RUNOFF REGULATION FOR HYDRO-POWER AND ITS EFFECT ON THE OCEAN ENVIRONMENT

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Abstract. It has not yet been recognized that modification of the natural seasonal discharge of rivers might result in significant consequences to the ecology of the adjacent marine environment. An example of such regulation is the St Lawrence system, where, in order to optimize power production, large quantities of water from the spring runoff are retained in storage lakes and returned to the river during the low natural discharge period of autumn and winter. It has been estimated that under present conditions the spring and summer runoff at the entrance to the Gulf of St Lawrence has been reduced by between one-third and one-half.

This drastic alteration of the natural pattern of runoff has caused significant changes in the physics and dynamics of the waters of the Estuary, Gulf and adjacent coastal region. It is argued that such modifications produce a profound impact on the biological balance of the whole ecosystem, as well as changes in the seasonal heat budget.

Régularisation d'écoulement pour obtenir l'énergie hydro-électrique et son impact sur le milieu marin

Résumé. Il n'a pas encore été établi qu'un changement du débit fluvial saisonnier et naturel puisse avoir des conséquences marquées sur le milieu marin adjacent. La régularisation du système du Saint-Laurent en est un exemple: afin d'obtenir le plus d'énergie hydro-électrique possible, on retient dans des lacs de très grandes quantités d'eau provenant de l'écoulement du printemps; cette eau emmagasinée est retournée au fleuve au cours de la période de faible débit naturel en automne et en hiver. On estime que, dans les conditions actuelles, l'écoulement du printemps et de l'été à l'entrée du Golfe Saint-Laurent a été réduit du tiers à la moitié.

Cette modification draconienne de l'écoulement naturel a changé de façon marquée les caractéristiques physiques et dynamiques des eaux de l'estuaire, du golfe et de la région côtière adjacente. On prétend que de telles modifications ont un impact profond sur l'équilibre biologique de tout l'écosystème, de même que sur les températures saisonnières.

INTRODUCTION

Since the turn of the century, hydroelectric power has become one of the major sources of energy and caters for increased industrialization and higher domestic electrical power consumption. Many rivers have been utilized for this purpose to the extent that over 50 per cent of Canadian electrical power is produced in this way.

The output of a river power station depends on the available discharge of the river and the difference in water level. The latter is usually fixed, but the runoff, if unregulated, varies seasonally, particularly in latitudes where precipitation during the winter is stored in the form of snow. In spring the melting snow adds large quantities of water to the system. This additional discharge can be several times larger than the average flow and, in some rivers, may be ten to twenty times the winter discharge.

Such wide variations in natural runoff limit economic development of power; therefore, great efforts are made to obtain more uniform flow by storing water during the high runoff season. Optimum power output is obtained when a river is so regulated that water is always available to meet the demand for power which is usually greater in winter than summer. To regulate the natural flow of rivers is to interfere with the hydrological cycle, that is, the circulation of water between the ocean, the atmosphere, the land, and its return to the ocean.

It is this last link of the cycle which is principally affected by regulation.

In our northern latitudes biological activity generally slows down during the late autumn and winter months thereby substantially reducing the requirement for water and nutrients. During this period most of the precipitation is stored in the form of snow and ice. In spring, when the reproductive cycle begins and biological activity is greatest, a large supply of water and nutrients is required. A substantial portion of this increased demand is provided by the melting snow of the previous winter. Man, in his desire to generate power, intervenes in this natural procedure without sufficient consideration of the consequences of his actions.

THE ST LAWRENCE DRAINAGE SYSTEM

The St Lawrence system incorporates the Great Lakes, the St Lawrence River, and the Gulf of St Lawrence (Fig. 1). More than 30 million people now populate this basin and use its resources.

Of the total catchment area of 1.5×10^6 km^2, about 40 per cent drains into the Great Lakes and the remainder directly into the River and Gulf. Due to their vast area, the Great Lakes have a large storage capacity and thus reduce the effect of seasonal variations in the discharge of their tributaries. Therefore the continuous availability of water favoured the development of hydro-power at Niagara, Cornwall, and Beauharnois near Montreal.

