 1958 has reduced the average maximum flow in summer and increased the minimum flow in winter (Fig. 6). The average maximum flow occurs in July and the minimum in January. There is also a deliberate sharp reduction at the end of December to induce the formation of a stable ice cover upstream from the power dams.

At the mouth of Lake Saint-François, the St. Lawrence flow passes directly, due to the near absence of level variations in the lake. The hydrological balance is influenced by the input of several tributaries, the most important of which are the Raquette, Saint-Régis, and Grass rivers, all located on the south shore. The total basin surface area of all tributaries is about 9000 km^2. The flow of the tributaries reaches a peak at the end of March to early April, with an average of 750 m^3/s; another small peak of 250 m^3/s occurs at the end of November as shown by the interannual daily average plotted in Fig. 7. The contribution of the tributaries is at a minimum in July and January–February.

Present regulation plan

Lake Ontario outflow has been regulated since 1958, i.e., since the commissioning of the Moses-Saunders, Long Sault, and Iroquois dams. Operation limits and dam specifications were set by the International Joint Commission (IJC) in the 1952 Order of Approval and the 1956 Supplementary Order. These orders of approval contain 10 criteria for flow regulation to satisfy four main objectives: reduction of extreme water levels in Lake Ontario, reduction of the risk of flooding in the Montréal area, sufficient depth for navigation, and sufficient flow for power generation. Moreover, there is an eleventh criterion that allows divergence from the plan in the event that flows are outside the range of those observed prior to 1954 (Yee 1995).

The International Board of Control is responsible for the application of the IJC rules on an operational basis. The 1958-D regulation plan, currently in use, was developed and tested with the historical data on Lake Ontario outflows and water levels from 1860 to 1954. This plan uses families of rule curves which function similarly to a stage–discharge relationship. The adjustment of the flow is generally calculated every week. It is a function of Lake Ontario water level and actual water supplies to the lake. Several flow limitations are imposed in order to reach the objectives of the orders of approval, and numerous issues are addressed by flow control (for details see Yee 1995), particularly in critical situations such as ice formation, ice breakup, and flooding. For Lake Saint-François, flow limitation is considered

Fig. 5. Changes in the St. Lawrence River flow discharge by regulation, as shown by interannual daily average flow at Cornwall and Iroquois.

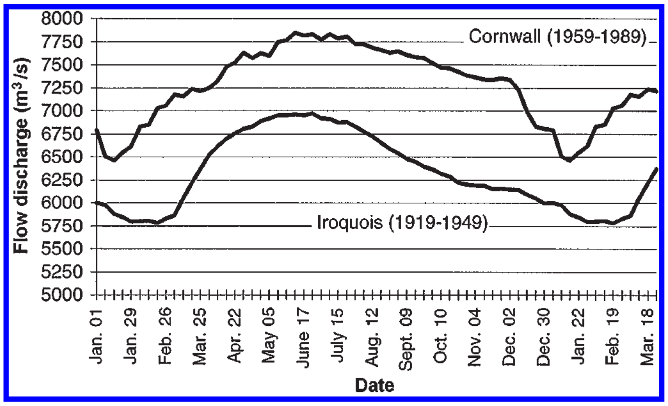


Fig. 6. Changes in the St. Lawrence River flow discharge by regulation, as shown by interannual monthly average of the simulated (natural) and measured (regulated) flow at Cornwall (1963–1995).

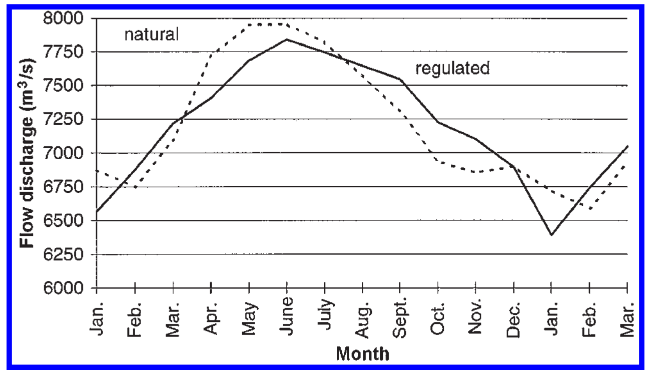
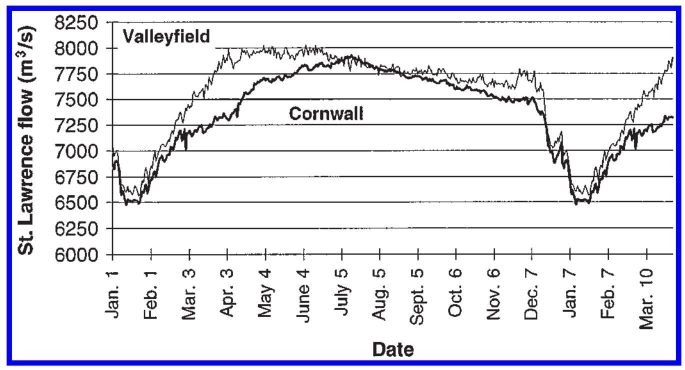


Fig. 7. Inflow (Cornwall) and outflow (Valleyfield) of Lake Saint-François as shown by the interannual daily average between 1963 and 1990.



only during winter in order to prevent high water levels induced by ice restriction between Cornwall and Summerstown. Lake Saint-François itself is regulated by the Beauharnois power dam and Coteau works within a small range of level variations of about 15 cm at Coteau (see the section Evolution of water levels).

The IJC criteria consider several interests but do not take into account the environmental impacts of water level management. However, this aspect may be addressed in future modifications to the criteria and regulation plan (Fay and Eberhart 1995).

Long-term flow discharge variations

The analysis of the evolution of monthly flow average reveals that the St. Lawrence River shows important flow fluctuations. These fluctuations are related to pluviometric variations over the hydrographic basin. As confirmed by spectral analysis, a cyclic signal of 20–35 years can be observed in the sequence. The cycles correspond to wet and dry periods, as often referred to in the literature. Dry periods, periods with the lowest hydraulicity, occurred around 1872, 1896, 1925, 1935, and 1965. The lowest monthly flow was recorded in January 1935 at 4500 m^3/s. Highest hydraulicity periods, wet periods, occurred around 1862, 1886, 1910, 1930, 1952, 1975, 1986, and 1993. The highest monthly average flow of 10 012 m^3/s was measured in May 1993 (Fig. 8).

