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VIEWPOINT

Viewpoint is a column which allows authors to express their own opinions about current events.

Man-Made Storage of Water Resources—A Liability to the Ocean Environment? Part I

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A primary reason for estuaries, embayments and continental shelves being among the most fertile and productive regions on earth is the supply of fresh water from land run-off which, on entering the ocean, induces mixing and the entrainment of nutrient-rich deep water into the surface layer. For temperate regions such as Canada, the natural fresh water supply varies sharply with season – being low during the winter when precipitation and run-off is stored as snow and ice, and very large during spring and early summer when the winter storage melts. Nearshore biological processes and adjacent ocean activities are attuned to this massive influx of fresh water – this is the time when reproduction and early growth occur. To modify this natural seasonal run-off for human convenience is to interfere with the hydrological cycle and with the physical and biological balance of the coastal region. Artificially storing the spring and summer run-off to generate power the following winter must have a significant impact on the ocean environment and on the climate of the maritime region.

Introduction

As demonstrated by western society in the last hundred years, the material quality of life improves with the availability of natural resources and with cheap and abundant energy. Today's energy crisis, which arises from the curtailment of the energy supply, threatens this rate of improvement. It is therefore understandable that the prime concern of industrial planners is to develop reliable energy sources. In Canada, hydro-power plays an important role in this concept.

The utilization of power from water is as old as human civilization. In fact, the invention of the water wheel was a key step in reaching our present level of technology. Initially, effects on the environment were minimal but by the turn of the century, when technology was able to modify entire river systems, the consequences became perceptible. The major impact, however, started after the second world war when huge storage lakes were built for power development capable of holding the run-off of large drainage areas and storing it over entire seasons, years, and even longer. Today, these schemes are changing the hydrology not only of regions but of entire continents.

For rivers, this conflict has been somewhat recognized and reported upon (Atton, 1975; Dickson, 1975; Duthie & Ostrofsky, 1975; Efford, 1975; Geen, 1974; Ruggles & Watt, 1975; Townsend, 1975), but with a few exceptions (Asvall, 1976; Skreslet, 1973 a, b, 1976) it is generally assumed that when the river water meets the ocean it is quickly dispersed with little or no impact. However, this is not the case. Fresh water is a major factor in providing nutrients to coastal waters and continental shelves such as the Grand Banks of Newfoundland, and in producing a moderation of the climate.

It should be realized that the prime concern of this paper is not the development of power but the modification of the run-off, particularly its seasonal cycle. As will be demonstrated, this regulation represents a severe interference with the basic concept and balance of activities in the ocean.

Seasonal Variation of Fresh Water

In northern latitudes, winter precipitation in the form of snow remains stored until the following spring. During this period, biological activities slow down and become dormant with little or no need for nutrients. With the onset of spring, the snow melts, creating large river flows particularly during the early part of the season. At the same time the annual growth cycle begins and the nutrients required to support the renewed activities are provided on the land by the fresh water directly, and in the ocean indirectly by increasing the entrainment of nutrient-rich deep ocean water into the surface layer.

A typical monthly run-off hydrograph of a snow-fed river is given in Fig. 1. It shows the Manicouagan River discharge with a maximum in May which is 30–40 times

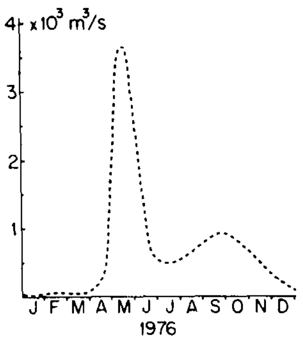

Fig. 1 Natural run-off to the Manicouagan River at Manic 5 power station.

larger than during the winter months. The seaward progress of the fresh water totals of the St. Lawrence and its tributaries, including the Manicouagan, is shown in Fig. 2a. These totals contain fresh water from melting surface ice which has formed in the system during the winter months. The estimated contribution at Cabot Strait is on the average about 4000 $m^3 s^{-1}$ and at its peak probably 6000 $m^3 s^{-1}$. The bulk of the spring freshet passes quickly through the estuary in May, then slows over the Magdalen Shoal in the southwestern Gulf in summer, and arrives at Cabot Strait by the beginning of August. From here it can be traced to Halifax and even to Georges Bank at the entrance to the Gulf of Maine in the autumn.