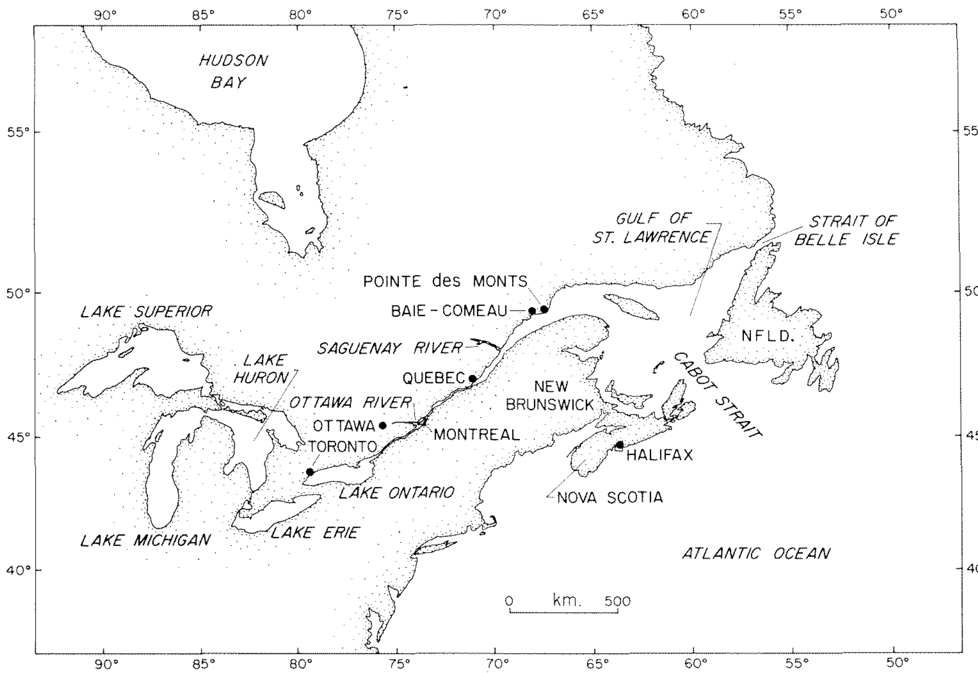


Fig. 1 – St Lawrence System.

In the basin of the St Lawrence River, Estuary and Gulf, the tributaries have relatively little natural storage. Their discharges are therefore variable, being low in the winter and high in the spring. To optimize their utilization for power generation, many large storage reservoirs have been constructed as shown in Fig. 2. Most of them lie north of the St Lawrence River where the physiography of the area and the low population density favour their construction. The major tributary water resources have been exploited down to Pointe des Monts at the entrance to the Gulf. Rivers along the north Shore below this point have not yet been utilized but their future development appears certain.

Long-term river discharge data have been available for the St Lawrence only down to Montreal. Recently, Jordan (1973) made estimates for the natural and regulated flow in the system to Pointe des Monts.

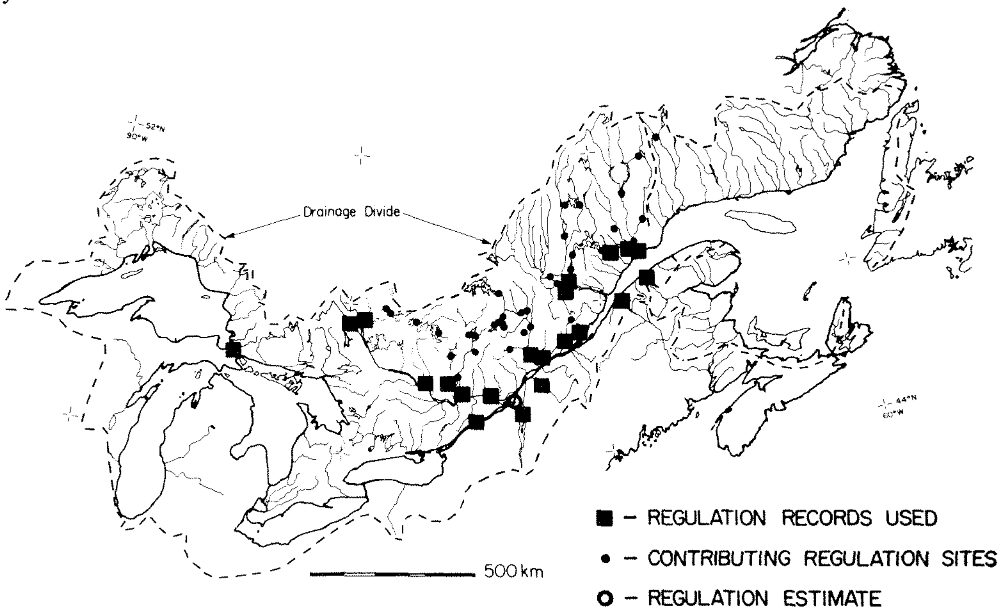


Fig. 2 – Major flow regulations below the Great Lakes.

RUNOFF AND REGULATION

The storage capacity of the Great Lakes is so great that the effect of individual tributary regulation is negligible. However, the total regulation of the Great Lakes since the turn of the century can be obtained from an analysis of the outflow above Montreal.