Evolution of water levels

In its pristine state, the water level in Lake Saint-François fluctuated in relation to the St. Lawrence flow. Lake level was controlled by two distinct thresholds on either side of Grande Isle: Coteau Rapids and the rapids upstream from the Beauharnois channel (Fig. 2*a*), the latter evacuating approximately one sixth of the total flow. This pristine stage–discharge relationship has not been recorded, since measurements of water level at Coteau-Landing began only in 1919.

The Beauharnois channel was dammed in 1849 and the flow was reduced to 280 m^3/s. A new stage–discharge relationship was established (see the section Reconstruction of natural conditions). This relationship lasted until 1901 when the flow was increased to 370 m^3/s. The last stage–discharge relationship controlled the lake level until the construction of the modern Beauharnois canal in 1932, which diverted part of the flow through the Beauharnois power dam.

Effects of civil works and water management

Water level data recorded since 1919 show a direct stage–discharge relationship prior to 1932. Periods of high flow coincided with high levels, and inversely low flow periods created low water levels (Fig. 9). During the early part of phase I of the commissioning of the Beauharnois power dam, the use of the canal did not have many observable effects on the water level because the diversion was of less than 600 m^3/s. The first important modification appeared when the Coteau I dam was erected in 1933; the general level of the lake was then raised during a period of low hydraulicity. Flow discharge transiting through the Beauharnois canal was increased to 2350 m^3/s in 1941 (phase I). The lake level was increased and stabilized after construction of the other Coteau dams (II, III, and IV) in 1942. The flow in the Beauharnois canal was 4500 m^3/s at the end of phase II. After the major transformations which occurred in 1958, i.e., construction of the Moses-Saunders, Long Sault, and Iroquois dams and the St. Lawrence Seaway, the St. Lawrence flow discharge was regulated, and the lake level was stabilized and became independent of the influence of the flow discharge. At the end of phase III in 1961,

Fig. 8. Long-term flow discharge fluctuations of the St. Lawrence River.

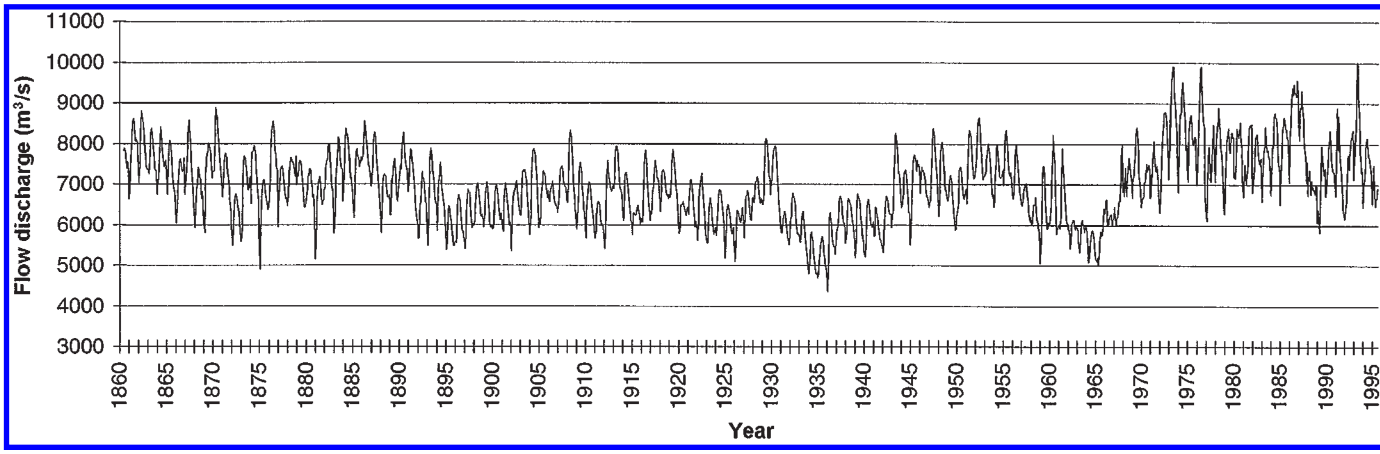
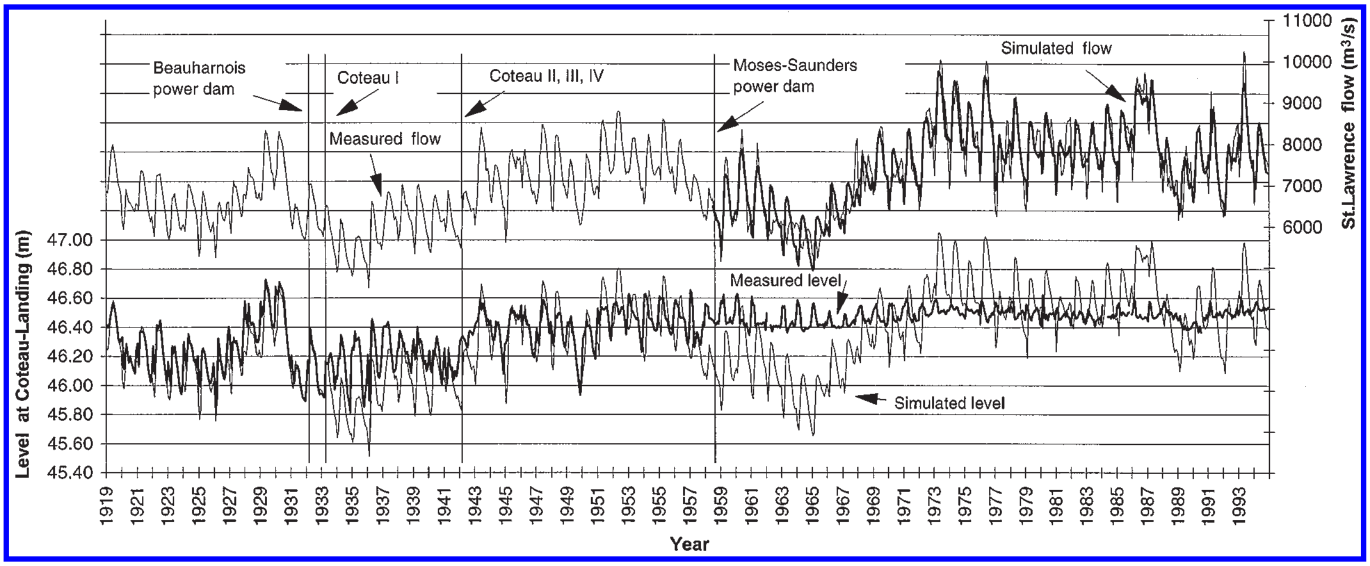