Similarly, although much larger in magnitude, one can consider the fresh water run-off from Hudson Bay and the Canadian North. Here, even more so than in the St. Lawrence, the winter run-off contribution is small but during the summer large quantities of fresh water are released which affect the surface layer of the coastal waters to a depth of 30–90 m. The peak of the fresh water arrives in July at Cape Chidley near the entrance to Hudson Strait with a discharge of about 300 000 $m^3 s^{-1}$ or about 30 times the flow of the St. Lawrence at Montreal – and in September between Newfoundland and Flemish Cap with a discharge of below 200 000 $m^3 s^{-1}$. This reduction in discharge is produced by a decline in speed over the Grand Banks region which lasts until the end of the year. A part of this fresh water continues along the coast of Nova Scotia – shown in Fig. 2b as a weak but noticeable drop in salinity at Halifax in January – reaching Georges Bank probably in the early spring. So, after being quickly transferred from the North and along the coast of Labrador during the summer, the fresh water affects the Grand Banks during the autumn, the Scotian Shelf during the winter and Georges Bank probably during the spring. The distance travelled by the fresh water wave during a period of 9 months is about 4000 km. On the Scotian Shelf, therefore, there are two freshening cycles annually, a

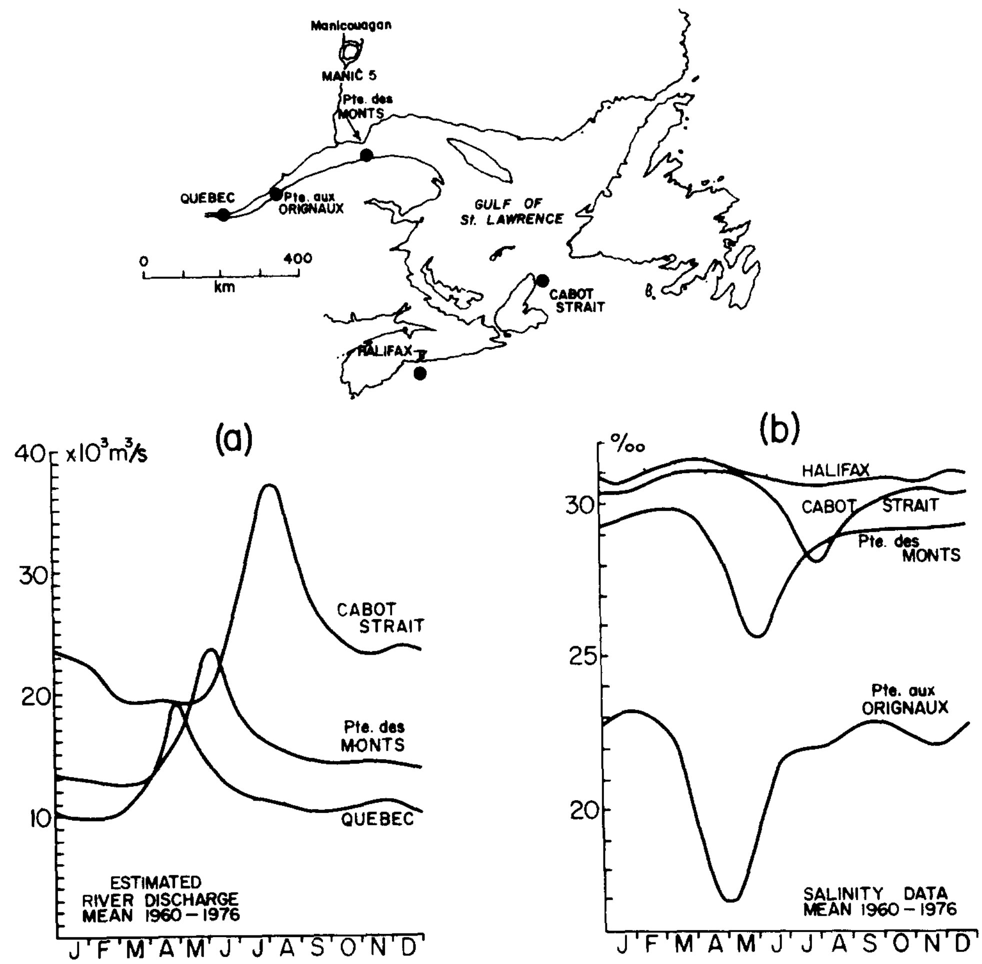

Fig. 2 Mean monthly (a) fresh water and (b) surface salinity variation for stations along the St. Lawrence system and Scotian Shelf.