Based on data from the Water Surveys of Canada, the five-year mean discharge for each month is plotted in Fig. 3. From the result it is evident that there are large cyclic variations in the discharge with periods of the order of 15 to 20 years. These variations are related to the periods of extreme high and low water levels of the Great Lakes such as have occurred at the beginning of the Fifties and in the middle of the Sixties respectively. Applying the method of least squares to the data, the trend of the regulation in each month since the turn of the century becomes apparent. Major reductions occur in May and June with a maximum of about 1500 m^3/s, while from September to March the average discharge is increased by a maximum of nearly 1200 m^3/s in February.

Downstream from the Great Lakes, the Laurentian Shield forms the major drainage area with rivers such as the Ottawa, Saguenay, Outardes, Manicouagan, and many others. In the Ottawa River system, there are 23 regulation schemes in operation, 12 of which are major.

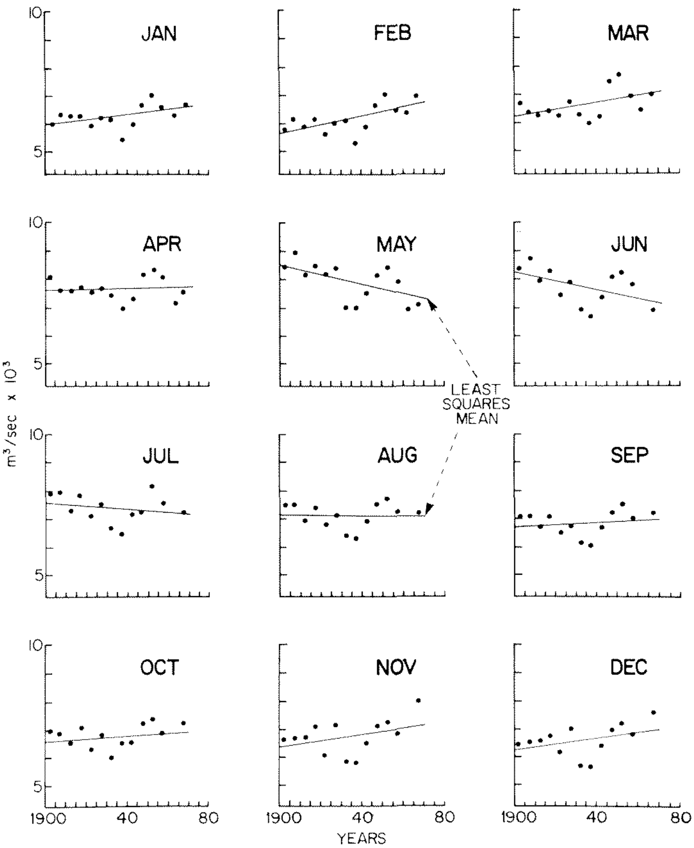


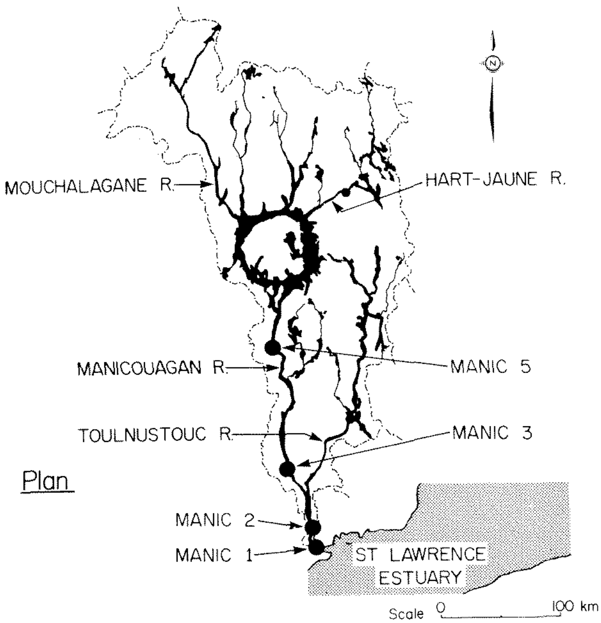
Fig. 3 – Five-year monthly mean discharge of the St Lawrence above Montreal.

The most outstanding recent examples of regulation schemes are those which have been constructed on the Manicouagan and Outardes rivers. Under natural conditions, their discharges varied from 220 m^3/s to 3200 m^3/s and from 42 m^3/s to 1800 m^3/s respectively. A series of large storage reservoirs installed since 1964 has resulted in almost 'total' regulation.

A plan and longitudinal section of the Manicouagan scheme are shown in Fig. 4. With the exception of the upper tributaries there is no stretch of the river in which the discharge is unregulated. Every drop of water must pass through a series of large artificial lakes the largest of which, Manic 5, has a storage capacity of about 142 km^3 which is comparable with Lake Nasser in Egypt. It would take the full discharge of the St Lawrence River at Montreal more than 200 days to fill Manic 5. This type of storage was designed to control the system completely and to govern the discharge solely by power demand.

