Plan Saint-Laurent
Pour un développement durable

Comité de concertation navigation

CLIMATE CHANGE AND MARINE TRANSPORTATION ON THE ST. LAWRENCE RIVER

EXPLORATORY STUDY OF ADAPTATION OPTIONS

Canada

Québec

ATTENTION

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A MESSAGE FROM THE CO-CHAIRS OF THE NAVIGATION CONSENSUS BUILDING COMMITTEE

In 2004, the Navigation Consensus Building Committee submitted the Sustainable Navigation Strategy for the St. Lawrence River, which was aimed at reducing the environmental impact of marine transportation while ensuring its development on the river. The Committee initially determined eight priority issues to which is associated a five-year action plan (2004-2009). The evaluation of adaptation options for commercial shipping with respect to water level fluctuations resulting from climate change is among these issues.

This study is the first-ever contribution toward addressing such options. Climate change is a very complex field and studying adaptation strategies with which to mitigate potential drops in water levels in the St. Lawrence is a very sensitive subject that gives rise to lively discussions. The study is thus a contemplation of what could be done to guard against the negative impacts of climate change on marine transportation; it does not propose a specific means of adaptation.

It is with pleasure that we present this exploratory study on climate change and marine transportation on the St. Lawrence River. In the light of the discussions of the Navigation Consensus Building Committee, we are well aware that the scope of this issue goes beyond the framework of navigation activities alone. We consequently hope that this work will give rise to new studies and ideas in this field and that the discussion will be broadened to include a larger pool of stakeholders.

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SUMMARY

This document is the fruit of an initial examination of certain potential technical and logistical adaptation strategies designed to address the impact of climate change on commercial shipping. This initiative arose from what the Navigation Consensus Building Committee recognizes as a real issue in the Sustainable Navigation Strategy for the St. Lawrence River. However, before seeking to confront situations of sustained low water levels using adaptation responses that involve the St. Lawrence River itself, directly and exclusively, and call on its unique resources and on those of its physical and human environments, it is presumed that recourse must first be sought in the opportunities offered by the management of the Great Lake–St. Lawrence System and particularly those available through the Moses-Saunders dam. The determination and analysis of these opportunities exceed both the framework of this study and the means available for it and are thus not part of it. Consequently, the absence or the more or less abundant quantity of information on any given option must not be interpreted as a position being taken in its regard.

Certain climate scenarios forecast a drop in the runoff from the Great Lakes–St. Lawrence River System. Such a drop could have appreciable impacts on certain activities, particularly commercial shipping on the St. Lawrence River. For this reason, the Navigation Consensus Building Committee felt that it would be judicious, from the perspective of sustainable navigation, to study the adaptation options that would make it possible to maintain the maritime and port activities at their current levels. This exploratory study is the first-ever exercise in matters of adaptation to climate change with respect to commercial shipping activities on the St. Lawrence River. Other studies are to follow in order to complete and provide more detail on the different scenarios analyzed.

The study is divided into two parts. The first part evaluates the anticipated drop in water levels in the fluvial sector of the St. Lawrence River (the Montréal-Québec sector) with respect to spatial distribution and amplitude. The evaluation is made using a numerical hydraulic model that incorporates the most recent climate scenarios for the Great Lakes basin and the Ottawa River, and those related to the rising of sea level. Simulations were

conducted using as a reference the water levels of an average hydrologic year and those of a year of low hydraulicity, from which had been subtracted the values obtained from climate projections. Should the hydrological conditions around the year 2050 correspond to an average hydrological year, the drops observed in the river would not hinder commercial shipping activities. In fact, for all months and in the four climate scenarios retained, the water depth at Montréal would be above the chart datum of marine charts. However, the anticipated impacts become more severe when the simulations use a low hydraulicity year as a reference. According to the most pessimistic climate scenario, WD (Warm and Dry), water levels could drop 1 m below the chart datum in Montréal and about 30 cm below in Trois-Rivières. This situation would extend over a number of consecutive months, which explains the concern about impacts. According to the simulations, the effect of drops in water levels would be felt downstream as far as the area of Bécancour. It should be noted that these simulations did not consider specific management procedures for the Moses-Saunders dam, where the water supply from Lake Ontario to the St. Lawrence is regulated. An adjustment to current procedures will likely be the first adaptation option implemented, because commercial shipping is one of the priority uses designated in the Boundary Waters Treaty between Canada and the US. If a scenario such as the WD were to occur, it would assuredly put this option to the test as regards its abilities to supply water. The new regulation plan soon to be adopted by the International Joint Commission will seek to share the impacts, that is, make it so that they are borne both upstream (Great Lakes) and downstream (St. Lawrence River) when the situations so require. This willingness to do so reflects the limits of water regulation and its incapacity to resolve everything. It seems realistic to assume that adaptation responses will have to be applied both upstream and downstream should the critical climate change scenarios occur.

Recurrence of a hydrological event of this amplitude is very difficult to predict because it is little likely that climatic conditions will reproduce the conditions of the past. However, a succession of years with water levels below chart datum would assuredly have more impact than if the event were to take place in alternation, that is, by following the fluctuations of a normal hydrological cycle. The uncertainties tied to the climate forecasts, notably the amplitude and direction of events to come, are reason to exercise caution in interpreting projections. The role played by a large number of elements still remains to be clarified. As such, the hydrological simulations carried out and their impacts on the water levels must be understood from a perspective whereby the anticipated climatic events would occur as they can currently be predicted. This, it is understood, will remain to be validated. These projections were used in particular to explore different adaptation strategies that would limit the impacts of the anticipated drops in water levels.

The subject of the second part of the study consists of a few adaptation options for commercial shipping that are explored with regard to the potential gains in water heights that they would produce. The options are divided into two categories: the first excludes any physical alteration of the river, whereas the second includes waterway development work. They are analyzed with respect to the sustainable development requirements, that is to say, by considering some of the economic, environmental and social impacts. Three classes of water level fluctuations were established, with a set of options associated with each:

1- Slight fluctuations (0 to <15 cm): evaluation of potential gains in water level obtained by having more precise *technical and technological tools*.
2- Moderate fluctuations (15 to <50 cm): evaluation of the potential gains obtained by waterway *development work* (dredging and hydraulic structures).
3- Large fluctuations (50 cm and more): evaluation of potential gains obtained using a *structural adaptation* (shape of ships adjusted to the conditions of the St. Lawrence) and *organizational adaptation* (re-engineering of port activities).

The analysis of potential gains in water heights which would make it possible to implement technological options (COWLIS network) and technical options (squat equation) reveals that the results would be limited. As regards the COWLIS network, it cannot predict river water levels with sufficient accuracy. The current difference between the predicted values and observed values exceeds, after only four days, the safety margin that carriers maintain for overseas loads. A reduction of this margin would result in a gain in water height that would vary between 20 cm and 30 cm. Substantial advances in meteorological forecasts are consequently indispensable for this option to be one of the adaptation strategies. As regards the squat equation, studies are under way on the St. Lawrence to verify whether the equation currently used is optimal for all types of vessels. In the light of experiments made on other waterways, it is apparent that, in certain cases, the use of a replacement equation makes it possible to gain a few additional centimetres. On the other hand, these new equations at times give values lower than those measured, sometimes dipping below the underkeel clearances. It will thus be necessary to wait for the results of the study conducted on the St. Lawrence to see whether or not gains may be obtained in this way.

The results of the analysis of the waterway development option make it possible to estimate that the drops in water level could be compensated through the use of this type of response. In the case of dredging, a preliminary calculation of the sediment volumes to remove was made on the basis of the drops predicted by the WD (the most pessimistic) and NWD (intermediate) climate scenarios. Sediment volumes were estimated at 1.6 million and 930 000 m^3 respectively. Approximate costs of $70 million (WD) and $42 million (NWD) had been estimated without, however, considering the cost of environmental impact studies, environmental compensation measures and residual effects. A very summary sketch of certain environmental impacts is presented; if this option were to be retained, the sketch should be completed and the impacts quantified. While the costs of the dredging option are relatively low, the effectiveness of dredging is equally relative, because deepening the channel does not make it possible to retain the water.

A few digital simulations were made on different types of hydraulic structures, dykes and a dam, located between Montréal and Trois-Rivières. These simulations were conducted using a reference scenario in which the river flow was reduced to 5 000 m^3/s at Sorel. This flow results in a drop in water levels of slightly more than 1 m in Montréal, which corresponds to the results produced by the WD climate scenario. The results obtained using the cross-stream dykes show a potential increase of 90 cm in the water level at Montréal when the simulations are conducted using a series of three dykes positioned a few kilometres apart. However, these dykes were located relatively close to Montréal, that is, between Lanoraie and Verchères. Even though the increase is significant, the level remains some 20 cm below chart datum. In addition, one problem observed with this type of structure is the formation of a downward movement of water at the dykes' outlet that would produce a drop of about 20 cm in water levels over a few tens of kilometres or so. Changes to the structures' design could correct this. Simulations were made on the same type of dykes, but this time located upstream from Trois-Rivières. The gain recorded would be 35 cm in Montréal and could be considered just as important given that the structures are 120 km from Montréal. Other simulations were also made using 7-km longitudinal dykes, coupled with cross-stream dykes in the Verchères sector. The observed increase in the water level would be 1.6 m in Montréal, bringing the levels nearly 50 cm above chart datum. The structure's diffuser-shaped outlet would appear to resolve the problem of the downward movement of water. One last simulation was made using a dam with a lock located upstream from Trois-Rivières. This structure raises the water level in Montréal by nearly 2 m (1 m above chart datum). Such a large increase would indicate that the side of the dam's surmountable sill should be adjusted downward to limit negative effects. Though interesting where hydraulics are concerned, since the entire surface of the water body lost due to climate change could thus be reclaimed, this option would have several environmental disadvantages because it would be an obstacle to the migration of species and would modify sediment transport, to name just two. Were there to be a marked interest in this option, studies on the design of the structures would be needed to take into account the environmental impacts and mitigate them. A general overview of these impacts, as tied to the construction of hydraulic structures, is presented in Section 2.3.6. The approximate cost of these structures varies between $50 million and slightly more than $500 million, to which must be added the costs associated with the environmental compensation measures, maintenance and operation.

The structural adaptation option analyzed involves the shape of vessels and is aimed at adapting vessel structure to the hydraulic conditions of the St. Lawrence by reducing draft. The last generation of vessels designed for the St. Lawrence adhered to this concept, with the hull being lengthened to 294 m and the draft increased to 10.78 m, while maintaining a 32.2-m beam. Certain limits appear to have been reached with this configuration, both where pressures exercised on the hull and manoeuvrability in river bends are concerned. There is thus a need to examine the possibility of widening vessels while reducing their draft. This aspect involves a number of constraints, such as a review of design standards of the shipping channel– which was designed on the basis of a model ship with a 32.2-m beam–and the construction cost of container ships, which is currently about US$60 million. At first glance, it would appear that this option would require a fleet of vessels specially reserved for the St. Lawrence or to structure-free waterways where the passage of vessels would not be limited by their beam. In a context of growing economic exchanges where marine transportation will be increasingly drawn on to transport merchandise overseas, a fleet's flexibility, that is, its ability to navigate on a number of waterways without constraints, would probably appear to be a major decisional criteria for shipowners.

The option of re-engineering port activities was analyzed while considering the direct costs of a partial transfer of activities from the Port of Montréal to a downstream port of the St. Lawrence River that would be less affected by drops in water levels. The exercise led to Section 2.5, which is aimed at obtaining a general idea of the direct costs that would result as well as the impacts associated with this option.

The scenarios analyzed include a partial transfer of merchandise, that is, certain bulk cargo and containers, to Québec City, Trois-Rivières, Bécancour or a combination thereof. The economic role of the Port of Montréal is first presented in a way to make the different issues clearly understood. Then, a characterization of each port was made, and the estimates of the direct costs calculated for a scenario of 400 000 containers. The estimated costs vary between $230 million and $260 million and involve only elements such as wharf construction, land acquisition, warehouses, etc. The addition of indirect costs such as the construction of railroads, roads and highways to ensure efficient intermodal transport would quickly increase the estimates. Railroad construction costs are in the order of $492 000/km, whereas those for a simple road or highway are $1.5 million/km and $7 million/km, respectively. These estimates do not include the costs of environmental studies. Considering these indirect factors and a total transfer of activities (approximately 1.2 million containers), the cost of port re-engineering would easily reach $1 billion. In addition, the environmental and social impacts of such an operation would not be negligible. Keeping the same ratio which now has wide currency in Montréal for the routing of merchandise to destination, specifically, 60% is transported by rail and the remaining 40% by truck, it would mean 450 more trucks on the roads to the reception port in the partial transfer scenario. Substantial pressure would thus be put on the local and regional road network, without counting the inconveniences for the public (congestion, noise, pollution, deterioration of roads, etc.). An increase in greenhouse gases could also be expected since marine transportation is more fuel efficient than the other modes of transportation and emits fewer greenhouse gases per tonne-kilometre of merchandise transported. One final point to underscore regarding the re-engineering of port activities has to do with the degree to which carriers would be interested in transferring their activities from one place to the other. Over time, the Port of Montréal developed the multimodal links that make it a hub in eastern North America. The port's main competitors are located not on the St. Lawrence River but on the US east coast. One of the challenges of this option would very probably be to find sufficient economic reasons to encourage carriers to favour another port on the St. Lawrence rather than to transfer their activities to a port on the US eastern seaboard.

With the port re-engineering option, cabotage could be an alternate solution that would maintain waterborne transportation on the river. How it would be possible to use vessels with shallower drafts to transport merchandise from a deep-water port to either Montréal or a city in the Great Lakes region must be looked at in more detail. This option would be more advantageous in environmental and social terms than would be the use of trucks and rail. Port re-organization for container storage and to accommodate handling equipment would also have to be contemplated. These investments, as well as those tied to activities (increase in the number of transshipments, acquisition of specialized vessels and infrastructures for container handling, increase in the risk of accidental spills, etc.), should be equitably amortized so as to make this option more attractive. The main advantage of cabotage is that it could be part of governments' and port authorities' long-term planning. This planning would likely reduce the economic impacts on the port cities and authorities most affected. Lastly, it must be pointed out that cabotage, though it appears potentially favourable for commercial shipping, would not resolve the problem of a water level drop and its impact on the other uses of the St. Lawrence River.

Thus, in an exploratory manner and with the objective of initiating an examination and contemplation of climate change adaptation measures, a few adaptation options were reviewed and, where possible, their economic, environmental and social impacts considered. This research made it possible to uncover certain limitations and opportunities specific to each option and to illustrate the complexity of their analysis on the basis of sustainable development criteria. Additional studies would therefore be necessary to be in a position to effectively determine those that are in line with this perspective and to discover new ones. A number of initiatives are emerging both in Canada and abroad so that adaptations to climate change be taken into consideration now. The impacts of climate change go beyond the framework of navigation activities alone, and the Navigation Consensus Building Committee believes that, in the coming years, an examination of the future vocation of the St. Lawrence from the perspective of sustainable development and a more integrated management must be undertaken.

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NOTICE

This document is the fruit of an initial examination of certain logistical and technical adaptation opportunities with which to address the impacts of climate change on commercial shipping. This initiative stems from an issue recognized by the Navigation Consensus Building Committee of the Sustainable Navigation Strategy for the St. Lawrence (D'Arcy, Bibeault and NCBC, 2004). The response to this issue is aimed at the:

> *documentation of adaptation options for the St. Lawrence that are both economically and environmentally acceptable.*

In particular, it is a matter of considering:

> *adaptation scenarios that rule out any physical alteration of the river and other scenarios that include alteration in order to ensure the transportation of merchandise.*

The report analyzes only the technical options and the waterway development work that would make it possible to maintain commercial shipping on the St. Lawrence River in the event of persistant low water levels. The options take into account, to a very limited degree, the commercial aspects, regional economic issues, environmental integrity and social acceptability.

Given the exploratory nature of this study, the results have a number of methodological limitations, tied notably to the uncertainties with respect to climate and its effects on the water levels of the St. Lawrence. In addition, we did not have sufficient financial resources to consider more options or to thoroughly examine the environmental and socio-economic consequences of the options in question. Before coming to any conclusion about the directions or recommendations of the Navigation Consensus Building Committee (and of its members as a whole), a comparitive study, conducted on the same basis, would need to be conducted. Lastly, the anticipated impacts of climate change go beyond the framework of navigation activities alone. In this regard, the Navigation Consensus Building Committee suggests that thought now be given to the future vocation of the St. Lawrence River. To be fruitful, any such examination must be based on sustainable development principles and on the integrated management of the St. Lawrence. As well, such an examination is needed to develop a more precise understanding of the situation.

Foreword

This project stems from a desire to more thoroughly explore, from the perspective of sustainable navigation and with respect to anticipated climate change, different adaptation options for the fluvial sector of the St. Lawrence River (Montréal-Québec City sector). A number of options analyzed here result from a round table held in the spring of 2002 that brought together stakeholders from the commercial and recreational navigation sector, governments and representatives of civil society. The objective of the round table was to validate the issues involved with a sustainable navigation strategy for the St. Lawrence River and also validate and improve the guiding framework (D'Arcy, Bibeault and NCBC, 2004).

However, before seeking to confront situations of sustained low water levels in the fluvial sector of the St. Lawrence River by introducing adaptation responses that involve the St. Lawrence River itself, directly and exclusively, and call on its unique resources and on those of its physical and human environments, in this study it is presupposed that recourse must first be sought in the opportunities offered by the management of the Great Lake–St. Lawrence system as a whole and particularly those available through the Moses-Saunders dam. The determination and analysis of these opportunities exceeds both the framework of this study and the means available for it and are thus not part of it. Consequently, the absence or more or less substantial quantity of information on a given option must not be interpreted as a position being taken in its regard.

Minimum flow episodes are a normal hydrological phenomenon. Such episodes occurred in the St. Lawrence River during the 1930s, 1960s and 1990s, which tends to suggest a recurring 30-year hydrological cycle. However, the increase in the frequency of minimum flow episodes beginning in the 1990s, combined with the extent of some episodes (1999 and 2001) and the possibility that they may occur more often with climate change, were of concern to the Navigation Consensus Building Committee and led it to retain this problematic in the Sustainable Navigation Strategy. This project aims to study it and in so doing constitutes a first-ever exploration as regards commercial shipping.

The impacts and disadvantages of low water levels for marine transportation and recreational activities, as well as for water supply, shoreline residents' quality of life and the environment, are known and have been described in recent research conducted by the International Lake Ontario–St. Lawrence River Study Board of the International Joint Commission (http://www.losl.org, consulted in May 2005). Freshwater fishing was also addressed since water levels have an impact on the habitat of certain key species.

One lesser known aspect, however, are the different adaptation options that would help mitigating these impacts. In this regard, it should be stressed at the outset that before an adaptation can be adopted or promoted in any way, it needs to be likely to satisfy the needs and interests of the users of the St. Lawrence and its water. This obligation will apply to any adaptation option, and regardless of the interest it presents for a particular use. This study is limited to an inventory and analysis of a few adaptations that could benefit maritime transportation in the event of long-lasting low levels on the St. Lawrence. Given the study's limitations, it was not possible to analyze the impacts that adopting them could have on the other uses. The need to do so is nevertheless there.

That being said, in a context of sustainable navigation where the objective is to reduce the environmental impacts of shipping activities while maintaining the activities' development potential, the study of different adaptation options nonetheless prepares the ground for giving careful consideration to them, based on the foundations of sustainable development. The 2002 Round Table made it possible to determine different options, such as hydraulic structures, dredging, port re-engineering, modification of vessel design, etc. These different options can be divided into two categories:

1- Adaptation of shipping activities to the environmental and hydraulic conditions of the St. Lawrence and the ruling out of any physical alteration of the river;
2- Consideration of waterway development as a means of maintaining marine transportation at at least its current level.

The Navigation Consensus Building Committee discussions also made it possible to highlight the lack of technical and scientific documentation on different adaptation options, particularly as regards their technical pertinence, economic efficiency and environmental impacts. This study will be able only to partially compensate for this deficiency in data on and knowledge of the adaptation options since the scope of the subject clearly requires more research. However, this will be an initial contribution to the evaluation of options not only on the basis of particular interests, but in the light of the precepts of sustainable development, which integrate both economic and environmental interests and social acceptance.

It is important to acknowledge from the outset that, in a situation of minimum flow episodes in the fluvial sector of the St. Lawrence River, it is assumed that recourse will first be sought through management of the hydrographic entity to which the St. Lawrence belongs: the Great Lakes-St. Lawrence System. Management of the system has, notably but among other possibilities, the capacity to alter the relative water levels, with respect to one another, of Lake Ontario (and, upstream from it, other Great Lakes) and of the fluvial sector of the St. Lawrence. This is accomplished via the Moses-Saunders dam which controls flows between Lake Ontario and the St. Lawrence. Management of the Great Lakes-St. Lawrence River System must satisfy a number of criteria, one of which is to equitably meet all the water requirements of the system's different components by achieving the most balanced distribution possible among needs and among parties.

The options are briefly presented here. None of them is the object of a feasibility study. Moving on to the next step would require much more substantial funding than that available. Lastly, the social acceptability of the different options must be discussed on a much broader scale than that of the Navigation Consensus Building Committee. This exploratory study may help ensure that such discussions take place.

For all the stakeholders of Québec, management of the water levels of the Great Lakes-St. Lawrence System upstream from the sites where adaptation solutions could be applied must clearly fall within the broader context of a consensus-building process that ensures the respect of all users, both upstream and downstream. The impacts of climate change upstream and the adaptation strategies advocated to address them must also be taken into consideration.

As such, this study remains pertinent since it is based on the current management mode in effect at the Moses-Saunders dam and thereby assumes that the upstream-downstream water ratios are not being questioned. Thus, while taking into account the current mode, the study proposes adaptation options for the hypothetical situation where the Great Lakes–St. Lawrence System would be affected by a drop in water levels due to climate change.

Lastly, we believe that this study is an interesting exercise and acknowledge that, in practice, it is but a partial study because it does not take into consideration the influence of regulation. The regulation criteria are under review and new plans will be submitted at the consultation held in the spring of 2006. If they were to be implemented, some of these plans would increase the runoff in the St. Lawrence. Regulation clearly must be taken into account in any real adaptation strategy. Consequently, this exercise would need to be repeated, with the appropriate modifications and from a perspective that goes beyond the context of commercial navigation alone.

Introduction

When the Sustainable Navigation Strategy was being developed in 2004, the Navigation Consensus Building Committee felt that the fluctuations in the water levels of the St. Lawrence could affect marine and port activities and that, consequently, there was a need to study adaptation options in relation with the principles of sustainable navigation (D'Arcy, Bibeault and NCBC, 2004).

Set in a global framework, the 2001 report of the Intergovernmental Panel on Climate Change stressed that a number of climate indicators observed during the 20th century converge on climate change (IPCC, 2001). However, the reliability of pre-industrial data is relative (McIntyre and McKitrick, 2005; Osborn and Briffa, 2004) and the quantitative importance of certain factors (greenhouse gases, solar magnetic field, etc.) that may contribute to climate change remains imprecise (Parker, 1999; IPCC, 2001). Moreover, the changes observed up to now would be valid for the northern hemisphere but not for the southern hemisphere (IPCC, 2001). In Canada, the regional variability of climate is clearly illustrated by observations made over a period of 50 to 100 years. The most notable changes have occurred in the western Arctic, in the Mackenzie Basin and in the Prairies which, during the 20th century, warmed by 1.5°C, nearly three times the average global warming (0.6° C). The warming experienced on the coast of British Columbia and the Great Lakes and St. Lawrence region was nearly identical to the global average. Less pronounced warming, approximately half of the global warming, was observed in northwestern Ontario, central Québec and in the Atlantic provinces (Canadian Council of Ministers of the Environment, 2003).

It is difficult to predict with certainty the direction of climatic variations on a regional level and their amplitude, notably because precipitation varies greatly and current atmospheric models are unable to account for certain atmospheric processes (Natural Resources Canada, 2002).

In the Great Lakes-St. Lawrence watershed, the first estimates based on a simulation that doubled atmospheric CO_2 point to a drop in the average annual river discharge of 3 100

m^3/s (≈40%), which would lower the water level at the Port of Montréal by approximately 1.25 m (Mortsch et al., 2000). More recent climatic simulations put the drop in the net water supply at between 4% and 24% in the Great Lakes watershed (Croley II, 2003). This variation, attributable to a greater increase in temperature than in precipitation, would result in increased evaporation.

Despite the scenarios' degree of uncertainty, authorities wanted to study the impacts that would be associated with them, both where economic activities and the public were concerned (Transport Canada – Canmore Workshop, 2003; Natural Resources Canada, 2002). As regards commercial shipping, the impacts for the Great Lakes (Caldwell et al., 2002; Quinn, 2002; Transport Canada – Canmore Workshop, 2003; Millerd, 2004) were more thoroughly assessed than those for the St. Lawrence. This apparent lack of interest could be explained, firstly, by the absence of a research organization dedicated to the issue and, secondly, by the confidence that maritime sector stakeholders have in their experience with and knowledge of river fluctuations (Baclet and Montagné, 2002).

A significant drop in water levels directly reduces vessels' load capacity. In the case of a regular service, this means that more trips or vessels would be required to transport the same quantity of cargo. According to certain climate scenarios, maritime carriers' operating costs on the Great Lakes could increase by 15% to 30% (Millerd, 2004). In this context, and if costs were to become too high, companies that deliver their merchandise via maritime transportation on the Great Lakes could consider other modes of transportation (Millerd, 2004).

The climatic simulations cannot accurately anticipate the period and frequency at which these changes will occur. The timeline obtained through simulations is usually around the year 2050. As it is on a fairly distant horizon, in the interim, modellers will be able to refine their predictions by becoming more confident about the direction and amplitude of changes. The intervening years will also provide the opportunity to explore different adaptation options for confronting these changes down the road. However, this aspect is often neglected, to the point where there could be said to be a growing and unacceptable deficit in adaptation research (Burton, 2004).

In general, there are different ways of adapting to change. In nature, adaptation is a reactive process whereas in humans, it can occur by anticipation (IPCC, 2001). The market is an example of this type of adaptation, which uses the price mechanism as a point of reference. Governments can also plan adaptation by anticipation to reduce the ecological, social and economic costs associated with climate changes. Surprisingly, there appear to be very few cases where decision-makers turned to an analytic framework to assess the adaptation options (IPCC, 2001). Clearly, the uncertainty tied to the long-term effects of climate change can curb major infrastructure investments (Transport Canada – Canmore Workshop, 2003; European Environment Agency, 2005). However, climate change should be considered in the context of risk management and the assessment of vulnerable areas (Natural Resources Canada, 2002) and, in that regard, the perspective of adaptation should be included in governments' planning of long-term development. Certain countries in Europe have recently begun to integrate climate change into their planning (European Environment Agency, 2005).

The typical adaptation options for marine transportation are fairly well known, being dredging, the erection of hydraulic structures, changes to hull design to reduce draft, and more intense use of intermodal transportation (Transport Canada – Canmore Workshop, 2003; Mortsch et al., 2000; Millerd, 2003; Quinn, 2002). A review of traffic management operational standards could, at some point, figure among the potential options. However, even though these options have been considered, no exhaustive study has been made of them. Documentation available on the options thus remains of varying consistency. This is because some options are historically better known and, above all, examined more abundantly. Others are relatively new and little known. What is more, cost determination is relatively new and this information must be treated as being for information purposes only rather than as actual project costs. However, the absence or abundance of information in this report is not to be interpreted as a preference on the part of the Navigation Consensus Building Committee for one option over another. A comparative analysis of impacts, costs and advantages, including different variations, would make it possible to better evaluate each option's adaptation potential. In addition, such an analysis would help determine the options that fall within sustainable development objectives.

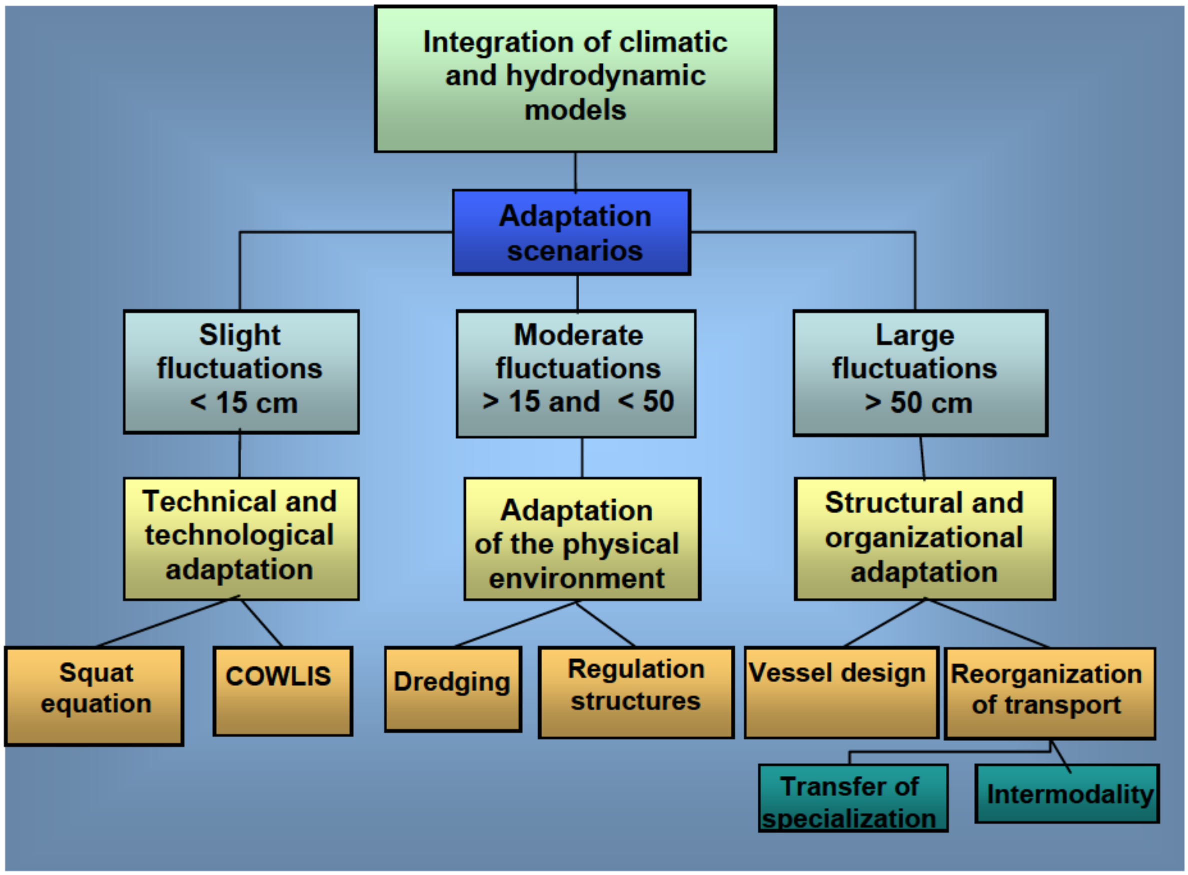
The goal of this study is to explore different adaptation strategies that would make it possible to maintain maritime and port activities at their current levels, assuming that climate change will result in a drop in water levels in the Great Lakes-St. Lawrence System. The study is divided in two parts. The first covers a hydraulic simulation of variations in water levels in the river, made using climatic and oceanic models. The simulation provides a means by which to estimate the amplitude of changes and the spatial distribution of water levels by considering both the drop in the Great Lakes' runoff and the increase in sea levels. The second part evaluates the potential gains in height that would allow a few adaptation options to be implemented, according to three classes of water level fluctuations. One category of option is associated with each of these classes:

1- Slight fluctuations (<15 cm): evaluation of potential increases in the water column obtained through the use of more precise *technical and technological* tools.
2- Moderate fluctuations (15<50 cm): evaluation of potential gains obtained with *waterway development* work (dredging and hydraulic structures).
3- Large fluctuations (50 cm and more): evaluation of potential gains obtained through an *adaptation that is structural* (vessel design adjusted to the conditions of the St. Lawrence) and *organizational* (re-engineering of port activities).

A brief discussion of the results and the potential of each option completes Part II.

It should be noted that the fluctuations and gains were originally divided into three classes corresponding to each option in an approximate manner, which explains the difference between the potential gains that are assumed and the results. Where appropriate, the options' environmental and economic impacts are summarily estimated. Figure 1 presents an overview of the analytical process involved in carrying out the study.

Figure 1 – Schematic presentation of the adaptation options analyzed



The initial results obtained are interesting but must be carefully interpreted. For example, the projections produced by the hydraulic simulation illustrate that the impact of climate change on river water levels would be close to nil if the future climate resembles a current average hydrological year. On the other hand, if the future climate is closer to a current low hydraulicity year, the drops in water levels will be more pronounced and, at certain times, will reach about 1 m at Montréal. Since the drops would extend over several months, the impacts would be more serious. However, certain adaptation options explored would be able to compensate for the losses sustained, if the frequency of episodes were to justify it. These results must be considered preliminary. Other studies would be needed both to address the climate scenarios in more detail and to more thoroughly examine the adaptation options. New options could also be explored as financial compensation measures to reduce economic pressure on carriers and port authorities.

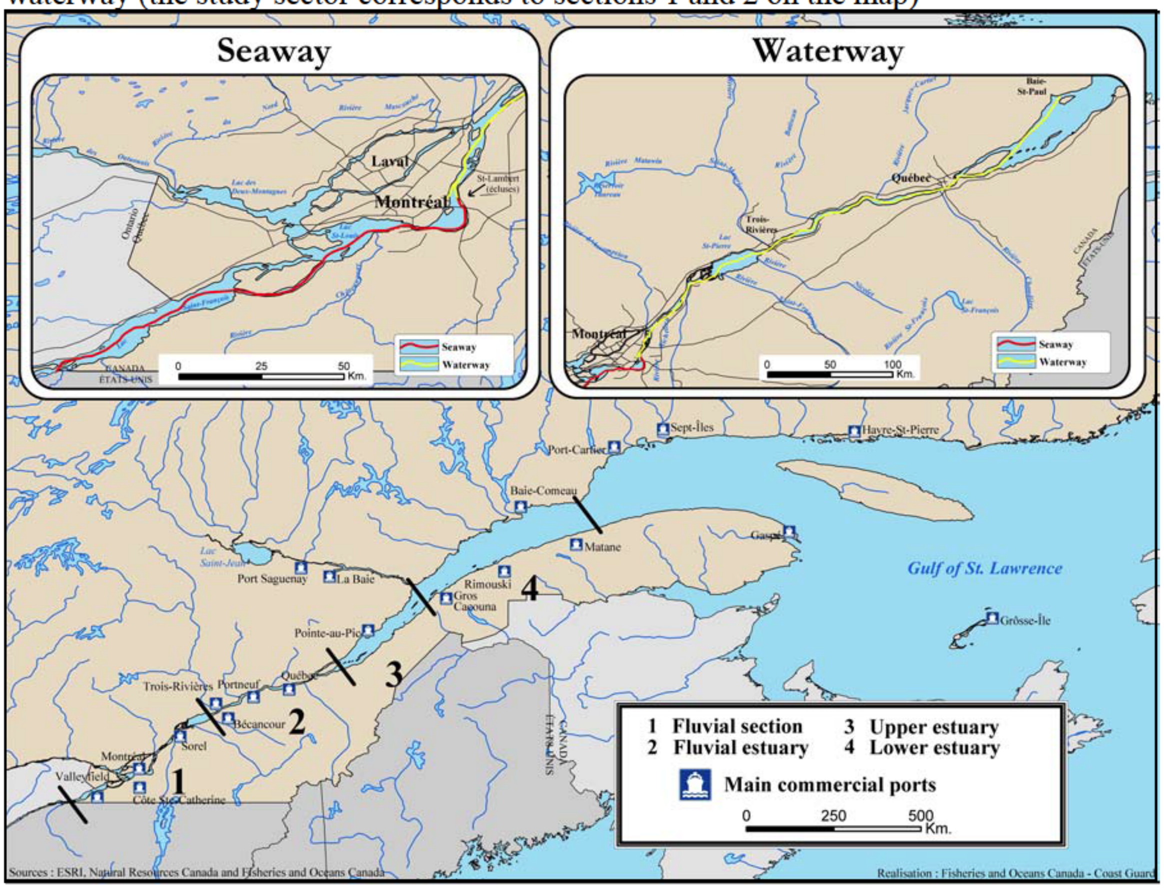
Part I

Integration of Climate Scenarios and the Rise in Ocean Levels into a Hydraulic Model of the Fluvial Sector of the St. Lawrence River

1.1 Context

The St. Lawrence River, in hydrological terms, takes its source from the Great Lakes and ends its course in the Gulf of St. Lawrence. The partial tide reaches into the fluvial section up to Lake Saint-Pierre where it can at times attain 30 cm. The shipping channel extends over a distance of approximately 300 km between Cap Gribane and Montréal, with a nominal depth of 11.3 m. Some places along the channel are less than 11.3 m deep but the height of the water in these sectors is compensated by the tidal effect, which ensures the safe passage of vessels.

Figure 2 – Map of the St. Lawrence River (fluvial and estuary), as well as the Seaway and waterway (the study sector corresponds to sections 1 and 2 on the map)



The climatic models forecast scenarios whose impacts on the water levels of the St. Lawrence would be the opposite. On the one hand, the water supply from the Great Lakes would decrease, due to the increase in evaporation (Croley II, 2003), whereas the water level would rise due to the melting of glaciers and the thermal expansion of the oceans (IPCC, 2001; Meehl et al., 2005). An evaluation of the combined effect of these two scenarios is needed to estimate the amplitude and spatial distribution of the impacts of climate change on the fluvial sector of the St. Lawrence River.