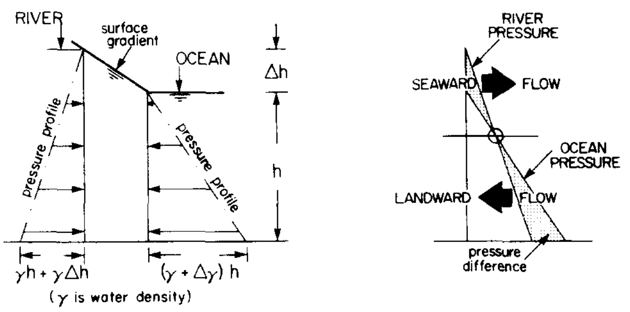

Fig. 3 Schematic diagram of pressure distributions for density currents.

larger one in summer from the St. Lawrence and a smaller one in winter from the Canadian North. On Georges Bank, these fresh water waves should arrive in autumn and spring respectively.

In assessing the man-made changes to water resources, it must be realized that the impact of river regulation on a physical property such as salinity declines the further north we go. The reason for this is that the fresh water deriving from melting sea ice increases relative to the land run-off. For instance, in the St. Lawrence estuary, the fresh water from sea ice is negligible; in the Gulf it increases to about one-fifth of the spring peak flow; in James Bay and southern Hudson Bay to between one-quarter and one-half and in Baffin Bay to between one-half and three-quarters of the spring and summer drainage. Thus, the further north, the smaller becomes the influence of the river run-off.

Obviously, the provision of large quantities of fresh water in spring and summer and the subsequent sweeping of the coastal region and continental shelf by this water are features of the Canadian North and the Canadian Atlantic region. It appears that this seasonal fresh-water movement is in tune with the relatively short reproduction cycle and growing season of the area. It is interesting to note that the two regions receiving major seasonal fresh water sources, the Grand Banks and Georges Bank, are ranked among the greatest fishing grounds in the world.

Fresh–Salt Water Interplay and its Seasonal Variation

The most outstanding feature in the encounter between fresh water and salt water is the formation of a current which oceanographers refer to as haline circulation and engineers as density current. The energy system which generates this motion is in principle the same as that which generates the winds in the atmosphere. While the winds are the result of inequalities in barometric pressure caused by non-uniform heating of the atmosphere under solar radiation, the density current in coastal waters and estuaries is primarily the result of the difference in density between the fresh water of the run-off and the salt water of the ocean.

There are basically two force components which generate this motion. First, fresh water entering the ocean raises the height of the water surface above the height of the ocean and establishes a horizontal pressure gradient. Water flows along this gradient resulting in a seaward flow of the surface water. The pressure gradient and thus the surface flows are maintained by the continuous input of river water. Second, sea water is more dense than river water and since pressure at depth depends on the water density times the water column height, there is a certain depth where the pressure from the low-density river water will be equal to the pressure from the denser sea water. As shown schematically in Fig. 3, below this depth the pressure difference is landward directed and above this point it is seaward directed. This arrangement imposes a two-layer flow system in which, as far as an estuary is concerned, the surface layer flows outward and the deeper layer flows inward. The major manifestation of this principle and the mixing involved is demonstrated by the large variation in salinity and temperature throughout an estuary.

Figure 4 shows salinity profiles at various locations along the St. Lawrence system to the Scotian Shelf. These profiles are in pairs to compare directly the two extreme seasons of winter and summer. The change in surface salinity along the system is also shown in Fig. 2b. As can be seen, the fresh water affects primarily the upper layer, consisting of a mixed layer, about 25 m thick, and a transition layer, about 50 m thick, in which the salinity increases from that of the mixed layer to that of the deeper layer. The water of the deeper layer is ocean water which originates off the continental shelf. It must be realized that this deep water enters the system and penetrates more than 1000 km upstream without any significant contact with the fresh water of the system.

The upper layer is deflected by the Coriolis force toward the right, thus forming (in cross-section) a triangular-shaped layer with the thicker side along the Gaspé Peninsula and the coast of Cape Breton. Evidently, the variation in salinity during spring and summer (Figs 2a, 2b and 4) is a function of the fresh water supply and is confined to the upper layer. The rate of change decreases toward the sea but can still be noticed on the Scotian Shelf.