Fig. 9. Impact of civil works on Lake Saint-François from monthly average flow at Cornwall and the water level at Coteau.



most of the St. Lawrence River was flowing through the Beauharnois canal.

Seasonal fluctuations

Prior to 1932, seasonal fluctuations in water levels exceeded 50 cm at Coteau-Landing (Fig. 9). Stabilization started with the erection of Coteau I and was increased with the advent of the other Coteau works in 1942. By the end of phase II of Beauharnois, seasonal variations in level were less than 40 cm annually. With the construction of the St. Lawrence Seaway and the dams in 1958, annual fluctuations were reduced to less than 20 cm, and are presently in the order of 15 cm. The current water level fluctuations are mainly caused by the ice-related winter management practices.

In the eastern part of the lake, under natural conditions, the St. Lawrence flood occurred during the summer, whereas the drought occurred in winter. This pattern of maximum water level in summer and minimum level in winter was normal in that part of Lake Saint-François until the completion of phase II of Beauharnois. Since then, the water level has been increased in winter to maintain the head at the Beauharnois power station. This is evident in Fig. 9, where water level variations are in phase with reconstructed levels, whereas post-1953 variations are reversed.

Present management practices

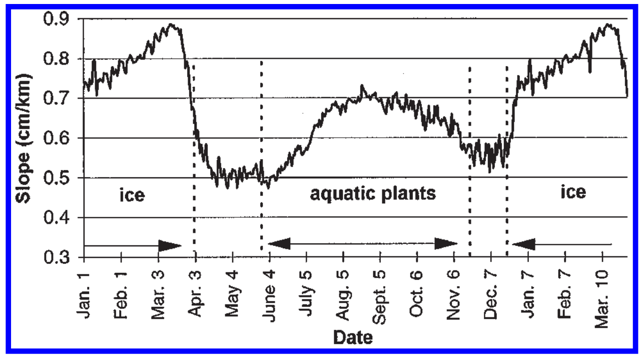
The water level in Lake Saint-François has been regulated by the Beauharnois Heat, Light and Power Company (BHLPC) and later by Hydro-Québec at the Coteau works and Beauharnois power dam since 1941, i.e., since the Privy Council of Canada allowed BHLPC to maintain a minimum level to increase hydropower production for wartime purposes. In 1941, the Privy Council authorized the minimum level of the lake to be 46.33 m (152 ft, measured at Coteau gauge); this regulation was maintained after the war. The St. Lawrence Seaway was designed for ships drafting 7.92 m (26 ft); consequently the minimum level has to be maintained at 46.36 m during the shipping season. Since 1960, Hydro-Québec has maintained the water level between 46.33 and 46.63 m, with an average of 46.50 m. Currently, the Seaway Authority admits ships drafting 8.0 m, so the minimum water level is maintained at 46.40 m during the shipping season. Water levels in the lake generally fluctuate between a minimum of 46.40 m and a maximum of 46.63 m.

During the ice-free season, the maximum water level is kept at 46.58 m (at Coteau) to avoid local flooding caused by winds (Robert 1995).

Energy slope in Lake Saint-François

The slope of the free surface in the lake varies throughout the year. In winter, there is significant friction caused by the occurrence of ice between January and March (Fig. 10). The slope is at its minimum in spring when ice has melted and there are no aquatic plants. During the summer, the annual growth cycle of aquatic plants induces an increase of the free-surface slope. The maximum slope is observed in September and October when plant biomass and density are the highest.

Fig. 10. Seasonal free surface slope variations in Lake Saint-François.



Reconstruction of natural conditions

To provide a description of the natural conditions of an environment which existed prior to 150 years of alteration requires a thorough examination. In its pristine state, prior to 1849, the water levels in Lake Saint-François were controlled by two thresholds on either side of Grande Isle. As explained earlier, the channel on the south side of Grande Isle was dammed in 1849, after which only 280 m^3/s were still transiting. In 1901, this flow was increased to 370 m^3/s and maintained at this level until 1932, i.e., until the Beauharnois canal was constructed. Also, 85 m^3/s were used from 1906 to 1915 at the Soulanges power station and 110 m^3/s from 1911 to 1951 at the Saint-Timothée power station. For 83 years, from 1849 to 1932, an altered stage–discharge relationship controlled the level of Lake Saint-François. These conditions lasted long enough that flora, fauna, and sedimentation probably reached a certain equilibrium with abiotic conditions, so one might be tempted to qualify these conditions as natural. However, for the sake of accuracy, the post-1849 conditions should be considered as altered.

Stage–discharge relationships

Three stage–discharge relationships occurred in sequence at Coteau-Landing: pre-1849, 1849–1901, and 1901–1932. The 1901–1932 relationship was characterized by the Beauharnois Heat, Light and Power Company in 1932 (BHLPC 1934). The flow diverted from Lake Saint-François for power generation prior to 1932 changed from 370 m^3/s in 1901 to 455 m^3/s in 1906 to 565 m^3/s in 1911 and finally to 480 m^3/s from 1915 to 1932. Because these values are relatively small compared with the total flow of the St. Lawrence River, an average flow of 480 m^3/s was used for the 1901–1932 stage–discharge relationship. This value was validated with available daily measurements of flow discharge and water level for that period.