1.2 Methodology

The integration of climate and oceanic scenarios into a hydraulic model in order to anticipate the water levels in the St. Lawrence during the 2050s (2040-2060) was carried out in the following manner (Lefaivre, 2005):

1. Estimate, using the numerical modeling of the atmosphere and the atmospheric conditions for the 2050s.
2. Apply this projection, using hydrological modeling, to the watersheds of the Great Lakes and the St. Lawrence to obtain the total runoff.
3. Estimate, using a projection of the average levels of the oceans for the section downstream from the St. Lawrence.
4. Integrate the flow and water level projections into the hydraulic model to estimate the corresponding water levels in the river.

1.2.1 Atmospheric conditions projection for the 2050s – Global atmospheric models

The global atmospheric condition projections for the 2050s are derived from two climate centres: the Canadian Centre for Climate Modelling and Analysis and the Hadley Centre for Climate Prediction and Research. Using different greenhouse gas emission growth hypotheses, 28 climatic projection calculations were made, from which four scenarios depicting the extreme values are defined. Modification of the values of two main variables—temperature and precipitation—results in the following four atmospheric conditions: *warm*, *not as warm, dry* and *humid*. The results used for the St. Lawrence River stem from calculations made by the two centres:

i) Canadian Centre for Climate Modelling and Analysis

- Model CGCM2, result A 21 – Warm and dry (**WD**)

- Model CGCM2, result B 23 – Not as warm and dry (**NWD**)

ii) Hadley Centre for Climate Prediction and Research

- Model HADCM3, result A1F1 – Warm and humid (**WH**)
- Model HADCM3, result B22 – Not as warm and humid (**NWH**)

First, a control period (1961-1990) is selected, where the actual climate conditions are reproduced using an atmospheric model. The projection relative to the future climate, based mainly on greenhouse gas variations, is made over the same number of years (2040-2069). The results obtained for the period studied are then subtracted from those of the control period (Lefaivre, 2005). The same procedure will be used to calculate total runoff, flow, and ocean and river water levels. Note that the validity of the projections rides on current world economic growth predictions and an increase in greenhouse gas emissions and, under such conditions, they should not be interpreted as predictions.

1.2.2 Projection of total runoff for the Great Lakes-St. Lawrence River watershed

The results of climatic projections were integrated into hydrological models to obtain runoff variations for the watersheds of the Great Lakes (Croley II, 2003) and Ottawa River (Fagherazzi et al., 2004). These variations are illustrated in Table 1.

Table 1 – Variations of total runoff (%) for the Great Lakes and Ottawa River watersheds, according to the four climate scenarios

Sectors / Scenarios	Great Lakes	Ottawa
WD	- 24%	- 7%
NWD	- 17%	- 4%
WH	- 21%	- 8%
NWH	- 4%	- 1%

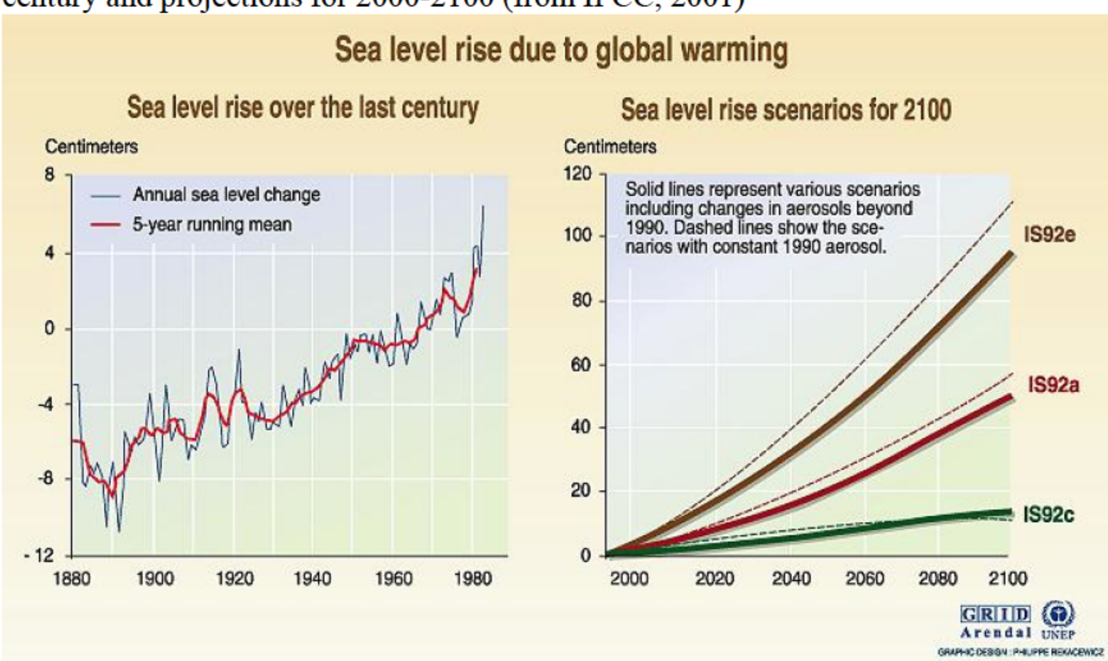
The hydrological cycle of the two watersheds would be modified by climate change, but less significantly for the Ottawa River. The water surfaces exposed directly to evaporation and the vegetative cover could explain this difference.

Variations in the basin of the Ottawa River have been extrapolated to other tributaries of the St. Lawrence between Montréal and Québec City on the basis of the actual relative percentage of the current runoff, with the exception of the Richelieu River. The variations in the Great Lakes have been attributed to the Richelieu River due to the similarity between Lake Champlain and Great Lakes runoffs. Lastly, the values in Table 1 for the Great Lakes are applied directly at the outlet of Lake Ontario, irrespective of adaptive management measures that could be implemented at the Moses-Saunders dam to mitigate the effects of these variations on the river flow.

1.2.3 Mean sea level

A number of uncertainties remain concerning the effects of climate change on the amplitude of the elevation of the mean sea level. Among them, there is the oceanic thermal expansion rate of the oceans, the speed of glacier melt as well as the isostatic movements (rebounding) of the earth's crust. These uncertainties explain the large variations in the long-term projections (right-hand portion of Figure 3).

Figure 3 – Evolution of the average sea level resulting from global warming over the past century and projections for 2000-2100 (from IPCC, 2001)

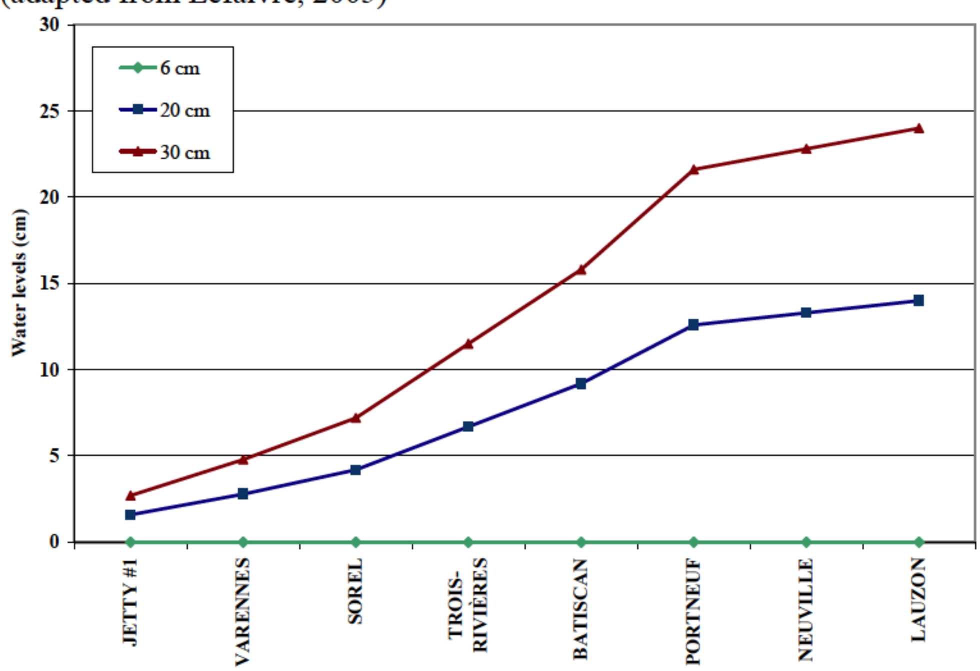


Source: Climate change 1995, The science of climate change, contribution of working group 1 to the second assessment report of the intergovernmental panel on climate change, UNEP and WMO, Cambridge university press, 1996; Sea level rise over the last century, adapted from Gornitz and Lebedeff, 1987.

According to the IPCC evaluation, the mean sea level has presumably risen about 12 cm over the past century (left portion of Figure 3) and this increase should continue during this century. Average estimations call for an increase of nearly 20 cm above the current level by around 2050, in comparison with the actual observations (right portion of Figure 3). However, the lack of accuracy is notable with values varying between 5 cm and 30 cm. The average value of 20 cm will be used for the purposes of our calculations.

Since the glacial recession more than 10 000 years ago, terrestrial rebound has been occurring. The degree of rebounding can, in certain cases, cancel or mitigate the effect of an increase in sea levels. Observations made at the Lauzon tidal station (opposite Québec City) have shown that water levels there did not change over the past century (Xu et al., 2004). This could mean that the rate of terrestrial rebound at this site might be about the same as the increase in mean sea level, 12 cm per 100 years. Assuming a constant terrestrial rebound, a value of 6 cm should be subtracted from the average increase of 20 cm in sea level for 2050. The value of 14 cm will thereby be used for hydraulic modeling. Figure 4 illustrates the effect of the increase in sea level along the St. Lawrence, with the three different values.

Figure 4 – Effect of the increase in sea level in the fluvial sector of the St. Lawrence River (adapted from Lefaivre, 2005)



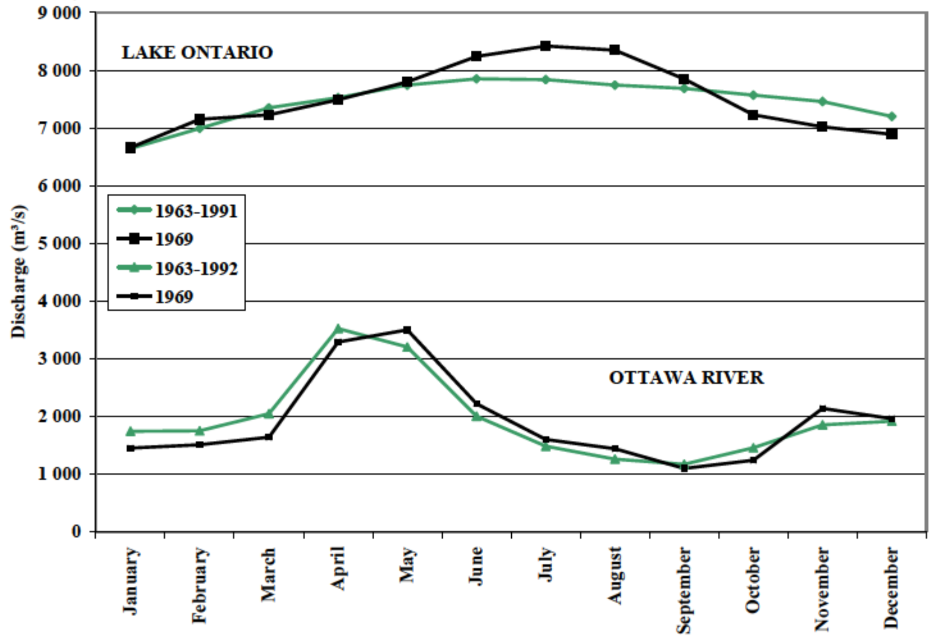
1.2.4 Modelling of St. Lawrence River water levels

Modelling has been carried out with a one-dimensional numerical model that reproduces the water levels of the St. Lawrence. This model has been first developed by researchers of the Massachusetts Institute of Technology (Dailey et al., 1972) and later applied to the hydrological conditions of the St. Lawrence River (Morse, 1990). Water levels can be obtained for the entire river by fixing upstream and downstream thresholds. Two boundaries are set upstream: the discharge measured at Lasalle and the sum of the discharges of the Mille-Îles and des Prairies rivers measured at Repentigny. The downstream boundary corresponds to the water level recorded at Lauzon.

The water levels of a year representative of the period 1961-1990 are first reproduced. Discharge and mean sea level projections from the different climate scenarios are then applied at the boundaries of the model for the typical year. The results are presented in the form of differences in level for each of the four climate scenarios relative to the levels of the typical year.

Discharges measured at the Moses-Saunders dam (Lake Ontario) and Carillon dam (Ottawa River) for the period 1961-1990 have shown that the closest average discharge for the whole period occurred in 1969 (Figure 5). It will thus be used as the typical or reference year.

Figure 5 – Comparison of average monthly discharges for the year 1969 at Cornwall and for the Ottawa River: Cornwall, 1963-1991; Ottawa River, 1963-1992 (adapted from Lefaivre 2005)



1.2.5 Results of the integration of climate change scenarios and the rise in sea level into the hydraulic model

The hydraulic modelling is aimed mainly at:

- evaluating the spatial distribution of the water height in the fluvial sector of the St. Lawrence River by considering the climatic variations and the increase in sea level;
- evaluating the amplitude of the drops in water levels;
- determining the sector where the variations become nil.

The results are presented with respect to the reference year (1969), which corresponds to a year of average water levels, and with respect to a low-level year (2001). This produces a range of contrasting results and is sufficiently realistic to depict what could happen. Moreover, it is important to keep in mind that it is the extreme situations that call for adaptation responses, not the average situations (IPCC, 2001). The calculations were made for a number of stations along the St. Lawrence, but this analysis is limited to Montréal (Jetty #1) and to Trois-Rivières. It was made on a monthly basis to take into account seasonal hydrological variations. The result is a non-linear drop in the percentage of water level variation attributable to each scenario. This explains why, for certain months, the result produced by the NWH climate scenario is higher than that for the reference year. Figures 6 and 7 present the variations with respect to the year 1969, whereas Figures 8 and 9 present them with respect to the year 2001.

Figure 6 –Monthly water level anticipated at Montréal (Jetty #1) with respect to reference year 1969, based on the four climate scenarios (warm and dry; not as warm and dry; warm and humid; not as warm and humid) (Source: Lefaivre, 2005. Adaptation: D'Arcy, 2005)

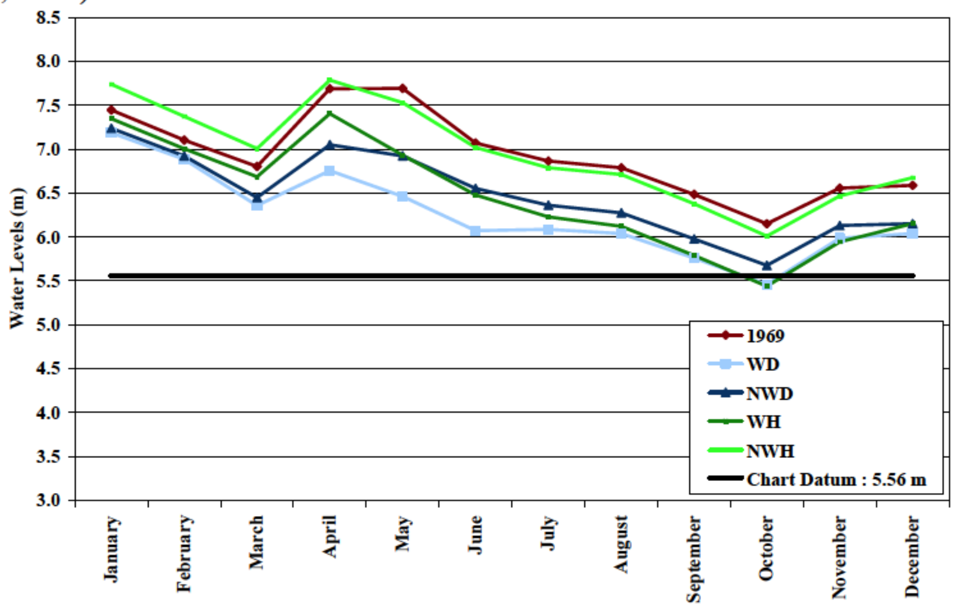
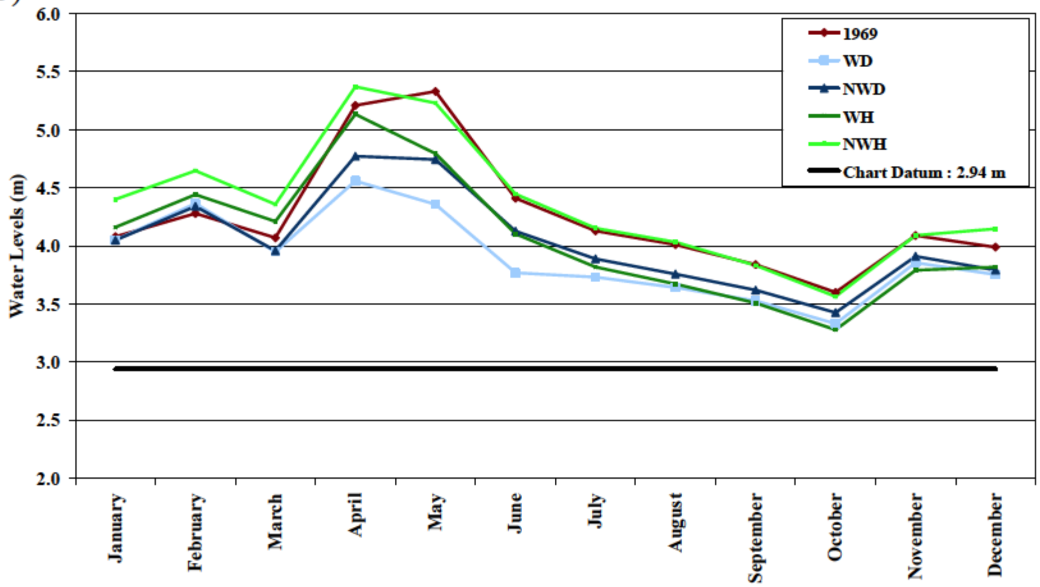


Figure 7 – Monthly water level anticipated at Trois-Rivières with respect to reference year 1969, based on the four climate scenarios (warm and dry; not as warm and dry; warm and humid; not as warm and humid) (Source: Lefaivre, 2005. Adaptation: D'Arcy, 2005)



In addition to the curves for each scenario, the figures indicate the value of the chart datum for each station. This value corresponds to the lowest levels observed in 95% of the time during a 100-year period. It is also from this value that the nominal depth in the waterway is measured.

Figures 6 and 7 illustrate that by subtracting the climate change values from those of an average hydrologic year, there are no effects observed in Montréal with regard to the chart datum, regardless of the climate scenario retained. For the most pessimistic scenario (WD), the greatest difference with the year 1969 occurs in the month of May, where it reaches slightly more than a 1 m. However, May is a month where water levels are usually high, which mitigates the marked drop due to the low level of snow accumulation. The difference decreases as the season progresses and the only time a value below chart datum occurs is in October. This situation is not unusual for the hydrology of the St. Lawrence because the quarter of August to October is the quarter during which levels are generally the lowest and occasionally fall below chart datum. It should be noted that the differences for the other scenarios are between +0.3 m and -0.75 m. In the scenarios involving a higher humidity (WH and NWH), certain months' values are higher than the reference year. At Trois-Rivières, the differences are smaller; none of the climate scenarios led to levels below chart datum.

These results suggest that climate change would not have any significant impacts on the current level of navigation activities on the St. Lawrence if it reproduces an average hydrological year. The same calculations will be done again, this time by taking a low-level year (2001) as a reference (Figures 8 and 9). This year, though outside the 30-year reference period (1961-1990), produces results similar to a low-level year that occurs during the period, such as 1964. The year 2001 was chosen solely because the episode is more recent, making it easier to have a concrete representation of the impacts associated with it.

Figure 8 – Monthly water level anticipated at Montréal (Jetty #1) with respect to a low water levels year (2001), based on the four climate scenarios (warm and dry; not as warm and dry; warm and humid; not as warm and humid) (Source: Lefaivre, 2005. Adaptation: D'Arcy, 2005)

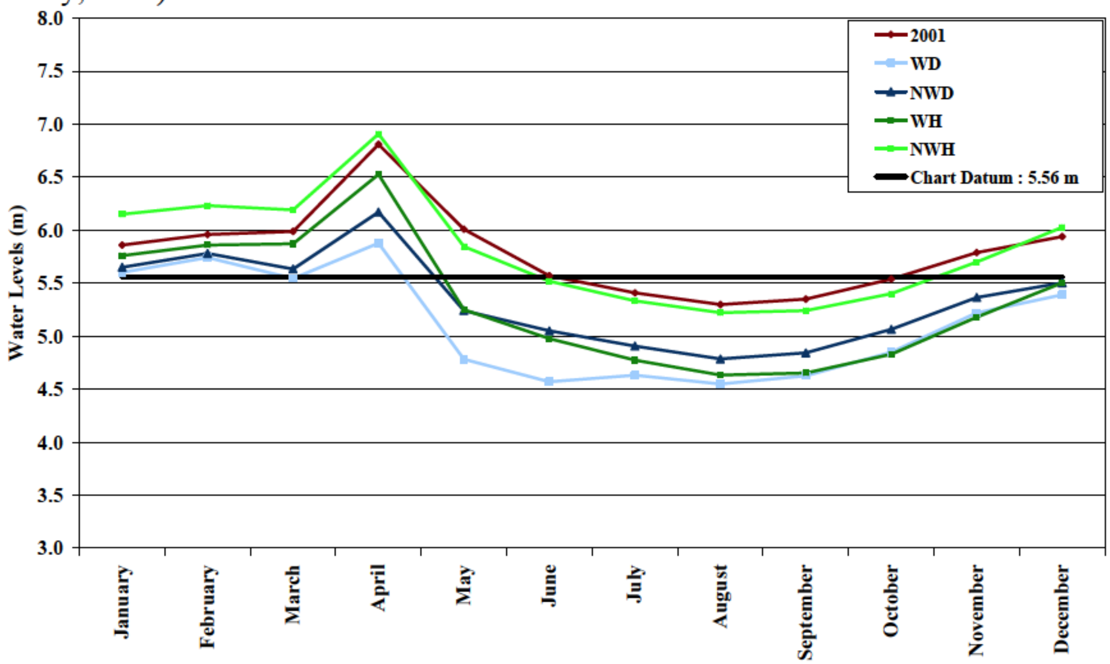
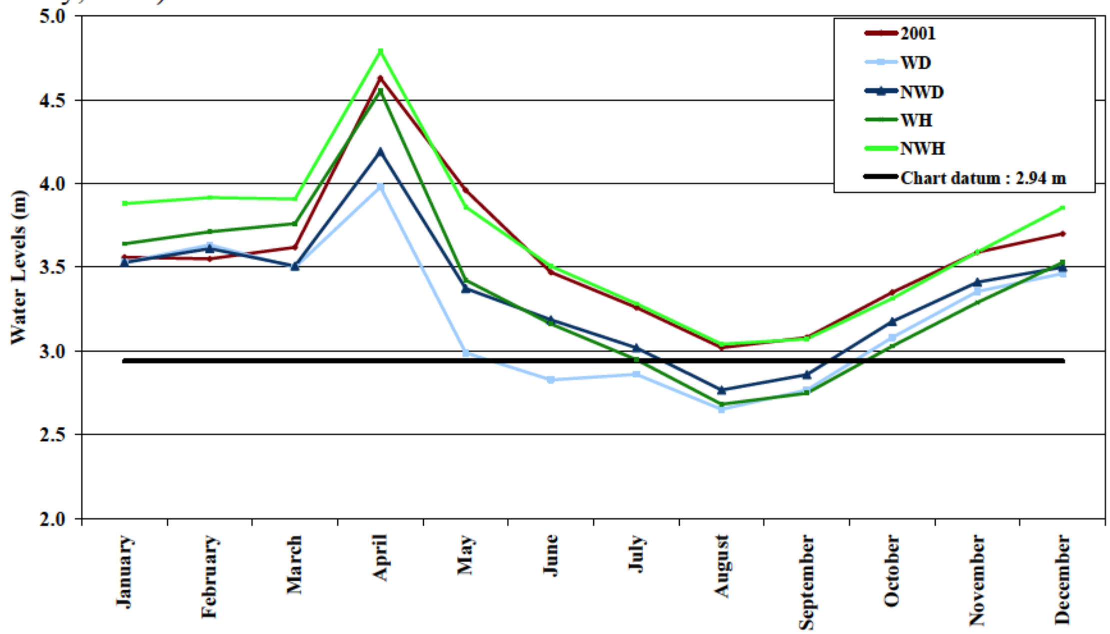


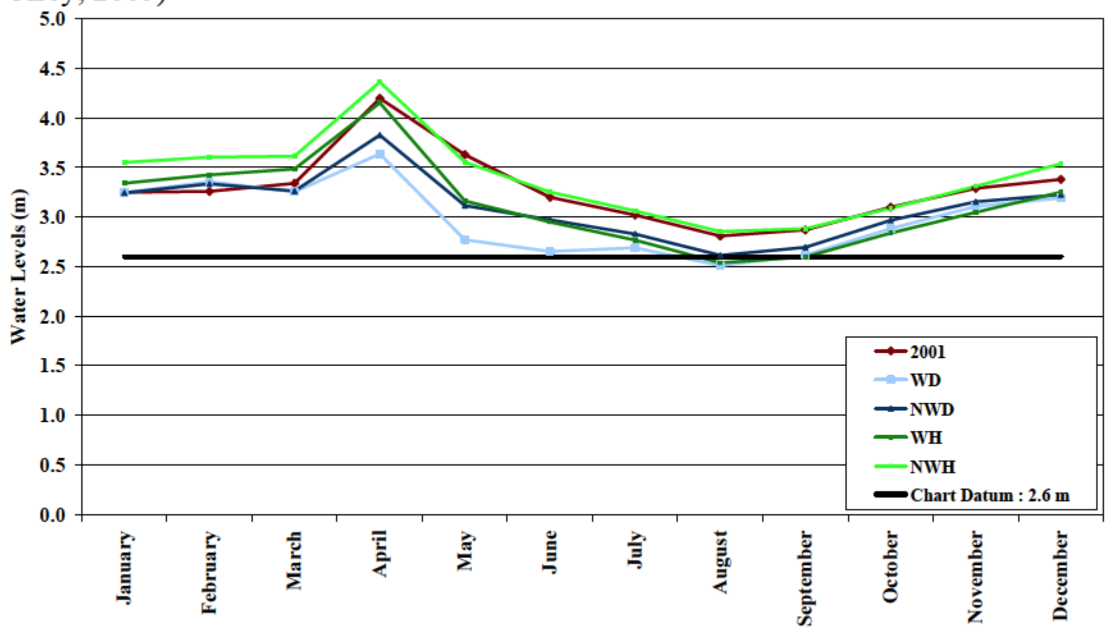
Figure 9 – Monthly water level anticipated at Trois-Rivières with respect to a low water levels year (2001), based on the four climate scenarios (warm and dry; not as warm and dry; warm and humid; not as warm and humid) (Source: Lefaivre, 2005. Adaptation: D'Arcy, 2005)



Simulations demonstrate that in the majority of climate scenarios, the water levels are significantly affected. At the Port of Montréal, they would be under the chart datum from May to December. The scenarios that generate temperature variations (WD and WH) generate the most significant drops–nearly 1 m–which would extend over a number of consecutive months. The other two scenarios show less substantial drops, but they would increase over time. The impacts would necessarily be fewer if the low-water years were not successive. There is a need to determine how to implement adaptive management procedures at the Moses-Saunders dam to compensate for this severe drop in water level for a number of months.

At Trois-Rivières, water levels would be under chart datum for a few months, with the greatest difference occurring in August with a drop of 0.30 m, under the WD scenario. The duration and amplitude of variations would be less severe at this location, reducing the need to turn to major adaptation options. When reference year 2001 is used, the drop in water levels on the river no longer has an impact downstream of Bécancour (Figure 10).

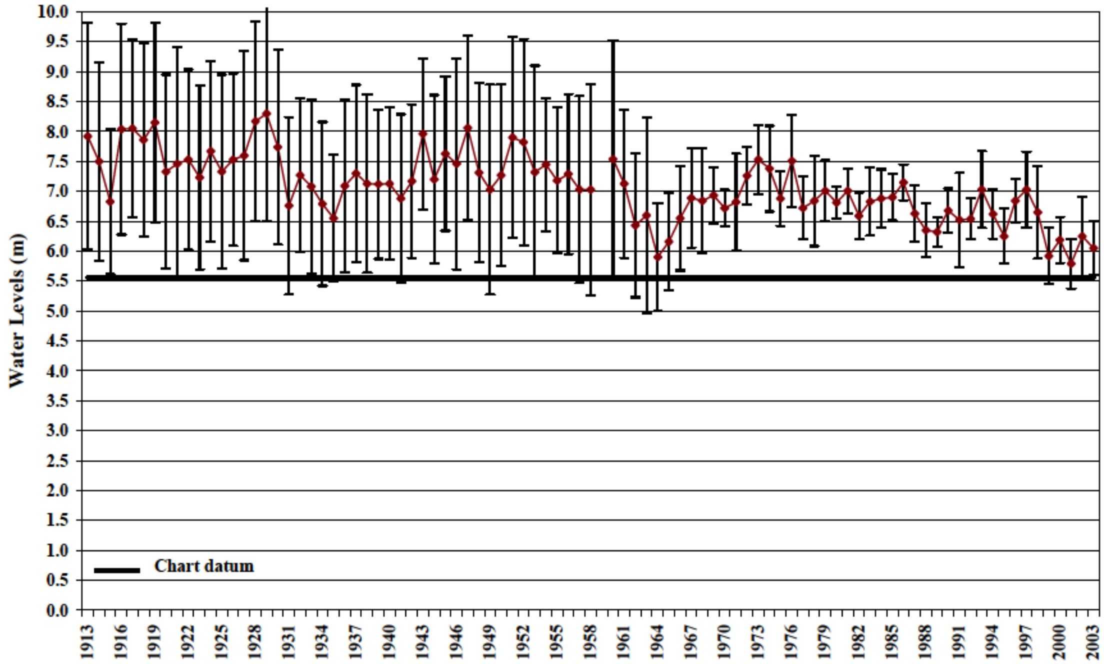
Figure 10 – Monthly water level anticipated at Bécancour with respect to a low water levels year (2001), based on the four climate scenarios (warm and dry; not as warm and dry; warm and humid; not as warm and humid) (Source: Lefaivre, 2005. Adaptation: D'Arcy, 2005)



The increase of sea level combined with the tidal effect in this sector would cancel out the drop in water levels.

The results of the hydraulic modelling show that the impacts on the water levels will be closely dependent on the hydrological conditions that predominate in 2050. In the case where the hydrological conditions would be akin to the average of the years 1961-1990, there would be no impact on navigation activities, even if the climate scenarios forecast a marked reduction in water supplies. On the other hand, when a low-level year is simulated, the impacts on commercial navigation and recreational boating are more significant and would also have repercussions on other sectors of activity, notably, water supply and treatment. However, it must be recalled that hydrological fluctuations are a normal phenomenon (Figure 11) and that it is very difficult to establish the statistical probability of these episodes recurring since the historical data may not be an assurance of episodes to come.

Figure 11 – Monthly water level variations at Montréal (Jetty #1) 1913-2003 (the vertical bar indicates the annual standard deviation; it is important to note that the standard deviation dropped once the Moses-Saunders dam went into operation in the late 1950s) (Source: Canadian Hydrological Service. Adaptation: D'Arcy, 2005)



Consequently, even though the models predict a substantial decrease in run-off, it could reproduce itself over a timeline that would make it possible to implement adaptation options. The most significant impact would be felt if a number of low-level years were to occur successively. Such a situation could become critical if man-made pressure were compounded with the climate change impacts.

The following part will present a few adaptation strategies designed primarily to meet the requirements of navigation activities on the St. Lawrence River.

Part II

Adaptation Strategies

2.1 Context

As noted earlier, the strategies retained have been identified a number of times, but have not been the subject of a study that would make it possible to put the costs and impact of each strategy into perspective. However, this exercise in comparison is indispensable to effectively determining the ones that are in line with sustainable development requirements. This part of the document will present the different adaptation options and try, where possible, to provide their estimated costs and their most salient environmental impacts. It should be remembered that they are but a partial assessment of the costs and potential impacts as a whole that a particular project may generate.

2.2 Technical and technological options

Two options will be explored here to estimate the gains in water height that they could produce. The first is a technological option, the COWLIS network, which may lead to improved long-term water-level forecasts so as to reduce the safety margin that marine carriers respect when loading for overseas transits. The second is more technical and concerns the squat equation. This empirical equation is applied in the same way to all types of vessels to calculate their degree of squat when proceeding through the water. However, this equation has not been scientifically verified. Other options belonging to this category could be explored; however, the work timetable for this project prevented us from doing so.

2.2.1 COWLIS

The acronym COWLIS stands for Coastal and Ocean Water Level Information System. The COWLIS network is a water level forecasts and observations operational system covering the St. Lawrence River from Montréal to Sept-Îles (http://marees.gc.ca/english/DataAvailable.shtml). The main components of the network are:

- a network of approximately 20 measuring devices placed at strategic locations along the St. Lawrence River;
- a digital water level forecast system of 0 to 48 hours and of 2 to 30 days;

- a database containing observations, forecasts and predictions;
- a visual data interface, known as Oceanus.

The COWLIS network provides mainly real-time data on water levels and makes predictions for a period of up to 30 days. These predictions are used by carriers when planning their overseas loading and give an approximation of levels that will be encountered when navigating on the St. Lawrence. This data is important because it enables carriers to optimize their loading capacity and thereby avoid having to offload vessels if levels are lower than forecast. Based on the transit time, companies allow a safety margin when loading, a margin that can vary by between 20 cm and 30 cm. It is essentially aimed at compensating for any inaccuracies in the predictions. If this margin could be reduced significantly, to 5 cm or 10 cm, for example, the companies could add more cargo. A 15 to 20-cm gain in water height may be used by the carriers and applied as an adaptation strategy in the case of a fluctuation of this order. Such a gain could eliminate the need of new development work on the river and would ensure that carriers could keep their loads at current levels. For the periods with no drop in water levels, this gain would mean an additional carrying capacity for the carriers without affecting the safety of river transportation.

The accuracy of predictions depends on long-term knowledge of a number of variables, notably precipitation, runoff from the Great Lakes and Ottawa River, ice, run-off from lateral tributaries, and winds and tides. Improvements were made to the forecast model with respect to certain variables but they apply more to the 0-2 day window (D. Lefaivre, pers. comm.). Despite these improvements, the margin of error remains substantial. Trials conducted at the Port of Montréal between 1994 and 1996, during the ice-free period, showed that the error on the thirtieth day of the prediction was 43 cm (Figure 12). No information indicates whether similar trials have since been conducted or improvements made to the forecasts.

Figure 12 – Accuracy of water level predictions with a 95% confidence interval for stations between Montréal and Québec City (statistics derived from the comparison of 443 daily forecasts and observations made between May and November for the period 1994-1996) (Source: D. Lefaivre, pers. comm. Adaptation: D'Arcy, 2005)

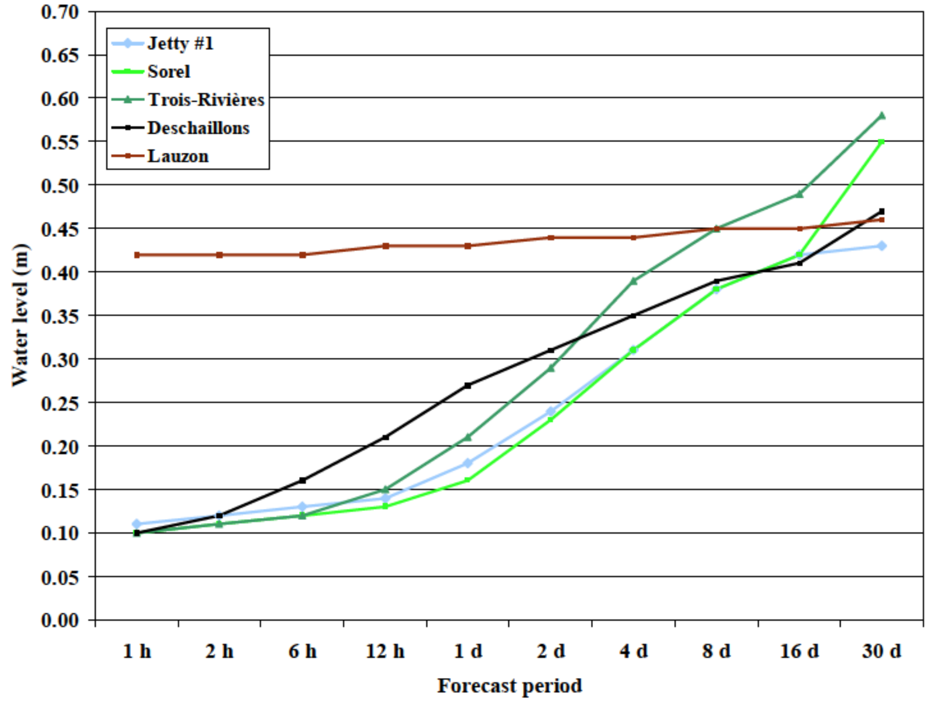


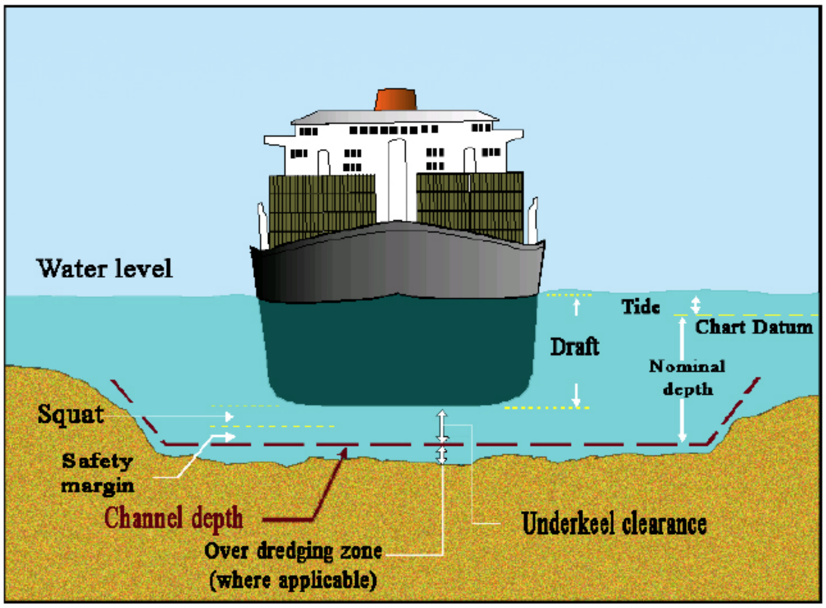
Figure 12 clearly illustrates the temporal limits of the model's forecasts. After only two days, the smallest error is approximately 22 cm at Sorel and becomes more than 30 cm after four days. Such values are above the safety margin that carriers allow. The predictions consequently cannot be used at this time as an adaptation strategy. Significant progress with respect to weather forecasts, among other things, will have to be made for this option to be counted as a climate change adaptation strategy.