The 1964 discharge and its regulation integrated along the St Lawrence River are shown for selected sites in Fig. 5. The shaded areas of the hydrographs indicate the increase (vertical shading) and decrease (dotted shading) in runoff due to regulation.

The fresh-water inflow to the system above Pointe des Monts has been increased artificially in February by 2500 m³/s and decreased in May by 10 000 m³/s. The average regulation for the period from 1963 to 1970 is given in Table 1, where the ratios between the monthly minimum winter discharge and the monthly maximum spring discharge are compared.



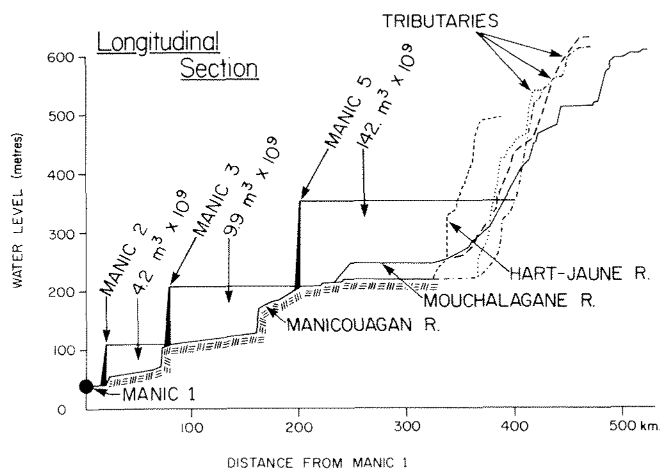


Fig. 4 – Manicouagan power development.

TABLE 1

Average ratio between annual minimum and maximum monthly discharges

	Ottawa River above Montreal	St Lawrence River above Montreal	St Lawrence River at Tadoussac	St Lawrence River at Pointe des Monts
Natural	1:6.0	1:1.7	1:3.0	1:3.4
Regulated	1:2.7	1:1.3	1:1.7	1:1.8

EFFECTS ON PHYSICS AND DYNAMICS

There are several effects resulting from the installation of dams for hydro-power development. The more obvious are the formation of lakes, the rise of subsoil water tables in the storage areas, and the reduction of flow in the natural river channel during spring runoff and rainy seasons. Concern has been expressed over many of the consequences of these changes, but no reference has been made to the region which possibly undergoes the most widespread environmental modification—the coastal waters of the ocean. The region most adversely affected is the area in which river water mixes with sea water. For the St Lawrence, this includes the Estuary, the Gulf, and to some degree the Scotian Shelf.

