REGIONAL ECONOMIC STUDY ON THE POTENTIAL IMPACTS OF CLIMATE-CHANGE-INDUCED LOW WATER LEVELS ON THE SAINT-LAURENT RIVER AND ADAPTATION OPTIONS

Synthesis of the findings from six sector-specific studies

April 2016

Natural Resources Canada / Ressources naturelles Canada

Canada

Fonds vert Québec

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SUMMARY

The potential impacts of climate change on the Saint-Laurent River, its ecosystems and the socio-economic activities that depend on them are a source of concern for many stakeholders in the province of Quebec. Various studies have drawn attention to possible decreases of Great Lakes water levels and more frequent or severe low flows and low-water-level episodes along the Saint-Laurent River.

With support from the Government of Canada (Natural Resources Canada) and the Quebec Government (Green Fund), and with the collaboration of experts and economists from different universities and institutions, Ouranos coordinated a regional economic study of the potential impacts of low water levels and potential adaptation measures for six different sectors of activity directly related to the Saint-Laurent River. The sectors are: 1) maritime transport, 2) municipal water supply and wastewater treatment, 3) ecological services and fishing, 4) recreational boating and tourism, 5) hydropower generation and 6) waterfront property values. The study area covers the Saint-Laurent River between the Québec-Ontario border and Trois-Rivières.

The main objectives of this initiative were to assess the economic costs of the potential impacts of climate-change-induced low water levels on the six target sectors; to conduct cost-benefit analyses of various adaptation options for which adequate information existed; and to complete an integrated analysis of these sector-specific studies to identify common findings.

The general methodology consisted of:

- Producing hypothetical hydroclimatic scenarios over a 50-year period (2015-2064);
- Identifying potential impacts of low water levels for the six target sectors and assessing their economic costs;
- Identifying adaptation options and performing cost-benefit analyses to compare options.

Results of this study suggest that the six sectors of activity could be economically affected by future low water levels episodes. The greatest economic impacts would be associated with the loss of ecosystem services. Adaptation options and their potential costs and benefits were identified and analyzed for three sectors: maritime transport, municipal water supply and ecosystem services.

This study deepened our understanding of the sensitivity of socio-economic activities to low water levels, and contributed to developing and improving methodologies and knowledge needed to support adaptation-planning strategies to cope with climate change. Considering the uncertainty of future climate conditions, the complexity of the Great Lakes and Saint-Laurent system in addition to socio-economic and political changes over the next 50 years, it remains a significant challenge to assess economic impacts over this time period. To support planning and implementation of adequate adaptation strategies, updating this kind of assessment and conducting complementary studies on specific adaptation options will be necessary.

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1. INTRODUCTION

The potential impacts of climate change on the Saint-Laurent River, its ecosystems and the socio-economic activities that depend on them are a source of concern for communities located along the river and for several other socioeconomic stakeholders. Various studies have drawn attention to possible decreases of Great Lakes water levels and more frequent or severe low flows and low-water-level episodes along the Saint-Laurent River.

As part of its program "Improving competitiveness in a context of climate change," Natural Resources Canada's Climate Change Impacts and Adaptation Division supported the Ouranos consortium in conducting a regional economic study of impacts and adaptations to climate change for the Saint-Laurent River[1]. The Quebec government, through its Green Fund, also contributed to this project to help assess the costs of impacts and adaptations to climate change in key sectors of the province's economy.

The two-year economic study focussed on the potential impacts of low levels along the Saint-Laurent River and potential adaptation measures for six different sectors of activity. These sectors are : 1) maritime transportation, 2) municipal water supply and wastewater treatment, 3) ecological services and fishing, 4) recreational boating and tourism, 5) hydropower generation and 6) waterfront property values. Experts and economists from different universities and organizations collaborated with Ouranos to conduct six corresponding sector-specific economic studies.

This report presents the context and objectives of the overall project (chapter 2), the hydroclimatic scenarios underlying the economic analysis (chapter 3), an overview of the findings from the six sector-specific studies (chapter 4), a broader discussion of the findings and limits of the study (chapter 5) as well as the main conclusions, including describing the need for future research.

A similar study on the Great Lakes was carried out by the Council of Great Lakes Region (CGLR) and the Mowat Center for Public Policy Innovation of the University of Toronto, with support of Natural Resources Canada within the same program. A complementary report[2] compares the two studies and presents their differences and common lessons and conclusions.

[1] Natural Resources Canada's support was delivered as part of the collaborative work program of the Economics Working Group of Canada's Climate Change Adaptation Platform.