2.2.2 Squat

Squat is the increase in a vessel's draft as a result of its motion through water. It is a hydraulic phenomenon whereby the water displaced creates an increase in current velocity past the moving hull causing a reduction in pressure that in turn results in a localized reduction in the water level. This leads to the vessel settling deeper in the water, at times more than 1 m deeper, under certain conditions. A number of factors explains this sinking, notably the vessel's speed, its beam and the physical characteristics of the channel. The shape of the riverbed, its breadth, the presence of islands and tributaries as well as jetties, are all elements that can influence squat (Dunker, 2004).

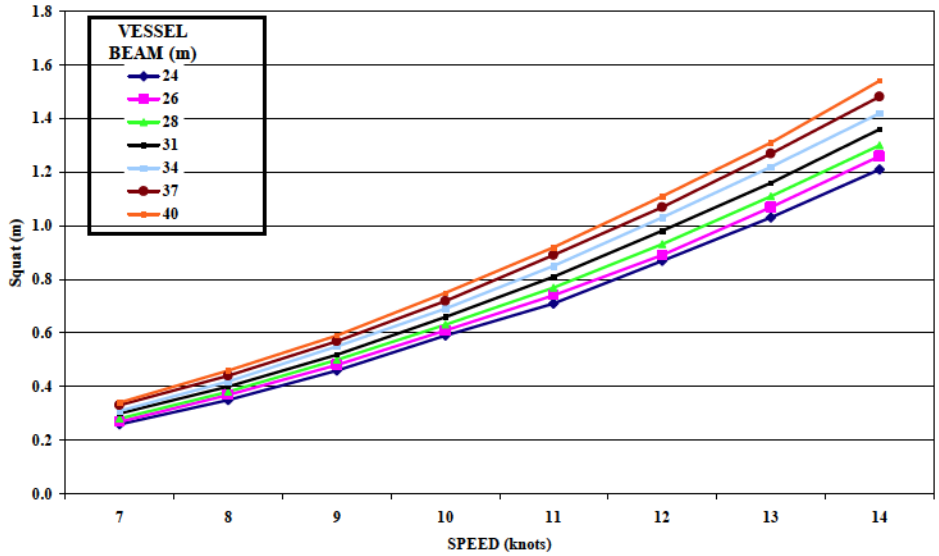
Squat is one of the elements to consider in calculating the underkeel clearance, which aims to maintain a sufficient distance between the vessel's hull and the sea bottom to ensure a safety margin in the navigable waterways.

Figure 13 – The components of an underkeel clearance.



Two of the main elements that influence squat are the vessel's beam and speed. For a vessel of a given beam, a change of speed from 7 to 14 knots increases sinkage by slightly more than 4.5 times (Figure 14).

Figure 14 – Vessel squat as a function of speed



The vessel's speed thus appears to be a determining factor in the degree of sinkage. Consequently, a reduction in speed could be an adaptation solution for drops in water levels; on the other hand, it would considerably increase delivery timeframes.

In the St. Lawrence River, the Coast Guard uses the Eryuzlu Equation, developed in the early 1990s, to calculate squat. This equation complies with the recommendations arising from the joint report of the Permanent International Association of Navigation Congresses (PIANC) and of the International Association of Ports and Harbours (IAPH) and applies to limited depth navigation channels (PIANC and IAPH, 1997). The advent of technological tools such as the DGPS led to reconsidering the different equations that, for the most part, had been developed empirically, with the objective being to experimentally check the validity of these equations and test, as required, new ones that would be adjusted to the vessels' actual sinkage or squat. Diverse studies have been undertaken at different locations in the world (Dunker, 2004; Briggs et al, 2004; Morse et al, 2002), but the results are not yet conclusive. One of the problems encountered is that certain equations sometimes give squat values that are lower than those measured (Briggs et al, 2004). The use of such equations could render vessels' real safety margins uncertain.

Studies involving different types of vessels are being conducted on the St. Lawrence. Based on the results, it will be possible to verify whether the equation that is applied permits optimal use of the water column by conserving a sufficient safety margin. The work and funds invested in this field must be considered in the light of the importance that each centimetre represents for loading vessels. For certain types of container vessels, one centimetre more increases their carrying capacity by nearly 60 tonnes.

2.3 Adaptation of the physical environment

From the perspective of comparing different adaptation options, the physical environment development option must also be explored. Historically, the St. Lawrence has undergone different development work, ranging from the deepening of the riverbed to the erection of control structures (Beauharnois and Moses-Saunders dams). This development work had major impacts on the fluvial ecosystems but, on the other hand, also contributed to the economic and social prosperity of the province and country. Despite all the inconveniences that the work involved, it must be recognized that, in the situations that require them, control structures notably improve the flexibility of operations and the network's capacity to buffer the effects of hydrological variability (Natural Resources Canada, 2002).

Before undertaking any initiative in this regard, however, the confidence level in forecasting climate change would need to be improved and, above all, the anticipated hydrological variations and their amplitude better estimated.

Two adaptation options for the physical environment will be analyzed here, that is, dredging and the erection of hydraulic structures.

2.3.1 Dredging

Dredging, or the removal of sediments, is a common practice carried out on a regular basis to maintain the nominal depth of the channel (maintenance dredging) or to deepen it (capital dredging). A widely used intervention method, dredging can be carried out quickly. On the other hand, dredging alters the river flow pattern and sediment transport in watercourses by helping concentrate currents in the centre of the dredged channels. This alteration can disturb certain riparian aquatic habitats (Lalancette et al., 2001). In addition, the chemical or organic substance contamination of sediments can prove to be a critical and costly problem for dredging operations.

However, dredging is subject to a stringent regulatory framework that aims to mitigate, indeed eliminate, the negative impacts associated with it. Such is particularly the case for operations involving large volumes of sediments.

2.3.1.1 Methodology and results

Analysis of the dredging option is based on two climate scenarios that use a low hydraulicity year as a reference, namely, 2001. Two scenarios are considered, that is, the most pessimistic–the Warm and Dry (WD)–and an intermediary, the Not as Warm and Dry (NWD). Volumes and areas of sediments to dredge will be evaluated. Estimates will be made for the Montréal-Bécancour sector, with a map illustrating the places where dredging would be required (Annex 1). Table 2 presents the values that were used with respect to the chart datum.

Table 2 – Drops in water level used to estimate the volumes and areas of sediments to dredge, based on the climate scenarios that use 2001 as a reference year and relative to the chart datum.

Stations	WD Scenario (m)	NWD Scenario (m)	Chart Datum IGLD85
Montréal (Jetty #1)	-1.01	-0.77	5.56
Varennes	-0.91	-0.73	4.84
Sorel	-0.43	-0.29	3.77
Trois-Rivières	-0.30	-0.17	2.94
Bécancour	-0.09	0.05	2.60

It is important to point out that the mapping is a preliminary estimate. Other work would be needed to have a more accurate idea of the actual quantities of sediments to dredge. However, it indicates that the volume to dredge would decrease going downstream, with the exception of a few sectors of Lake Saint-Pierre. Moreover, by somewhat generalizing the characterization of sediments that was made during the selective dredging of shoals (SDS) between Montréal and Cap-à-la-Roche in 1998 and 1999, the sediments to be dredged, at the depths provided by the climate scenarios, are largely composed of hard materials (indurated clay and rocks). Volumes and areas of sediments to dredge, based on the scenarios, are presented in Table 3, as are the approximate costs, which are based on those of the selective dredging of shoals. Port access was not included in this first estimate nor was the cost of sediment decontamination.

Table 3 – Estimated volumes and areas of sediments to dredge in the waterway according to the WD and NWD climate scenarios (2001 as reference year) and approximate costs (Source: Fisheries and Oceans Canada, Coast Guard, Waterways Management, 2005)

	SCENARIOS					
	WD			**NWD**		
Sector	Volume x 10^3 (m^3)	Area x 10^3 (m^2)	Costs ($M)	Volume x 10^3 (m^3)	Area x 10^3 (m^2)	Costs ($M)
Port of Montréal (10.7 m)	400	650	20	231	424	13
Port of Montréal (from 11.0 m)	330	560	18	185	430	12
Montréal-Sorel (11.3 m)	1 250	2 500	55	660	1 500	30
Lake Saint-Pierre (11.3 m)	295	885	10	230	700	8
Trois-Rivières – Bécancour (11.3 m)	66	230	5	40	70	4
Total	**2 341**	**4 825**	**108**	**1 346**	**3 124**	**67**
Total Sect. 11.3 m	***1 611***	***3 615***	***70***	***930***	***2 270***	***42***
Selective dredging of shoals	***191***	***435***	***7.8***			

* The total area of the Montréal – Bécancour section is 38 161 000 m^2.

Note: The estimated costs include sediment disposal but not decontamination costs nor those for compensation for the loss of fish habitat that would be added to this total.

The calculations included the sectors of the Port of Montréal where the depths maintained are less than 11.3 m (sectors maintained at 10.7 and 11.0 m). Since the volume of sediments to dredge in these two sectors is equivalent to one-third of the total volume of the Montréal-Bécancour section, options other than dredging should be evaluated for these locations. The shaded row in Table 3 indicates the values obtained by keeping only the sectors that are maintained at 11.3 m. The costs would thereby be reduced to $70 million for the WD scenario and to $42 million for the NWD scenario. The last row in the table illustrates, for comparison purposes, the values obtained for the selective dredging of shoals. It must be remembered that the purpose of this dredging was to deepen the navigation channel from 11 to 11.3 m wherever this depth was not reached. Consequently, this type of dredging is closer to shoal-reduction dredging.

As a result of this comparison, for the most pessimistic scenario (WD), the estimated volume of sediments to remove would be nearly 8.5 times higher than that dredged during the selective dredging of shoals. It would be around five times higher for the NWD scenario. The estimated volumes may thus appear considerable, particularly for the most pessimistic scenario (WD). The cost would be about the same, that is, nine and five times higher, as for the selective dredging of shoals. However, these costs have been estimated on the basis of a single deepening operation. If the procedure chosen were to favour sequential dredging, that is, in a number of steps, the costs would be higher.

As regards dredging that is carried out elsewhere in the world, some of the work involves sediment volumes that are much larger than those estimated here and is not conducted as an adaptation to climate change. For example, a volume of 1.5 million cubic metres of sediments, on average, had to be dredged annually from the Fraser River estuary from 1997-2002 to maintain the navigation channel (FREMP, 2002). The Princes Channel project involved having to remove 2.5 million cubic metres of material to give larger ships access to the Port of London (Port of London Authority, 2004). In the Yangtze River in China, the second phase of widening and deepening the navigation channel will require dredging 7.3 million cubic metres of sediments along 73 km of the waterway (Dredging News Online, 2004). Each year in the United States, the Corps of Engineers and private dredging companies remove between 190 and 230 million cubic metres of material from congressionally authorized navigation channels (American Association of Port Authorities, 2003). There are also a number of deepening projects being conducted at international container ports that are designed to enable the ports to accommodate the post-Panamax generation of vessels. The latter will require that the depth of channels be increased from 13.7 m to 16.1 m (American Association of Port Authorities, 2005). These few examples make it possible to put the dredging option into perspective in the context of climate change.

2.3.1.2 Environmental and social aspects

A set of laws and regulations provides a framework for the environmental assessment of all dredging projects. In the case of capital dredging, the promoter must provide several studies that justify the project and describe the characteristics of the physical environment of the area to be dredged as well as the environmental and socio-economic impacts that could result from the dredging. The environmental impacts of dredging activities result from the excavation of sediments, their transportation and their disposal. Generally, these impacts consist of increased water turbidity, an increase in the concentration of suspended matter, contaminant dispersion and, in certain cases, an increase in the chemical oxygen demand, a drop in dissolved oxygen and an increased dispersion of nutrients. In terms of biological impacts, dredging can result in the benthic fauna being buried or disturbed, fish eggs or larvae being smothered, the temporary or permanent loss of habitats and the exposure of organisms to toxic contaminants. The commercial and recreational activities that depend on biological resources can also be affected. However, diverse mitigation measures can be used to confront these impacts with varying degrees of effectiveness, depending on the context specific to the environment in question (Environment Canada, 1994).

Citizens' reservations with regard to dredging activities centre around the very justification of projects and their impacts on the ecosystems. Where project justification is concerned, these reservations generally stem from the idea that certain shipowners want to build more imposing vessels only to make transits more profitable. This trend can now be observed, notably, by the coastal ports wanting to accommodate post-Panamax vessels. However, it is not so much the case in ports located in the inland waterways where the idea of using smaller vessels is gaining ground. As regards impacts on the ecosystems, the concerns are as much on the biological level (alteration of the environment) and toxicologic level (contamination of the environment) as they are on the human level (disturbance of fishing areas).

During the selective dredging of shoals, the proposal put forth most often was to ask the International Joint Commission to increase the water levels by letting more water pass at the Moses-Saunders dam (Les Consultants Jacques Bérubé inc., 1997). Another often proposed solution to have deep-draft vessels stop at the ports that have sufficient natural depths. This option will be described shortly, from the angle of port re-engineering (Section 2.5).

In the context of climate change, it is important that each option be considered in the light of sustainable development principles. As such, the dredging option probably does not constitute an ideal solution if a drop in water levels were to become recurrent. However, it may prove to be a transitional option in a process of long-term adaptation and would need to be planned in considerable detail. All stakeholders concerned will need to be involved early in this process (Working Group on the Integrated Management of Dredging and Sediments, 2004).

2.3.2 Control structures

2.3.2.1 Preliminary review of the literature on development projects for the fluvial sector of the St. Lawrence River

First, a review of literature was made to identify the locations where public decision-makers had considered erecting control structures to raise water levels for navigation needs in view of the impacts of climate change. Whether in Europe, the United States or in Canada, most of the structures listed were mainly intended to prevent sedimentation or protect against shoreline erosion (Consultants Ropars, 2005). The port of Antwerp proved to be an exception; longitudinal dykes were built there to optimize flow and maintain depths in the navigable channel. Large locks were also built there to give vessels having 15.5-m beams berth access (Consultants Ropars, 2005).

On the basis of the proximity of seas and oceans, certain structures have been designed with a view to protect against tidal storm surges that can lead to major flooding. Two examples of this type of structure appear below.

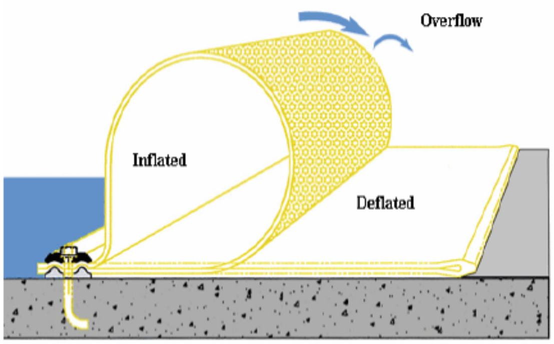
On the left, a mobile dam on the Tamise southeast of London, built to protect the city against flooding[a]. On the right, the Maeslant dam in Holland, in the closed position.[b]

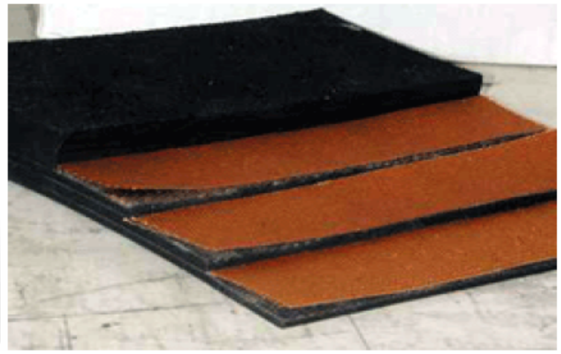
[a] http://www.travellondon.com/templates/attractions/barrier.html

[b] http://www.keringhuis.nl/engels/home_noflash.html

Another type of structure that has been operated since the 1950s is the inflatable dam. This dam is used for different purposes, notably to raise thresholds, create artificial lakes, act as an obstacle to the upwelling of saltwater in estuaries, control floods and replace gate systems (Consultants Ropars, 2005). Figure 15 illustrates how the dam operates and the materials used to make it.

Figure 15 – Operation of an inflatable dam: on the left, air is injected to inflate it; on the right, the multiple layer membranes used[a].





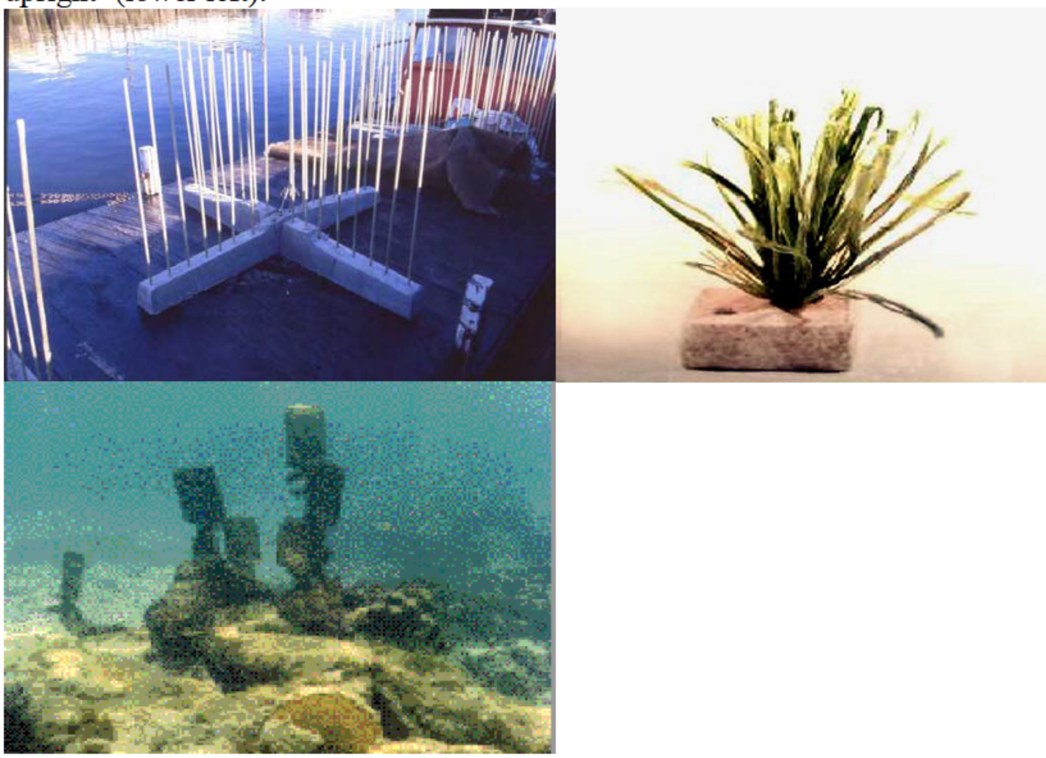
[a] http://www.trelleborggr.com/Content/Product_Flexidam4.asp

The main advantage of these structures resides in their mobility. They can be used on an as-needed basis, and then set to free the water body. Though very interesting options for navigation, they are difficult to apply to the St. Lawrence River because, among other things, of its dimension and the ice regime. However, they could serve as inspiration for future solutions tailored to the river conditions.

Another method for raising water levels consists in using different obstacles to increase the roughness coefficient at the bottom of the watercourse. Slowing the flow results in the retention of the water upstream. The bottom roughness (resistance) can be increased by replacing a sandy bottom with stones or pebbles or by increasing aquatic vegetation (Consultants Ropars, 2005). Promoting the growth of natural algae can bring with it more disadvantages, because of the ecological invasion, than advantages, and is therefore difficult to propose as a lasting solution. In addition, the limited growing period means that there is no guarantee that the desired effect of raising the water level will occur at the optimal moment.

One solution to this disadvantage would be to use artificial algae (Consultants Ropars, 2005). Different models were designed (Figure 16) to respond to specific needs. The efficiency of these artificial plants in raising the water level is closely dependent on the area and water height to cover. What is more, these plants tend to deteriorate with time and thus involve recurring maintenance and replacement work.

Figure 16– Different types of artificial aquatic plants used to raise water levels, prevent shoreline erosion or reduce sedimentation; artificial cross-shaped reef[a] (upper left), artificial algae on a block of sandstone[b] (upper right); artificial algae eight months after installation: this unit had begun to deteriorate, and a number of algae are no longer upright[c] (lower left).



[a] http://scaphpro.com/recifs.html

[b] From Schreider et al., 2003.

[c] http://www.unesco.org/csi/pub/source.ero11.htm

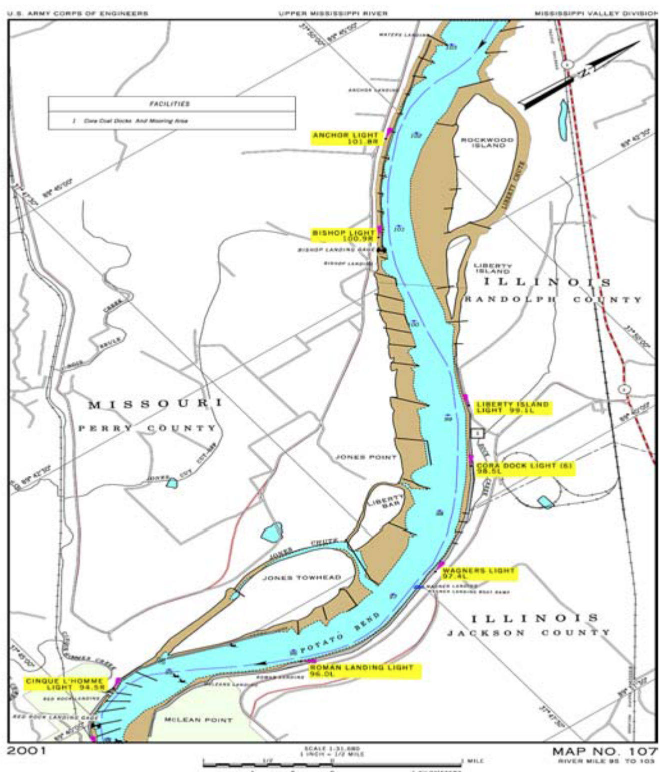
The use of this option alone in the St. Lawrence River would not result in the desired increase in water level (Consultants Ropars, 2005). The plant option would have to be combined with one or more other options if conclusive results are to be obtained.

This brief review of the literature shows, on the one hand, that no adaptation strategy has been proposed to raise water levels for navigation requirements. On the other hand, the structures listed are difficult to use on the St. Lawrence River, given its hydrological features and size, without major modifications being made to them. Unless the situation becomes critical to the point that the costs inherent to erecting these structures on the river are considered secondary, the more traditional solutions, such as the regulation of the Lake Ontario runoff and dredging, can obviously meet anticipated needs.

2.3.2.2 Selection of regulation structures for the St. Lawrence River

The structures regularly mentioned to raise water levels for navigation requirements are jetties, longitudinal dykes, sills, dams, parallel channels and locks (Consultants Ropars, 2005). The jetties, or cross-stream dykes, are relatively efficient in a river environment for concentrating the flow in the main channel, stabilizing the channel geometry, limiting the work involved in maintenance dredging and protecting shorelines against erosion. However, in certain watercourses, they require very significant development work, as Figure 17 illustrates (Consultants Ropars, 2005). The dykes parallel to the watercourse, or longitudinal dykes, are mainly designed to prevent overflowing during high flows. However, in the Fraser River (British Columbia) these dykes are used in the outer portion of the estuary to avoid having to move the shipping channel and to limit dredging.

Figure 17 – Cross-stream dykes (in black) on the shores of the upper portion of the Mississippi[a]



[a] Extracted from Map 107 –

http://www.mvr.usace.army.mil/navcharts/UMRNNavChartsIdx05.asp

The erection of sills is another option for raising water levels. Those in the Sorel islands archipelago in 1931 were put in place to raise the water level at Montréal during minimum flow episodes. The five sills had the desired effect. The gains during minimal flow episodes were 28.5 cm at Sorel and 12.5 cm at Montréal (Simard, 1983). The flow in the shipping channel went from 25% to 80% with respect to the total flow. However, the sills were subject to severe erosion, since they are almost always submerged, and their effectiveness was greatly diminished during the minimum flow episodes of 1964 (Simard, 1983). This ineffectiveness can be explained by deterioration due to erosion and a 41% increase in the cross-section of the channel. The sills were rebuilt in 1965-1966.

To successfully increase the water level by 50 cm or more, several sills would have to be built, in the secondary channels. They would also have to effectively block the cross-sectional area of the river so as to obstruct the flow. This would have different impacts, both in terms of the environment and with respect to restricting boaters' access to these waterways because the sills are fixed and made of riprap. Lake Saint-Pierre is little conducive to the installation of heavy structures given its geotechnical characteristics (Consultants Ropars, 2005) and its width. However, certain sectors downstream from the lake could prove to be more suitable for such structures and optimize their effectiveness.

One fallback option to these fixed sills would be inflatable ones whose use would be limited to periods of minimum flow. However, given the complexity of the mechanics of this type of structure, there would be a tendency to limit their number and to place them relatively close to shorelines so that the activation devices may be accessible and protected (Consultants Ropars, 2005).

One of the most effective solutions for water level management is the construction of a dam. Two dams are in operation on the river, upstream from Montreal: the Moses-Saunders dam at Cornwall and the Beauharnois dam. There is no dam downstream from Montréal. The best sector for building such a structure would be at the outlet of Lake Saint-Pierre, where the river narrows (Consultants Ropars, 2005). The dam should be equipped with a lock so that vessels may circulate. Different constraints are associated with the construction of a dam on the river and will be addressed shortly. A more in-depth study could be made of one solution in particular that combines a full sill, one lock and inflatable structures. The sills would replace the dam and would most often be submerged. An inflatable dam could be fixed on the sill crest and deployed during minimum flow episodes (Consultants Ropars, 2005).

As to the technical feasibility of a lock, the example of the port of Antwerp (500 m x 68 m) shows that it is possible to build this type of large-size structure downstream from Lake Saint-Pierre. However, this lock should be coupled with a dam, given the width of the river at this location (Consultants Ropars, 2005).

Among the options identified above, some have not been retained for the time being, notably, those that modify the roughness of the river bottom (riprap, artificial algae) and the one involving the inflatable, adaptable sills, given the absence of information. The increase in roughness would require a massive intervention and many plants, whose consequences on the benthic habitat could exceed any gains. As well, the option's capacity to raise the water level enough to compensate for the anticipated loss remains uncertain (Consultants Ropars, 2005). With respect to inflatable sills, a number of difficulties associated with this option makes it less practical. One or two series of these sills in pairs would be needed for them to function somewhat like a lock. In addition, lateral cross-stream dykes should first be put in place and concrete sills poured at the river bottom to serve as a support. A complex mechanism that is used to control the filling and emptying of these dams should also be installed. The risks of mechanical system malfunction, the maintenance costs and the absence of any guarantee that such an installation would be durable, particularly under the effect of ice, add to the uncertainty. Lastly, this type of structure does not appear to be used elsewhere in the world on this scale (Consultants Ropars, 2005).

The options that were retained for the first study are the following:

1- cross-stream and longitudinal dykes that partially block the cross-sectional area of the river.

2- A dam with a lock.

These structures are designed to raise the water level by at least 50 cm from the outlet of Lake Saint-Pierre up to Montréal.

2.3.2.3 Geometry and positioning of the structures

A) Cross-stream and longitudinal dykes

The cross-stream dykes modelled are of the riprap sill type. They force the river flow into the main channel during minimum flow episodes and are submerged during high water periods (Consultants Ropars, 2005). They are positioned along the main navigation channel and, as required, in the secondary channels. Hydrological modelling was carried out on dykes having an opening of 250 m and of 120 m. The 120-m opening would require special management of marine traffic, for safety reasons, requiring that one vessel pass at a time. Figures 18, 19 and 20 illustrate the structures' geometry.

Figure 18 – Longitudinal cross-section of a series of dykes with 250-m (top) and 120-m (bottom) openings (Source: Consultants Ropars, 2005. Adaptation: D'Arcy, 2005)

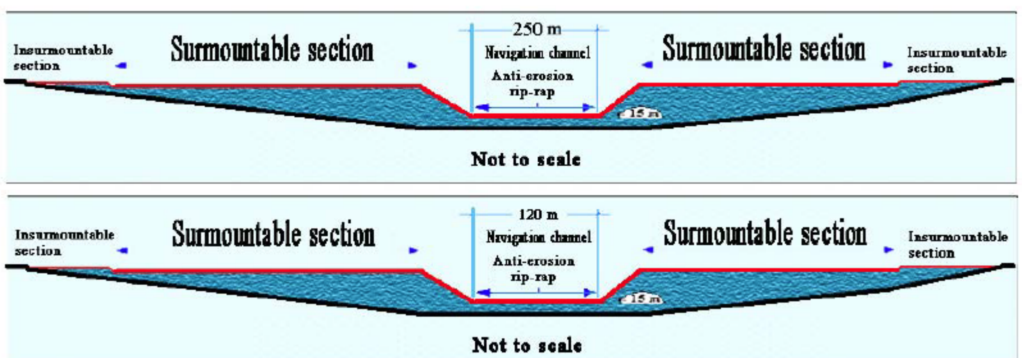


Figure 19 – Cross-section of the insurmountable sections of the dykes (Source: Consultants Ropars, 2005. Adaptation: D'Arcy, 2005)

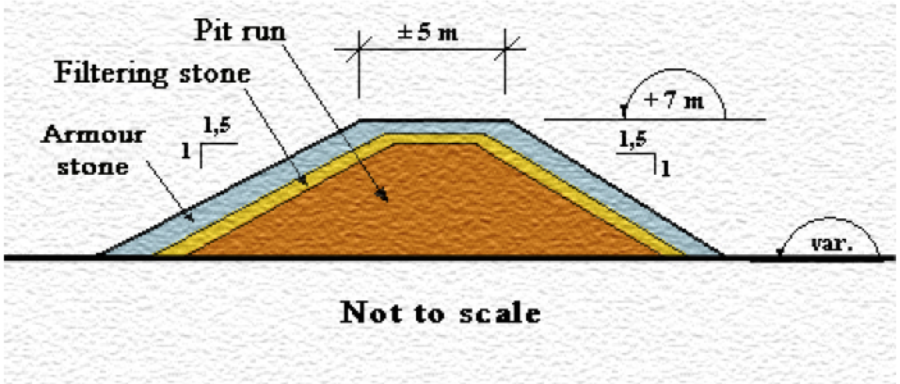
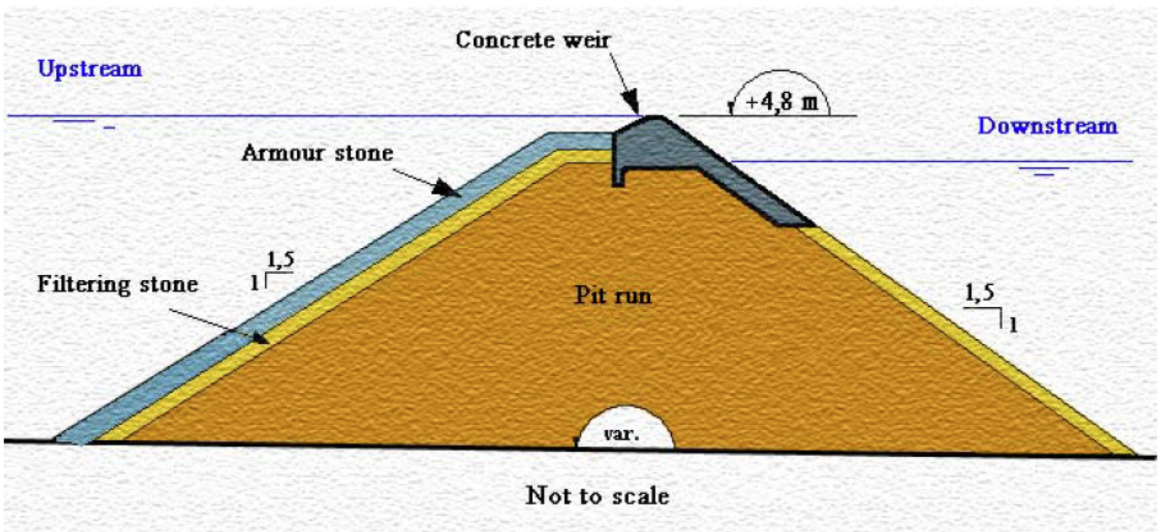


Figure 20 – Cross-section of the insurmountable sections of the dykes (Source: Consultants Ropars, 2005. Adaptation: D'Arcy, 2005)



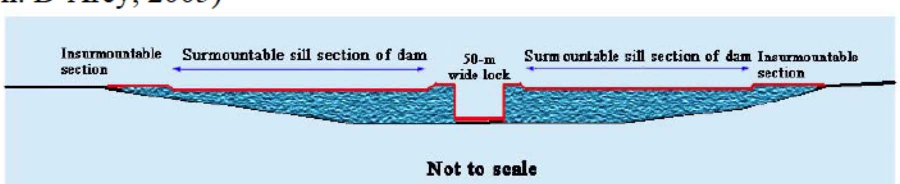
Another modelling was conducted on two 7-km longitudinal dykes, running along the shipping channel, to which cross-stream dykes are connected at the lower end. These dykes had to be used in a straight line sector for safety reasons and consequently restricted the width of the navigation channel between the dykes to 120 m. The sidewalls are very rough, being made out of 1 to 3-tonne armour stones (Consultants Ropars, 2005). The geometry of these dykes is similar to that of the cross-stream dykes; the breadth at the bottom of the structure is about 50 m.

B) Dam

As previously mentioned, the dam would be coupled with a lock and be located downstream from Lake Saint-Pierre, but upstream from the Laviolette bridge to preserve the water-retaining effect of the bridge's pillar (Consultants Ropars, 2005). However, it would be very difficult to construct such a structure because of the components' dimensions, the natural conditions (particularly in winter) and the fact that there will doubtless be a temporary interruption or significant slowdown in navigation during the time it takes to put the lock into operation (Consultants Ropars, 2005). The dam should ensure evacuation of ice during a jam and limit risks of flooding. Devices such as a sill, booms or bubble curtains should thus be put in place so that the dam would not create ice jams (Consultants Ropars, 2005).

For most species of aquatic fauna, a dam is an insurmountable obstacle and therefore should, at a minimum, include devices that allow free circulation between upstream and downstream. Such a circulation could be facilitated by sills, though other devices, such as fish-passes, are worthy of consideration in order to limit the impacts as much as possible. Figure 21 illustrates the dam's geometry.

Figure 21 – Longitudinal view of the dam with a lock (Source: Consultants Ropars, 2005. Adaptation: D'Arcy, 2005)



The cross-sectional view of the surmountable sections of the dam is identical to the view appearing in Figure 20.

C) Positioning of structures

The positioning of structures is critical to optimizing their performance while minimizing environmental impacts. Five cross-stream dykes (#1a, 1b, 7, 8 and 9) were selected for the modelling, as well as one longitudinal dyke (#8) and one dam with a lock. Figure 22 illustrates the location of these structures in the Montréal–Trois-Rivières section. It should be noted that Dyke #1a is located at the same place as the dam.