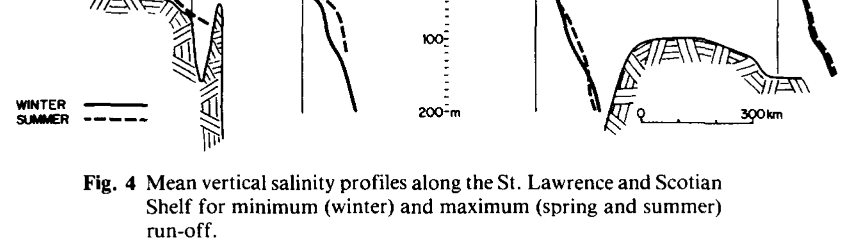

Fig. 4 Mean vertical salinity profiles along the St. Lawrence and Scotian Shelf for minimum (winter) and maximum (spring and summer) run-off.

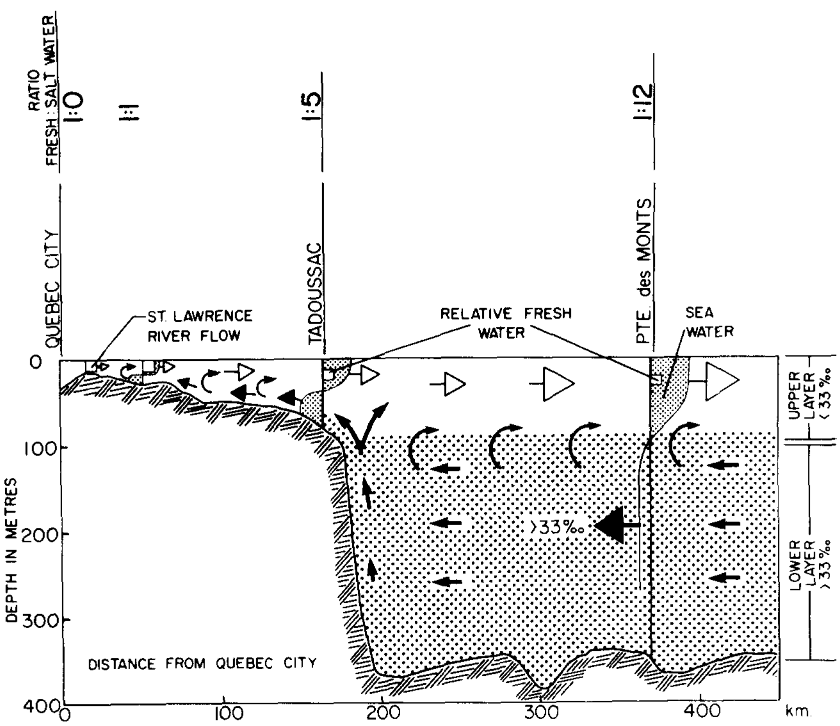

Fig. 5 Schematic presentation of density current in the St. Lawrence Estuary.

The waters off the coast of Labrador, and on the Grand Banks display the same behaviour.

The transport involved in the density current of an estuary can be demonstrated by the continuity principle. As shown in the schematic presentation for the St. Lawrence system in Fig. 5, the seaward directed upper layer contains the fresh water discharge of the river plus the salt water entrained from the landward directed deeper layer, the net flow of salt through the system being zero.

Between Ile d'Orleans and Ile aux Coudres, the average salinity of the upper and deeper layers are 11‰ and 22‰ respectively. Mixing equal volumes of river water (S = 0‰) and saltier water (S = 22‰) results in a salinity of 11‰ for the mixture; therefore, to one unit volume of river water was added the same amount of saltier water at this point. This ratio quickly increases seaward. Taking 33‰ as the reference salinity for sea water, these ratios are 1:5 at Tadoussac and 1:12 at Pointe des Monts, while further seaward they increase to about 1:25 at Cabot Strait, and even more along the coast of Nova Scotia where also fresh water from sources in the Canadian North is present. Obiously, the two-layer current system acts like a large natural pump which constantly transports large quantities of deep ocean water onto the continental shelf and then into the embayments and estuaries. The amount of ocean water required to maintain the level of salinity on the shelves of Atlantic Canada, the embayments and inland seas such as the Bay of Fundy, the Gulf of St. Lawrence and Hudson Bay included, varies from about 2 Sverdrup to more than 7 Sv (1 Sv = 1 million $m^3 s^{-1}$), depending on the season of the year and the salinity limits chosen.