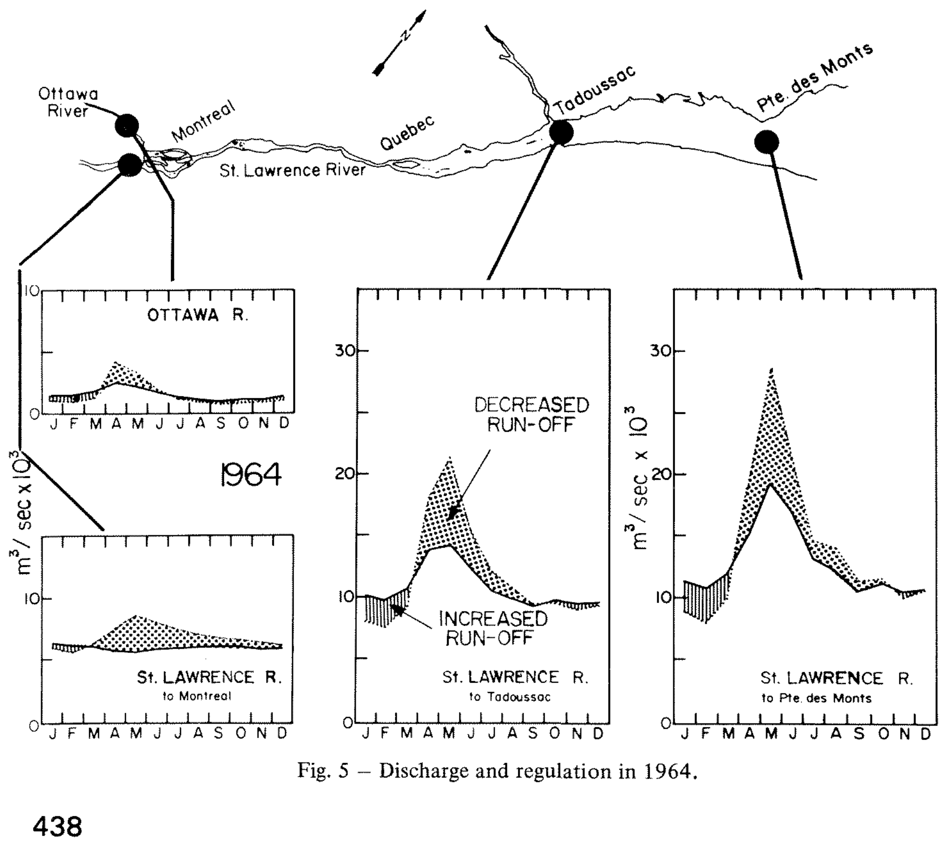


Fig. 5 – Discharge and regulation in 1964.

HALINE CIRCULATION

When river water meets the ocean, a circulation is induced in the latter which the oceanographer calls a haline circulation and the engineer a density current. The characteristics of this circulation are governed by five dynamic influences:

(a) the density difference between the river water and the ocean water;
(b) the head needed to produce a net seaward flow of fresh water;
(c) the tide with its currents;
(d) the wind-induced currents;
(e) the Coriolis force, friction and the effects of bottom topography.

The role of these forces and their primary effects have been studied widely in the field and laboratory. For the purpose of this discussion, only the factors (a) and (b) are described. They form the basis for the large-scale internal circulation by which salt water is transported into the Gulf and Estuary. The other factors also play an important role in the circulation of the system, 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.

In a long estuary such as that of the St Lawrence (Fig. 6) the concept of this circulation is based on a two-layer flow system in which the lower layer flows upstream while the upper layer flows seaward. This process is shown schematically in Fig. 7. The estuary is clearly divided into two parts: a shallow section extending from Quebec City to Tadoussac and a deep section, the Laurentian Channel, from Tadoussac to the ocean. In the section below Tadous-

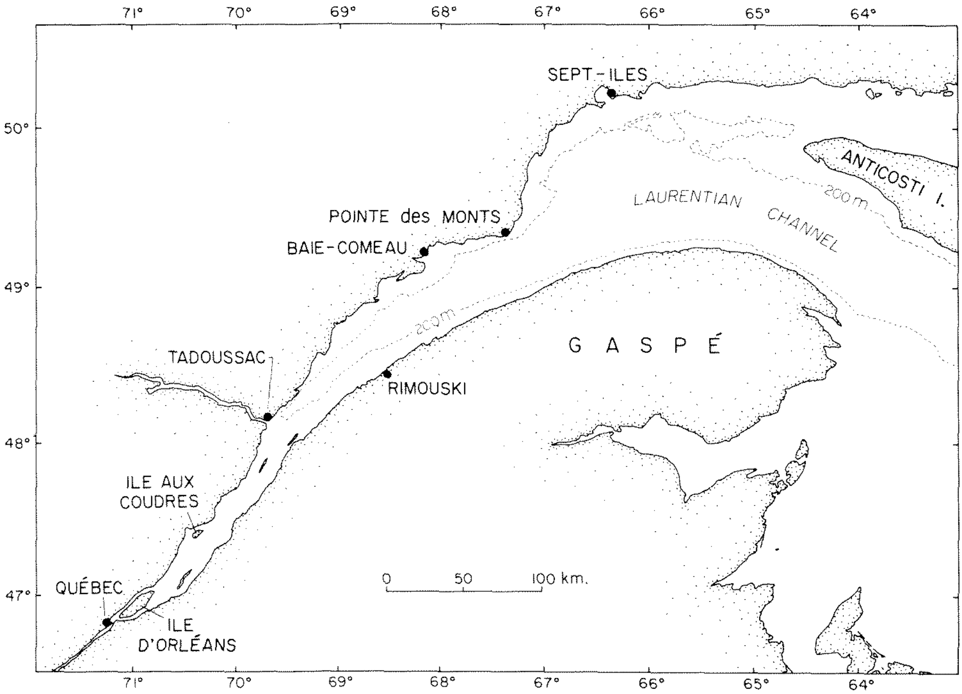


Fig. 6 – St Lawrence Estuary and Upper Gulf.