Figure 22 –Locations of the hydraulic structures

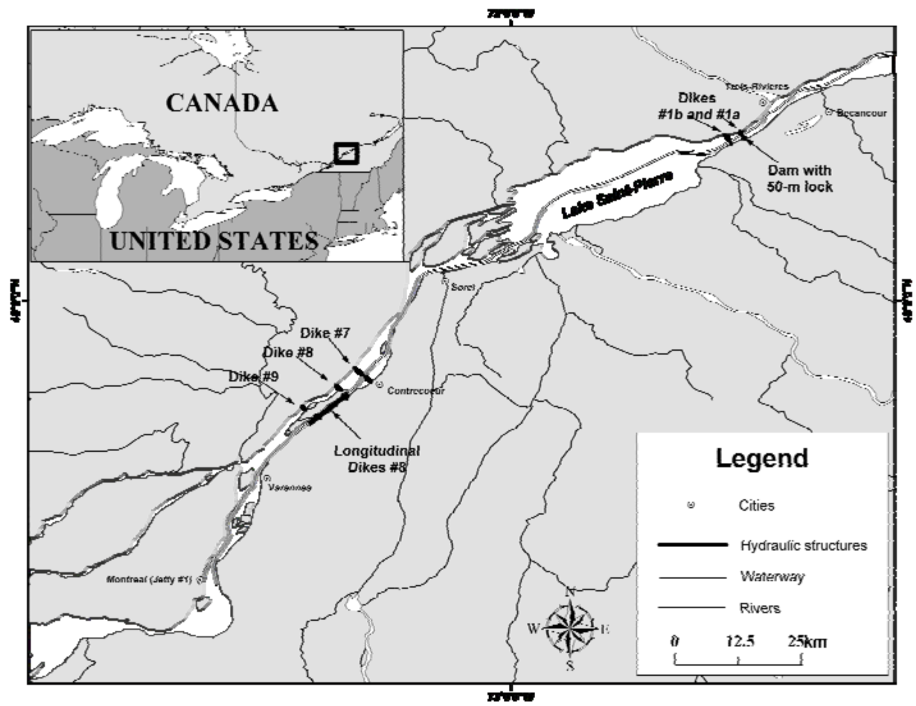
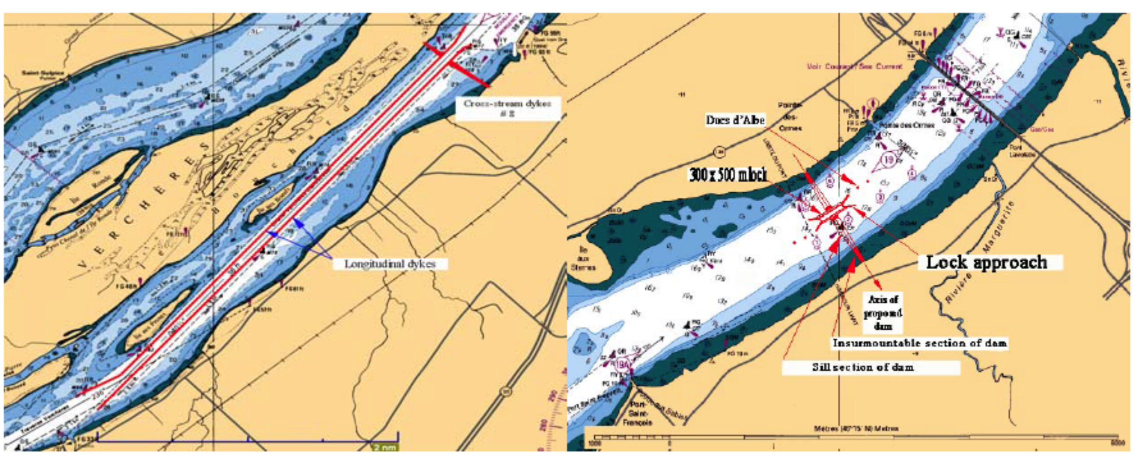


Figure 23 presents a larger-scale view of longitudinal dyke #8 and of the dam with a lock.

Figure 23 –Larger-scale representation of longitudinal dyke #8 (on left) and of the dam with a lock (on right) (from Consultants Ropars, 2005)

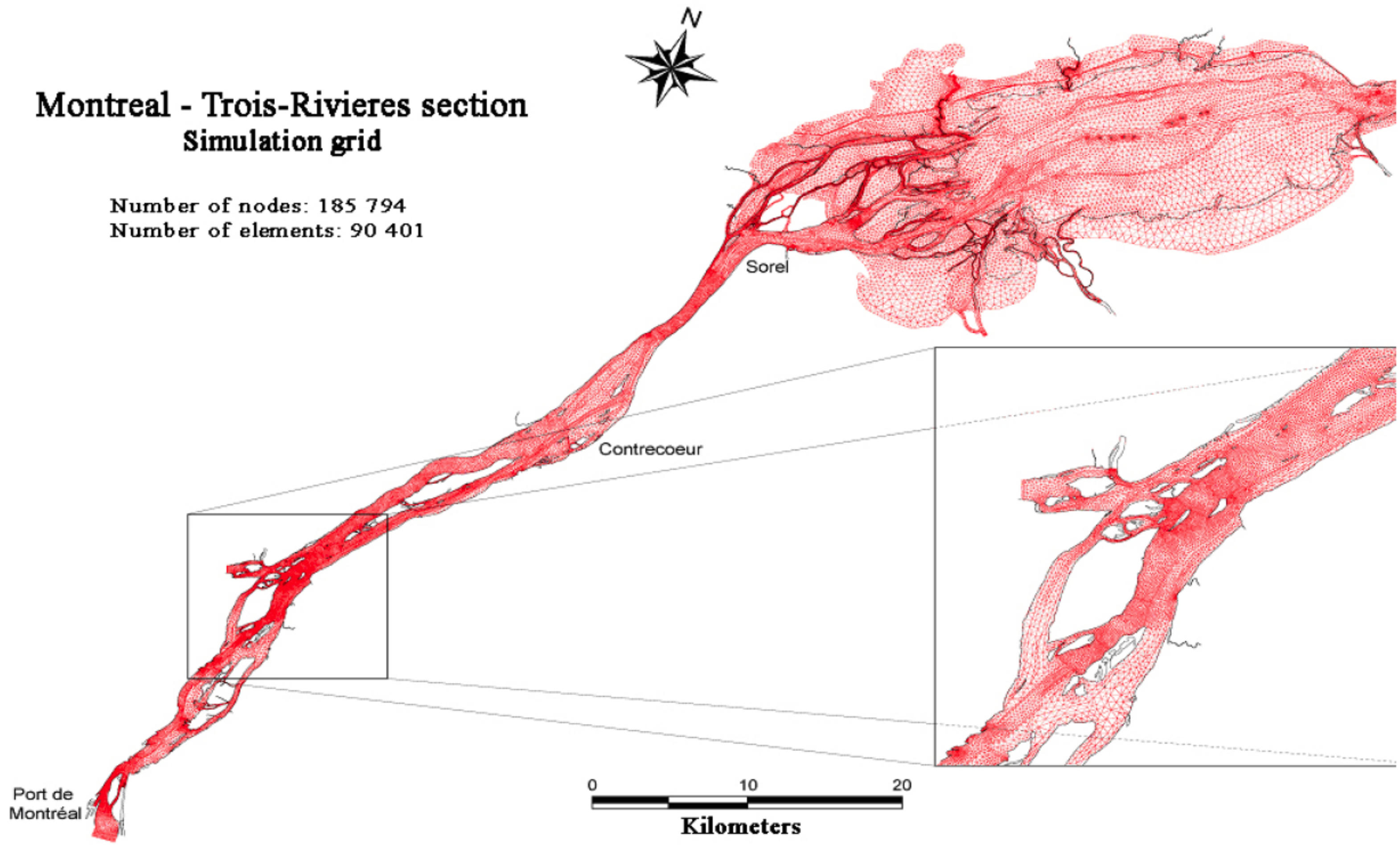


2.3.2.4 Hydraulic modelling - methodology

Digital simulations conducted using a 2D hydrodynamic model, *Hydrosim*, developed at INRS-Eau, were used to evaluate the hydraulic structures' relative efficiency in raising water levels. Flow velocity and water depths are computed according to the finite element method. The simulations take advantage of the digital terrain model (DTM) of the St. Lawrence developed by Environment Canada (Fortin, 2002; Fortin et al., 2004). The program *Modeleur*, also developed at INRS-Eau, was used to format the geospatial data sets used to make the DTM. Other tools were used to make hydraulic structures, including the geographic information system *Mapinfo* and the spreadsheet *Excel* (Doyon et al., 2005).

The study area to which the model is applied extends over 130 km between the Port of Montréal and Trois-Rivières. The grid covering the area, illustrated in Figure 24, is made of 185 794 nodes and 90 401 elements.

Figure 24 – Simulation grid covering the study area (from Doyon et al., 2005)



The bathymetric data for the deep zones was obtained from the Canadian Hydrographic Service and, for the shallow zones, from the Meteorological Service of Canada – Hydrology. The overall data set was put together by the Meteorological Service of Canada. The land portion of the study area was obtained via airborne laser (Fortin et al., 2002). The resulting digital elevation model provides an exhaustive representation of the study area (Figure 25).

The roughness of different materials determines the local value of the Manning's roughness coefficient in the hydrodynamic model (Doyon et al., 2005). Figure 26 illustrates the roughness map produced by it, presented in the form of roughness coefficients (Manning's n), and applied in the hydrodynamic model. It should be noted that an identical coefficient was assigned to the sectors covered by vegetation (Doyon et al., 2005).

Insertion of the hydraulic structures into the model is a very delicate stage because it requires that the junction between the structure itself and the riverbed be delimited to ensure that only the highest mark between the dyke and the river depth will be kept for each grid node (Doyon et al., 2005). Annex 2 outlines the steps involved in designing and inserting structures into the model.

Calibration of the hydrodynamic model's parameters was based on the hydraulic events of the springs of 1996 and 1999. These events represent high and low water episodes, respectively (Morin et al., 2001). The results are validated by the control of water levels over the entire study area.

Figures 27 and 28 compare the water levels obtained by simulation with those measured for the two hydraulic events.

Figure 25 – Digital elevation model of the study area (from Doyon et al., 2005)

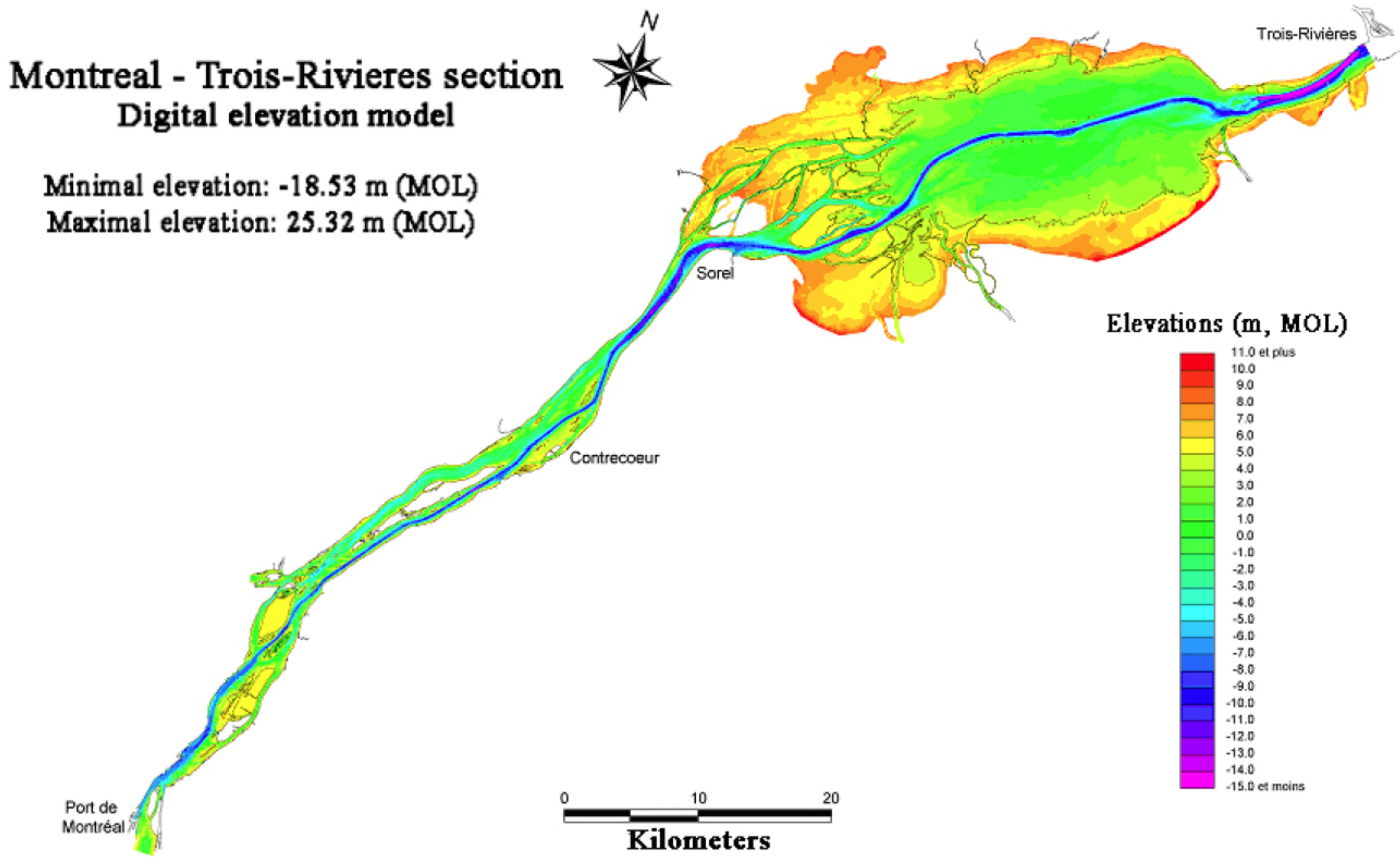


Figure 26 – Hydraulic roughness map (roughness coefficient) of the study area (from Doyon et al., 2005)

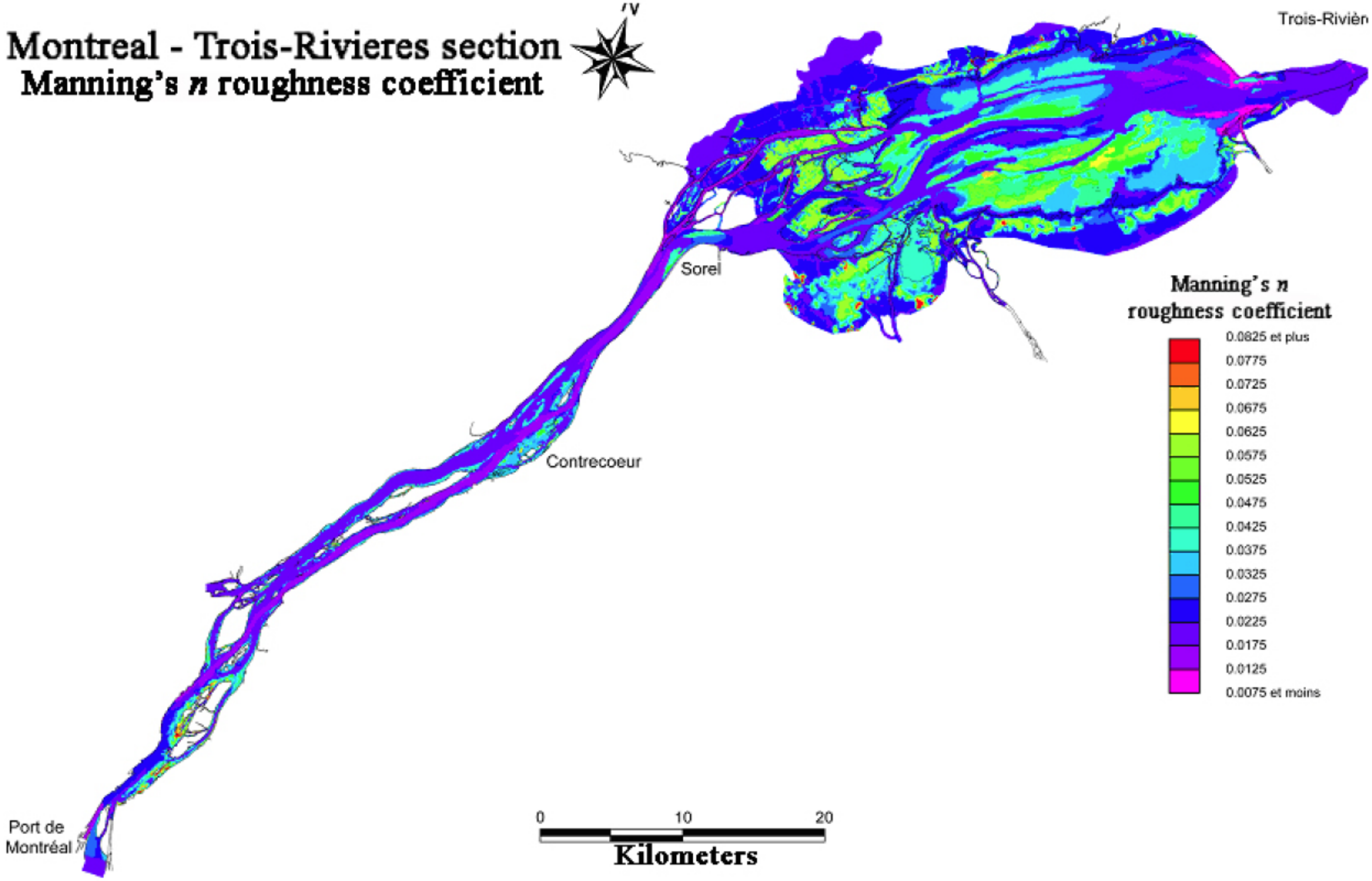


Figure 27 – Water slope profile as measured and the slope obtained by simulation for the hydraulic event of the spring of 1996 used for calibration (from Morin et al., 2001).

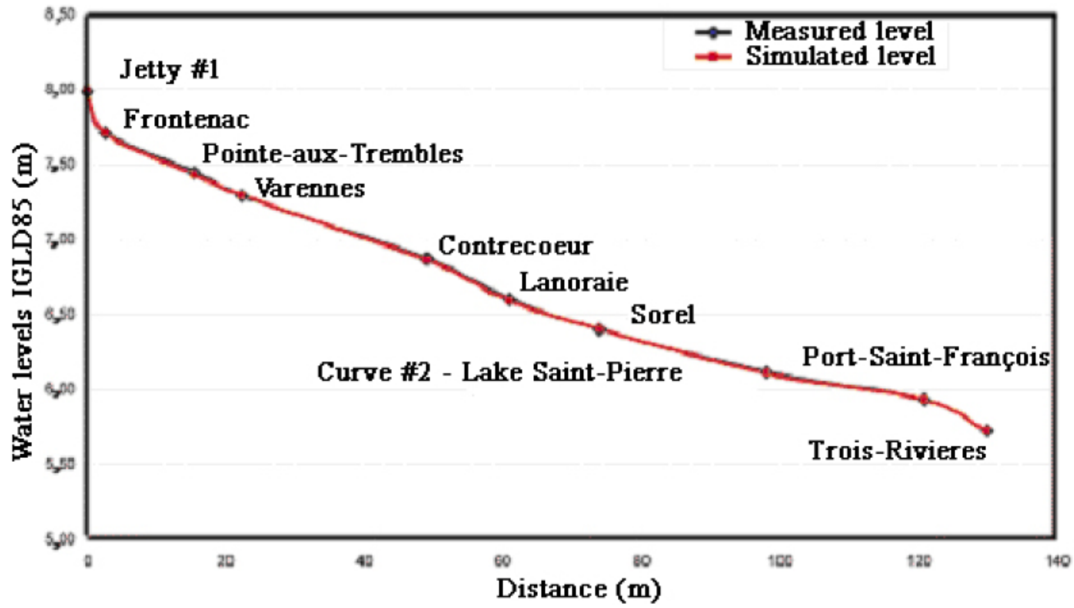
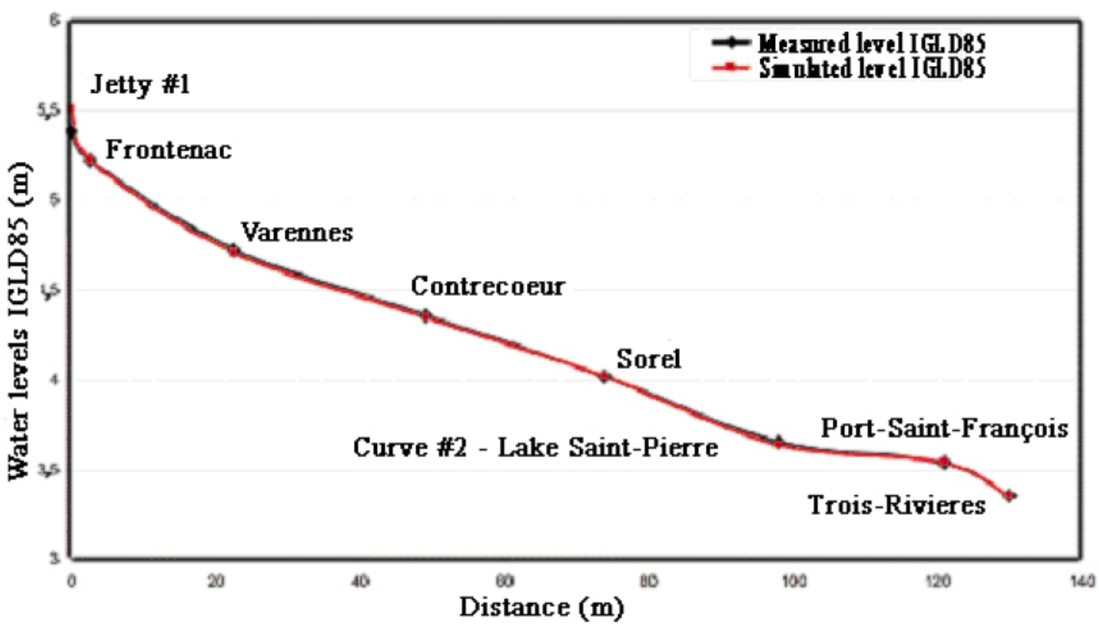


Figure 28 – Water slope profile as measured and the slope obtained by simulation for the hydraulic event of the spring of 1999 used for calibration (from Morin et al., 2001)

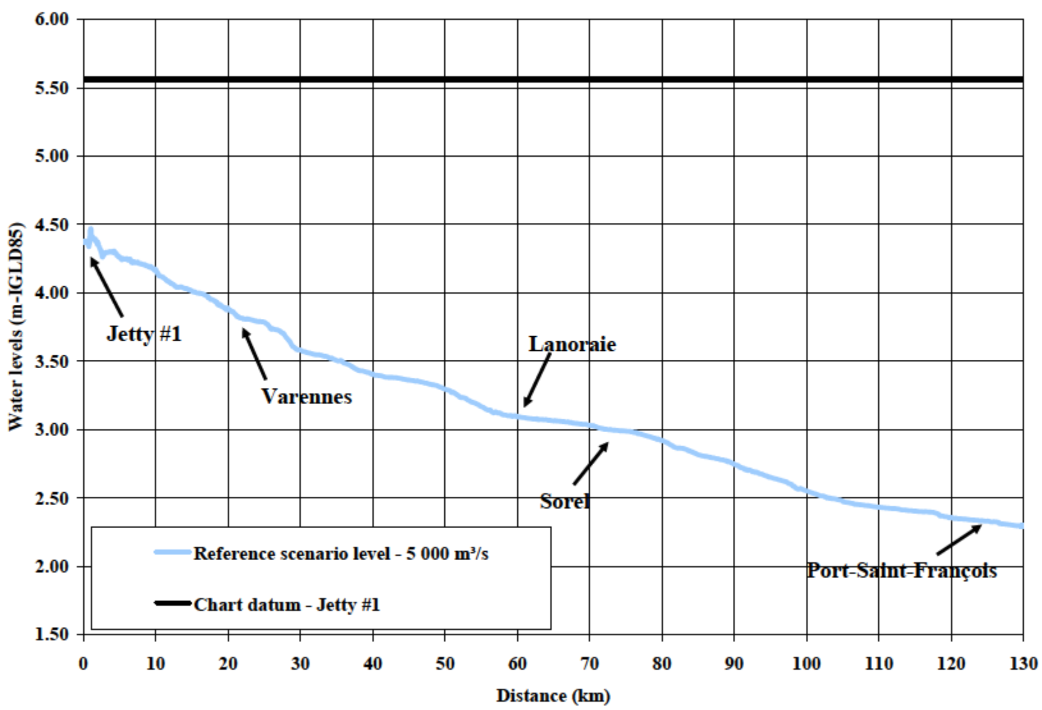


The differences between the levels measured and those obtained by simulation are systematically less than 2 cm for all the stations. The model adequately reproduces the water line for this section for the discharge values at Sorel, which range from 7 600 to 14 500 m^3/s (Doyon et al., 2005).

2.3.2.5 Hydraulic modelling – results

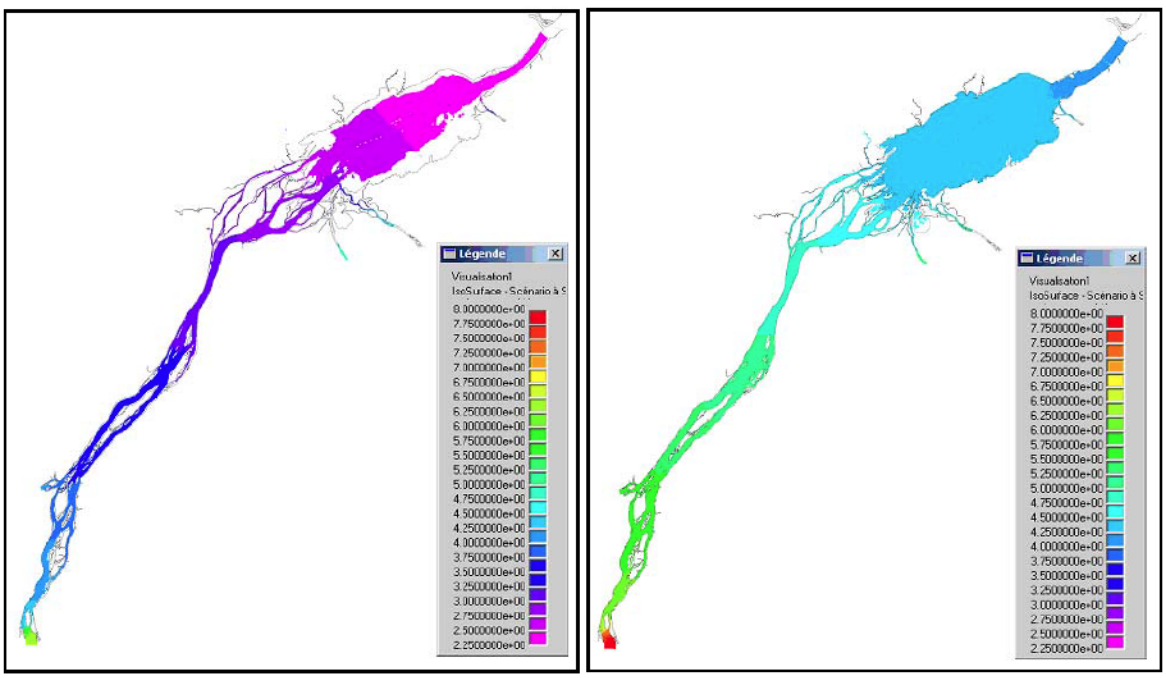
The initial objective was to simulate the hydraulic impact of climate change with a reference flow of 5 000 m^3/s at Sorel. This simulation produced a drop in the water level of slightly more than 1 m below the chart datum (5.56 m) at Montréal. This reduction complies with the results obtained by Lefaivre for the most pessimistic scenario (WD) illustrated in Figure 8. Figure 29 presents the spatial distribution of water levels between Montréal and Trois-Rivières based on this reference flow.

Figure 29 – Water levels obtained by simulation between Montréal and Trois-Rivières, based on the reference scenario of 5 000 m³/s at Sorel (Adapted from Doyon et al., 2005)



The hydraulic structures' efficiency in raising water levels for intermediate (50 cm) and extreme (1 m) climate scenarios can thus be evaluated. Two elements are to be taken into account with respect to the modelling. On the one hand, the discharge of 5 000 m^3/s is equivalent to a 20% drop in the minimum reconstituted flow and, consequently, is outside the window of values from which the calibrations are made. However, such an extrapolation is a common practice used in hydrology to assess the impacts of extreme events when data are not available for estimating the impacts (Doyon et al., 2005). On the other hand, the reference scenario is simulated with a DTM characterized by the presence of aquatic plants whose height and distribution are based on the conditions usually observed during the pronounced low-water months. A discharge of 5 000 m^3/s calculated from the river's average daily and weekly flows for the period 1960-1998 is estimated to recur every 4 000 and 10 000 years respectively (Morin et Bouchard, 2001). However, this estimate should be treated with caution because of the time window on which it is based as well as the low probability that the climatic conditions to come will be similar to those that occurred in the past. Figure 30 compares the reference scenario discharge with the average discharge recorded at Sorel.

Figure 30 – Comparison of water levels obtained according to the reference scenario with a discharge of 5 000 m³/s at Sorel (on left) with those obtained with an average discharge of 9 500 m³/s (from Doyon et al, 2005)



Comparison of the reference situation with the average hydrological conditions makes it possible to estimate the loss of aquatic habitats that would occur according to the most pessimistic climate change scenario. Indeed, the aquatic area lost in the Montréal–Trois-Rivières sector would be equivalent to 160 km^2, 131 km^2 of which would be for Lake Saint-Pierre alone. The area of Lake Saint-Pierre between Sorel and Port-Saint-François is 387 km^2. One-third of the aquatic area of Lake Saint-Pierre would thus dry up. This would affect the wetlands, in particular.

The first simulations were made using Dyke #8 A with a 250-m opening (Figure 31).

Figure 31 – Water levels obtained between Montréal and Trois-Rivières according to the reference scenario of 5 000 m³/s at Sorel with Structure #8 having a 250-m opening (Source: Doyon et al., 2005. Adaptation: D'Arcy, 2005).

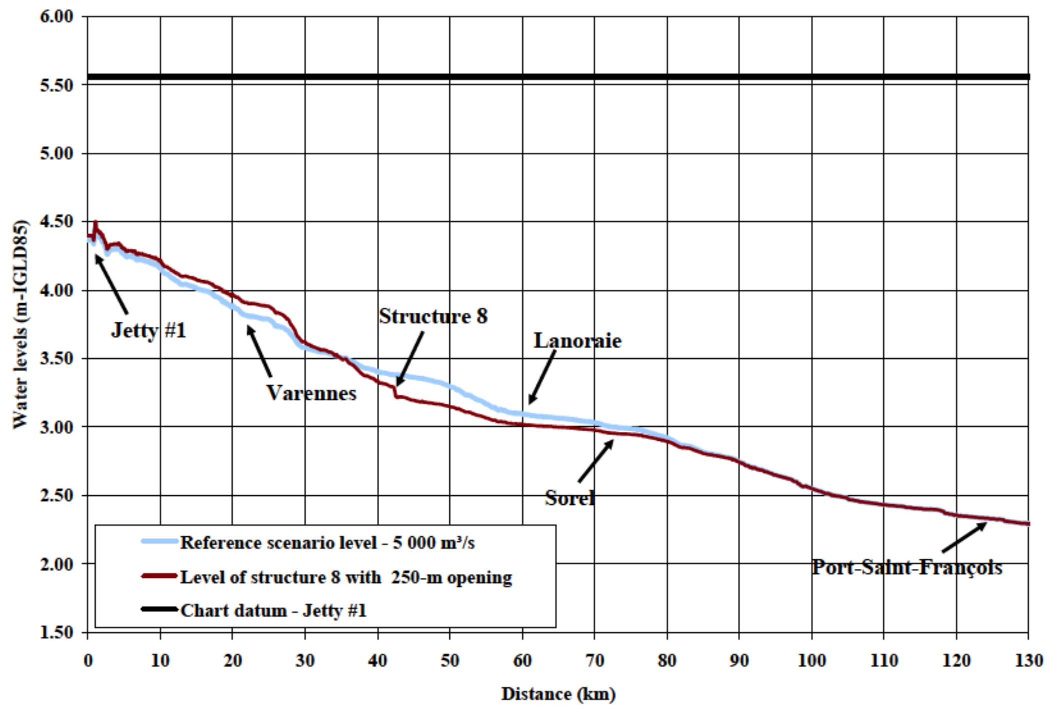


Figure 31 illustrates that a single dyke with a 250-m opening does not significantly increase the water level at Montréal. In fact, gains are almost nil. In addition, a downward movement of water occurs downstream from the structures, decreasing water levels by more than 10 cm with respect to the reference level over a distance of nearly 40 km. This water depression may be produced by a funnelling effect of the dykes that accelerates the water flow which in turn generates a downward movement of the water (Consultants Ropars, 2005).

Given this low gain, the simulations were conducted on the same structure, but with the opening of the dyke reduced to 120 m.

Figure 32 – Water levels obtained between Montréal and Trois-Rivières according to the reference scenario of 5 000 m³/s at Sorel with Structure #8 having a 120-m opening (Source: Doyon et al., 2005. Adaptation: D'Arcy, 2005)

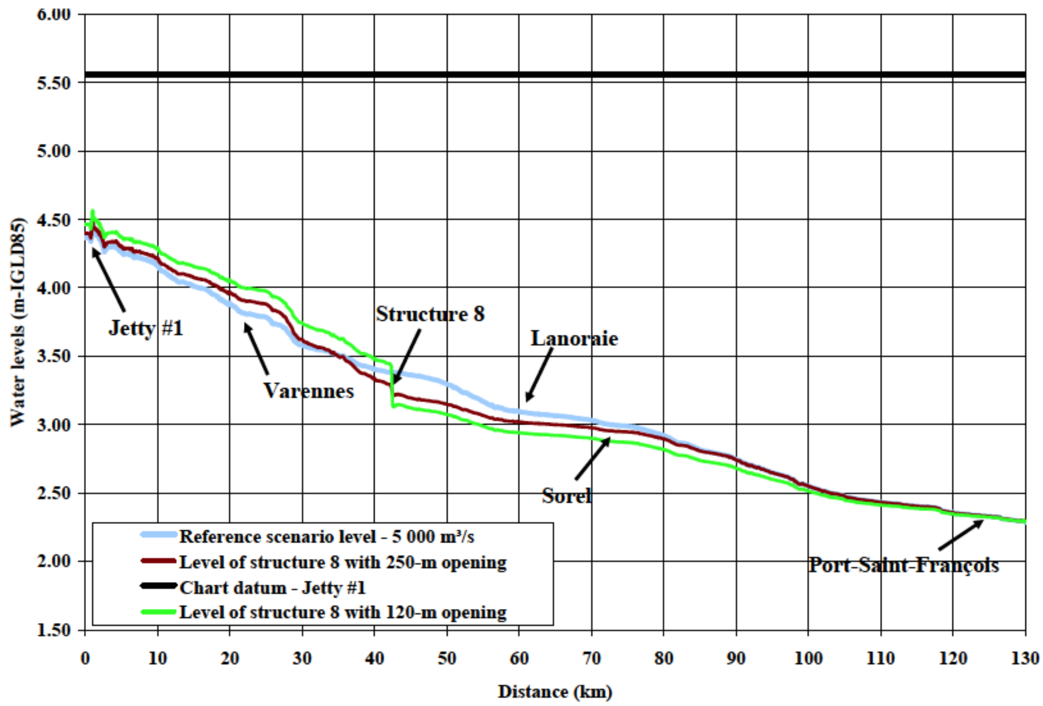
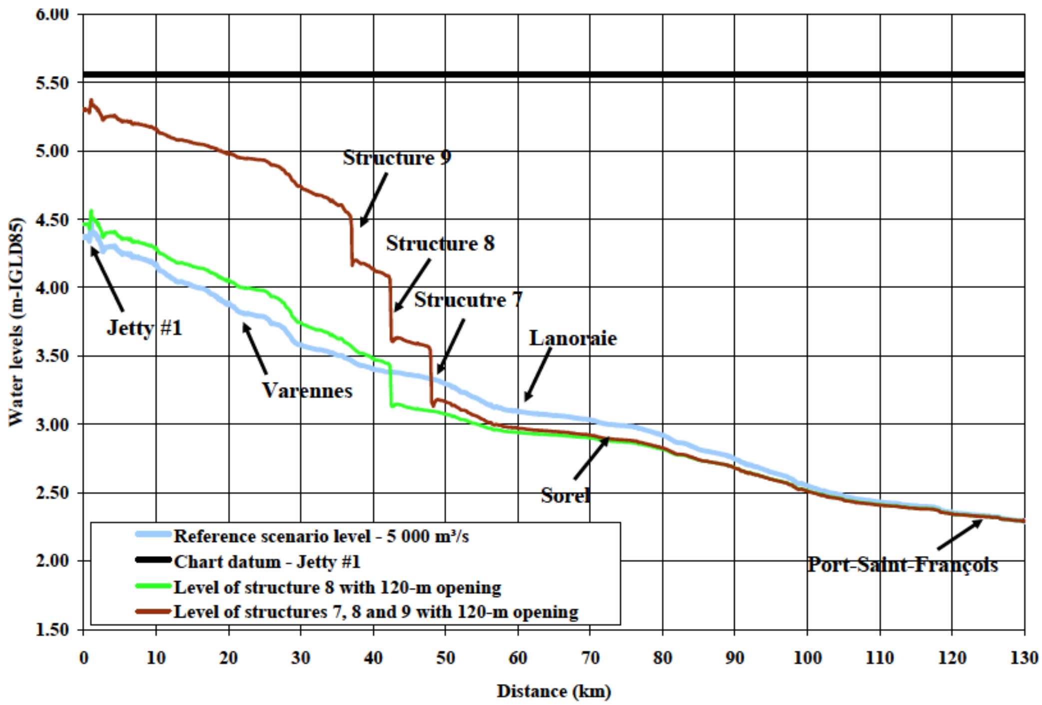


Figure 32 presents the results obtained with Dyke #8 having a 120-m opening in comparison with those obtained with a 250-m opening. The gains are more notable when the opening is made smaller, but would be only around 10 cm at Montréal. On the other hand, the depression downstream from the structure is larger than before and extends over more than 60 km. These individual structures thus do not make it possible to attain the objective of raising the water level by 50 cm.