The 1849–1901 relationship is basically the same as that for 1901–1932, with a difference in the discharge of water flowing in the channel south of Grande Isle, i.e., 280 m^3/s. The pristine stage–discharge relationship (pre-1849) was rebuilt using the same basic relationship, on which the effect of the natural flow in the south channel is taken into account. The accurate bathymetric maps (1907, 1928, and 1988) of the south channel were examined to estimate the dimensions of the control section. This control section can be represented by a rectangular section of 240 m in length with its base at 43.93 m. The following threshold equation is used to evaluate control sections with flat bases:

$$[1] \qquad Q = 1.5l(h - h_0)^{3/2}$$

where Q is the flow discharge (m^3/s), l is the length of the section (m), h_0 is the base of the section (m), and h is the water level over the threshold (m). This relation allowed us to calculate the distribution of the flow between the north and south channels around Grande Isle (Fig. 11). Approximately one sixth of the flow passed through the south channel. The resulting pristine stage–discharge relationship for Lake Saint-François is shown in Fig. 12.

The original control section of the south channel probably lies under the dam built in 1849. There is no map available for this part of the river prior to 1849. However, a close examination of old bathymetric maps reveals a restricted section 200 m upstream of the dam site, which is considered to be an equivalent control section. Preliminary bidimensional simulation of the old Lake Saint-François confirms the assumption that this section is restricting the flow considerably. The calculated hydraulic capacity of this section corresponds to the discharge of 1133 m^3/s (40 000 cfs) reported by Legault (1968) quoting a study of Lanthier (1874). Using the long-term average flow of the St. Lawrence River (7100 m^3/s), the flow in the south channel would be 1165 m^3/s.

Natural flow

Flow measurements are available as monthly averages between 1860 and 1958 from measurements at Iroquois, whereas from 1958 onward the flow has been measured at the Moses-Saunders power dam (Cornwall). There is only one small tributary input to the St. Lawrence flow between Iroquois and Cornwall, but tributaries are not negligible in the Lake Saint-François area, especially during the spring thaw. In order to reconstruct a credible series, the average monthly tributary inputs have been added to the St. Lawrence flow. These were calculated using the difference of flow between Cornwall and Beauharnois–Coteau from 1960 to 1990. Because the St. Lawrence River flow has been regulated since 1958, the natural flow simulated for the period 1958–1994 was used (D. Fay, Environment Canada, personal communication, 1996).

Fig. 11. Ancient stage–discharge relationships of Lake Saint-François.

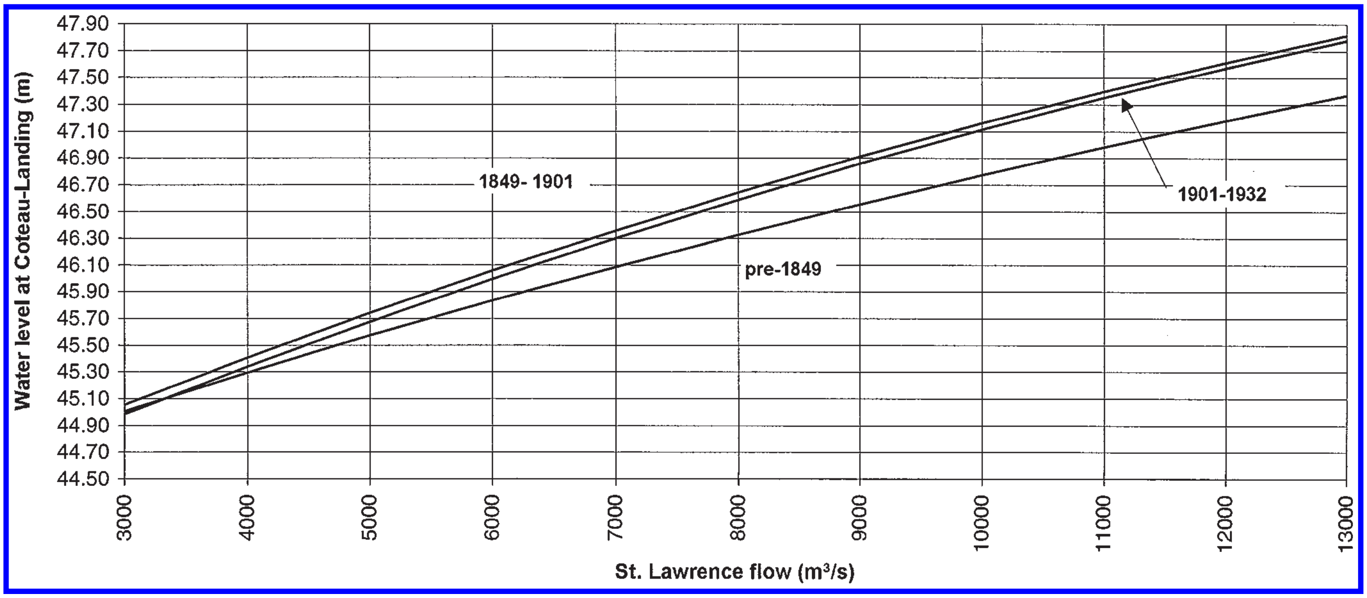
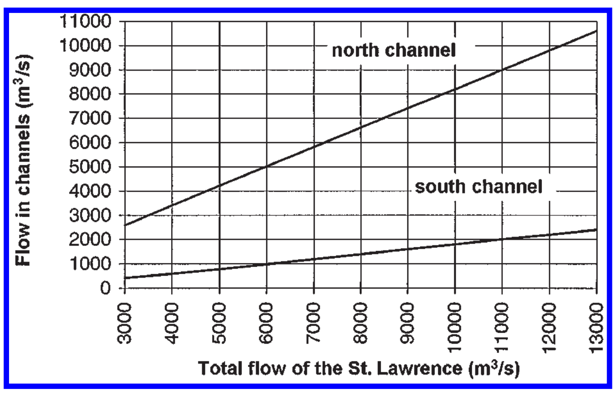


Fig. 12. Ancient flow distribution around Grande Isle.