Just as for the winds in the atmosphere, the magnitude of the current is proportional to the pressure difference. Hence in times where more fresh water enters the ocean, the longitudinal gradient seaward increases and with it the strength of the current system. From this it follows that in estuaries the density current varies with the seasonal run-off, being at a minimum during the low discharges in winter and at its peak during the large discharges in spring and summer. In coastal waters which are some distance away from the fresh water source (i.e. the Grand Banks, the Scotian Shelf and Georges Bank) there can be delays of from several months to almost a year before the freshwater peak arrives.

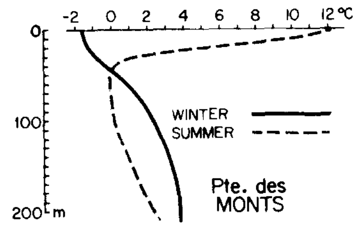

Fig. 6 Vertical temperature profile at Pointe des Monts in winter and summer.

Concerning the temperature of the water, similar variations occur but in this case not exclusively due to fresh water but to seasonal warming and cooling also. As shown in Fig. 6, the upper layer warms during the summer and cools during the winter. This trend is reversed in the deeper layer where during the summer an intermediate colder layer forms as a residue of preceding winter cooling, and is sandwiched between two warmer layers. This 'cold water' layer is characteristic of most of the coastal waters in the western North Atlantic. Although temperature, particularly during warming in spring, plays an important role in the biological activities of the upper layer, it has less influence on the density of the water, and hence on the motion and mixing, than the fresh water of the river.

There are other factors which also play a role in this large-scale circulation, especially the wind and the tide. They greatly affect the intensity of mixing in a particular section of the system; however, the haline circulation and its transport as a whole would prevail in their absence.

Principle of Regulation

In higher latitudes during the winter, river run-off is at a minimum while power demand is at its maximum. This is shown in Fig. 7, where an average hydrograph and the seasonal power demand of a city in northern regions are plotted. As can be seen, water supply and power demand are out of phase by nearly half a year.

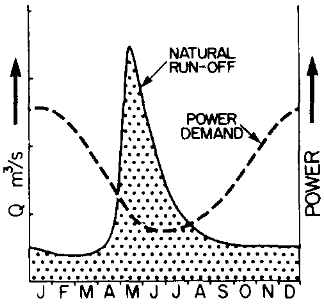

Fig. 7 Typical hydrograph and seasonal power demand.

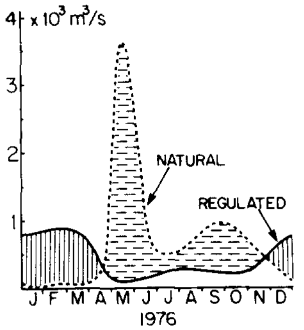

Fig. 8 Natural and regulated discharge of the Manicouagan River at Manic 5 power station.

Developers of electrical energy view this as an inconvenience of nature; thus they reverse the natural run-off cycle by storing the spring and summer flow in artificial lakes to be released during the winter. An example is shown in Fig. 8 for the Manicouagan River at Manic 5 power station.

The ultimate limit of seasonal regulation is achieved when spring and summer flows are completely stopped and the entire annual run-off is released during the winter months. Obviously, such a hydrograph is unrelated to and in outright conflict with natural conditions. Run-off is transferred from the biologically active to the biologically inactive period of the year. This is analogous to stopping the rain during the growing season and irrigating during the winter, when no growth occurs. Even if there were no scientific proof available to verify the danger of such modification, logic alone would show that seasonal regulation ignores the natural consequences of fresh water discharge.

Effect of Regulation on Physics and Dynamics of the Ocean

Reducing the flow of fresh water during spring and summer and increasing it during the winter changes the seasonal composition of the water in the surface layer and the seasonal strength of the density current.

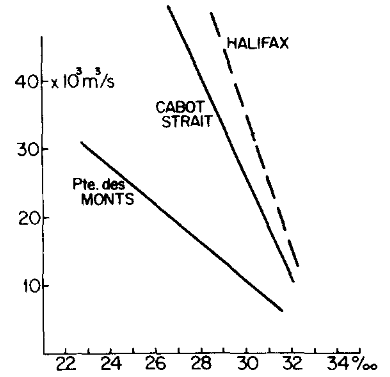

Fig. 9 Run-off versus surface salinity in the St. Lawrence and on the Scotian Shelf.