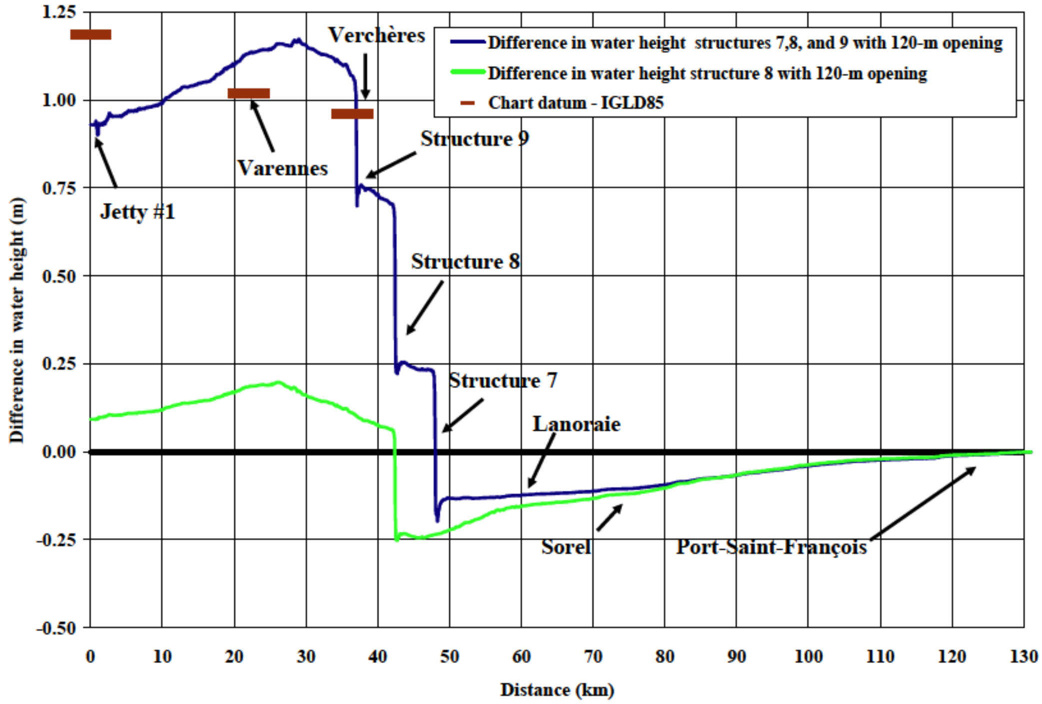
In order to measure the synergy effect of a number of successive dykes, a simulation was conducted with Dykes #7, 8 and 9 (Figure 33). The main dykes along the navigable waterway have a 120-m opening, whereas the secondary dykes were considered obstacles to the flow (Consultants Ropars, 2005).

Figure 33 – Water levels obtained between Montréal and Trois-Rivières according to the reference scenario of 5 000 m³/s at Sorel with Structures #7, 8 and 9 having a 120-m opening (Source: Doyon et al., 2005. Adaptation: D'Arcy, 2005).



The increase in water levels made possible by this succession of dykes is very significant, reaching slightly more than 90 cm at Montréal with respect to the reference scenario. Only about 20 cm more would be needed to reach the chart datum mark. However, not every structure produces the same level-raising effect, as evidenced by Figure 34.

Figure 34 – Difference in water height obtained with successive Structures #7, 8 and 9 having 120-m openings and with Structure #8 having a 120-m opening (the chart datum corresponding to the difference in water height for the stations Jetty #1, Varennes and Verchères is also illustrated; water height 0 is equivalent to the baseline without structures). (Source: Doyon et al., 2005. Adaptation: D'Arcy, 2005)



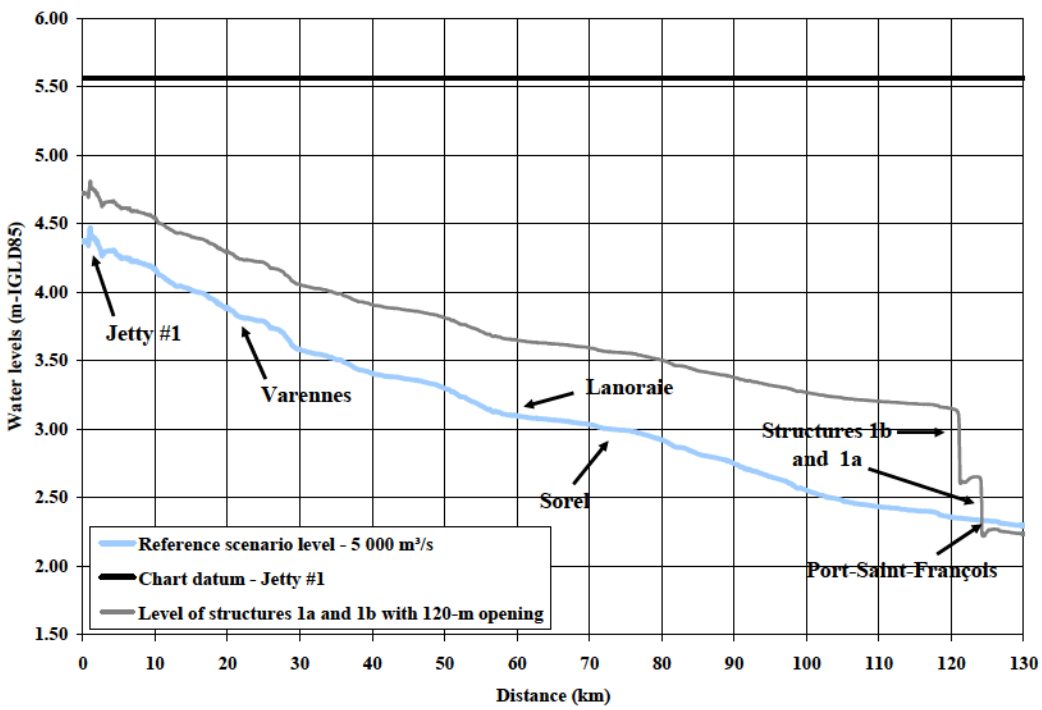
The individual gains obtained with Structures #7, 8 and 9 would be 25, 50 and 40 cm, respectively, when the maximum point attained upstream from Verchères is used as a reference. It drops gradually at Jetty #1 in Montréal to reach slightly more than 90 cm there. Of note is the fact that the gains obtained exceed the local chart datum at Varennes and at Verchères, then gradually drop thereafter. This maximum rise is also observed at the same location with Structure #8 alone. Attainment of this culminating point in this sector could be explained by the combined effect of the arrival of the Rivière des Prairies in the area and the presence of the Verchères archipelago which undoubtedly produces a water-retaining effect.

The cumulative effect of the three consecutive dykes results in a rise of about 90 cm at Jetty #1, illustrating their effectiveness. This increase would be sufficient to cope, at this location, with a climate scenario such as the NWD (-0.77 m) and, at most, with the WH

(-0.93 m). Nevertheless, there would be no benefit for the sector downstream from the structures. The downward movement of the water downstream from Structure #7 would not be resolved, even though it would be a few centimetres lower with respect to that produced with Structure #8 alone.

Models were made of the two series of successive cross-stream dykes (#1a and 1b) at the outlet of Lake Saint-Pierre in order to verify application of the preceding concept (Figure 35).

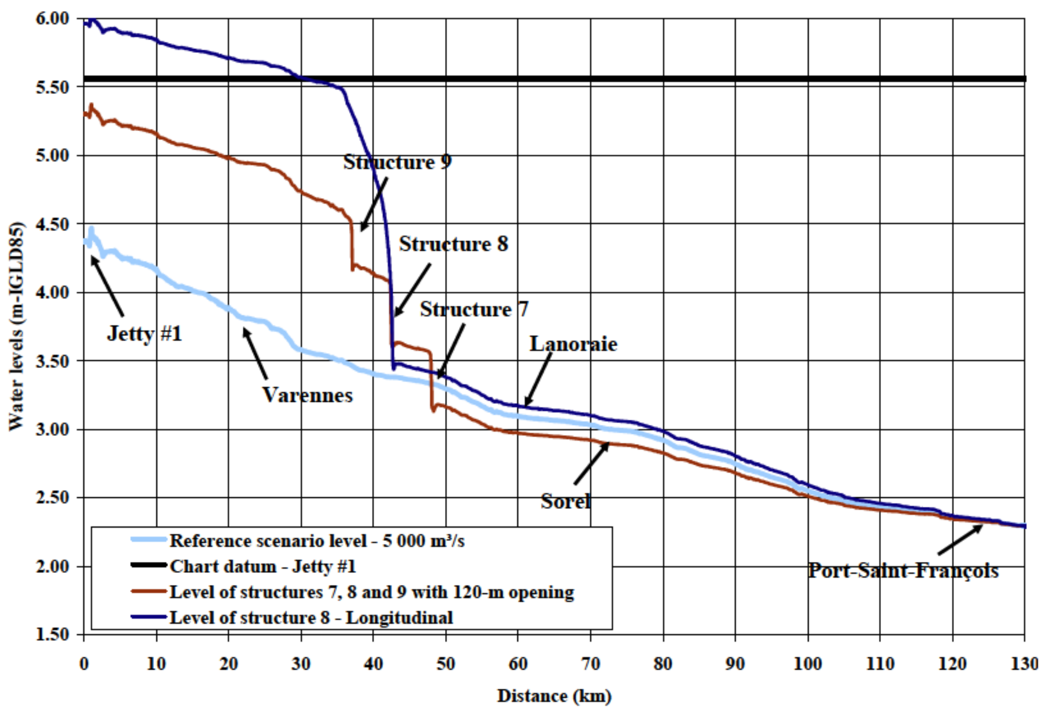
Figure 35 – Water levels obtained between Montréal and Trois-Rivières according to the reference scenario of 5 000 m³/s at Sorel with Structures #1a and 1b having 120-m openings (Source: Doyon et al., 2005. Adaptation: D'Arcy, 2005)



The combination of two nearby dykes whose openings are not aligned makes it possible to significantly raise the water level upstream from the structures (Consultants Ropars, 2005). The gain at Structure 1b is 75 cm while it reaches approximately 35 cm at Jetty #1. This is a noteworthy gain, given the distance that separates the dykes from Montréal. The water depression still occurs downstream from the structures (about 10 cm), but the consequences are less significant there due to the available water depth (Consultants Ropars, 2005). In addition, this sector appears to be strategic since it makes it possible to raise levels in the entire affected area between Trois-Rivières and Montréal. However, the non-alignment of the structures' openings could require special manœuvring of vessels.

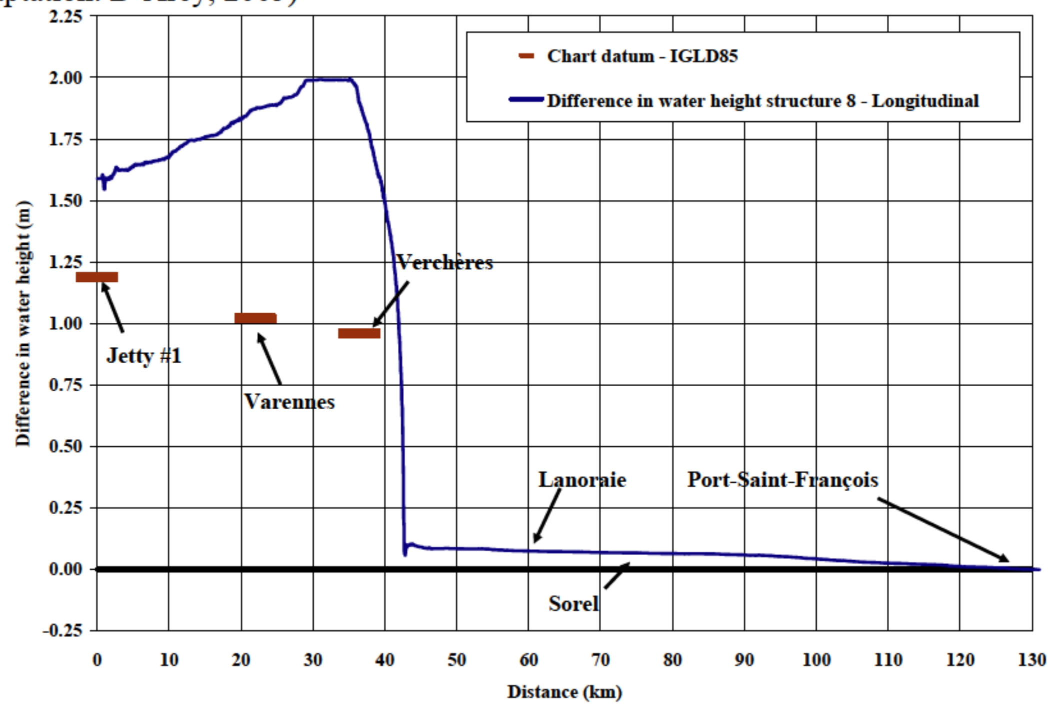
The objective of the simulation involving Structure #8, longitudinal dyke version, was to increase the sidewall's roughness to slow down the water flow. It would then be possible to verify whether slowing the flow between the two longitudinal dykes, as a result of the roughness, would decrease the accelerated flow observed between the cross-stream dykes alone (Consultants Ropars, 2005). The modelling took into account the obstacles created by the #8 series of cross-stream dykes in conjunction with the effect of the nearly 7-km longitudinal dykes. The results presented in Figure 36 show the structures' efficiency in raising water levels.

Figure 36 – Water levels obtained between Montréal and Trois-Rivières according to the reference scenario of 5 000 m³/s at Sorel with Structure #8, longitudinal dyke version (Source: Doyon et al., 2005. Adaptation: D'Arcy, 2005)



The maximum increase is 2 m, reached between Varennes and Verchères (Figure 37). It then decreases to approximately 1.6 m at Montréal. Another noticeable result is a slight increase (10 cm) in water levels downstream from the structures.

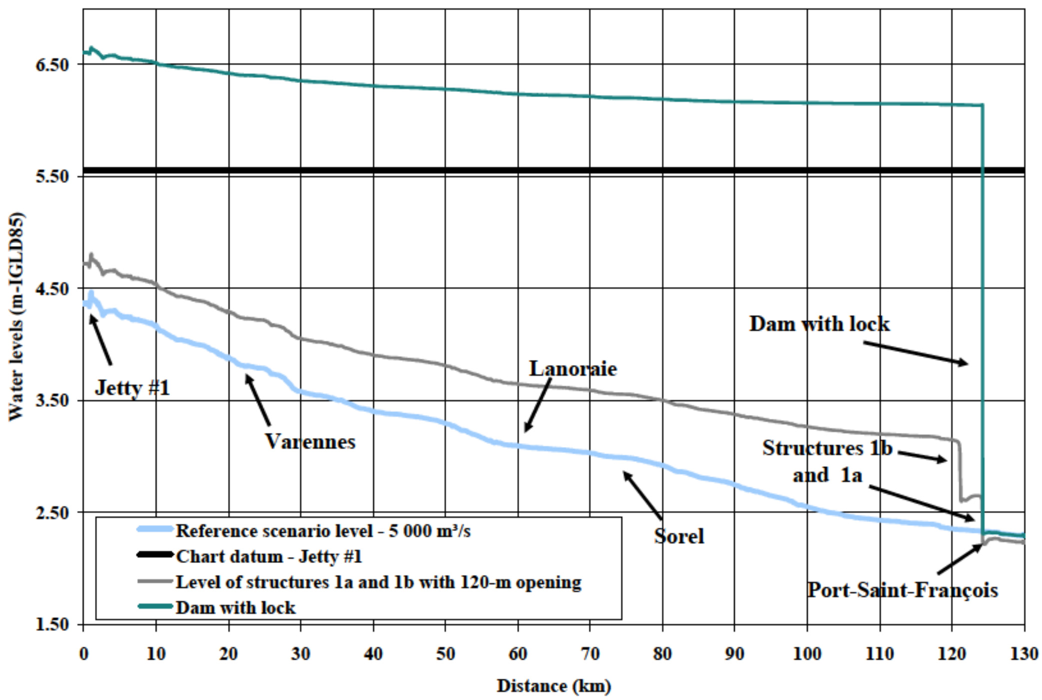
Figure 37 – Difference in water height obtained with Structure #8, longitudinal dyke version, having a 120-m opening (the chart datum corresponding to the difference in height of water for the stations Jetty #1, Varennes and Verchères is also illustrated; water height 0 is equivalent to the baseline without structures) (Source: Doyon et al., 2005. Adaptation: D'Arcy, 2005)



There is not yet a clear explanation for this increase in levels downstream. The diffuser-shaped design used at the lower end of the dykes, combined with the marked roughness of the sidewalls, may be a factor (Consultants Ropars, 2005). The efficiency of these longitudinal dykes at the outlet of Lake Saint-Pierre should be verified and the lengths needed to raise the water levels by about 1 m at Montréal determined (Consultants Ropars, 2005).

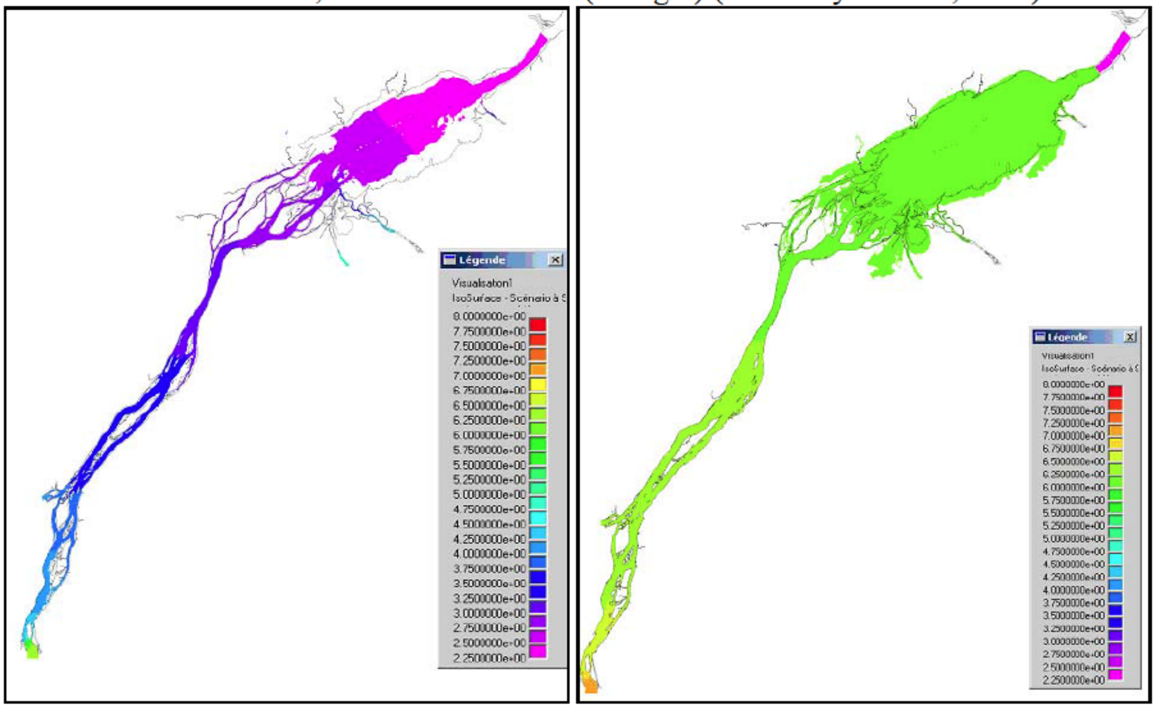
The last numerical simulation was carried out on a dam with a lock, located slightly upstream from the Laviolette bridge in Trois-Rivières. The surmountable portions of the dam (Figure 20) consist of a two-section sill, with the section on the north side of the dam being just under 415 m and the one on the south side close to 520 m. The elevation of this sill's crest was fixed, as an initial approximation, at +3.6 m (average sea level). The results are shown in Figure 38.

Figure 38 – Water levels obtained between Montréal and Trois-Rivières according to the reference scenario of 5 000 m³/s at Sorel with a dam with a lock (Source: Doyon et al., 2005. Adaptation: D'Arcy, 2005)



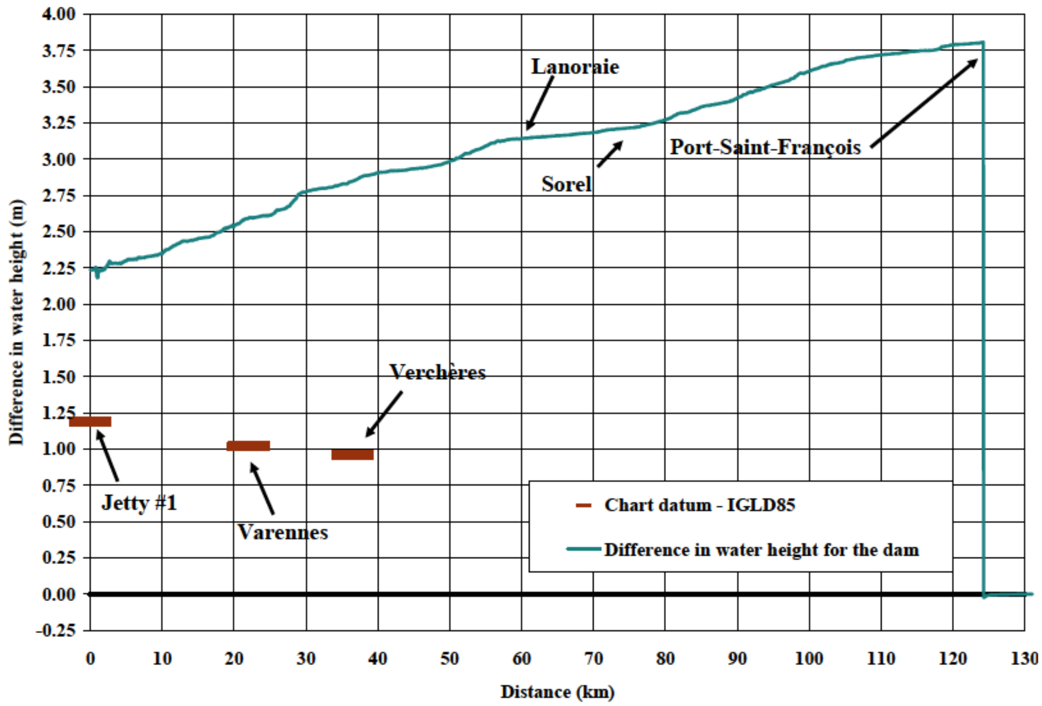
The gain directly upstream from the dam is approximately 3.8 m, while it reaches 2.25 m at Jetty #1 (Figure 40). The levels were thus raised, relative to the chart datum, by slightly more than 1 m at Montréal which would give the vessels a significant safety margin. In fact, the surmountable side of the dam is probably too high; additional simulations would be needed to adjust it to an optimal level (Consultants Ropars, 2005). Figure 39 illustrates the area recovered with respect to the base scenario. The waters go above the strand line at Lake Saint-Pierre; this would result in the flooding of a few shoreline cottages and infrastructures.

Figure 39 – Comparison of water levels obtained with the reference scenario, with a 5 000 m³/s discharge at Sorel (on left) and with the water levels obtained with the simulation with the dam, with the same flow (on right) (from Doyon et al., 2005).



These initial modellings confirmed that the installation of hydraulic structures at certain strategic locations along the river would make it possible to raise the water level at Montréal to a level sufficient to contend with the most pessimistic climate scenarios. However, a number of other simulations would be needed to learn more about the impacts associated with these structures. There was insufficient time to proceed with a simultaneous simulation of hydraulic structures downstream and upstream from Lake Saint-Pierre as well.

Figure 40 – Difference in water height obtained with the dam (the chart datum corresponding to the difference in water height for the stations Jetty #1, Varennes and Verchères is also illustrated; water height 0 equals the baseline without any structures) (Source: Doyon et al., 2005. Adaptation: D'Arcy, 2005)



These tests could permit a combination of structures that would produce gains equivalent to that produced by the dam, but which would result in fewer impacts on the fluvial ecosystem. It must be remembered that a dam is an obstacle to migration in the river and, if this option were retained, a structure enabling species to circulate freely would need to be designed. The combination of cross-stream and longitudinal dykes downstream from Lake Saint-Pierre could prove to be a promising solution: they are not difficult barriers to cross, nor do they require any delicate mechanisms (especially in view of ice) or operator (Consultants Ropars, 2005). Other options should also be studied with regard to technological advances.

Preliminary estimates of the cost of the hydraulic structures were made and are presented in Table 4. More details on the structures' features are presented in Annex 3.

Table 4 – Estimates of hydraulic structure costs (from Consultants Ropars, 2005)

HYDRAULIC STRUCTURES	COSTS ($M)
Series of Dykes #1a	50.3
Series of Dykes #1b	57.2
Series of Dykes #7	50.4
Series of Dykes #8	50.4
Series of Dykes #9	50.4
Series of Dykes #8 – longitudinal	35.9 per km
Dam with a lock	469.6

$M: Millions of dollars (Canadian)

The estimates are based on approximate evaluations of the quantity of materials necessary, the unit costs in 2005, the possible construction methods, currently available equipment as well as other technical considerations. The costs of environmental compensation measures, public consultations and the diverse studies needed, given the sensitive nature of the project, are not included (Consultants Ropars, 2005), nor are the costs of operating and maintaining the structures. The table thus presents a summary assessment of the structures' basic costs, which provide a general idea of the expenditures to anticipate.

2.3.2.6 Hydraulic modelling – impacts

A) Ecosystems and water resources

The framework of this project is such that it was not possible to proceed with a detailed analysis of the environmental impacts of each structure or even of the drop in water levels. The main elements of these impacts will be presented, but it must be kept in mind that if such options were contemplated, studies in good and due form would have to be conducted.

The environmental impacts are at least of two orders: on the one hand, those caused by a substantial drop in water levels such as illustrated by the warm and dry (WD) scenario and, on the other hand, those linked to the erection of hydraulic structures. In the first case, the drop in water levels and flows would be significantly detrimental to both the ecosystems of the St. Lawrence and water quality. A decrease in water volumes increases the concentration of chemical elements (pollutants and nutrients) because of the water's lower dilution capacity. The result is deterioration in the quality of the aquatic environment. A drop in runoff modifies a watercourse's sediment transportation capacity and leads to an increase in particle sedimentation. New areas of sediment accumulation can form and alter the dynamic of ecosystems.

The losses in aquatic habitats in the Montréal–Trois-Rivières sector would be major. Lake Saint-Pierre, which is a UNESCO biosphere reserve, would undergo considerable changes with respect to the area occupied by the wetlands and their composition. Currently, the wetlands cover around 8 000 hectares of this area and are a major biological resource for the flora and fauna. A number of migratory birds (800 000) stop over when the floodplain is submerged in the spring and the largest heron colony in North America, 5 000 individuals, is found in the area surrounding the lake. The Lake Saint-Pierre archipelago counts around 50 islands and the lake supports commercial fishing, with average annual catches being approximately 565 tonnes (comm. pers., Ministère de l'Agriculture, des Pêcheries et de l'Alimentation du Québec, 2006). There are consequently many spawning areas around the lake and in the tributaries flowing into it. Lastly, the chances of survival of the endangered species in Lake Saint-Pierre could well be compromised.

The natural factors that govern the diversity of the fish communities are the presence of varied and good quality habitats, water level fluctuations and the hydrodynamic conditions (Painchaud and Villeneuve, 2003). These natural factors would all be modified significantly by severe climate change, and the consequences on the aquatic environment upstream from Trois-Rivières could in certain cases prove extremely disruptive.

Boaters would also experience serious problems safely accessing marinas. The acceptable difference between the minimum and maximum water levels was established for the boaters of Lake Saint-Pierre at between 4.25 m and 5.25 m, whereas it is between 6 m and 10 m in the Montréal-Contrecœur sector (Connelly et al., 2005). The possible losses in navigation-days vary according to the month and the water levels recorded. Based on the WD scenario in Sorel for reference year 2001, the drop in water levels under the chart datum (3.77 m, IGLD85) ranges from 10 cm to 40 cm from May to October. For a 10-cm drop, the losses in navigation-days for Lake Saint-Pierre would vary from 2 500 (October) to 10 000 (July), whereas for a 40-cm drop they would oscillate between 2 500 (October) and 11 000 (July) (Connelly et al., 2005). The net economic value lost with a 10-cm drop would be between $0.5 million and $1.8 million, and between $0.5 million and $2.5 million for a 40-cm drop. These losses would be even greater in the Contrecœur area. Dredging is often marina operators' recourse for coping with severe minimum flow. However, this solution is costly and needs to be repeated, to the point where the marina operators have questioned the economic viability of pursuing their activities. The operating costs due to the mitigation measures would double during low-water level years (Connelly et al, 2005).

In the case of the hydraulic structures option to raise the water level, the environmental impacts would be significant, though of a different amplitude, depending on the structures. The dam with a lock would without question be the option that would put the greatest pressure on the ecosystems since current state of knowledge indicates that, for the most part, they have a number of negative impacts on ecosystems. These impacts are complex, varied and differ according to the case. This complexity makes it difficult both to arrive at certain generalizations and to predict in detail changes that would result from the construction of a dam, according to the World Commission on Dams (2000). The Commission divided environmental impacts into three categories:

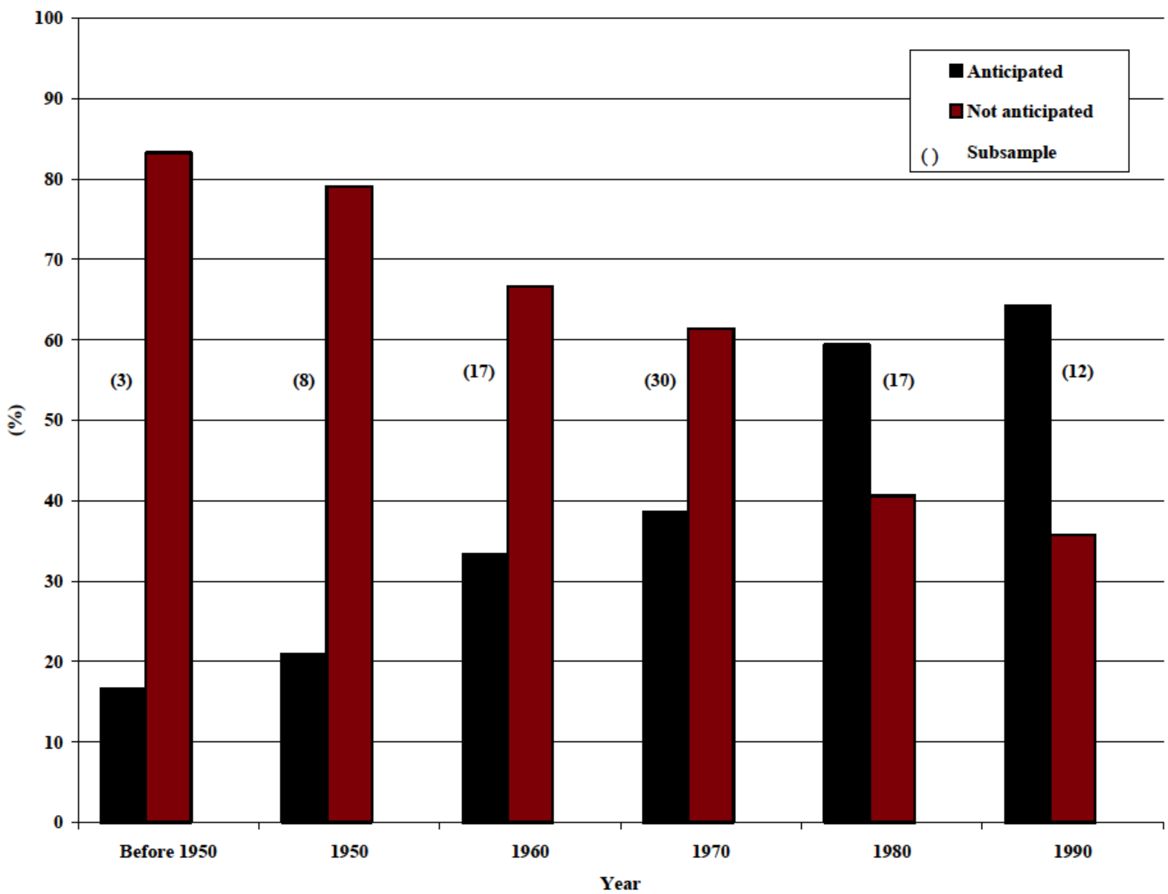
- *first order* impacts consist of physical, chemical and geomorphologic consequences resulting from blocking a river and altering the natural distribution and flow periodicity;
- *second order* impacts consist of changes in the primary productivity of the ecosystems, including the effects on shoreline and riparian flora and fauna as well as on the habitats downstream, such as the marshes;
- *third order* impacts consist of changes in animal populations, such as fish, caused by the effect of first-order impacts (obstacle to migration) or of second-order impacts (decrease in plankton availability).

In addition, modification of the fluvial ecosystem can lead to a change in the natural biochemical cycle. The formation of a reservoir by the dam interrupts the free flow of watersheds' organic carbon going downstream and results in the rotting of flooded terrestrial vegetation, thereby increasing greenhouse gas emissions such as methane and carbon dioxide, which contribute to climate change (World Commission on Dams, 2000). In a number of cases, dams have been found to lead to the irreversible loss of species and ecosystems. The alteration of the natural distribution of flow and its periodicity compromise rivers' dynamic. The development of habitats and the presence of different species in the natural rivers are dependent on their runoff cycle, the type and quantity of sediments in motion and the composition of the river bed and shores. The constituent element of rivers and the integrity of their ecosystems is indeed the dynamic of alternating periods of strong and weak flows, not the stable dynamic of average conditions that result from a control structure (World Commission on Dams, 2000). The runoff cycle is thus the cornerstone of the aquatic ecosystems downstream. The duration of the flood season and its frequency are critical elements for the survival of communities of flora and fauna living downstream. Weak flood episodes can trigger the migration of fish and invertebrate. Most unregulated fluvial systems are made up of a network of complex biological communities that have adapted to the natural fluctuations of flows. In the context of the stable runoff conditions of regulated rivers, this composition can vary significantly (World Commission on Dams, 2000).

The reduction in sediment and nutrient transport downstream from a dam has direct impacts on the channel's profile, the floodplain and the morphology of deltas and results in habitat losses for fish and other species. As mentioned earlier, a dam constitutes a physical obstacle between upstream and downstream and, consequently, results in an interruption in the migratory movements of species, a modification of the composition of the fauna and, in certain cases, the extinction of species (World Commission on Dams, 2000). Environmental monitoring conducted at Lake Saint-François confirms these observations. The erection of hydroelectric dams has a negative impact on the diversity of fish communities (Painchaud and Villeneuve, 2003), which may be attributed to the suppression of migratory paths and the stabilization of water levels. The most widespread mitigation measure to correct this disturbance has been the incorporation of fish passes into the structures of dams. However, the effectiveness of this measure is very relative, and in many cases, the results are other than as anticipated (World Commission on Dams, 2000). One last point to consider with dams is that they can generate cumulative impacts when a number of structures are located on the same watercourse. The greater the number of structures, the greater are the losses in ecosystems and in resource quality.

Though the overview of environmental impacts associated with the construction of dams is not very encouraging, substantial progress is being made in anticipating and confronting the impacts. According to a verification made by the World Commission on Dams on 87 dams around the world, around 60% of the environmental impacts were not anticipated in the case of dams constructed prior to the 1970s. This trend has since been reversed, as Figure 41 illustrates.

Figure 41– Anticipated and unanticipated environmental impacts for a sample of 87 projects (the figures next to the bars represent the number of subsampled projects) (Source: World Commission on Dams, 2000. Adaptation: D'Arcy, 2005)



Anticipation of impacts does not reduce them. However, it provides planners with a reference framework for finding solutions that are better for the ecosystems.

The environmental impacts of other hydraulic structures need to be estimated more accurately. Though these structures are not as imposing as dams, they are nonetheless an obstacle to the flow of water. As well, when the flow is forced through a 120-m opening, as is the case with cross-stream dykes, the current accelerates and can prevent certain species from passing. A number of analyses are still needed to determine the optimal design of structures, both where efficiency in raising the water level and the capacity to result in as few environmental impacts as possible are concerned.

Finally, other impacts to be taken into consideration have to do with the movement of ice on the St. Lawrence River. The erection of structures would alter the movement, which could increase the risk of ice jams, hinder vessel movement and result in flooding. Studies addressing the water height reached during ice jams would be needed in order to adjust the elevation of the surmountable sills to a level that would allow ice to pass freely (Consultants Ropars, 2005). Particular attention should also be given to how structures could affect the stability of the ice cover on Lake Saint-Pierre, which is maintained by booms.