Other flow data

Flow data prior to 1860 are rare and only monthly averages from 1860 to 1917 could be found in the "official" records. As described earlier, the flow of the St. Lawrence River was relatively high during the late 19th century. The average monthly flow was reconstructed from instantaneous records measured at Coteau. A map from the Public Archives of Canada (NMC 14784, see List of maps) reports two water level records measured at Coteau-Landing: 47.47 m on 18 April 1862 and 47.41 m on 2 April 1888. The flows associated with these water levels are 11 600 m^3/s in 1862 and 11 200 m^3/s in 1888, as calculated by the stage–discharge relationship. These estimates are probably overly conservative because of a lack of data in that range of discharge. The lowest flow of 3940 m^3/s was recorded on 7 February 1936 at Iroquois. In Lake Saint-François, the total flow, including an input of 155 m^3/s from tributaries (monthly average for February), would have been about 4100 m^3/s.

Also worth mentioning is the calculated maximal probable flood of 18 500 m^3/s at the outlet of Lake Saint-François (Spark 1993). This calculation comprises a flow of 12 000 m^3/s at Cornwall and 6500 m^3/s from local tributaries.

Direct impacts on the ecosystem

Assessing the magnitude of impacts produced by water level stabilization is a difficult task. The evolution of the system is relatively slow and data, when available, are limited to recent years. However, some answers can be obtained by conducting basic analyses of the system hydraulics.

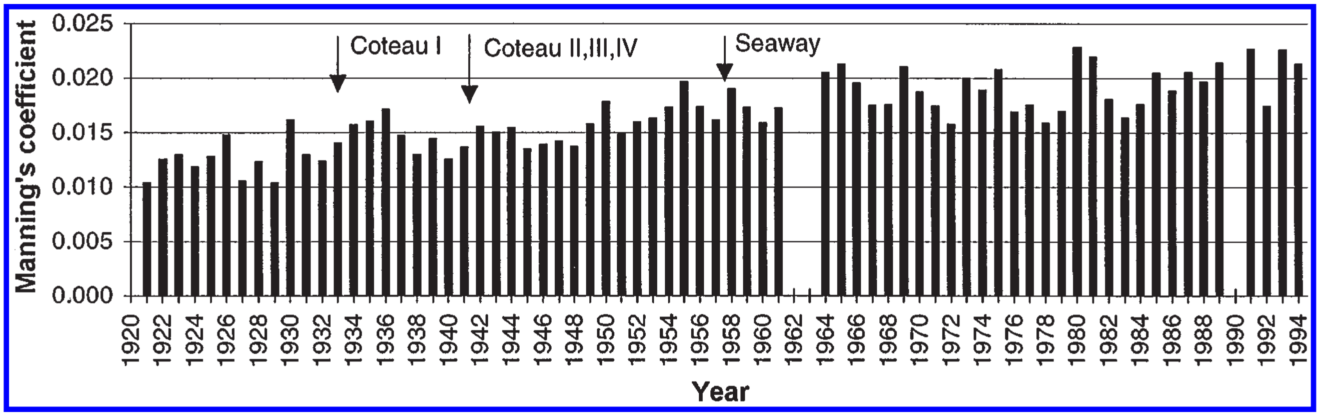
Evolution of aquatic plant biomass

Complaints by lakeshore residents concerning aquatic macrophyte overabundance in Lake Saint-François have been common since the end of the 1950s (St. Lawrence Rap Team 1992; Environment Canada 1994). Presently, plants almost completely cover the bottom within the photic zone and their biomass is obviously important. Information on the evolution of plant abundance in the area is scarce; only two available documents (Owen and Wile 1975; Beak Consultants 1989) provide qualitative observations with limited information on species composition. In order to assess the evolution of plant abundance, water level measurements from two stations in Lake Saint-François from 1920 onward were analyzed.

It is recognized that plants have an important effect on the free surface slope of Lake Saint-François because of the resistance to flow they induce (see the section Evolution of water level). Three seasonal periods of different slopes can be distinguished: spring, winter, and summer. Spring has the lowest friction, caused only by sediments on the bottom. The winter slope is caused by the added effects of sediments and ice, whereas summer friction results from the combined effects of sediments and plants. The effect of plants alone is obtained by subtracting spring friction from summer friction, and the effect of ice by subtracting spring friction from winter friction.

Mean monthly water levels, measured at Coteau-Landing and at Summerstown, were calculated from 1920 to 1994.

Fig. 13. Evolution of Manning's friction coefficient associated with aquatic plants.



Summerstown is located 35 km upstream from Coteau-Landing on the north side of the river. An aggregated version of Manning's equation was used to estimate the monthly average friction from water level data ($h(t)$):

$$[2] \qquad \bar{n} = \frac{1}{Q} A R^{2/3} S^{1/2}$$

where $\bar{n}$ is the global equivalent Manning's coefficient of Lake Saint-François, Q is the flow discharge (m^3/s), A = volume/length is the average area of the section considered (m^2), R = volume/surface area is the hydraulic radius or depth (m), $S = (h_0 - h_1)$/length is the slope of the free surface, h is the water level (m). The friction was calculated using the average monthly "natural" flow (see the section Natural flow discharge) and the average monthly water levels. In order to isolate the effect of plants, the calculated Manning's coefficient for May (substrate only) was subtracted from the average coefficient for August and September (plants and substrate).

The friction forces that control flow resistance are added like scalars in one dimension and as vectors in two and three dimensions. These forces are always a quadratic function of both flow velocity and Manning's coefficient:

$$[3] \qquad \tau = f(n^2 v^2)$$

where τ is the resistance force, n is Manning's friction coefficient, and v is the velocity (m/s). Thus Manning's coefficients must be considered in a quadratic space (Boudreau et al. 1994):

$$[4] \qquad n_{\text{total}}^2 = n_{\text{substrate}}^2 + n_{\text{plants}}^2$$

where n_{plants} is the Manning's coefficient due to aquatic plants resistance to flow, $n_{\text{substrate}}$ is the Manning's coefficient due to substrate resistance to flow (May), and n_{total} is the total Manning's coefficient that comprises the effect of plants and of substrate (August and September). The result is a sequence of residual friction coefficients which represents the annual impact of plants on the energy slope. For validation purposes, the same methodology was adopted to quantify the effect of ice, using the months of January to March as the ice-cover season.