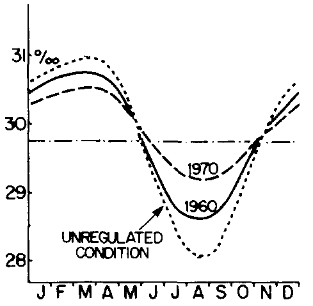

Fig. 10 Seasonal surface salinity variation on the west side of Cabot Strait prior to regulation and in the sixties and seventies.

In Fig. 9, the salinity variation of the surface layer versus fresh water discharge is given for the St. Lawrence and the Scotian Shelf. As can be seen, a reduction of the spring flow of 10 000 $m^3 s^{-1}$ increases the salinity at Pointe des Monts by 4‰, at Cabot Strait by 1.8‰, and near Halifax by 0.9‰. From this relationship, estimates were made of the seasonal variations which occurred at the south side of Cabot Strait for two periods of time, i.e. before regulation commenced and in the seventies. The results are given in Fig. 10. The solid line is the monthly salinity based on the 10 years mean from 1955 to 1964, referred to as the 1960 condition. At this stage, the spring flow was reduced by about 4000 $m^3 s^{-1}$. From the data of Fig. 9 mean monthly salinities were derived for the period prior to regulation, that is for natural conditions, and for the 1970 period when regulation in spring was increased to an average of 8000 $m^3 s^{-1}$. It can readily be seen that drastic modifications have been made to the salinity of the surface layer and that much of the cyclic variation has disappeared by 1970. The remaining seasonal difference will probably be gone with the development of the rivers along the north shore of the Gulf of St. Lawrence, which is already planned and will be implemented soon. As this trend continues, the cyclic variation will be reversed, the surface salinity becoming saltier in spring and summer, and fresher in the winter. This represents a fundamental change in the seasonal salinity patterns of the coastal region and continental shelf.

Concerning the temperature of the water, there will also be changes but since this property is non-conservative, it is difficult to predict the full effect. There is a definite possibility that both winter and summer temperatures of the surface layer will increase; in winter due to an increase in upwelling of deeper warmer water, and in summer due to slower surface currents which will allow the surface layer to absorb more heat during its passage through the system. It can be assumed therefore that fresh water regulation modifies the climate of the coastal region to be more continental-like in the summer and more maritime-like in the winter.

The greatest consequences will arise, probably, from changes imposed on the density current. This current determines the transport of deeper water from the ocean onto the shelf and from there into the embayments and estuaries. Reducing the flow of fresh water during the spring and summer decreases the strength of the density current to the point where, if taken far enough, it could be stopped altogether, while increasing the fresh water during the winter increases the current. Except where nutrients are produced locally, their rate of supply is directly related to the volume of salt water which carries them. A reduction in the transport of this water therefore decreases the influx of nutrients – the natural food supply – during the biologically active season of the year. An increase of supply during the winter does not compensate for these losses since primary and secondary production does not occur during this period, and the nutrients will return to the ocean body without being utilized.

Taking the St. Lawrence as an example, where today more than 8000 $m^3 s^{-1}$ (approximately one-quarter to one-third of the peak discharge) is held back in spring (Fig. 11), the seasonal inflow of ocean water into the Gulf must already be significantly modified. The reduction of the amount of water and with it the quantity of nutrients entering the system during the biologically active season must be in the order of 20–30% of its initial supply. According to El-Sabh (1975), the inflow into the Gulf through Cabot Strait is, at its peak in August, between 600 000 and 700 000 m^3 s^{-1}. Before regulation was implemented it probably was closer to a million cubic metres per second with all the extra nutrients that volume implies.

Beyond any doubt, similar reductions in the shoreward transport of sea water and nutrients have occurred at other places during the summer, such as in Hamilton Inlet below the Churchill Falls power development in Labrador, and will now occur in James Bay after the first power scheme there is in operation.

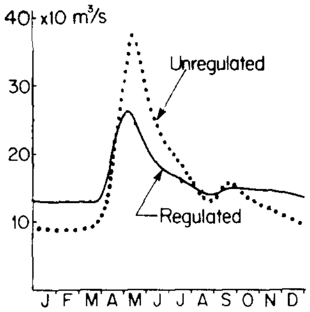

Fig. 11 Regulated and unregulated flow of the St. Lawrence at Pointe des Monts for 1976.

This article will be continued in the next issue of the Bulletin. In the second part, the effect on marine biology will be discussed and related to major schemes in Canada and Russia, the two countries where hydrological control on a continental scale is already contemplated. Their largest freshwater resources will be reviewed relative to the global hydrology, and alternative solutions to offset some of the negative effects will be suggested.

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