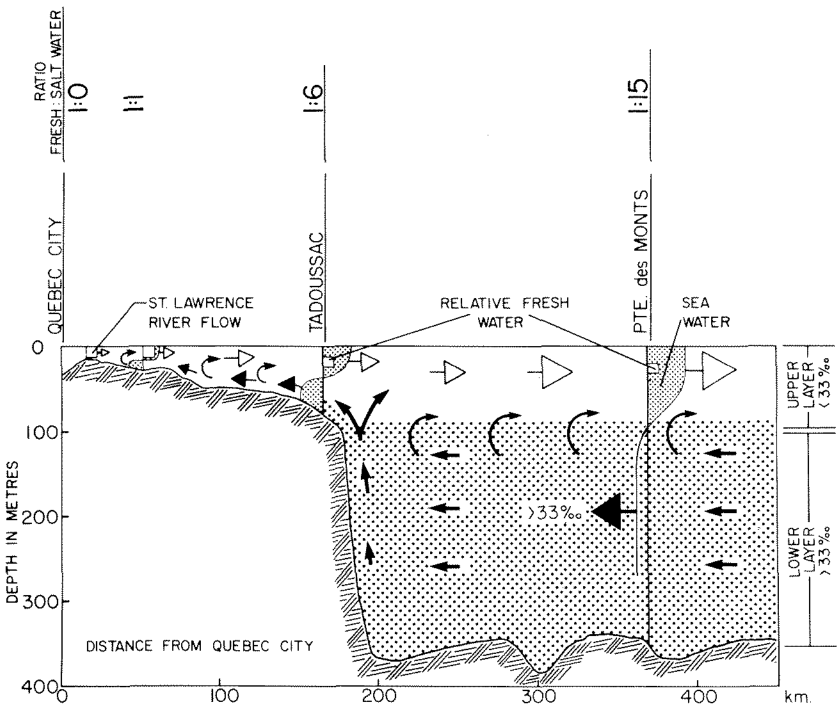


Fig. 7 – Schematic presentation of haline circulation.

sac, water with a salinity in excess of 33 ‰ fills the deep part of the Laurentian Channel (Fig. 8). For all practical purposes, this water is undiluted ocean water which flows into the Estuary over a distance of more than 1000 km. On its way inward, it mixes into the less saline upper layer with which it returns to the ocean. In the shallow section above Tadoussac, conditions are similar, although there is no sublayer of undiluted ocean water.

Salt water invades the system as far upstream as Ile d'Orleans near Quebec City where the intrusion is stopped by the outflowing fresh water of the river. Downstream of this point, the average salinity of the water increases quickly (Neu, 1970), indicating that salt water is being added to the system. Between Ile d'Orleans and Ile aux Coudres, the average salinity in the upper layer is about 17‰ which, compared with the salinity of undiluted sea water (33‰), shows that at this point an equal quantity of salt water has been added to the river water. Farther seaward, at Tadoussac, where the average salinity of the upper layer is between 28 and 29‰, there is 6 to 8 times more salt water than fresh water in the upper layer while at Pointe des Monts, there is 15 to 20 times more. Farther seaward the ratio between fresh water and salt water continued to increase until it reaches $1:\infty$ in the open ocean. In order to maintain these ratios and thus the steady-state condition in the system, a large amount of salt water is continuously required. It is transported by the circulation from the ocean into the Estuary and returned to the ocean mixed with the runoff from the river. The quantity of salt water circulated by this natural pumping action depends on the river's discharge and the distance from the sea. If, for instance, the fresh water discharge were to be stopped completely for, say, half a year, the haline circulation would cease and, in the absence of other driving forces, the system would fill with sea water up to the foot of the

Lachine Rapids in Montreal. The entire body of water would become relatively stagnant in character except for motions induced by tide and wind.

Variations in the discharge as imposed by power production on the St Lawrence River and its tributaries are smaller in effect, though similar in nature. They modify the circulation and thus the inflow of sea water into the system, decreasing the flow in spring and early summer and increasing it during the winter. An estimate of the effect of the reduced river discharge on the quantity of salt water involved can be made by assuming that the fresh/salt