The evolution of Manning's coefficient for aquatic plants reveals a constant increase since the beginning of the century (Fig. 13). Manning's coefficient was 0.012 in the 1920s and is presently about 0.022. The construction dates of the main civil works were superimposed over the evolution of Manning's coefficient, highlighting the influence of water level stabilization on the friction due to aquatic plants. There is a significant and constant increase of the friction coefficient starting around 1950 which appears to coincide with the increasing stabilization of the water level as shown in Fig. 9.

The evolution of Manning's coefficient related to ice reveals relatively stable conditions since the 1920s (Fig. 14). Only what appear to be natural fluctuations of ice properties, such as thickness and smoothness, vary through time.

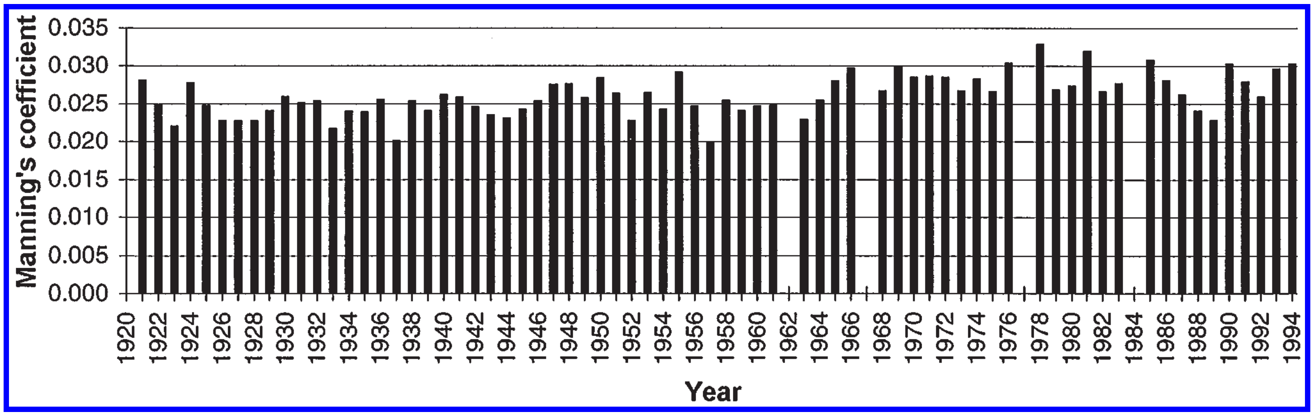
Lake Saint-François wetlands: the Lake Saint-François National Wildlife Reserve

Lake Saint-François National Wildlife Reserve is a wetland located on the south side of the lake close to the border between Quebec and New York State. Vegetation formations have changed considerably since 1949 (Jean and Bouchard 1991, 1993). Stabilization of water level is certainly responsible in part for these changes. One way to understand the impact of water level management is to determine what would have happened if the system had remained natural with respect to water level behavior.

In order to evaluate the differences between the natural flood–drought cycles of the river and present regulated water levels, the water level for every month was calculated for the Summerstown station assuming it would have remained under natural conditions. This station is located on the north side of the river facing the wetlands of the Lake Saint-François National Wildlife Reserve; the water level is similar on both sides of the river. First, water levels at Coteau-Landing were calculated using pre-1849 and 1901–1932 stage–discharge relationships with the reconstructed natural flow series to eliminate anthropic influence. The 1849–1901 stage–discharge relationship is similar to that for 1901–1932, so only the latter was used. Water levels at Summerstown were calculated using Manning's equation. For Manning's coefficient, an interannual monthly average of the coefficients already estimated for the period 1921–1931 was used (see the section Biomass evolution of aquatic plants). This period has the most representative data available for the natural state of aquatic plants.

The result is the evolution of the water level fluctuations as it would have been had the system evolved with natural

Fig. 14. Evolution of Manning's friction coefficient associated with ice.



stage–discharge relationships according to two different scenarios. Comparison with measured data shows that calculations are consistent with data from before 1932 (Fig. 15). National reserve wetlands are distributed from an elevation of 46.80 m to approximately 48.00 m, with important zones between 46.90 and 47.20 m. Figure 16 shows that wetlands were partially flooded in 1929 and 1930 during the entire growth season and that important flooding never occurred during summers after 1930. After 1953, observed peaks occurred in winter or in early spring and did not last long enough to have an effect on vegetation. From 1860 to 1994, if the system had fluctuated according to the 1901–1932 relationship, important flooding would have occurred regularly from 1860 to 1892, in 1908, in 1929, in 1930, between 1946 and 1956, from 1972 to 1986, and in 1993.

The calculations using the pre-1849 stage–discharge relationship show that the present wetlands would have never been flooded. Consequently, these wetlands would be very different if the system had remained in its pristine state.

Discussion

Effects of dredging on hydrodynamics

The impact of dredging on hydrodynamics is not well known. Dredging prior to the construction of the St. Lawrence Seaway was unimportant and probably had only minor impacts, but dredging of the seaway channel certainly produced substantial impacts on Lake Saint-François hydrodynamics. Generally, dredging is believed to result in a concentration of the flow in the main channel and in a reduction of water velocities in shallow areas (Environment Canada 1994). Velocities are also reduced in secondary channels because of the disposal of dredged material. The only way, in our opinion, to quantify these impacts would be to compare the results of a pristine-state hydrodynamic model based on the past bathymetry and hydrology with the results of a model representing present conditions. It seems reasonable to conclude that, because of the stabilization of water levels in Lake Saint-François, the negative impacts are less than in other sections of the St. Lawrence River.

Effect of water level stabilization on velocities

The stabilization of water levels in Lake Saint-François possibly affects hydrodynamics more than dredging does. During dry periods, when the flow of the St. Lawrence River is relatively small, the natural level of the lake would have been lower and the velocity in the main channel greater. During the winter of 1965, the average flow was 5 000 m^3/s; the natural water level would have been lower by approximately 70 cm. This means that shallow areas would have become uncovered and the flow would have concentrated in the main channel. Because the mean depth is about 6 m, the artificial elevation of the water level has reduced the velocities by about 10%. Inversely, large flows, such as in the summer of 1973, would have produced a natural water level 70 cm higher, resulting in an average velocity increase of about 10%.