B) Social impacts and balancing of uses

The most serious social impact that comes with the construction of hydraulic structures, and particularly dams, is flooding and the resulting displacement of people. In the Cornwall–Trois-Rivières section, about 6 000 dwellings were inventoried and are located on the St. Lawrence's 100-year floodplain (Doyon et al., 2005). The majority of them (90%) are family residences. Using the stage-damage relations developed for the international study of Lake Ontario and the St. Lawrence River as a basis, Doyon et al. (2005) estimated that, with a dam upstream from Trois-Rivières and a reference flow of 5 000 m^3/s at Sorel, around 11 dwellings would undergo some flooding. The residences concerned are all located around Lake Saint-Pierre and are concentrated in four municipalities (Doyon et al., 2005). As mentioned earlier, the current grade of the simulated dam sills appears to be too steep. Were the elevation to be adjusted, it could reduce, if not eliminate, the risk of flooding and, above all, any risks to persons and goods.

Another social impact is tied to the commercial and recreational fishing that takes place on Lake Saint-Pierre. Nineteen commercial licenses are currently allocated, to 17 fishers. All species combined, the average catch for the period 1994-2004 was 565 tonnes, for an economic value of about $1.5 million (personal. comm., ministère de l'Agriculture, des Pêcheries et de l'Alimentation du Québec, 2006). Recreational fishing is practiced year-round and, for statistical requirements, activities are broken down into open-water fishing and ice fishing. The first one accounted for 35 950 person-days in 2003, for total expenditures of $1 313 041 (BCDM Conseil inc., 2005a). The catches represent, all species combined, slightly less than 45 tonnes (Daigle et al., 2005a). Ice fishing represented 58 800 person-days, for expenditures of $931 920 (BCDM Conseil inc., 2005b). Total catch exceeded 160 000 for yellow perch, northern pike and walleye (Daigle et al., 2005b). The overall annual economic value of the commercial and recreational fisheries is about $4 million for the region of Lake Saint-Pierre. Any change to the composition of the fish community following the construction of hydraulic structures downstream from the lake could weaken the entire regional economy.

Alteration of the esthetic quality of the landscape is another social impact to be considered. Large structures such as dams do not necessarily enhance the landscape. Where possible, preference should be given to hydraulic structures that are largely submerged.

Consideration should also be given to harmonizing the installation and operation of structures with the shoreline municipalities' development plans, both with respect to the development of water bodies and to safety and sanitation conditions near shorelines.

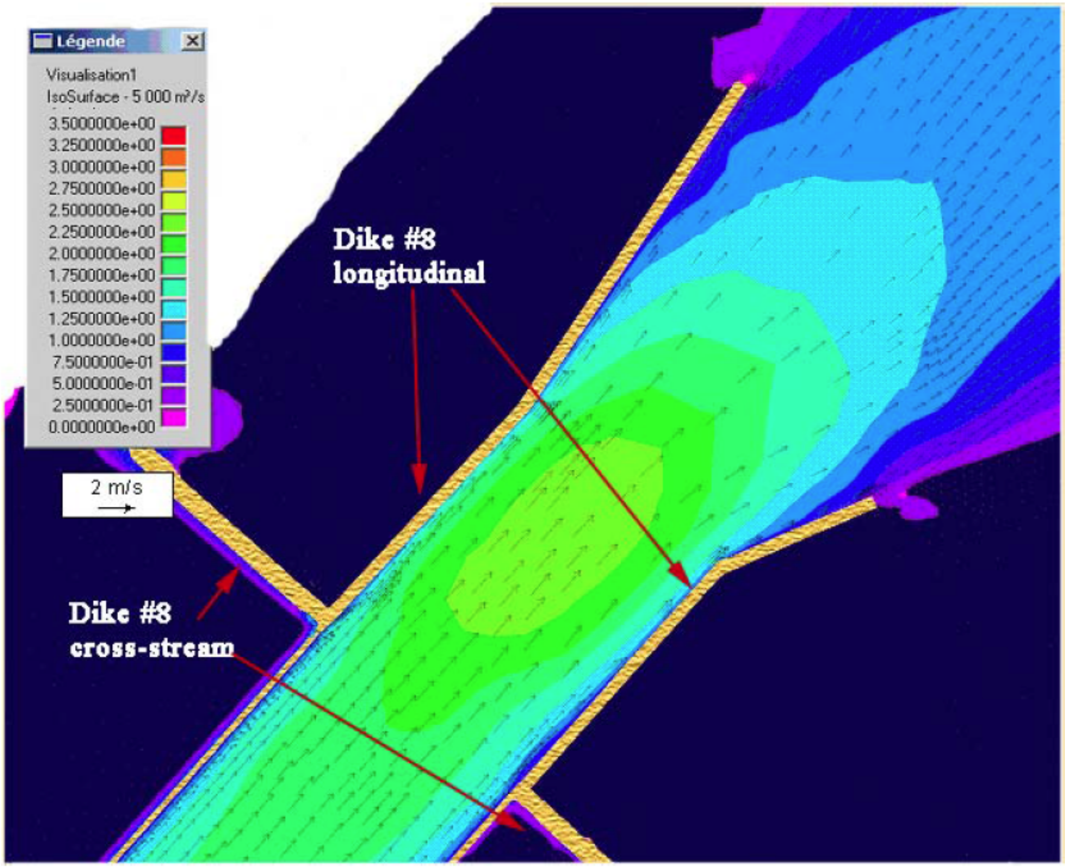
C) Impacts on marine traffic and safety

All the scenarios studied involve navigation constraints for commercial and recreational traffic. One-way traffic should most probably be imposed when vessels pass cross-stream dykes having a 120-m opening. This practice would slow down traffic on the river and could even bring it to a halt occasionally when there are too many vessels. This would undoubtedly be the case with a dam with a lock. Though such slowdowns would probably not have any significant impact on long-duration transits (from 30 to 40 days), they could on transits of about 10 days. Included among the anticipated impacts are the loss of priority at the port of destination and additional waiting time.

In the Québec City–Montréal sector, the estimated average rate of traffic is one vessel per hour. However, this average does not accurately reflect reality since traffic density is above all concentrated in the period during which the St. Lawrence Seaway is open (April to December). Nonetheless, it is an indication that the St. Lawrence is still far from reaching a point of congestion and that a slowdown, if the traffic were to stay at its current level, would be very unlikely.

The cross-stream and longitudinal dykes result in an increase in current velocity in the narrow sections and could make it more difficult to manœuvre vessels and increase the risk of accidents (Consultants Ropars, 2005). The average current speed in the fluvial sector upstream from Trois-Rivières is 0.30 m/s (0.58 knots) and reaches 0.60 m/s (1.16 knots) in the shipping channel (Centre Saint-Laurent, 1996). These values increase markedly with the spring freshet. Channelling of the water in Structure #8- longitudinal generates a current speed of about 2.0 m/s (3.88 knots), that is, slightly more than three times the average speed (Figure 42). Though this value appears high, it is not exceptional for the fluvial sector of the St. Lawrence River.

Figure 42 – Speeds obtained with a 5 000 m³/s discharge at Sorel at the outlet of Longitudinal Structure #8 having a 120-m opening (Source: Doyon et al., 2005. Adaptation: D'Arcy, 2005)

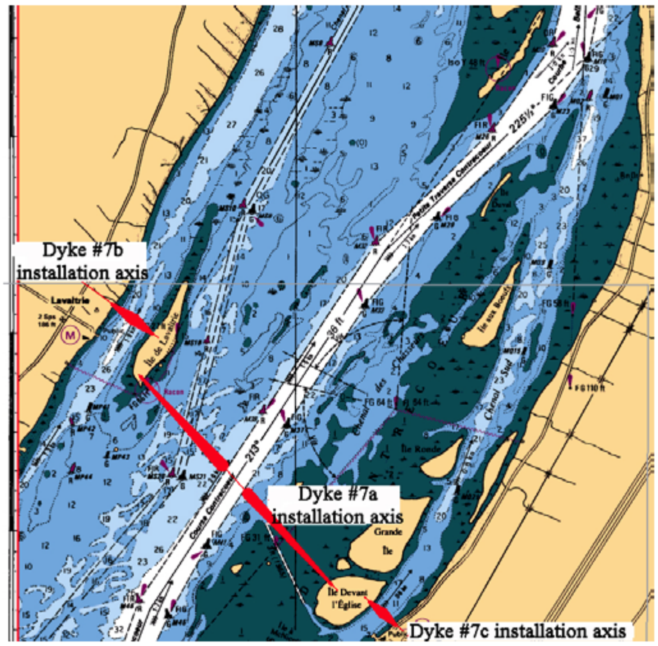


The current reaches speeds of between 2.05 m/s (4 knots) and 2.57 m/s (5 knots) in certain sectors downstream from Trois-Rivières (Fisheries and Oceans Canada, 1997). The principal difference resides in the width of the navigation channel, which is currently 245 m, whereas it would be 120 m inside the structure's walls. Special conditions could be put in place to ensure that vessels are able to manœuvre safely. For example, the Seaway channel, whose minimum width outside the locks is 137 m, was designed to support a maximum flow of 8 800 m/s without exceeding vessels' manoeuvring speed, which is 1.22 m/s (2.37 knots) (St. Lawrence River–Lake Ontario Plan Study Team, 1999). Though it cannot be transposed to the hydrological conditions that could occur in Structure #8, this means of controlling current velocity in the Seaway points to the need to pay special attention to this matter, all the more so since the speed of 2 m/s in Structure #8 was calculated for a reference flow of 5 000 m³/s and not for a flood discharge.

D) Impacts on boating

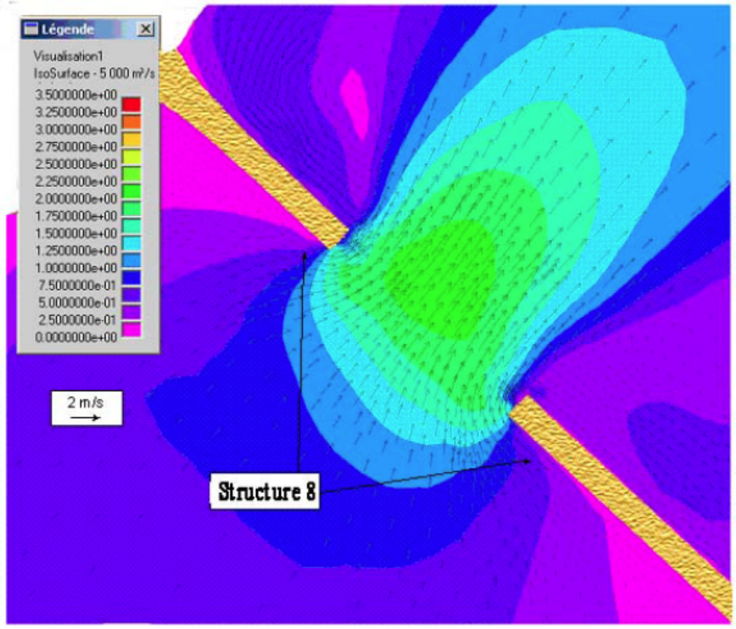
The impacts on recreational boating would very likely be more significant than those anticipated for commercial shipping. The positioning of the cross-stream dykes means that not only is the water along the navigation channel blocked, but also the water in the adjacent channels, to increase the dykes' efficiency (Figure 43).

Figure 43 – Location of Dykes #7 (from Consultants Ropars, 2005)



Recreational boats would have to pass by the dyke's opening to cross this sector. Current velocity increases at the opening (Figure 44), as well, though over a short distance. The dyke also generates a gyrating motion in the water behind it, making it more difficult and riskier for less experienced boaters to manœuvre.

Figure 44 – Speeds obtained with a 5 000 m³/s discharge at Sorel at the outlet of Structure #7 having a120-m opening (Source: Doyon et al., 2005. Adaptation: D’Arcy, 2005)



An alternate solution for secondary channels would be to use inflatable dams that could be operated only during severe minimum flow episodes.

To summarize, the following question will need to be answered: Would a decision to not take action with respect to the physical environment result in more or fewer environmental impacts than would a decision to take action?

2.4 Modification of vessel shape

The option involving altering vessel design is founded on the fact that the St. Lawrence River has been modified, over time, to accommodate vessels with increasingly imposing maximum dimensions and that we may be at the point where, from now on, we need to plan to adapt vessels to the river's current physical conditions. The nominal depth maintained in the Trois-Rivières–Montréal section is currently 11.3 m. A drop in water levels due to climate change would mean a decrease in the height of water available for the vessels. This decrease would be equivalent to a loss in loading capacity and revenue. For example, a 30-cm reduction in available draft corresponds to a loss in loading capacity of 114 twenty foot equivalent unit (TEU) containers for a vessel with a 1 800-container capacity (Commercial Navigation Technical Working Group, 2005). If each container is attributed an average value of $2 000, the loss in revenue would total close to $250 000 per vessel.

To ensure that a given transit remains profitable, any alteration made to a vessel's structural design would have to preserve its optimal loading capacity. Other than the draft, the two structural elements that can be modified to reach this objective are vessel length and beam.

The most recent generation of vessels transiting the St. Lawrence River has been adapted to its nominal depth for navigation. The vessels have a maximum length of 294 m and a maximum draft of 10.78 m. Their nominal cargo capacity is 4 400 containers (TEU). Increases in vessel length changed the length-beam ratio, creating the potential for damage to the hull from the pressure exercised on it when the vessel is in open seas. In addition, one-way traffic has been imposed for safety reasons at certain locations because of vessels' decreased manoeuvrability in river bends. These constraints suggest that where vessel length is concerned, the limit appears to have been attained on the St. Lawrence.

Changes to the beam remain an option worthy of exploring. In the context of climate change, however, an increase in the beam should go hand in hand with a reduction in vessels' draft to compensate for the loss of water height.

Any widening of the structure of the vessels in a fleet must be made in compliance with the recommendations that provide a framework for shipping channel design. The Permanent International Association of Navigation Congresses published the first recommendations on channel dimensions in the 1960s. These recommendations had more to do with the development of deep-water ports and evolved with advances in technical and technological knowledge (PIANC and IAPH Working Group, 1997).

Application of these guidelines led to a number of parameters being established for safe channel design, notably parameters related to ship design, the waterway's physical characteristics, pilotage, traffic planning, safety, the environment, etc. The shipping channel of the St. Lawrence River was designed on the basis of these recommendations.

As regards the total width of a channel, the following equation serves as a reference:

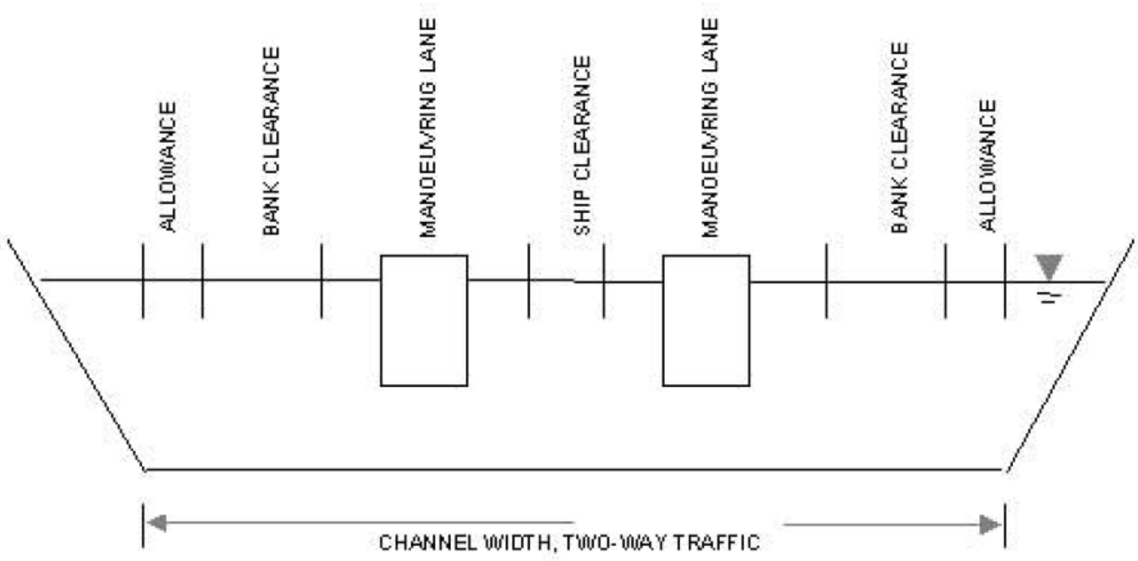
$$\text{Total width} = \text{design width} + \text{allowances}$$

Design width refers to the summation of width requirements to take into account the following elements:

- vessel manoeuvring;
- hydrodynamic interactions between meeting and passing vessels in two-way traffic;
- counteracting cross-winds and cross-currents;
- counteracting bank suction effect; and
- aids to navigation (including pilot services).

Allowances refer to the additional width increases to compensate for bank slumping and erosion, sediment transport and deposit, as well as the type of bank material (http://www.ccg-gcc.gc.ca/mns-snm/main_e.htm). Figure 45 illustrates the design parameters of a two-way channel.

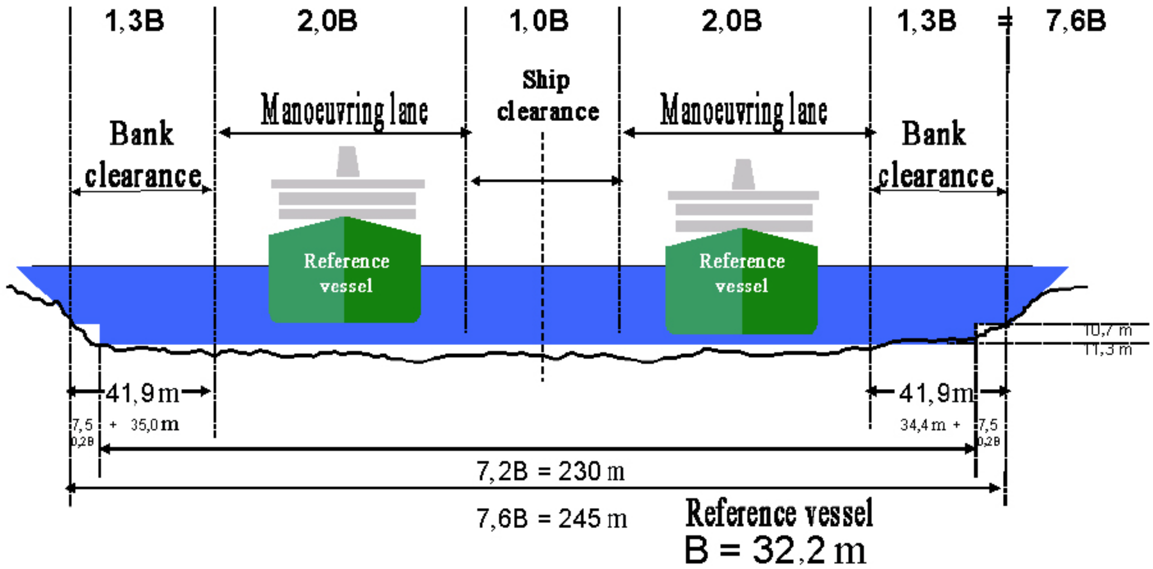
Figure 45 – Interior channel width elements (from: http://www.ccg-gcc.gc.ca/mns-snm/main_e.htm)



These criteria ensure safe navigation while maintaining sufficient safety margins to cope with unforeseen situations. The current width of the shipping channel between Québec City and Montréal is 245 m. This width permits the two-way movement of Panamax vessels (32.2-m. beam). Figure 46 illustrates the calculation of distance elements to consider during the design of a two-way channel.

Authorizing the passage of wider vessels would require a review of the channel's design standards and possibly traffic management standards as well (increase in the number of one-way traffic sectors). This could slow traffic and mean delivery delays for short-distance carriers.

Figure 46 – Design of the St. Lawrence River navigation channel (1.3B means 1.3 x 32.2 m, B represents the beam of the reference vessel (B = 32.2 m) used on the St. Lawrence) (from the Canadian Coast Guard, Waterways Management, 2004)



However, technological and electronic advances could prove to be a considerable plus for traffic management. Already, navigation data are obtained and transmitted in real time, and improvements in this field are ongoing. This information may one day help reduce risks to navigation and lead to a review of channel design standards. A number of studies will definitely be needed before reaching that point, but it is important that this opportunity not be excluded, in terms of adaptation strategies.

For carriers, having a new fleet of vessels built with increasingly large dimensions and shallower drafts can prove to be a costly undertaking. For example, the current cost of building a containership with an operating capacity of about 4 000 TEUs is between US$55 and US$60 million. And the strong demand in this sector is constantly pushing the cost upward. If the new fleet could not be used on other waterways, because of the vessels' dimensions, these costs would be a considerable investment for shipowners. In a context of growing economic trade where marine transportation will be increasingly drawn on to transport merchandise overseas, the flexibility of a fleet, that is, its ability to navigate on as many navigable waterways as possible, will probably become a major decisional criteria for shipowners. When considering such an option, the presence of structures such as locks on a number of navigable waterways around the world may be a limiting factor.

2.5 Re-engineering of port activities

The option of re-engineering port activities also falls in line with adapting navigation to the St. Lawrence's hydrological conditions. Given that a number of deep-draft vessels sail up to the Port of Montréal and that the section that is most at risk for drops in water levels is between Trois-Rivières and Montréal, there is reason to consider the possibility of these vessels stopping in ports that are not subject to these fluctuations. However, consideration of such a scenario must take into account the different economic, environmental and social aspects that are involved and the consequences associated with them.

Marine activity is closely tied to Montréal's economic development and to the status of metropolis that the city had until recently. It was during the 19th century that Montréal succeeded, at the administrative level, in breaking the monopoly that Québec City held and that ensured it the control of pilotage, the shipping channel and port facilities from Lake Saint-Louis to the Gulf of St. Lawrence (Lasserre, 1980). By successfully exercising its authority from Portneuf up to the provincial limits upstream and by taking advantage of the advent of more powerful steamboats, Montréal was better positioned to defend its interests. Promotion campaigns were run to permit work to deepen the channel so that the largest vessels could sail up to Montréal. This work, which began in 1850, marked the gradual transfer of maritime activities from Québec City to Montréal. To wit: in 1851, 1 194 vessels stopped at Québec City whereas only 275 docked at Montréal. Nearly 90 years later, Québec City was the destination of only 394 vessels whereas Montréal topped the thousand-vessel mark (Lasserre, 1980).

Activities at the Port of Montréal did not cease to progress to the point that it became a hub for the transportation of cargo, and particularly for international trade. Montréal's geographic situation, the development of the container market and that of intermodal services made it possible for the port to position itself as a strategic point for marine carriers and contributed to Montréal's expanding economic activity. It is with this backdrop that the re-engineering of port activities must be studied.

The port re-engineering scenarios retained centre around a partial transfer of cargo from the Port of Montréal to the ports of Québec City, Trois-Rivières, Bécancour or a combination thereof. Certain features of the ports need to be addressed in detail at the outset so as to better gauge the implications of the scenarios.

A) Features of the ports of Montréal, Québec City and Trois-Rivières

Montréal's geographic position provides overseas carriers with waterway access to the interior of the North American continent without vessels having to make stops between the port of origin and the port of destination. This is a very important economic and competitive advantage. Its strategic position, combined with its container specialization, has made the Port of Montréal a hub for commercial trade between North American and European countries. Though shipping lines connect Montréal with more than 100 countries worldwide, the majority of trade (95% in 2002) was between the countries of northern Europe, the Mediterranean and central Canada, and the American Midwest and Northeast (Montreal Port Authority, Annual Report, 2002). The introduction of an integrated intermodal transportation service contributed significantly to the success and economic growth of the Port of Montréal.

The Port Authority operates its own railway network, which includes 100 km of railroad and serves most of the berths. This dock service eliminates intermediate transshipments that add to delivery costs. The railroad network is tied to the networks of Canadian National and Canadian Pacific. Nearly 45 trains, with an average length of approximately 1.7 km, leave each week for the major urban centres of Ontario and the Midwest. Departing from Montréal, a container shipped via rail to Toronto takes 10 hours, 25 hours to Detroit, and slightly more than 30 hours to Chicago. Effectively, the Montréal-Chicago transit by train is 122 km shorter than that of New York/New Jersey-Chicago. Nearly 60% of the container traffic handled at the Port of Montréal is shipped by rail (http://www.port-montreal.com).

The remaining portion of cargo is transported by truck and, once again, Montréal benefits from a favourable situation because it is located near the major Canadian and North American axial highways. Some 25 road transportation companies look after the delivery of containers in Québec, Ontario and in the US northeast.

It should be emphasized that the number of empty containers that pass through the Port of Montréal is very low (8.5% in 2003), when compared to that of New York (30%) or Halifax (15%). The highways to Montréal are thus an economic advantage for carriers, when compared with other ports (Rioux et al., 2005).

The infrastructures available for the largest international shipping lines consist notably in four container terminals covering close to 80 hectares, two multifunctional terminals, heavy-duty cranes and special ramps for road traffic. The port has been handling more than 1 million containers per year since 2000, with the exception of 2001, when the total was slightly less. In 2004, it reached 1.2 million containers, which represents close to 11 million tonnes of cargo.

Table 5 – Number of jobs, gross revenue and asset values at the ports of Montréal, Québec City and Trois-Rivières (adapted from Rioux et al., 2005)

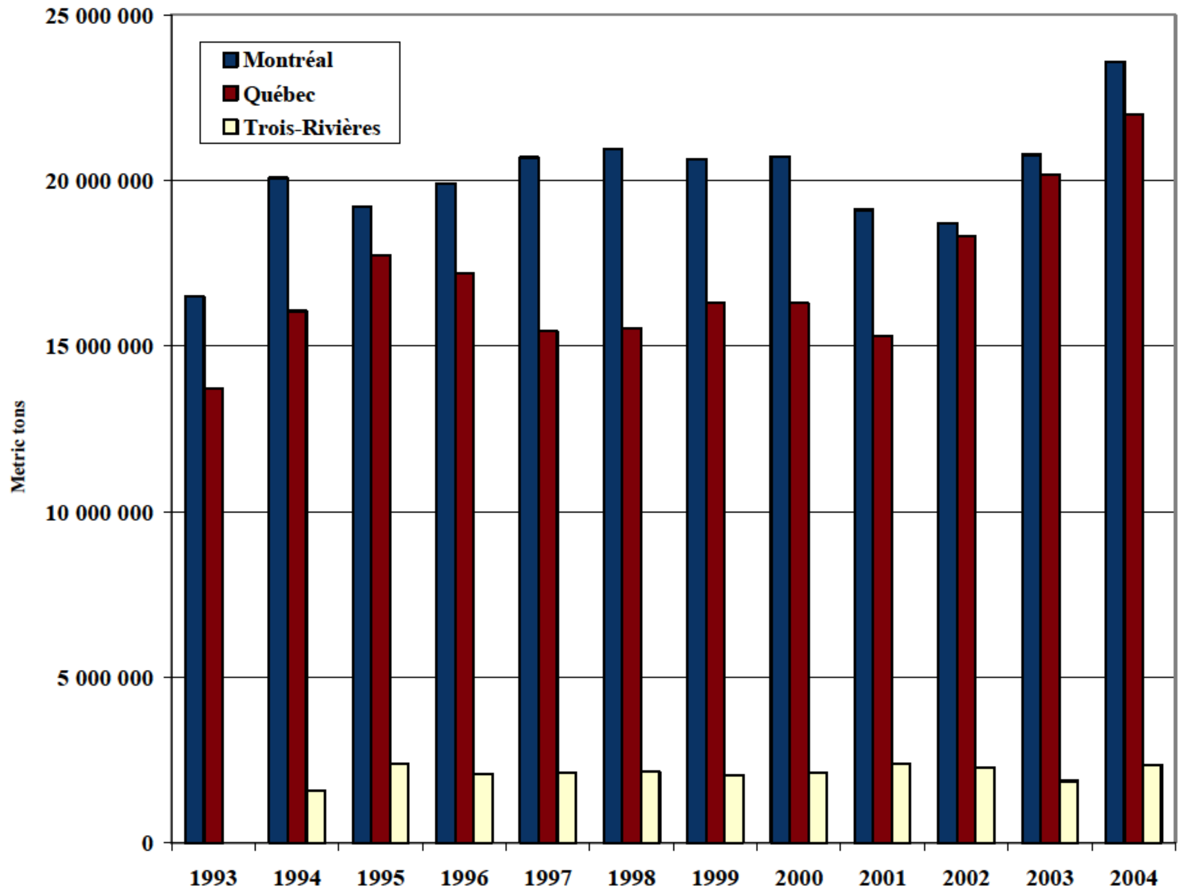
	Montréal	**Québec City**	**Trois-Rivières**
Jobs [a]			
- Port authority	325	60	6
- Dock workers and checkers	1 000	100	50
Total	***1 325***	***160***	***56***
Gross revenue [b] ($M)	65,2	13,2	3,5
Asset value ($M)	297	125	40

[a] Dock workers and checkers are not employed by the Port Authority but by the Maritime Employers Association.

[b] Data for 2003. Financial revenue is not included.

With regards to the cargo handled, the ports of Montréal and Québec City have fairly similar profiles, and the quantities handled generally remained between 15 and 25 million tonnes per year (Figure 47, Table 6). At the Port of Québec, petroleum products handled at the Ultramar refinery in Saint-Romuald account for nearly two-thirds of the tonnage. During 2001 to 2003, monthly traffic at the Port of Trois-Rivières varied from 5 to 40 vessels, approximately; at the Port of Québec, 40 to 110; and at the Port of Montréal, 50 to 220.

Figure 47 – Tonnage handled at the ports of Montréal, Québec City and Trois-Rivières - 1993-2004 (Data: Rioux et al, 2005. Adaptation: D'Arcy, 2005)



With respect to infrastructures, it was mentioned earlier that the Port of Montréal had four container terminals covering nearly 80 hectares. The Bickerdyke terminal has a minimal depth of 8.8 m; the three other terminals have a minimal depth of 10.7 m. Other facilities are dedicated to non-containerized merchandise (grains, liquid and solid bulk goods and petroleum products).

In Québec City, port activities are carried out in four distinct sectors: three on the north shore (Beauport, the estuary and Anse-au-Foulon), and one on the south shore (Ultramar's private docks) where nearly all petroleum products are handled (Rioux et al, 2005). Three terminals are specialized in liquid cargo and one, which has a 45 000-tonne hangar, is reserved for different mineral ores and concentrates. Bunge Canada's grain terminal, one of the port's biggest assets, is not operated at its maximum since grain products are transferred from the Prairies to the ports of Western Canada. A number of wharfs in the estuary sector, and one at Pointe-à-Carcy, have depths of less than 10 m at low tide; the other docks offer depths that range from 10 to 16.7 m.

Table 6 – Summary of some development features of the ports of Montréal, Trois-Rivières and Québec City based on the year 2003 (Rioux et al, 2005)

	Montréal	**Trois-Rivières**	**Québec City**
Merchandise (tonnes)	20 780 294	1 864 000	20 200 000
Trucking companies	25	12	20
Investments last 25 years ($M)	384	35	150
Cruise ships (passengers)	33 427	300	59 000
Dock workers- checkers	850 150	50 N/A	100 N/A
Containers (TEU)	1 108 837	N/A	200
Ship's agencies	46	6	9

The Port of Québec, located 1 400 km within continental North America, is considered a deep-water port and can accommodate vessels with up to a 150 000-tonne capacity. The railroad network serving the port is relatively accessible and developed. Three companies do business with the port authorities: Canadian National, the Chemin de fer Charlevoix and the Chemins de fer Québec-Gatineau. The latter works in close collaboration with the Chemin de fer Saint-Laurent et Hudson to reach the North American markets. Unlike Montréal, where rail plays a major role in the transportation of merchandise, in Québec City, 84% of the merchandise handled is transported by truck (Rioux et al, 2005).

At the Port of Trois-Rivières, the primary activities are concentrated on handling general cargo, particularly forest products and liquid and dry bulk cargo. The water depths at the docks are similar to those at the Port of Montréal (Rioux et al, 2005).

Port activities are mainly oriented toward serving the immediate region, which has a single railroad: the Chemins de fer Québec-Gatineau. This seems to meet current needs, but an increase in volumes transhipped could quickly lead to a congestion problem. About half of the cargo at this location is transported by truck (Rioux et al, 2005). Certain other details concerning the Port of Trois-Rivières are presented in Tables 5 and 6 as well as in Figure 47.

B) Competition between ports

Given its specialization in containers, the Port of Montréal is not in competition in that regard with the other ports of the St. Lawrence. Indeed, Montréal is the only port to have the specialized facilities needed to handle containers. It is also the only one to be served by the regular marine shipping lines transporting containers between northern Europe and certain regions of North America (Rioux et al, 2005). When compared with other ports, the Port of Montréal's major asset is its integrated intermodal transportation network.

Montréal also plays an important role for serving the interior. Around 40% of the non-containerized cargo handled in Montréal comes from other ports in Québec or is destined to them. Generally, the Port of Montréal sees close to one third of the marine traffic on the St. Lawrence (Rioux et al, 2005). In this regard, it seems more appropriate to speak in terms of complementarity between the different ports of Québec than of a veritable competition.

Despite its geographical location, approximately 1 600 km from the Atlantic, Montréal is considered an Atlantic coast port and, in this context, its competitors are the ports of Charleston, Norfolk, New York-New Jersey, Baltimore, Philadelphia and Halifax (USACE, 2001). Montréal's main advantage over its competitors resides in the total transit time of a vessel. The USACE's report estimates that it is least one day less than that of other ports of the Atlantic coast. With respect to the number of containers handled, Montréal was third ranking among the ports of the Atlantic coast in 2004 (Table 7).

Table 7 – Containers handled in 2004 at the major ports along the Atlantic coast

Port	Containers (TEU)
New York – New Jersey [a]	3 163 197
Charleston [a]	1 421 251
Montréal [b]	1 226 296
Norfolk [a]	1 206 034
Halifax [c]	525 553
Baltimore [a]	354 180
Philadelphia [a]	132 223

[a] http://www.marad.dot.gov/MARAD_statistics/

[b] http://www.port-montreal.com

[c] http://www.portofhalifax.ca/

The Port of Montréal has developed the European market in particular (95.5% of the port's volume in 2001) and, in this regard, its closest competitor is the Port of New York-New Jersey (Table 8).

Table 8 – Containerized cargo handled at North American ports in 2001 by region of origin and by destination, in millions of tonnes (from O'Keefe, 2003)

Port	Europe	Middle East and Africa	Asia and Oceania	Central and South America	Total
Long Beach, CA	0.81	0.09	22.19	0.67	23.76
Los Angeles, CA	1.16	0.29	19.92	0.69	22.06
New York-New Jersey	7.91	1.55	7.01	2.90	19.38
Vancouver, BC	0.13	0.08	9.57	0.30	10.08
Charleston, SC	4.69	0.86	2.68	1.66	9.89
Montréal, QC	**8.02**	**0.29**	**0.05**	**0.04**	**8.40**
Oakland, CA	1.12	0.10	6.91	0.16	8.29
Houston, TX	4.10	1.00	0.51	2.17	7.78
Norfolk, VA	3.42	0.62	2.55	0.90	7.49
Savannah, GA	1.49	0.55	4.39	0.53	6.96
Seattle, WA	0.17	0.04	6.23	0.10	6.53
Miami, FL	1.20	0.13	0.74	3.83	5.91
Tacoma, WA	0.01	0.10	4.68	0.00	4.79
Halifax, NS	2.18	0.38	0.95	0.40	3.91

Intermodal links with rail and road transportation are key elements in a port's competitive edge. These interconnections are increasingly at the core of the logistics of companies that entrust their supply chain (supply, product transportation and storage) to third parties. Such an approach ("door-to-door service") positions the ports as a link in this chain and transforms the regular lines into intermodal logistics enterprises. The enterprises can thereby ensure that the gains made at sea will not be lost on land (Rioux et al, 2005).

The Port of Montréal developed an intermodal transport system that places it among the most efficient ports in America for vessel-rail-truck links. The idea of re-engineering port activities as an adaptation option to climate change must be viewed in light of this efficiency. Is it possible to transfer a portion of the Port of Montréal to another port of the St. Lawrence while preserving this efficiency and particularly the economic activity that is intimately associated with it? At what cost?

C) Port re-engineering scenario options

A number of different aspects are involved in relocating port traffic–aspects that exceed purely technical considerations. They involve, notably:

- **The relocation of clients**. Merchandise delivered to Québec City for a client in Montréal will lead to supplementary costs and transportation. If carriers' profit margins were to be substantially reduced, it could be sufficient reason for them to ship their merchandises to destination other than via the St. Lawrence River.
- **Business conditions.** Like other modes of transportation, shipping is closely tied to the health of national economies. An economic recession, particularly in Europe, would probably result in a drop in maritime traffic in the St. Lawrence without transportation costs playing a role in it.
- **Workforce expertise**. A complex port, like that of Montréal, develops a management expertise over time that is difficult to acquire in the short term.
- **The role of a port as a link in a supply chain.** The quality of linkages with the other modes of transportation is a major factor for providing just-in-time service and reducing delivery costs (Rioux et al, 2005).

The options retained are assessed with respect to direct economic costs (in the main tied to the infrastructures) and to certain environmental and social impacts involved with a partial transfer of containers (400 000 TEU) and bulk cargo from Montréal to Québec City, Trois-Rivières or Bécancour. A combination of choices will also be explored. The set of variables associated with the relocation of port activities could not be taken into account within the framework of this project; it is therefore important to underscore that a partial transfer of activities could result in the loss of the economies of scale obtained with a particular volume of cargo, notably in the case of rail connections. In addition, a 600-m berth could not accommodate more than one vessel at a time (two, if the vessels were not too long), and this would slow down transshipping activities considerably. Lastly, it was assumed, for example, that labour would be available at the receiving port or that the terminal operators would have the financial capacity to move the equipment necessary or to acquire new equipment (Rioux et al, 2005). These points, and others, such as the road and rail infrastructures' capacity to handle the transportation of a substantial additional volume of cargo, warrant a more in-depth study. Attention was thus focussed on direct costs. Table 9 presents the scenarios analyzed. It should be noted that the scenarios are limited to the ports located in the river section having sufficient water depth and land to accommodate the infrastructures needed for the relocation. The ports located in the estuary or Lower North Shore, like Sept-Îles, were not retained because more elaborate studies need to be conducted before being able to estimate the relative advantages for carriers to transship at those locations rather than at Halifax or at the ports on the US east coast.