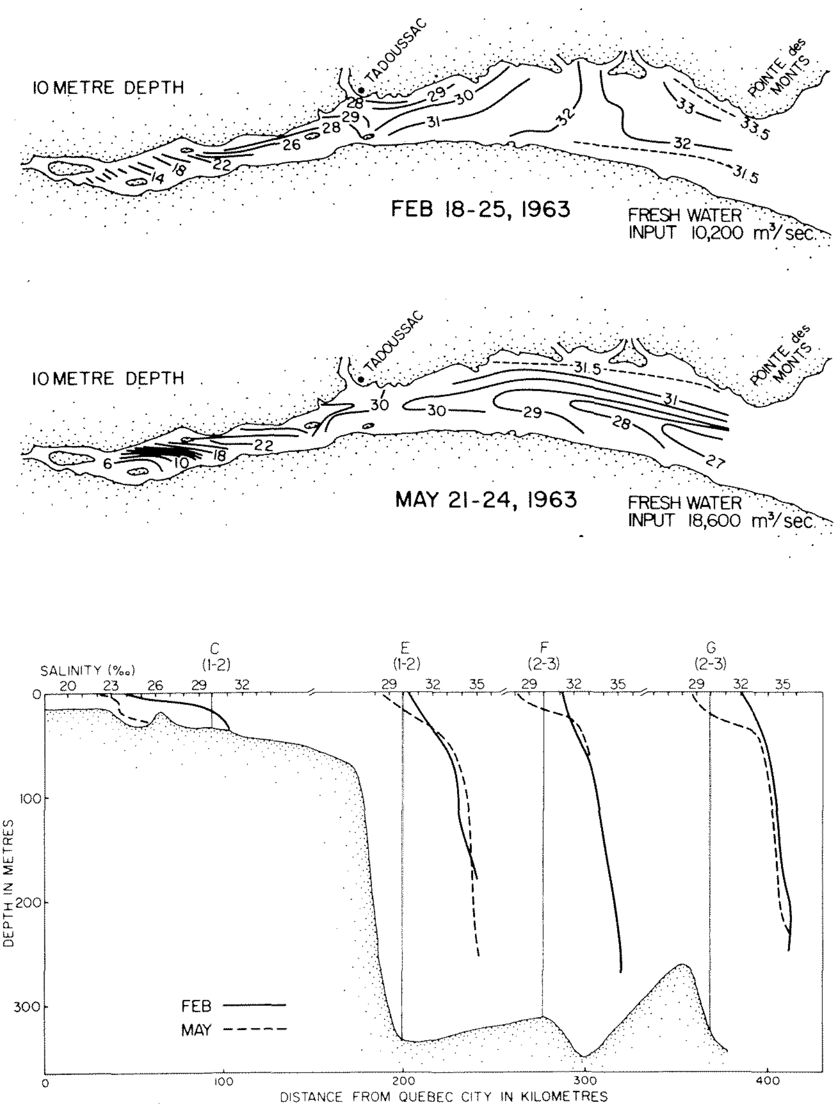


Fig. 8 – Horizontal and vertical salinity distribution in the Estuary.

water circulation ratio remains constant at a given location. This applies only to the deep section of the system. For Pointe des Monts, it appears that this ratio is at least 1 : 15. Therefore, a reduction of 10 000 m^3/s in the spring discharge of 1964 decreased the inflow of sea water to the Estuary by about 1.5×10^5 m^3/s, or 35 per cent of its natural volume, an amount equivalent to 17 times the flow of the St Lawrence at Montreal. On the other hand, during January and February 1964, the river discharge was augmented through regulation by about 2500 m^3/s. This must have increased the flow of salt water into the Estuary by 0.4×10^5 m^3/s or 31 per cent above the natural condition.

The effect of such changes on the salinity of the surface layer is shown on Fig. 9. On this graph, the approximate monthly river discharges and the respective surface salinities are given for two locations, one on the south side of Pointe des Monts and the other on the Nova Scotian side of Cabot Strait. Also provided are the variations in the extreme seasonal salinities with changes in the river discharge. It is shown that a fresh-water regulation of 10 000 m^3/s causes a change to the salinity of the surface layer at these two locations by 3.5 and 1.3 ‰ respectively. Changes can even be noted as far south as Halifax.

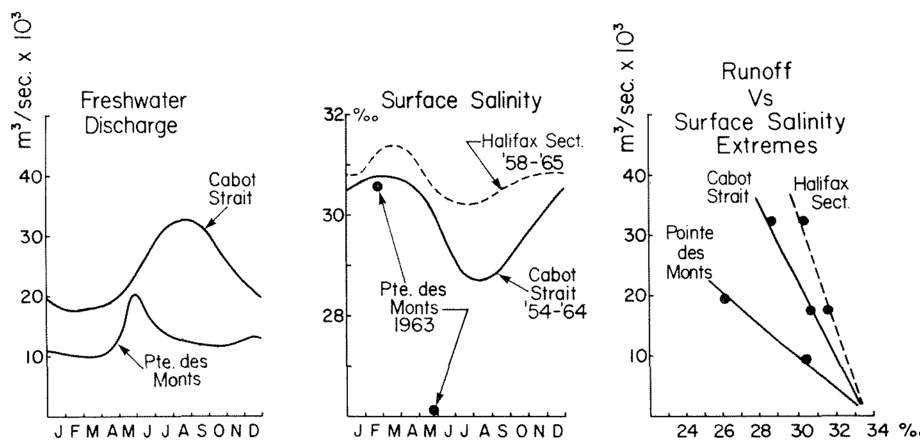


Fig. 9 – Effect of runoff on surface salinities.

SUMMARY

Regulation of river discharge in the St Lawrence system for power production since the turn of the century has caused appreciable changes in the dynamics and physics of the water of the Estuary, Gulf, and adjacent Scotian Shelf as follows.