Implications for sedimentation

Sedimentation is controlled by the combination of natural and anthropic influences on flow discharge variations. In Lake Saint-François, no sediment deposited before around 1870 was found through core sampling (Lorrain and Carignan 1992). This seems very peculiar, since there were no written records of periods when flows would have been strong enough to erode accumulated sediments. It is believed that the flow must have been greater than 10 100 m^3/s; indeed, such a value was recorded in 1993 with noticeable, albeit limited, impacts on accumulated material (Rukavina 1995). It is important to note that the 1993 event was artificially produced to release from Lake Ontario an important accumulation of water resulting from record high supplies to that lake.

The occurrence of exceptionally large discharges in 1862, as extrapolated from record levels reported on map NMC 14784 (se the List of maps), is probably associated with the high-energy conditions required to remobilize sediments before 1870. The 1888 discharge conveyed about the same energy but did not have the same effect on sediments, possibly because it lasted for a shorter period. These large flow events coincide with important precipitation periods over the Great Lakes (Quinn 1997). It is probable that our estimation of the flow discharge associated with the record levels is too conservative. The lack of data in this range of flow discharge brings imprecise estimates. Also, the area near the control sections in Lake Saint-François is relatively flat, thus the discharges associated with these very unusual levels are not precise and are certainly underestimated. Therefore, the discharge associated with these events was probably greater than 11 500 m^3/s.

Fig. 15. Water level evolution in Lake Saint-François wetlands as measured, compared with simulated natural conditions.

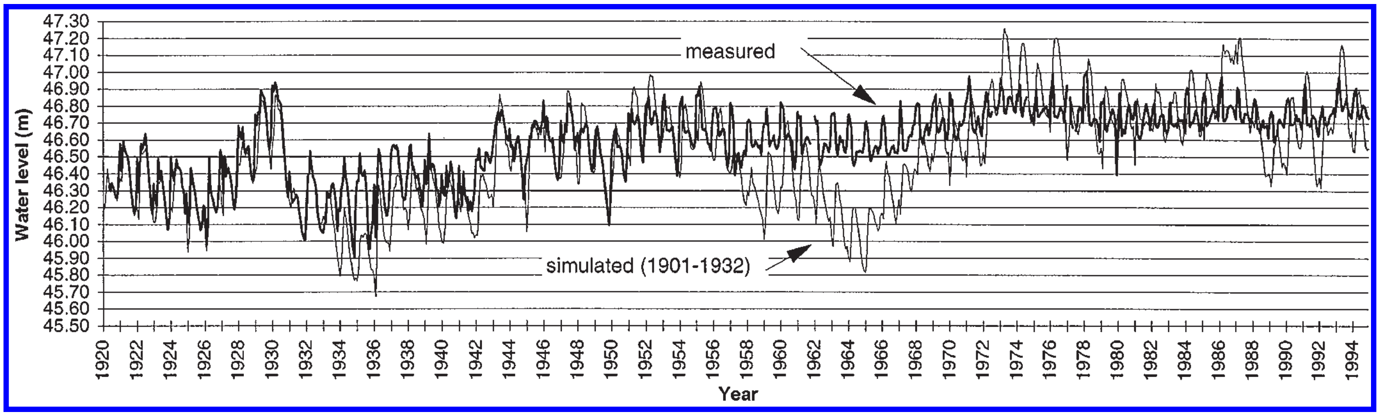
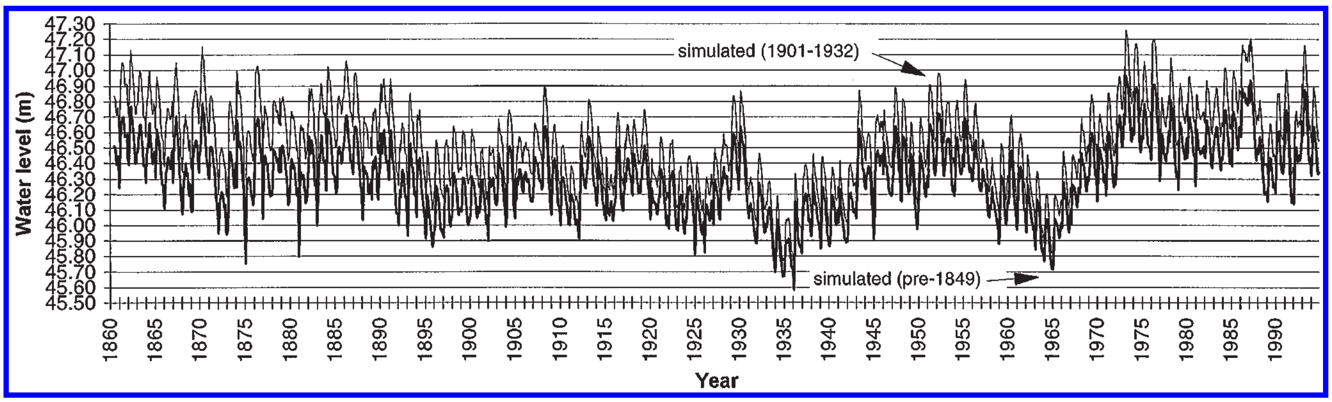


Fig. 16. Natural variations in water level for Lake Saint-François wetlands, simulated from 1901–1932 and from pristine state (pre-1849) stage–discharge relationships.



Water level stabilization in Lake Saint-François implies that the same erosive event could occur with a flow 10% smaller. A flow of approximately 11 000 m^3/s for a certain period during the spring would have a similar effect. Another unconformity in the recent sedimentary sequence in the lake appears to correspond to important changes in the Lake Saint-François hydrology (Carignan et al. 1993). Major impacts are related to construction of the Beauharnois canal and the Coteau works and to dredging of the seaway.

Impacts on aquatic plants

Aquatic macrophyte habitats are controlled by several abiotic variables limiting their growth. In Lake Saint-François, these variables are light penetration, wave action, substratum (nutrient and rooting), and currents (Morin et al. 1996). Water level fluctuations could be very important in limiting the growth of aquatic plants (Howard-Williams et al. 1995). Drawdowns of water levels, especially in winter, are critical for submerged plants because the perennial parts of the plants are sensitive to freezing (Nichols 1991).