Table 9 – Description of the port re-engineering scenarios (from Rioux et al, 2005)

SCENARIO	DESCRIPTION	IMPLICATIONS
Option 1 Trois-Rivières	- Transshipment of containers on trains and trucks toward their final destination. - Same thing for non-containerized merchandise and bulk.	- Construction of a 600-m straight dock in steel sheet-pile - Construction of a bulk warehouse (55 000 t) - Development of a 20-ha lot for handling 400 000 TEU
Option 2 Québec City	Same as Scenario 1	Same as Scenario 1
Option 3 Combination* Trois-Rivières and Québec City	- Containers at Québec City - Bulk at Trois-Rivières	
Option 4 Combination Trois-Rivières and Bécancour	- Bulk at Trois-Rivières - Containers at Bécancour	This scenario concentrates all the traffic in the region of Trois-Rivières and eliminates the problem of land acquisition in Trois-Rivières.
Option 5 Transportation of containers to Montréal by cabotage	- Transportation of containers by barge from Québec City, Trois-Rivières or Bécancour	This scenario involves a transshipment the first port of destination and another at Montréal before the merchandise is conveyed by truck or train.

* With this option, each port is allocated the traffic that imposes the least constraints on it.

The investments needed for the receiving ports depend on the quantity of merchandise that would have to be transferred. The handling capacity is generally sufficient and does not require investments in the case of a partial transfer involving liquid and solid bulk cargo and grains. The problem emerges with containers, for which substantial investments would be necessary. In the case of a transfer of 35% of the container traffic (approx. 400 000 TEU), Québec City port authorities pointed out that they could develop the service, but that it should be done in cooperation with Montréal. At Trois-Rivières, this scenario would involve the expropriation of a portion of the downtown area, which would most likely not be realisable. This is why one would have to, in this case, turn to the Port of Bécancour (Rioux et al, 2005).

Different data sources were used to calculate the investment costs, notably from the Port of Vancouver (expansion project to increase its capacity by 400 000 TEU), the Port of Montréal, the Ithaque terminal project at the Port of Sept-Îles and from discussions with experts at Public Works and Government Services Canada. By way of indication and to provide a better idea of what must be considered in constructing a container terminal, some information from the Port of Vancouver is presented below:

- Filling a 20-hectare site for operations and container storage;
- Construction of a 420-m long dock to create a new (container) berth;
- Construction of an exit station for trucks;
- Construction of a berth for tugs including a floating dock and a channel dredged to 6.5 m;
- Lengthening of the channel by 350 m and dredging to a depth of 16 m;
- Construction of 23 000 additional feet of railway lines;
- Installation of a lighting system;
- Purchase of three cranes for unloading the vessels;
- Dredging of 3.6 million cubic metres of sediment;
- Etc.

The total cost of this work is estimated, in the initial analysis, at between $200 and $250 million (Rioux et al, 2005). As previously mentioned, only the direct costs of the scenarios, that is, the cost of the dock and of developing a 20-hectare site for container storage, were estimated. Equipment (crane) costs, and the cost of constructing a building or other types of facilities were not taken into consideration. Nor were dredging costs included, because of the multiple uncertainties surrounding the matter.

The favoured construction technique would be a dock made of steel sheet-pile with cathodic rust-protection. A well-known technique that makes it possible to have solid mooring bollards, its life cycle varies between 25 and 50 years. It is also less costly than docks on pilings or caissons. The basic estimates were made for a 600-m long dock able to accommodate two 4 000-TEU containerships, with a water level of 12 or 16 m and an elevation of +8 m. The 16-m option costs $48 million, to which must be added $24 million for the additional 8 m, for a total of $72 million. The development costs for storing the 400 000 containers on a 20-hectare lot are estimated, according to the information from the Port of Vancouver, at $90 million, or around $450/m^2. This involves land-filling, concrete slabs, and sewage, water and electrical networks (Rioux et al, 2005). By including the related development costs (fencing, lighting, etc.) of around $20 million and those (approx. 10%) for unforeseen situations, the base amount fluctuates around $200 million. This figure should nonetheless be adjusted according to the economic conditions of each port (Table 10).

Table 10 – Summary of the direct costs per element for each port (from Rioux et al, 2005)

Element	Québec City	Trois-Rivières	Bécancour
Land acquisition ($/m^2)	25	80	8
Construction of a straight dock, 600 m long, 16 m deep and 8 m high ($/m)[a]	131 667[b]	131 667	131 667
Land development ($/m^2)	495[b]	495	495
Warehouse ($/m^3)	440	440	440
Road construction cost ($/km)[c]	1 500 000	1 500 000	1 500 000
Highway construction cost ($/km)[c]	7 000 000	7 000 000	7 000 000
Rail line construction cost ($/km)[c]	492 000	492 000	492 000

[a] Does not include the environmental compensation costs.

[b] Includes unforeseen situations.

[c] Ministère des Transports du Québec. These costs are based on an average.

By applying these estimates to the different options analyzed, we obtain the approximate costs for a partial transfer of traffic (Table 11).

Table 11 – Summary of the direct costs estimated ($M) for the partial transfer of Montréal's traffic to another port in the fluvial sector of the St. Lawrence River – scenarios involving 400 000 TEU (from Rioux et al, 2005)

Costs	SCENARIOS				
			Combination of Two Ports		
	Québec City	**Trois-Rivières**	**Québec City Containers**	**Trois-Rivières Bulk**	**Combination Trois-Rivières (bulk) and Bécancour (containers)**
Construction of a 600-m straight dock (with no dredging)[a]	79	52.8	79	- - -	52.8
Land cost (where applicable)	5	16[b]	- - -	- - -	1.6
Development work for containers	99	99	99	- - -	99
Other development work (fence, electricity, etc.)[c]	20	20	20	- - -	20
Rail lines in the port area	50	50	50	- - -	50
Warehouse	7	7	- - -	7	7
TOTAL	**260**	**244.8**	**248**	**7**	**230.4**
			255		

[a] The difference in cost between Québec City and Trois-Rivières can be explained by the greater depth of water at Québec City (Beauport sector).

[b] Does not include expropriation costs.

[c] Data from the Ithaque terminal project.

The direct costs give only a general idea of the global costs that can be associated with this type of operation. The indirect costs are added to the expenditures and can be equivalent to the direct costs. For example, if one were to retain the same ratio for Montréal for conveying merchandise to its final destination, specifically, 60% by rail and 40% by truck, improvements (e.g. adding a rail line) would most likely have to be made to the railway network between Québec City and Montréal. It would cost around $125 million to add one rail line between Québec City and Montréal, and this estimate does not include the costs of the environmental studies or the other costs involved with a project of this scope. As regards road transportation, the same ratio would result in 160 000 containers being shipped by this mode, the equivalent of approximately 450 containers per day. These figures include only imports, not exports. At present, about 1500 trucks pass through the Port of Montréal daily (entries and exits). If one third of the operations were moved to Québec City, close to 500 more trucks per day would be using the Old Capital's road network. This would exert considerable pressure on the urban road network and development work would be needed to ensure quick access to the highways. On average, it costs $1.5 million per kilometre to build a simple road and $7 million per kilometre to build a highway. The initial estimate (direct costs) could easily climb by a few million dollars, just to bring the road network up to standard. In addition, development of the network would have to be done in such a way as to avoid social consequences such as urban congestion and traffic jams. This would surely not be easily done in a locality like Québec City where a good part of the port infrastructures is located in the Old City and would most likely involve supplementary costs. If the number of containers transshipped were to increase, the social impact of the pressure on the road network would not only rise, but be quickly felt. The financing of roads and highways is already problematic and keeping them adequately maintained is a challenge. It would surely not be easy for public authorities to contemplate a decision to increase the element that contributes largely to the deterioration of the network.

D) Cabotage

Another means of transporting merchandise up to Montréal would be to use shallow-draft vessels that would not be affected by a drop in water levels. This option has a number of environmental advantages associated with it, notably the fact that it leads to less air, noise and dust pollution than the other modes of transportation. What is more, cabotage provides a means by which to avoid the additional pressures put on road and rail networks as well as cohabitation problems among neighbouring parties. Lastly, by building a fleet adapted to the Seaway, cargo destined to the Great Lakes ports could, in season, be conveyed to the centres, thereby avoiding a transshipment at Montréal. However, the timeframes for a direct route could be longer than with a transshipment in Montréal. As well, this option has certain disadvantages: it involves handing containers a number of times (transshipments), increasing costs for the carrier. Currently, transshipment costs are, on average, close to $190 per container. In total, three transshipments would be necessary to ship a container to Montréal, namely, one off-loading and one loading at Québec City, and another off-loading at Montréal. This handling alone would add $380 per container, without counting the wharfage fees (currently about $8 000 for two days), equipment acquisition (cranes), storage and the other costs inherent to this operation. In addition to financial costs, the handling would also mean having to factor in an additional delay of a couple of days. Barges or vessels adapted to container transportation would also have to be acquired. In the case of barges, there is no guarantee that they could be used in ice. That said, even if this option involves a number of economic constraints, it must not be excluded, because it offers the advantage of maintaining transportation by waterway even in the most pessimistic climate change scenarios. Were this option to be examined in greater depth, a review of how the additional costs could be distributed would be appropriate.

E) The scenarios' advantages and disadvantages

In the context of this inventory of options that would enable marine transportation to confront long-duration low water levels in the St. Lawrence River, while essentially maintaining the same level of global development, the re-engineering of port activities proves to be an option that could bring with it real and significant solutions, but also disadvantages that are difficult to neutralize, at least in the short term. The advantages and disadvantages of re-engineering depend on diverse aspects of marine transportation and differ according to the given scenario.

Movement of goods lies within a global dynamic called a supply chain (Rioux et al, 2005) which has fluidity as its main characteristic. In relation thereto, the Port of Montréal possesses a great advantage because of its intermodal connections and by being served by two major railway companies, which is not the case for Québec City or Trois-Rivières (Rioux et al, 2005).

Table 12 presents a qualitative comparison of the options analyzed on the basis of economic, social and environmental variables, whereas Table 13 presents a summary of some of the direct impacts of the development. Before interpreting the data, a few clarifications need to be made (Rioux et al, 2005):

- In Trois-Rivières, the development of container handling faces major constraints where available land for storage and the building of a yard are concerned. Expansion could be made only by expropriating a considerable portion of the downtown area, which appears little realistic.
- There are few arguments to convince, in the short term, a carrier to move to another port. On the one hand, the time scale over which climate change is expected to occur is outside the framework of usual planning. The entrepreneur will legitimately hesitate to invest considerable sums to move his or her infrastructures since there remains considerable uncertainty with respect to the amplitude, frequency and duration of the impacts of climate change.
- A carrier's presence in a transportation corridor is a business decision. Not being able to determine in advance the growth of the North American-Northern Europe trade route, carriers will exercise caution before planning such a move. In addition, transportation costs and quality of services are decisive variables in a carrier's choice of location and, as such, will encourage the carrier to either remain on the St. Lawrence or find a new location.
- Lastly, the partial transfer of Montréal marine traffic to another port involves, to a degree that varies significantly according to the scenario,

environmental and social costs that would need to be carefully considered. Even if the aquatic environmental impacts would be limited, those sustained by the land and atmosphere could increase because of a more intensive use of road and rail transportation. This modal transfer would result, among other things, in increased greenhouse gas emissions, a consequence that does not fall within the perspectives of sustainable development.

Table 12 – Comparison of scenarios on the basis of the economic, social and environmental aspects (adapted from Rioux et al., 2005)

	Trois-Rivières	**Québec City**	**Trois-Rivières and Québec City**	**Trois-Rivières and Bécancour**	**Cabotage**
Road connections	The cost of network maintenance will increase because of more intense use. Load restrictions are imposed during periods of thaw.	Increase in traffic on the Champlain and de la Capitale boulevards, giving rise to congestion problems. Is added to the two elements of the Trois-Rivières scenario.	Same impact as the first two scenarios, but less extensive.	Same impact as the first two scenarios, but less extensive.	Avoids any impact on the network.
Rail connections	A single major company serves the region. The extension of the network represents a significant cost. No space for a yard.	Same impact as the preceding scenario.	Same impact as the first scenario, but less extensive.	Same impact as the first scenario, but less extensive.	Avoids any impact on the network.
Environmental impact	**Habitat conservation and protection.** Application of environmental compensation measures (no net loss of habitat). **Pollution:** Increase in atmospheric pollution.	Same impact as the preceding scenario.	Same impact as the first scenario.	Same impact as the first scenario.	Increase in the number of vessels. Limited risk as a result of marine traffic control measures on the river. **Pollution.** Less air, noise and dust pollution compared to the other scenarios.

	Trois-Rivières	**Québec City**	**Trois-Rivières and Québec City**	**Trois-Rivières and Bécancour**	**Cabotage**
Urban cohabitation	Increase in noise, dust and urban congestion.	Increase in noise, dust and urban congestion.	Increase in noise, dust and urban congestion, but, in all, less than with the two preceding scenarios.	Increase in noise, dust and urban congestion but, in all, less than in the first two scenarios.	Appreciably fewer problems with neighbouring parties, compared with the other scenarios.
Legal status	Port authority, within the meaning of the *Canada Shipping Act.*	Port authority, within the meaning of the *Canada Shipping Act.*	Port authority, within the meaning of the *Canada Shipping Act.*	The port of Bécancour is managed by the Société du parc industriel et portuaire de Bécancour, which is under provincial jurisdiction. More complex arrangements than for the other options would have to be agreed upon.	Does not apply.
Expertise	None in the field of containers.	None in the field of containers.	None in the field of containers.	None in the field of containers. Moreover, Bécancour has expertise serving a local and regional clientele.	To be acquired, regardless of the scenario.
Social acceptance	Opposition to be expected: increase in road traffic and expropriation of a significant portion of the downtown area.	Opposition to be expected: city's tourism status and recognition as a UNESCO world heritage site.	Same impact as for scenarios 1 and 2.	Same impact as scenario 1 for Trois-Rivières.	Should not meet with any opposition.

When a qualitative comparison of certain impacts is made, using the status quo as a reference point, the transfer of traffic, while offering interesting possibilities at least in the long term, would, in the short term, involve difficult and costly constraints to overcome.

Table 13 – Qualitative evaluation of the impact of certain variables of port re-engineering (adapted from Rioux et al, 2005)

Variable	Trois-Rivières	Québec City	Trois-Rivières and Québec City	Trois-Rivières and Bécancour	Cabotage
Atmospheric pollution	higher Trains and trucks from three to seven times	higher Trains and trucks from three to seven times	higher Trains and trucks from three to seven times	higher Trains and trucks from three to seven times	higher if a portion of transport is done by road or rail
Loss of habitat	higher	higher	higher	higher	higher
Urban cohabitation (noise, dust, etc.)	higher	higher	higher	higher	similar
Delivery time	higher	higher	higher	higher	higher
Transportation costs	higher	higher	higher	higher	higher

In addition to these considerations, it should be added that the private sector would have to assume a portion of the costs of this re-organization. Terminal operators are also the owners of the fixed and mobile equipment and would either have to move it to the new port or purchase new equipment. Moreover, this partial transfer does not exclude the possibility that a company could be forced to operate in another port while maintaining its operations in Montréal. This duplication of activities, personnel and equipment would have a direct impact on companies' profitability, explaining the unlikelihood of them opting for such a strategy. It must also be remembered that a certain volume of containers was being handled in Québec City in the 1970s and, at that time, companies decided to transfer all of their activities to Montréal for economic and delivery time reasons. The situation would have to be very constraining for carriers to choose the opposite. Lastly, marine transportation is currently the transportation mode that has the least social and environmental consequences and that emits the fewest greenhouse gases into the atmosphere per tonne of cargo transported (SLV 2000 – SODES, 2000). In this context, the advantages of stopping the vessels downstream from Montréal would very much have to exceed the inconveniences involved.

3 Discussion

The initial hypothesis assumed that climate change will occur over the coming decades and that it would lead to a drop in water levels in the Great Lakes–St. Lawrence River System. In light of the current knowledge and tools that have been developed, an estimate of the magnitude of water level fluctuations and their spatial distribution was first made for the fluvial sector of the river. Different adaptation options were then briefly examined on the basis of their potential capacity to maintain the river's current nominal depth for shipping requirements, on the anticipated direct costs of implementing the options as well as on certain associated environmental impacts. Though it is premature to compare the different options because certain data is not available or lacks homogeneity, Table 14 presents a summary of the most significant elements among those noted.

Table 14 – Summary of findings

Options	Estimated gains in water height (cm)	Costs	Environmental impacts (qualitative)
Technical and technological (COWLIS and squat)	< 15	Does not apply	Low
Waterway development Dredging Hydraulic structures	> 50	$70 M and + Between $50 and $500 M	Significant
Modification of vessel design	On the basis of the drop	One container ship 4 000 TEU = between US$55 and $60 M	Low
Port re-engineering	Does not apply	Between $250 M and $1 G	Low in aquatic environments and high in terrestrial environments, the atmosphere and in terms of social consequences if the cargo is shipped by land

These findings show marked differences both in costs and environmental impacts. While the technical or technological option (COWLIS and squat) does not have environmental impacts, it does not appear to lead to an increase in water height of more than 15 centimetres, barring substantial progress in terms of long-term weather forecasts.

The waterway development option (dredging and hydraulic structures) produces more significant results for raising the watercourse, but also involves substantial environmental impacts. Dredging, if conducted in a single operation, is relatively low-cost when compared with the other options. However, this solution does not appear sustainable if major and recurring drops in water levels (> 50 cm) were to occur, because the area would have to be continually dredged. Dredging could, on the other hand, be considered a transitional solution until we better understand the direction that climate change will actually take.

The findings obtained with the hydraulic structures differ. In the case of cross-stream dykes, a succession of dykes needs to be erected to obtain a significant increase in water level. The simulations conducted showed that the dykes' efficiency in raising the level depends on the distance between them (dykes #7, 8 and 9) and Montréal. In addition, this option alone would not resolve the problem in the sector of Lake Saint-Pierre. It would have to be combined with other structures built downriver from the lake, which would lead to a multiplication of structures on the river and thereby result in more cumulative environmental impacts and obstacles to navigation. Lastly, the design of these structures should be reviewed to correct the downward movement of water observed downstream from them.

For their part, the longitudinal dykes produce interesting results both where raising the water level and correction of the problem of the downward movement of water are concerned. Simulations placing these structures at other locations, notably downstream from Lake Saint-Pierre, would make it possible to measure their efficiency over a greater distance. However, this type of structure requires a rectilinear run over a rather long distance, which would substantially limit the choice of sites. In addition, the estimated costs are significant and very close to those of a dam. In this regard, a more exhaustive comparison of the environmental impacts of this type of structure with those of the dam is needed.

The simulations made for the option of a dam at Trois-Rivières showed that the increase in the water level would be more than 2 m at Montréal. This rise would fully compensate, and even over-compensate, for the decrease in water levels. Adjustments would have to be made to the size of the structure in order for the gains in water height to correspond to foreseeable needs, based on the most pessimistic scenario in the long term. One major interesting aspect of this option is that in addition to raising the water level, this type of structure can retain the water, as required. This latter point would be an important element to consider if climate change were to evolve, in a recurring manner, in the direction of the most pessimistic scenarios. If this situation were to arise, fluvial uses other than commercial shipping would probably also be affected. The nature, duration and extent of the impacts would encourage decision-making aimed at the best long-term response strategy. In this context, an option such as a dam could be examined collectively, within a framework such as integrated management, where all fluvial uses of the river could be taken into consideration.

As regards the hydraulic structures, many other studies would be needed to accurately evaluate the gains and disadvantages that would result from erecting them on the St. Lawrence. Certain ones, such as movable dams, were not specifically analyzed. Though the current costs of these structures and their maintenance can be dissuasive, their ability to be moved may reduce the environmental impacts and, as such, global costs would be reduced. This type of analysis would have to be conducted before any decision could be made. Other points would need to be examined more closely, notably, the structures' environmental impacts, their design (to enable the free movement of aquatic fauna), the optimal location for them and how to finance them and make them cost-effective. Moreover, the simulations conducted in this study used a reference flow of 5 000 m^3/s in Sorel. Other simulations should be made using different high flows to evaluate a larger range of impacts resulting from the hydraulic structures, in terms of flooding, the ice regime, etc. Lastly, where waterway development options are concerned, one challenge will be to comply with current and future policies, notably as regards environmental compensation associated with the principle of no net loss of habitat.

The option to modify vessel design appears, *a priori*, to have a number of limitations. The characteristics of the river upstream from Québec City, such as the bends and even the shipping channel width, can lead to the assumption that the limit, in terms of vessel length and manoeuvrability, seems to have been attained. Consideration would now need to be given to widening vessels. This option could be viewed as an adaptation option only in the case where the vessels' drafts would also be reduced. The margin for ensuring safe navigation in a restricted channel like the navigable waterway is not without its limits, even if navigation instruments are becoming increasingly precise over the years. Introducing one-way marine traffic could in certain cases constitute a solution, but the impacts of such an approach on the overall fluidity of river traffic would have to be well analyzed. Studies on the limits of vessels' beam that could be imposed on the river, on the basis of the corresponding gains in draft and profitability, should be conducted to clearly define this option's potential. By adapting its fleet of vessels in the St. Lawrence, a shipowner runs the risk of the fleet becoming less flexible, that is, of the vessels not being able to transit waterways with locks narrower than the vessels' beams. At nearly US$60 million per container ship (4 000 TEU), for a shipowner to decide to invest in the construction of a new fleet rather than send its vessels to ports unaffected by drops in water levels, the St. Lawrence clearly must be seen as the most attractive choice.

The analysis of the partial transfer of merchandise from Montréal to another port in the fluvial sector of the river, though incomplete, sheds light on certain limitations of implementing this option. In the first place, it would appear little likely that the role of hub played by the Port of Montréal in container transportation in the northeastern US could be assumed by another port of the St. Lawrence. The economic benefits would, at least in the short term, be very limited for the carriers, whereas the environmental land impacts and social consequences associated with this reorganization could, in a number of scenarios, be considerable. Barring a major change in transportation logistics, of a well affirmed political will or governments establishing major economic incentives, at this stage, this option would appear to have more disadvantages than advantages. Cabotage, for its part, would provide a means by which to maintain waterborne transportation and, as such, would reduce a number of the environmental impacts mentioned earlier. All the same, cabotage has certain disadvantages, including the duplication of infrastructures for handling a large volume of containers, the many transshipments and dock fees, to name just a few. The main advantage of cabotage is that it can be put in place gradually. In the context of long-term planning that would call upon the government, port authorities and shipowners, it is conceivable that a way of reorganizing port activities without compromising the role played by the Port of Montréal could be found.

The simulation of the variations in water levels using current oceanic and climatic models appears to be a first-ever estimate of this type for the St. Lawrence River. The exercise is interesting because of the contrasting findings; however, it must be kept in mind that the simulations still contain a number of uncertainties and that climate forecasts undoubtedly need to be refined. The few studies conducted on water level variations due to climate change produce variable results, particularly with respect to the amplitude of the drops at Montréal. Millerd et al. (2004) thereby developed an index of the climate change impacts on marine transportation in the Great Lakes–St. Lawrence System using three different climate scenarios (CCC GCM1, CCCma2030 and CCCma2050). Their results suggest that the impacts, if any, at Montréal would be minimal given the depth of water available at low-water chart datum (IGLD 85), even for their most pessimistic scenario. However, it is not possible to clearly establish, in terms of methodology, whether their estimate was made only for the vessels that transit the Seaway (available water depth: 8.2 m) or whether deeper draft vessels that sail to Montréal (available water depth: 11.3 m) were also taken into consideration. The work of Mortsch et al. (2000) pointed to a 40% reduction in the Great Lakes' runoff and, using a flow-level relation, concluded that water levels would drop about 1 m at Montréal. Croley II (2003) revised the reduction in the Great Lakes' runoff downward, and estimated it at roughly 24% for the worst scenario. However, he made no projections regarding water levels. Lefaivre (2005) used the estimates of Croley II and those of Fagherazzi et al. (2004) to calculate the water level variations in the St. Lawrence for this study. His estimates come close to those made by Mortsch et al. (2000) for Montréal, specifically, a drop in water levels of close to 1 m. But it should be pointed out that his calculations are based on a 24% decrease in runoff whereas Mortsch estimated it at 40%. These differences attest to a field of research that is in constant evolution and, as such, the estimates produced must be considered with caution.

Knowledge of the amplitude and frequencies of water level fluctuations must be considered as an element complementary to the objective of this study. Nonetheless, by examining the most recent climate scenarios, it has been possible to verify the opportunities and limitations of the different adaptation options analyzed.

Lastly, as explained earlier, the scenarios analyzed do not take into account new management procedures, specific or adaptive, for the Moses-Saunders dam with which to address navigation requirements. According to the Boundary Waters Treaty, between Canada and the US (1909, art. 8) and the regulation plan for Lake Ontario and the St. Laurence (1958D), navigation is among the priority uses and, as such, management procedures will be drawn on as the first resort. However, in the light of discussions held on the International Joint Commission's new regulation plan and the final report of the Lake Ontario and St. Lawrence River Regulation Study Board, it must not be taken for granted that this alone would always suffice.

Though the Great Lakes account for close to 18% of the world's fresh water reserves, they are not immune to natural and man-made pressures that could reduce water levels below critical thresholds. The climatic projections made for the Great Lakes basin point to an increase in evapotranspiration and air temperature (Croley II, 2003). According to these scenarios, the estimated drop in the water supplies to the lakes would be between 4% and 24%. A 24% drop would most likely affect the balance between water supplies and outflow. Given that the leeway for water management and regulation to satisfy the different uses is rather narrow, a significant and constant decrease in the water reserve could only mean having to make some difficult choices. That is why now is the time to give thought to water management vis-à-vis climate change. If nothing else, this exercise and documentation makes it possible to foresee certain negative effects, to measure the limitations of the current infrastructures and to explore different solutions, despite the uncertainties regarding the models' forecasts. Having conducted this type of exercise for the Colorado River basin in the United States, Christensen et al. (2004) believe that it is unlikely that a change in the operating policy of the basin's reservoir system would be sufficient to mitigate the hydrologic effects associated with climate change. The fact that these reservoirs serve multiple uses (consumption, hydroelectricity, flood control) and that the possibilities of off-setting the losses in water supply are minimal, they conclude that requests to reduce water consumption will have to be made if the climatic forecasts prove to be accurate.

This prognostic clearly illustrates the challenge that water management in the Great Lakes–St. Lawrence River System would represent, as well as its degree of complexity, if all uses and users' interests are to be taken into consideration.

Conclusion

In the context of implementing the Sustainable Navigation Strategy prepared in 2004, the Navigation Consensus Building Committee believes that the fluctuations in water levels on the St. Lawrence River could affect marine and port activities and that, in this regard, adaptation options should be studied in relation to the sustainable navigation principles (D'Arcy, Bibeault and NCBC, 2004).

With the objective of initiating thought and discussion about climate change adaptation strategies, a few options were studied in an exploratory manner and, where possible, their economic, environmental and social impacts were examined. The study made it possible to discover certain limitations and opportunities specific to each option. However, there is a need for additional studies in order to clearly establish the options that are in line with sustainable development.

The range of environmental impacts of certain adaptation options could not be estimated here, given that this is an initial evaluation of the options' potential capacity to raise the water level. The positioning of hydraulic structures chosen for the simulations is, for example, far from being definitive. Other simulations will be required to take into account more factors, notably a varied range of high flows, ice movement, fluvial sediment transport and the impact on wildlife habitats, to name but a few. These points and others warrant more thorough analysis so that the scenarios' actual impacts can be properly evaluated.

To the best of our knowledge, this initiative to study different adaptation options for marine transportation with respect to climate change appears to be a first of its kind for the St. Lawrence. The exercise itself was conducted in view of supporting the opinions and ideas of the Navigation Consensus Building Committee, which brings together stakeholders of varying and different interests. This broadened examination made it possible, among other things, to highlight the complexity and pertinence of certain options when analyzed with respect to sustainable development requirements. Investing additional resources and efforts into renewing this exercise would be justified because, while certain potential solutions have been presented, a good number of questions remain only partially answered.

The uncertainties regarding the actual impacts that climate change will have are many. However, it would be wise, in terms of adaptation, to begin to give thought now to the actions that will be required to limit the negative effects of the change. A number of countries in the European Community have already adopted this approach by considering the potential effects of climate change when drafting their medium and long-term development plans (European Environment Agency, 2005). This is a concrete example of the precaution principle being applied, where the objective is to have a proactive rather than reactive attitude toward future climate problems. In common with many other countries, Canada's efforts, in terms of adaptation, are still very timid. An intergovernmental working group was recently set up to establish a national framework for adaptation to climate change (Intergovernmental Climate Change Impacts and Adaptation Working Group, 2005). Six elements make up this framework: awareness, coordination, policy integration, stimulation of research, support of knowledge-sharing networks and the design of tools for planning the adaptation option. Governments are given two roles in the adaptation process: on the one hand, they themselves need to adapt and, on the other, they need to be catalysts of the adaptation option in the other sectors of society. The authors encourage a proactive approach, which would provide a better safety margin for avoiding or limiting damage, spread costs over time and invest in new markets. By acting now, we will be able to make the best decisions possible about land use, infrastructure, resource management and other aspects of public policy and investment, and avoid committing ourselves to courses of action that may not be sustainable (Intergovernmental Climate Change Impacts and Adaptation Working Group, 2005).

This study mirrors the invitation to move into action. Inertia is probably the least preventive attitude to adopt in the field of climate change. Too often the costs resulting from impacts exceed those that would have been generated by prevention. Hence the grounds for exploring new opportunities now in order to ensure that such activities such as navigation on the St. Lawrence River continue, for many generations to come.

Moreover, the anticipated impacts of climate change go beyond the framework of navigation activities alone. For this reason, the Navigation Consensus Building Committee believes that, in the coming years, an examination of the future vocation of the St. Lawrence must be initiated. However, for this endeavour to be fruitful, it should be founded on sustainable development principles and on the integrated management of the St. Lawrence, not on the defence of particular interests.

Bibliography

AMERICAN ASSOCIATION OF PORT AUTHORITIES. 2003. Testimony of Rear Admiral Richard M. Larrabée (USCG-Ret.), Director, Port Commerce Department, Port Authority of New York and New Jersey, Before the House Transportation and Infrastructure Subcommittees on Coast Guard and Maritime Transportation and Water Resources and Environment, 11 p.

AMERICAN ASSOCIATION OF PORT AUTHORITIES. 2005. Current Issues Facing the Industry. www.aapa-ports.org/industryinfo/currentissues.html. Consulted on 2005-07-21.

BACLET, A. and F. MONTAGNÉ. 2002. Évaluation de l'adaptabilité des organisations liées à la navigation commerciale sur le Saint-Laurent, dans un contexte de changements climatiques. Rapport de stage d'option scientifique. Université du Québec à Montréal, Département d'humanités et de sciences sociales. 48 p.

BCDM CONSEIL INC. 2005*a*. Rapport IV : La pêche sportive au lac Saint-Pierre en 2003. Pêche en eau libre : évaluation des retombées économiques. Pour le ministère des Ressources naturelles et de la Faune, Direction de la recherche sur la faune, Québec. 89 p.

BCDM CONSEIL INC. 2005*b*. Rapport III : La pêche sportive au lac Saint-Pierre en 2003. Pêche sur la glace : évaluation des retombées économiques. Pour le ministère des Ressources naturelles et de la Faune, Direction de la recherche sur la faune, Québec. 67 p.

BRIGGS, M., S.T. MAYNORD, C.R. NICKLES and T.N. WALLER. 2004. Charleston Harbor Ship Motion Data Collection and Squat Analysis. US Army Corps of Engineers. ERDC / CHL CHETN-IX-14. 20 p.

BURTON, I. 2004. Climate Change and the Adaptation Deficit. In FENECH, A., D. MACIVER, H. AULD, R. BING RONG and Y. YIN (Eds). Climate Change: Building the Adaptative Capacity. Meteorological Service of Canada, Environment Canada. Toronto, Ontario, Canada, pp. 25-33.

CALDWELL, H., K.H. QUINN, J. MEUNIER, J. SUHRBIER and L. GRENZEBACK. 2002. Potential Impacts of Climate Change on Freight Transport. 14 p. www.climate.volpe.dot.gouv/workshop/002. Consulted 2005-06-15.

CANADIAN COUNCIL OF MINISTERS OF THE ENVIRONMENT. 2003. Climate, Nature, People: Indicators of Canada's Changing Climate. Prepared by the Climate Change Indicators Task Group of the Canadian Council of Ministers of the Environment. 51 p.

CENTRE SAINT-LAURENT. 1996. Rapport synthèse sur l'état du Saint-Laurent. Volume 1 : L'écosystème du Saint-Laurent. Environnement Canada – région du Québec, Conservation de l'environnement. Éditions MultiMondes. Coll. Bilan Saint-Laurent.

CHRISTENSEN, N.S., A.W. WOOD, N. VOISIN, D.P. LETTENMAIER and R.N. PALMER. 2004. The Effects of Climate Change on the Hydrology and Water Resources of the Colorado River Basin. Climatic Change, 62: 337-363.

COMMERCIAL NAVIGATION TECHNICAL WORKING GROUP. 2005. Commercial Navigation – Contextual Narrative. Report prepared by the International Joint Commission in the framework of the international study of Lake Ontario and the St. Lawrence River. 13 p.

CONNELLY, N.A., J-F BIBEAULT, J. BROWN and T.L. BROWN. 2005. Estimating the Economic Impact of Changing Water Levels on Lake Ontario and the St. Lawrence River for Recreational Boaters and Associated Businesses. A Final Report of the Recreational Boating and Tourism Technical Work Group (International Joint Commission). Executive Summary. 17 p.

CONSULTANTS JACQUES BÉRUBÉ INC. 1997. Dragage sélectif des hauts-fonds dans la voie navigable du Saint-Laurent entre Montréal et le cap à la Roche. Document complémentaire à l'étude environnementale préparé pour le compte du Port de Montréal dans le cadre de la procédure fédérale. 71 p. + appendices.

CONSULTANTS ROPARS. 2005. Adaptation du transport maritime aux changements climatiques – Option de régularisation fluviale. Report prepared for the Navigation Consensus Building Committee. 66 p. + annex.

CROLEY II, T.E. 2003. Great Lakes Climate Change Hydrologic Impact Assessment I.J.C. Lake Ontario-St. Lawrence River Regulation Study. NOAA Technical Memorandum GLERL – 126. 77 p.

DAIGLE, G., E. RENY-NOLIN, L.-P. RIVEST, Y. MAILHOT and M. LEGAULT. 2005*b*. Rapport I : La pêche sportive au lac Saint-Pierre en 2003. Pêche sur la glace : effort de pêche, succès et récolte des principales espèces de poissons. Ministère des Ressources naturelles et de la Faune du Québec, Direction de la recherche sur la faune. Université Laval, Service des consultations statistiques. 67 p.

DAIGLE, G., E. RENY-NOLIN, L.-P. RIVEST, Y. MAILHOT, M. LEGAULT and B. BÉLANGER. 2005*a*. Rapport II : La pêche sportive au lac Saint-Pierre en 2003. Pêche en eau libre : effort de pêche, succès et récolte des principales espèces de poissons. Ministère des Ressources naturelles et de la Faune, Direction de la recherche sur la faune, Québec. 97 p.

DAILEY, J.E., and D.R.F. HARLEMAN. 1972. Numerical Model for the Prediction of Transient Water Quality in Estuary Networks. Massachusetts Institute of Technology. Report No. MITSG 72-15.

D'ARCY, P., JF BIBEAULT AND NAVIGATION CONSENSUS BUILDING COMMITTEE. 2004. Sustainable Navigation Strategy for the St. Lawrence. 111 p. + appendices.

DOYON, B., D. RIOUX and O. CHAMPOUX. 2005. Adaptation du transport maritime aux changements climatiques : simulations numériques de scénarios exploratoires d'interventions physiques sur le fleuve Saint-Laurent. Technical Report MSC-Hydrology, RT-138, Environment Canada. Report prepared for the Navigation Consensus Building Committee, 62 p.

DREDGING NEWS ONLINE. 2004. Second Round of Dredging Starts at Mouth of Yangtze River. www.sandandgravel.com/v_dno/print.asp. Consulted 2005-07-21.

DUNKER, S. 2004. Analysis of Waterway Factors on the Underkeel Clearance of Sea-going Vessels. Squat Workshop, Elsfleth/Oldenburg, Germany, pp. 150-172.

ENVIRONMENT CANADA (1994). Environmental Impacts of Dredging and Sediment Disposal. Prepared by Les Consultants Jacques Bérubé inc. for the Technology Development Section, Environmental Protection Branch, Québec and Ontario Regions, Environment Canada, 99 p.

EUROPEAN ENVIRONMENT AGENCY. 2005. Vulnerability and Adaptation to Climate Change in Europe. EEA Technical Report no. 7. 106 p.