(1) Changes in the seasonal strength of the haline circulation. The reduction in the quantity of sea water entering the system could exceed 150 000 m^3/s in the Estuary in spring and subsequently up to 2 or 3 times more in the Gulf at Cabot Strait in summer.

(2) Changes in the salinity of the water of the surface layer and changes in the seasonal heat budget. From a comparison of all the data available along the southern side of the system the surface salinity has, since the turn of the century, increased in spring at Pointe des Monts by about 3.5‰ and in summer at Cabot Strait and near Halifax by 1.3‰ and 0.8‰ respectively. The temperature has probably increased in winter as well as in summer.

DISCUSSION OF ENVIRONMENTAL CONSEQUENCES

In the Estuary and Gulf of St Lawrence these changes should have had a significant impact on the environment and on the marine biology of the lower St Lawrence system and offshore region, probably as far south as the New England states (Neu, 1970, 1971, 1973, 1968). They are bound to have modified the heat budget and temperature structure. In both the warmer seasons, i.e. spring and summer, and the colder seasons, i.e. autumn and winter, the surface temperatures of the water in the Estuary must have increased. These changes, no matter how small they might be, must have affected the formation and melting of ice and influenced the atmospheric temperature of the region. In the biological field, it is well established that the major activities in the ocean occur in the coastal zone, including the Continental Shelf. This is the area where changes due to runoff regulations have their major impact. A reduction in circulation and upwelling during spring and summer decreases the nutrient supply from the deeper water of the ocean to the upper layer, which is referred to by biologists as the 'life' layer. This, in addition to the change in the saline composition of the water of the upper layer, must have affected the reproduction of many marine species and thus the structure of the biomass of the region. Lillelund (1964) made extensive studies on this subject and reviewed the research of others. He demonstrated that these long-term changes in the physical properties of the water, particularly temperature, have a great effect on the fish population. Spawning, incubation, size of larvae and eggs, their mortality and the development of the young fish have been adversely affected by such changes. Sweet and Kinne (1964), who used Teleostoi for their tests, concluded that, 'these environmental effects during very early ontogeny are of paramount importance for the functional and structural properties of the individual (fish) and may modify its ecological capacities'. Sutcliffe (1972, 1973) compared fish catches in the Gulf of St Lawrence with long-term (10 to 20 years) variations in the fresh-water runoff, and inferred from the results that for certain species there is a close correlation between the two; the larger the runoff the greater the yield. It is therefore not unreasonable to presume that large-scale changes have already been inflicted upon the marine life of the Atlantic region of Canada and may even have adversely affected the fish stocks of the entire western North Atlantic.

The question which immediately arises is: what have been the magnitudes of these changes? Unfortunately, this cannot be answered at this stage. The complex interdependence of the biological elements and the fresh/salt water environment make the exact prediction of consequences difficult or even impossible. No past data exist with which to compare present day conditions. It is obvious that the assessment of these consequences, qualitatively and quantitatively, emerges as one of the most urgent problems facing modern science.

CONCLUSION

Fresh water from the drainage of rivers plays a prominent role in the generation of large-scale motions in the coastal environment. In the St Lawrence system, it initiates a circulation in which huge quantities of sea water are transported from the ocean into the Gulf and up the Estuary, a distance of more than 1500 km. As the seasonal flow of fresh water is modified for power production, the strength of this circulation is altered and with it upwelling, mixing, flushing of the system and near-coast water masses, and the composition of the water with respect to salinity and temperature. These changes must result in climatic modifications which influence the heat budget and therefore the ice conditions.

A reduction in upwelling during spring and summer has decreased the nutrient supply and this, in addition to the change in the composition of the water in the upper layer, must have affected the reproduction of many species. It can, therefore, be concluded that seasonal discharge regulation, as implemented in the St Lawrence for power production since the turn of the century, has imposed large-scale modifications upon the ecosystem of the Estuary, Gulf and coastal zone. This applies to any other system in which similar conditions prevail.

Power developments are, for all practical purposes, irreversible; if they were stopped, much of industry would come to a standstill. Of greater concern at this stage is the increasing activity in this field with very large power developments in the design or construction stage. The energy 'crisis' is accelerating this trend. In the light of current knowledge on the subject, we should question whether it is beneficial to continue this development without a knowledge of the consequences. Considering all the ramifications of this problem the indications are that hydro-power, which has been considered a 'clean' power resource, may prove to be less 'clean' than has been assumed.

Acknowledgements. The author gratefully acknowledges the constructive criticisms of the subject by a number of colleagues, in particular that of E.S. Turner of the National Research Council and the assistance given by F. Jordan in preparing the paper.

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