Manning's coefficient associated with plants is a function of the total area of leaves exposed to the water (leaves area index LAI), i.e., higher plant density equals stronger resistance to the flow. There is a linear relationship between flow restriction or friction and LAI (Petticrew and Kalff 1992). Given that the relationship between LAI and biomass is a constant for a similar species composition (Duarte and Kalff 1990), it is a good approximation to consider that Manning's coefficient varies proportionally with the biomass of plants. Manning's coefficient is now twice as high as it was in the 1920s, therefore plant biomass must also have doubled over the same period. The relationship between Manning's coefficient and plant biomass should be investigated in detail for a more precise quantification.

Short-term fluctuations in Manning's coefficient (Fig. 13) could be related to natural causes such as light input, water temperature, nutrient load, water velocity, and winds. Variations in water level during the summer and winter must also be taken into account. Random errors are present in the discharge and water level series; the estimated precision of Manning's coefficient is ± 0.003. Systematic water level measurement errors were reduced by subtracting the coefficient of periods without plants and ice (May) from the coefficient of periods with maximal plant biomass (August and September).

The analysis of the evolution of Manning's coefficient in Lake Saint-François suggests that water level fluctuation or stabilization had an impact on aquatic plant biomass. The reduction of annual and long-term fluctuations in water level has probably favored the productivity of aquatic plants. However, the stabilization of water levels was associated with an increase in nutrient load.

Nutrient-load peaks that were present in the 1960s and early 1970s (Stevens and Neilson 1987; Carignan et al.

1993) did not have a marked effect on submerged plant biomass as shown by Manning's coefficient. As suggested by Chambers and Prepas (1994), nutrients are available to submerged plants almost exclusively from the substratum rather than from the water. Integration of these nutrients in the sediment is a relatively slow process that has to come from plankton growth and from adsorption to suspended load. Sedimentation of these small particles was probably influenced by the regulation of Lake Saint-François.

Impacts on wetlands

It is recognized that wetlands dynamics in the Great Lakes – St. Lawrence system involves short- and long-term cycles of flooding and drought (IJC 1993). Long-term flooding during one or two growth seasons is necessary to eliminate shrubs and trees and to allow other species to complete their life cycle. This dynamic allows plant species to complete one or several reproductive cycles and ensure their preservation in the local seed bank (Wilcox 1988; Keddy and Reznicek 1986).

The Lake Saint-François wetlands have been maintained artificially by annual burning. This practice was stopped in 1978; since then, important internal modifications have been observed in the wetlands (Jean and Bouchard 1991). The absence of water level fluctuations favors the growth of trees and shrubs. The situation is problematic for long-term preservation of the habitat diversity.

Wetlands of the Lake Saint-François National Wildlife Reserve would have been very different without the damming of the south channel of the St. Lawrence River in 1849. Prior to 1849, fluctuations of the St. Lawrence flow were certainly similar to those of the present day. Water levels were fluctuating around an average of 46.40 m. This level corresponds to a large area of shoals in the middle of the lake which are now covered with macrophytes during the summer (Morin et al. 1996). Prior to damming, existing shoals were most likely covered by wetlands, probably similar in terms of vegetation to those of the Lake Saint-François National Wildlife Reserve and others along the St. Lawrence River.

Conclusions

From its pristine conditions, Lake Saint-François has undergone a long sequence of anthropic modifications, greatly transforming its hydrology. These modifications are mainly associated with the occurrence of two large rapids sections upstream and downstream from the lake which were a concern for navigation and attractive for hydropower generation.

The hydrology of Lake Saint-François was significantly altered for the first time in 1849 with the construction of a dam in the south channel of the St. Lawrence River. The reconstruction of the former stage–discharge relationship allowed us to estimate that the average flow passing through the south channel was 1100 m^3/s under natural conditions and that the water level after the damming raised by 25 cm the average level in the eastern portion of the lake. The construction of the Beauharnois canal in 1932 was the first of a series of modifications that allowed the diversion of the entire river flow toward the Beauharnois power dam. Water level control works were built at the mouth of Lake Saint-François between 1933 and 1942. In the 1960s, navigation channels were dredged, and the Moses-Saunders power dam was built upstream from the lake.

The flow of the St. Lawrence River has been regulated by the Moses-Saunders power dam since approximately 1962. Regulation of the flow has slightly modified the seasonal fluctuation of the river. The flood typically occurred in June and drought in February under natural conditions, whereas the present regulation moves the maximum flow discharge to July and the drought to January. Long-term variations of the flow are related to cyclicity in the precipitation. These cycles, of approximately 20–35 years, have a range of flow discharge varying from 4500 to 10 000 m^3/s.

Water level is now stabilized to about 15 cm of annual fluctuation. Under pristine conditions the average annual fluctuation at the mouth of Lake Saint-François was about 60 cm. Long-term water level fluctuations associated with flow discharge variations were around 1.5 m under natural conditions. These fluctuations no longer exist. Regulation of the water level started in the 1930s with the commissioning of the Coteau works and the Beauharnois power dam. Since then, seasonal fluctuations have been gradually decreased to facilitate navigation and to reduce flooding risks.

Stabilization of the water level has created ideal conditions for submerged macrophyte growth. The analysis of Manning's friction coefficient shows that since 1920 friction from plants alone has more than doubled; presumably, the associated plant biomass has also doubled. Even if the biomass increases are temporally associated with periods of water level stabilization, other causes are probably implicated. Nutrient load increases occurred during the same periods.

The reconstruction of ancient stage–discharge relationships allowed us to recreate the water level fluctuations as they would have occurred if the conditions had remained natural. It shows that the present wetlands would have been flooded periodically, and that the diversity of the wetland would have been maintained. The pre-1849 stage–discharge relationship shows that under pristine conditions, the wetlands in the Lake Saint-François were certainly different prior to the damming of 1849 and that the present wetlands are partially anthropogenic. Pre-1849 wetlands were likely located on the numerous shoals present in the central part of the lake.

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List of maps

The reference numbers of the National Map Collection (NMC) of Public Archives Canada are given at the end of each map reference.

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