FAGHERAZZI, L., R. GUAY and T. SASSI. 2004. Analysis of Climate Change Impacts on the Ottawa River System. Preliminary report to the I.J.C. Lake Ontario-St. Lawrence River Regulation Study. Manuscript under review, July 2004.

FORTIN, P. 2002. Acquisition and post-processing of bathymetric data in shallow waters for the section of the St. Lawrence River between Cornwall and Trois-Rivières. Technical Report MSC-Hydrology RT-118, Environment Canada. 29 p.

FORTIN, P., A. MORIN, N. ROY and B. DOYON. 2004. Cueillette des données bathymétriques et actualisation du modèle numérique d'élévation du fleuve Saint-Laurent. Technical Report MSC Québec Region – Hydrology RT-129, Environment Canada. 26 p.

FORTIN, P., S. MARTIN and A. PLANTE. 2002. Post-processing validation and integration of LIDAR data into the St. Lawrence River Digital Terrain Model. MSC-Hydrology RT-120, Environment Canada. 43 p.

FRASER RIVER ESTUARY MANAGEMENT PROGRAM (FREMP). 2002. Sediment Budget and Dredging Activities. Annual report for the fiscal year 2002. Prepared by FREMP's Dredge Management Advisory Committee. 7 p.

INTERGOVERNMENTAL CLIMATE CHANGE IMPACTS AND ADAPTATION WORKING GROUP. 2005. National Climate Change Adaptation Framework. 23 p.

INTERGOVERNMENTAL PANEL ON CLIMATE CHANGE (IPCC). 2001. Climate Change 2001: The Scientific Basis. 93 p.

INTERGOVERNMENTAL PANEL ON CLIMATE CHANGE. 2001. Climate Change 2001: Impacts, Adaptation, and Vulnerability. 97 p.

LALANCETTE, J., N. LALONDE, G. SILLS and J. CYR. 2001. Portrait des activités de dragage sur le Saint-Laurent – Les aspects opérationnels et environnementaux. Rapport préparé pour le ministère des Transports du Québec dans le cadre du Plan d'action Saint-Laurent Vision 2000. 58 p. + appendices.

LASSERRE, J.-C. 1980. Le Saint-Laurent, grande porte de l'Amérique. Cahiers du Québec, Les Éditions Hurtubise HMH. 753 p. Coll. Géographie.

LEFAIVRE, D. (FISHERIES AND OCEANS CANADA). 2005. Effets des changements climatiques sur les niveaux d'eau du fleuve Saint-Laurent entre Montréal et Québec. Projections pour les années 2050. Report prepared for the Navigation Consensus Building Committee. 34 p.

McINTYRE, S. and R. McKITRICK. 2005. Hockey Sticks, Principal Components, and Spurious Significance. Geophysical Research Letters, vol. 32, L03710.

MEEHL, G., W.M. WASHINGTON, W.D. COLLINS, J.M. ARBLASTER, A. HU, L.E. BUJA, W.G. STRAND and H TENG. 2005. How Much More Global Warming and Sea Level Rise? Science, vol. 307. pp. 1769-1772.

MILLERD, F. 2003.The Impact of Water Level Changes on Commercial Navigation in the Great Lakes and St. Lawrence River. Canadian Journal of Regional Studies at the University of New Brunswick. 12 p.

MILLERD, F. 2004. The Economic Impacts of Climate Change on Canadian Commercial Navigation on the Great Lakes. 41 p.

MONTREAL PORT AUTHORITY. 2002 Annual Report. www.port-montreal.com/documents/en_8_2.pdf.

MORIN, J., P. BOUDREAU, P. FORTIN, D. RIOUX, O. CHAMPOUX, C. POMARES and J.-F. CANTIN. 2001. Hydrodynamique du quai Tarte, Port de Montréal. Technical Report MSC-Hydrology RT-114, Environment Canada. 15 p. + 12 plates.

MORIN, J. and A. BOUCHARD. 2001. Les bases de la modélisation du tronçon Montréal/Trois-Rivières. Scientific Report MSC – Hydrology RS-100, Environment Canada. 56 p.

MORSE, B., S. MICHAUD and J. SILES. 2002. Maximization of Ship Draft in the St. Lawrence Seaway. Volume 2: In-Depth Analysis of Squat and UKC. Report prepared for Transportation Development Centre of Transports Canada and The St. Lawrence Seaway Management Corporation. TP 13888E. 48 p. + appendices.

MORSE, B. 1990. St.Lawrence Water-Levels Study: Application of the One-D Hydrodynamic Model. Report to Transport Canada, Waterways Development Division, Canadian Coast Guard.

MORTSCH, L, H. HENGEVELD, M. LISTER, B. LOFGREN, F. QUINN, M. SLIVITZKY and L. WENGER. 2000. Climate Change Impacts on the Hydrology of the Great Lakes-St. Lawrence System. Canadian Water Resources Journal, vol. 25, no. 2. pp. 153-177.

NATURAL RESOURCES CANADA, CLIMATE CHANGE IMPACTS AND ADAPTATIONS DIRECTORATE. 2002. Climate Change Impacts and Adaptations: A Canadian Perspective–Transportation. 19 p.

O'KEEFE, D. 2003. The Future for Canada-U.S. Container Port Rivalries. Transportation Division, Statistics Canada. 12 p.

OSBORN, T.J. and K.R. BRIFFA. 2004. The Real Color of Climate Change. Science, Vol. 306. pp. 621-622.

PAINCHAUD, J. and S. VILLENEUVE. 2003. Portrait global de l'état du Saint-Laurent – Suivi de l'état du Saint-Laurent. Saint-Laurent Vision 2000. 17 p. Website: www.slv2000.qc.ca.

PARKER, E.N. 1999. Sunny Side of Global Warming. Nature, vol. 399, 3 June. pp. 416-417.

FISHERIES AND OCEANS CANADA – CANADIAN HYDROGRAPHIC SERVICE. 1997. Atlas of Tidal Currents for St. Lawrence Estuary from Cap de Bon-Désir to Trois-Rivières. 108 p.

PIANC and IAPH WORKING GROUP. 1997. Approach Channels – A Guide for Design. Final report of the joint Working Group PAINC and IAPH, in cooperation with IMPA and IALA. Supplement to Bulletin no 95. 108 p.

PORT OF LONDON AUTHORITY. 2004. Princes Channel development – Phase II Dredging. Environmental Assessment Report.

QUINN, F.H. 2002. The Potential Impacts of Climate Change on Great Lakes Transportation. 9 p. www.climate.volpe.dot.gouv/workshop/002. Consulted 2005-06-15.

RIOUX, C., J.C. MICHAUD, E. GUY, and M. CHARBONNEAU. 2005. Étude sur les perspectives de réorganisation des ports du Saint-Laurent relativement aux changements climatiques. Report prepared for the Navigation Consensus Building Committee. 105 p. + appendices.

SCHREIDER, M.J., T.M. GLASBY and A.J. UNDERWOOD. 2003. Effects of Height on the Shore and Complexity of Habitat on Abundances of Amphipods on Rocky Shores in New South Wales, Australia. Journal of Experimental Marine Biology and Ecology,

Vol. 293. pp. 57-71. Website:
http://www.eicc.bio.usyd.edu.au/scripts/database/view.pl?Choice=ViewRec&DB=pubs&id=361.

SIMARD, L. 1983. Effet des reversoirs des îles de Sorel sur les niveaux d'eau. Report prepared for Transport Canada – Coast Guard. 26 p.

SLV 2000 – SODES. 2000. Étude comparative des impacts environnementaux des modes de transport de marchandises dans l'axe du Saint-Laurent. Report presented to the St. Lawrence Vision 2000 Navigation Committee and the St. Lawrence Economic Development Council, Québec City. 131 p. + appendices.

ST. LAWRENCE RIVER–LAKE ONTERIO PLAN STUDY TEAM, 1999. Plan of study for Criteria Review in the Orders of Approval for Regulation of Lake Ontario-St. Lawrence River Levels and Flows. Prepared for the International Joint Commission.

TRANSPORT CANADA – CANMORE WORKSHOP. 2003. Impacts of Climate Change on Transportation in Canada. Final Workshop Report. 21 p. + annexes.

US ARMY CORPS OF ENGINEERS (USACE). 2001. Great Lakes and St. Lawrence Seaway Potential Container Transport Savings. Attachment 4. Economic Appendix. Prepared by Tennessee Valley Authority for US Army Corps of Engineers.

WORKING GROUP ON THE INTEGRATED MANAGEMENT OF DREDGING AND SEDIMENTS. 2004. Orientation Document on Integrated Management of Dredging on the St. Lawrence River. Report prepared for the Navigation Consensus Building Committee, 21 p.

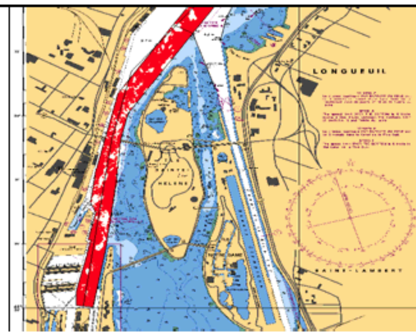
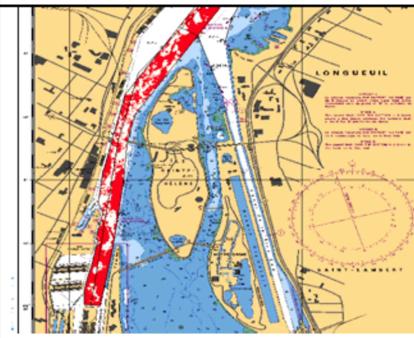
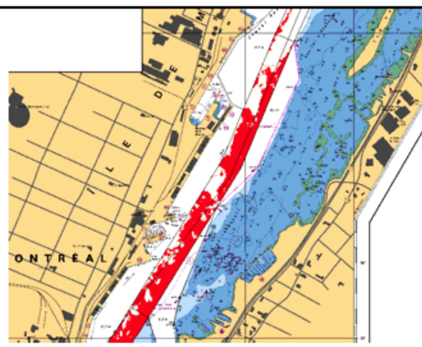
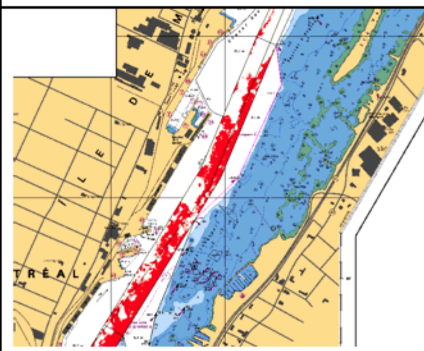
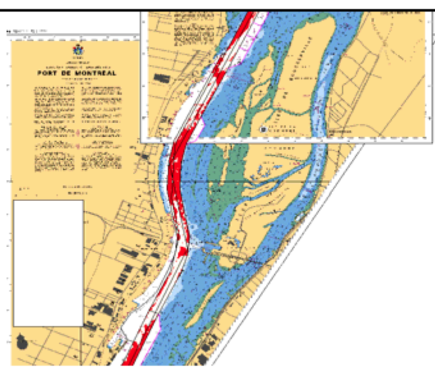
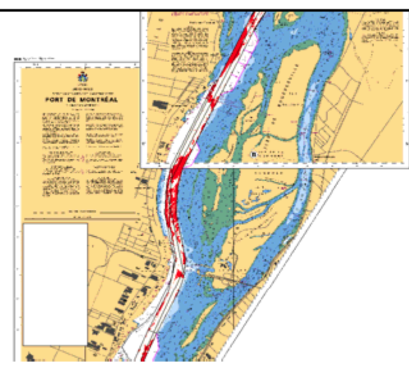
WORLD COMMISSION ON DAMS. 2000. Dams and Development – A New Framework for Decision-Making. The Report of the World Commission on Dams. EarthScan Publications. 356 p.

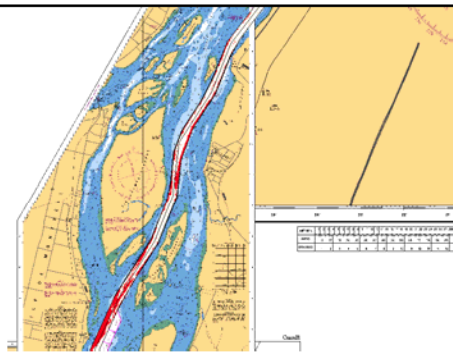
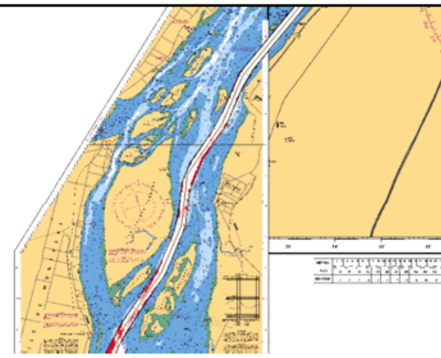
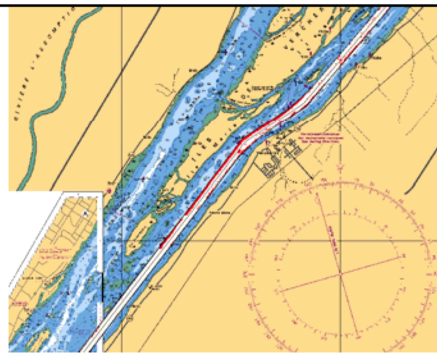
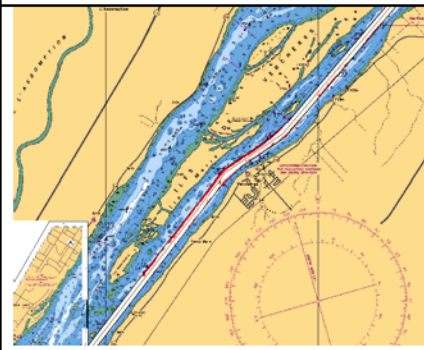
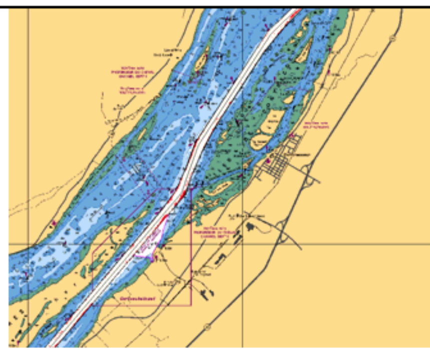
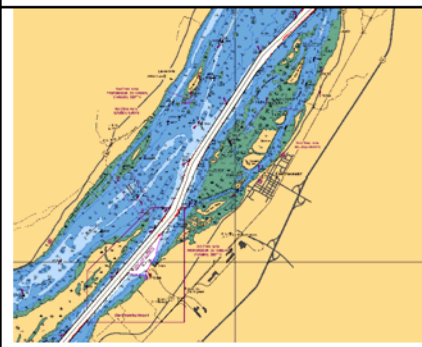
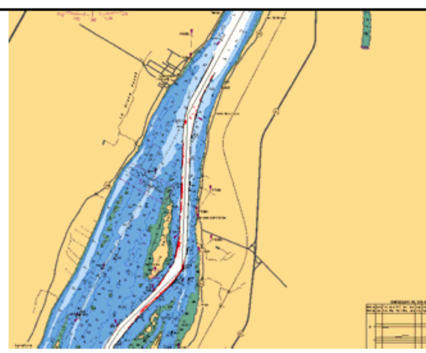
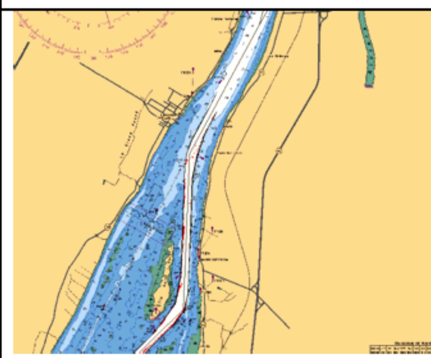
XU, Z., F.J. SAUCIER and D. LEFAIVRE. 2004. Water Level Variations in the Estuary and Gulf of St. Lawrence – A Working Progress Report. Ocean Sciences Branch, Maurice-Lamontagne Institute. Manuscript under review, August 2004.

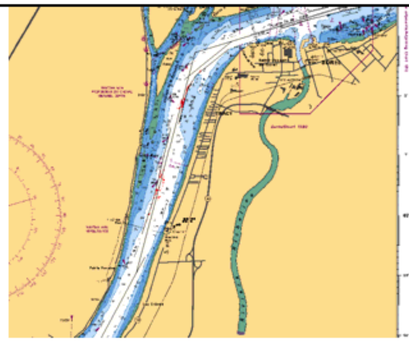
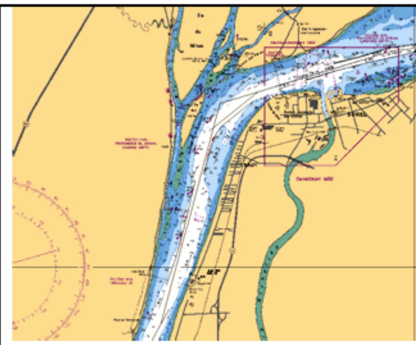
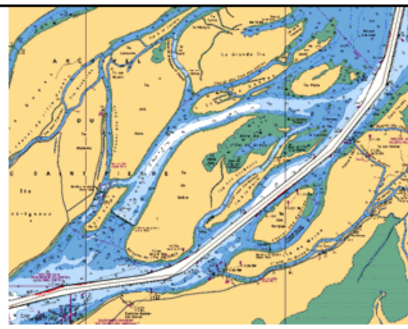
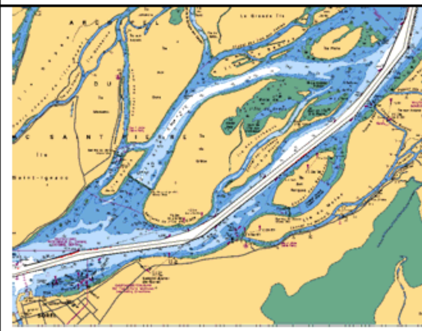
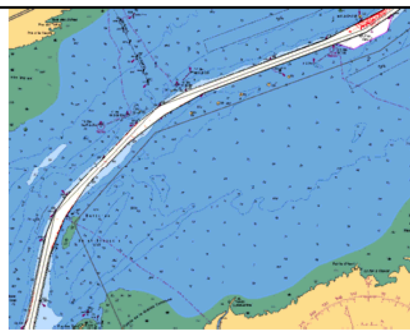
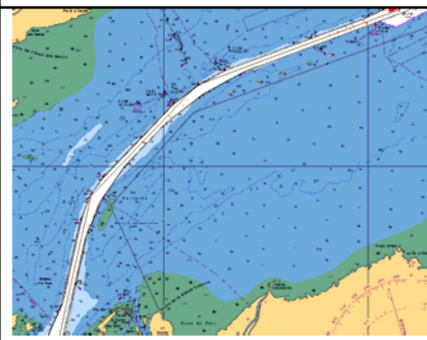
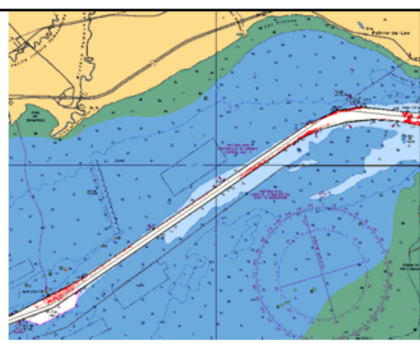
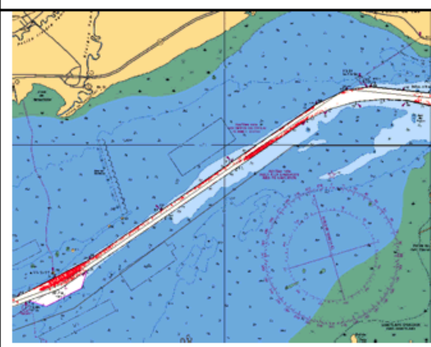
ANNEX 1

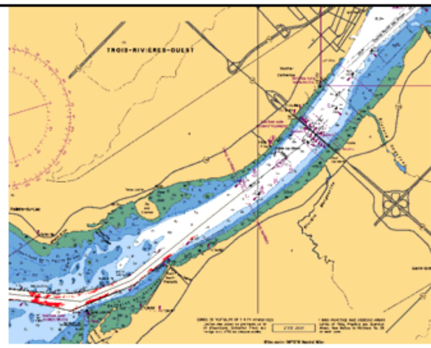
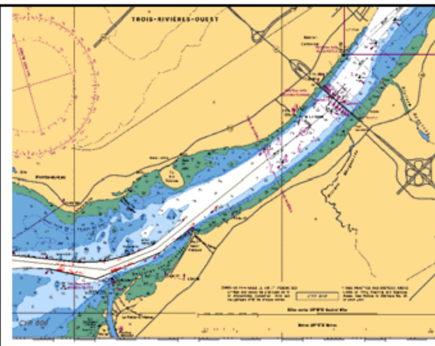
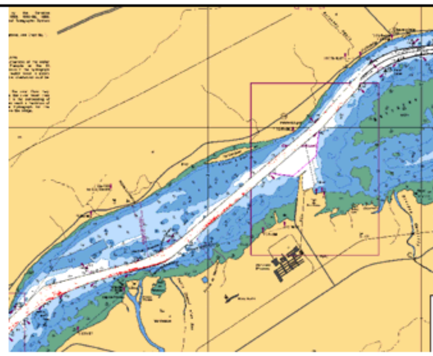
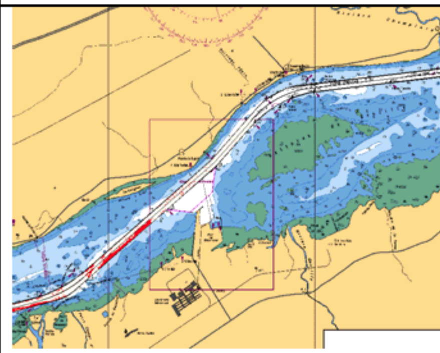
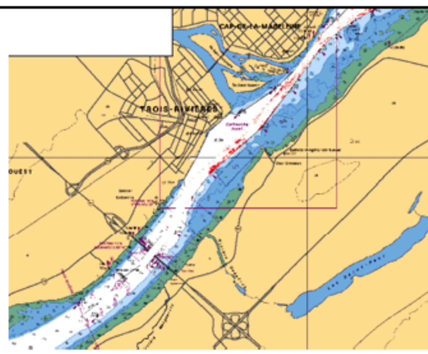
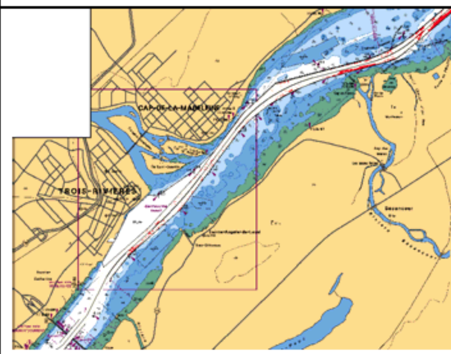
Mapping of the sectors where dredging would be needed

Sectors where dredging would be needed (in red) in the waterway, according to climate scenarios WD and NWD and with reference to year 2001 (Source: Fisheries and Oceans Canada, Coast Guard, Waterways Management, 2005)

Sector	**Scenario**	**Scenario**
	WD	**NWD**
Montréal Sector maintained at 10.7 m		
Montréal Sector maintained at 11.0 m		
Montréal -Sorel Sector maintained at 11.3 m		

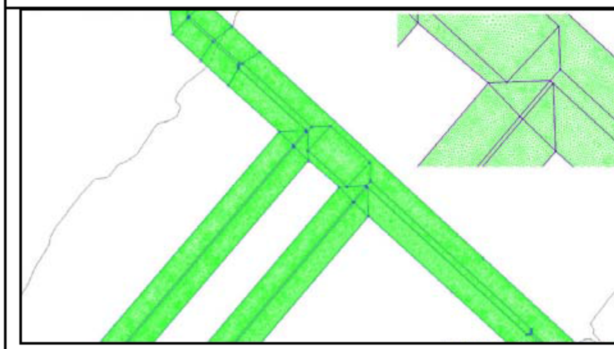
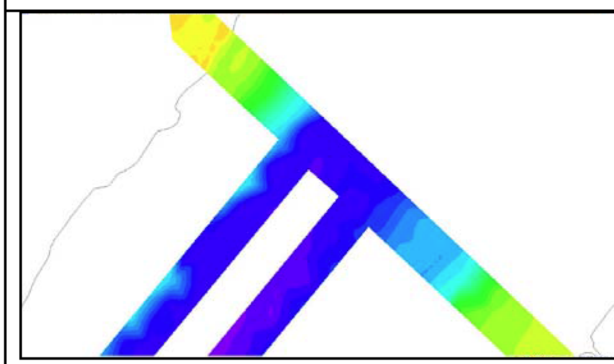
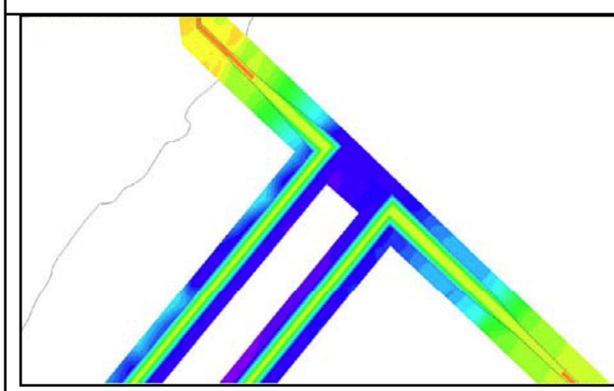
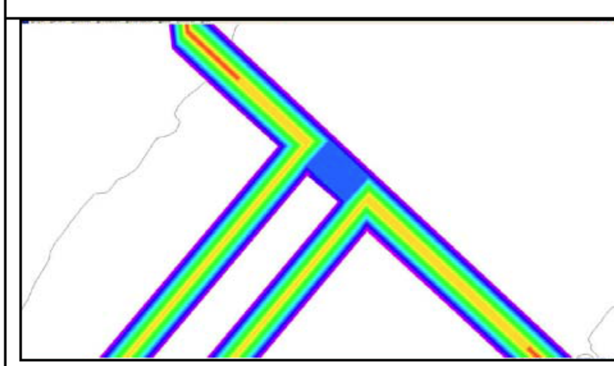
		
		
Lake Saint-Pierre Sector maintained at 11.3 m		
		

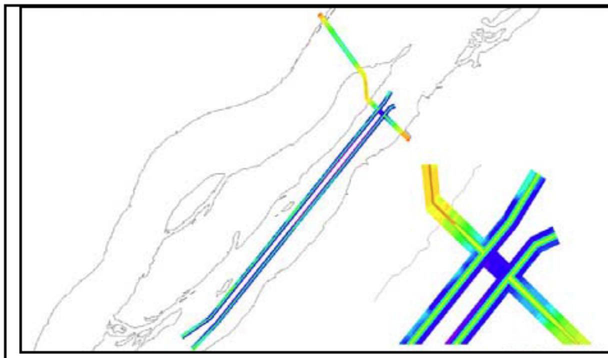
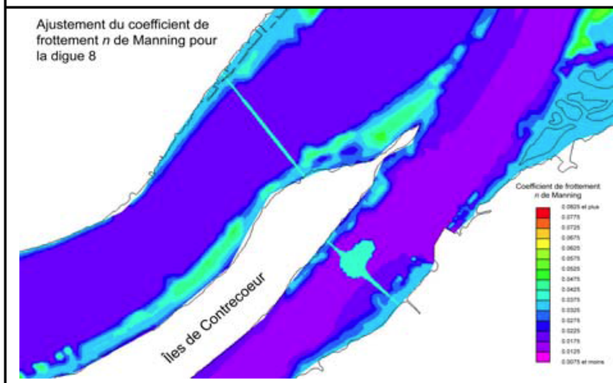
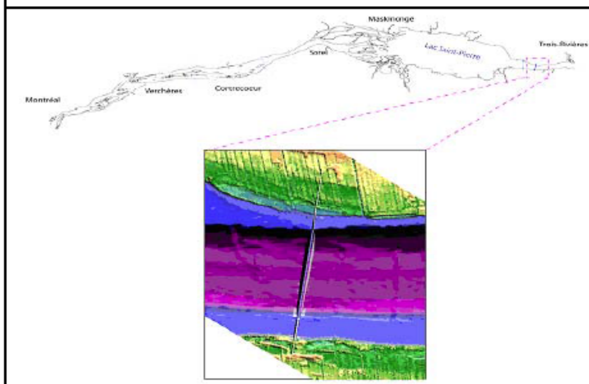
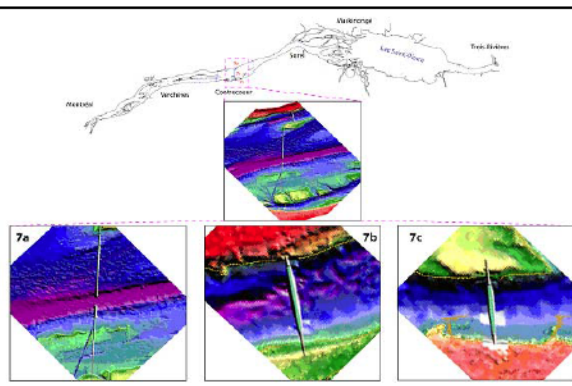
Trois-Rivières–Bécancour Sector maintained at 11.3 m		
		
		

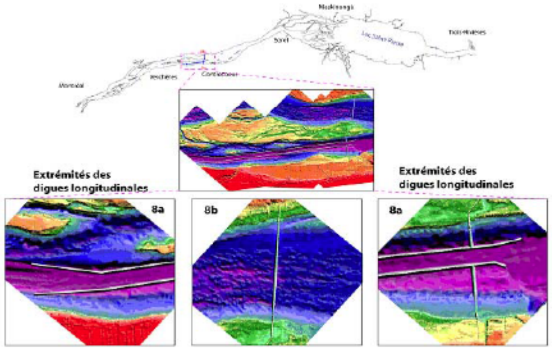
ANNEX 2

Steps for the Design and Insertion of Hydraulic Structures into the Hydrodynamic Model

The steps involved in the design and establishment of hydraulic structures in the hydrodynamic model (from Doyon et al, 2005)

Figure	Description
	Grid that supports the "elevation" information layer for the dyke (Longitudinal dyke #8).
	Topography of the river where the dyke is to be installed.
	Partial view of the DTM of the modified river, including Dyke #8.
	View of the dyke once its design is completed.

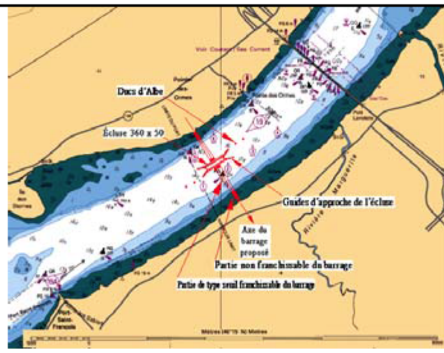
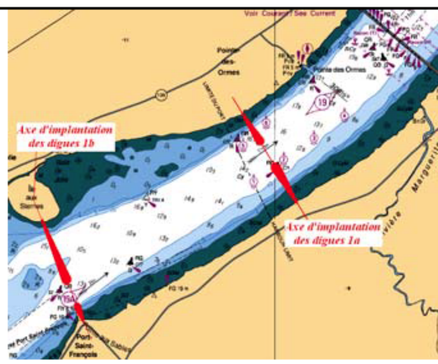
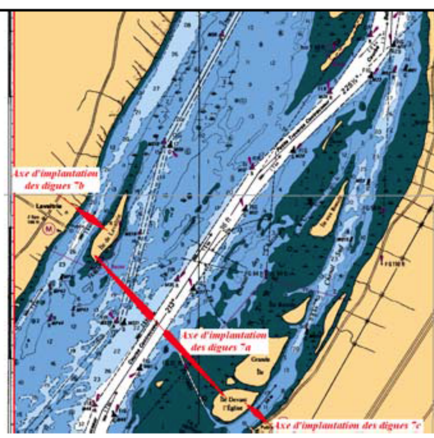
	Illustration of Dyke #8 completed and integrated into the river's DTM.
	Example of adjustment of the local roughness coefficient.
	3D view of the dam with a lock.
	3D view of the Section #7 dykes.

	3D view of the Section #8 dykes (with longitudinal dykes)

ANNEX 3

Features of the Hydraulic Structures

Features of the hydraulic structures (crest height)

Structure	Positioning	Side of crest Insurmountable area (m, NMM)	Side of crest Insurmountable area (m, NMM)
Dam		7.5	3.6
Dykes #1*a* and 1*b*		7.5	3.6
Dykes #7		8.3	5.0

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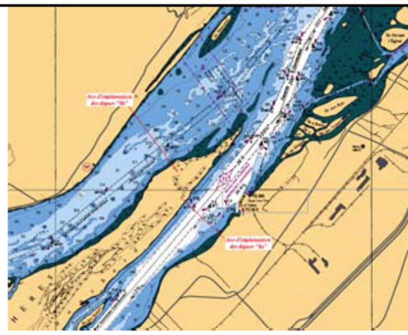
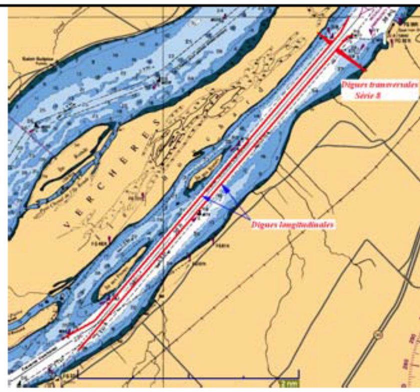
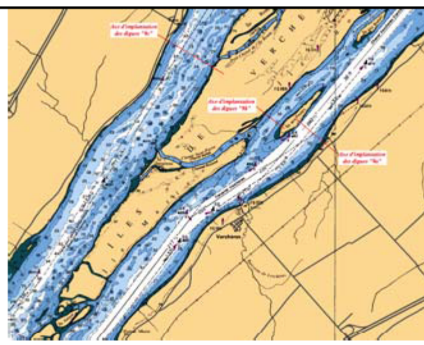
<tr><td>Cross-stream dykes #8</td><td></td><td>8.3</td><td>5.0</td></tr>
<tr><td>Longitudinal dykes #8</td><td>
</td><td>8.3</td><td>5.0</td></tr>
<tr><td>Dykes #9</td><td></td><td>8.5</td><td>5.0</td></tr>
</table>

ANNEX 4

Cost Breakdown – Hydraulic Structures

Cost breakdown of the hydraulic structures (approximate costs) (from Consultants Ropars, 2005)

Dam

Elements	**Unit**	**Quantity**	**Unit price ($)**	**Cost ($M)**
Lock's caissons	m^3	420 000	400	168.0
Caisson foundation (stone)	m^3	120 000	40	4.8
Lock floor (concrete)	m^3	26 000	800	20.8
Lock chamber	Unit	4	11 500 000	46.0
Building for the lock	Global			3.0
Mechanics-hydraulics	Global			15.0
Service area	Global			2.0
Stone in the dykes	Tonne	1 070 000	18	19.3
Concrete in the dykes	m^3	20 000	600	12.0
Waterway signs	Global			5.0
Access roads	Global			6.0
Subtotal - construction				***301.9***
Unforeseen expenditures (20%)				60.4
Organization of the job site (8%)				29.0
Engineering and monitoring (20%)				78.3
GRAND TOTAL				**469.6**

Dykes #1a

Elements	Unit	Quantity	Unit price ($)	Cost ($M)
Stones in the dykes	Tonnes	810 000	18	14.6
Concrete in the dykes	m³	17 000	600	10.2
Scour protection	Global			2.5
Waterway signs	Global			2.0
Access roads	Global			3.0
Subtotal - construction				**32.3**
Unforeseen expenditures (20%)				6.5
Organization of the job site (8%)				3.1
Engineering and monitoring (20%)				8.4
GRAND TOTAL				**50.3**

Dykes #1b

Elements	Unit	Quantity	Unit price ($)	Cost ($M)
Stone in the dykes	Tonnes	985 000	18	17.7
Concrete in the dykes	m^3	19 300	600	11.6
Scour protection	Global			2.5
Waterway signs	Global			2.0
Access roads	Global			3.0
Subtotal - construction				**36.8**
Unforeseen expenditures (20%)				7.4
Organization of the job site (8%)				3.5
Engineering and monitoring (20%)				9.5
GRAND TOTAL				**57.2**

Dykes #8 (Note: The costs for Dykes 7 and 9 are similar)

Elements	Unit	Quantity	Unit price ($)	Cost ($M)
Stone in the dykes	Tonnes	1 003 000	18	18.1
Concrete in the dykes	m^3	8 000	600	4.8
Scour protection	Global			2.5
Waterway signs	Global			2.5
Access roads	Global			4.5
Subtotal - construction				**32.4**
Unforeseen expenditures (20%)				6.5
Organization of the job site (8%)				3.1
Engineering and monitoring (20%)				8.4
GRAND TOTAL				**50.4**

Dykes #8 – longitudinal (costs per kilometre)

Element	Unit	Quantity	Unit price ($)	Cost ($M)
Stones in the dykes	Tonnes	1 150 000	18	20.7
Concrete in the dykes	m^3	150	600	0.1
Scour protection	Global			1.5
Waterway signs (included in the cross-stream dykes)	Global			0.0
Barge rental	Global			0.8
Subtotal - construction				**23.1**
Unforeseen expenditures (20%)				4.6
Organization of the job site (8%)				2.2
Engineering and monitoring (20%)				6.0
GRAND TOTAL				**35.9**

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