[2] Desjarlais and Fisher (2016)

2. CONTEXT AND OBJECTIVES

In Québec, the Saint-Laurent River is a major waterway supporting many uses and activities. In recent decades, the potential impacts of climate change on the Saint-Laurent have been a source of concern for many actors and sectors. Many studies have highlighted the possibility of lower flows and water levels during the next several decades. At the turn of the century, studies suggesting a possible decrease of about 40% in the average annual flow raised concerns among experts and users (Mortsch et al., 2000). The years 1999 and 2001 were characterized by particularly dry summers, and new studies indicated once again that lower flows and water levels could be an issue for the coming decades. These studies revised the range of reductions (between -4% and -24%) while highlighting the great uncertainty of these projections (Croley II, 2003). Since then, various hydroclimatic studies have assessed the likely evolution of water inflows in the Great Lakes/Saint-Laurent system. Some of them draw a more moderate picture of evaporation losses due to higher temperatures (Lofgren et al., 2011). Understanding the influence of climate change on the Great Lakes and Saint-Laurent water regime remains characterized by high uncertainty related to the complexity of the system, but it seems to be reasonable to expect lower inflows and episodes of low water levels in the Saint-Laurent.

Various studies, particularly within the work of the International Joint Commission and International Lake Ontario - Saint-Laurent River Study Board, have been carried out on the potential impacts of fluctuating water levels on human uses and natural environments. These studies sought to support the development and evaluation of new regulation plans to provide a better balance among all interests in the Lake Ontario and Saint-Laurent River system. They have helped highlight the sensitivities and vulnerabilities of specific natural environments and industries to low water levels. Few studies, however, have examined the economics of climate change impacts and sector-specific adaptation options on the Saint-Laurent River.

In this perspective, the main objectives of the project presented in this report were to assess the economic costs of the potential impacts of climate-change-induced low water levels on the six target sectors; to conduct cost-benefit analyses of various adaptation options for which adequate information existed; and to complete an integrated analysis of these sector-specific studies to identify common findings.

Figure 1 shows the study area covering the Saint-Laurent River between the Québec-Ontario border and Trois-Rivières (Trois-Rivières is just downstream from Point-du-Lac).

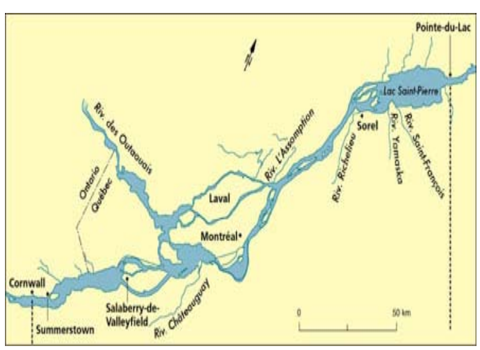

Figure 1. Study area: Saint-Laurent River between the Québec-Ontario border and Trois-Rivières (without the tributaries)

As summarized below and in the following section, the research teams used common economic assumptions and hydroclimatic scenarios. A few different economic-assessment methodologies were nevertheless applied in each study to address sector-specific issues. These methodologies are presented in the corresponding sector-specific final reports.

SUMMARY OF METHODOLOGY AND ASSUMPTIONS

Focus on low water levels

Projected climate change impacts on the Saint-Laurent River are varied and complex**.** This study focused on the impacts of low water levels and on related adaptation options. It does not address issues other impacts possibly related to climate change, such as flooding, erosion or water quality.

Study area

The general study area is limited to the section of the Saint-Laurent River between the Quebec-Ontario border and Trois-Rivières. Some sector-specific studies focused on smaller segments of the river (e.g. Lake Saint Pierre).

Scenarios and time frame

The analysis of impacts and adaptation options in this study refers to three hydroclimatic scenarios: a reference scenario based on historical data and two hypothetical (what-if) scenarios over a 50-year period (2015-2064). The scenarios are closely related to historical observations and no probabilities are associated to them. The methodology underlying these scenarios is presented in the next section of this report.

Impacts and adaptation options

Potential impacts of low water levels and adaptation options were identified through literature reviews, modelling of impacts and analyses of existing data. For some sector-specific studies, field investigation and on-line surveys were conducted to collect complementary data and information. Experts and stakeholders were also consulted to identify or validate impacts and adaptation options.

Cost-benefit analysis

The costs of potential impacts of low water levels within proposed hydroclimatic scenarios were evaluated for all of the economic sectors under consideration. The costs and benefits of adaptation options were quantified for only three economic sectors: maritime transport, municipal water supply, and ecosystem services and fisheries. A set of key assumptions was developed to make all sector-specific studies comparable. Analyses were conducted based on the status quo rather than on projected socio-economic scenarios. The reference year for constant-dollar calculations was 2012. The discount rate applied in sector-specific analyses was 4%, while some of these analyses also conducted analyses using discount rates of 2% and 6%.

3. CLIMATE SCENARIOS[3]

To conduct the economic analyses in a coherent manner, Ouranos prepared scenarios of hydrological conditions for all sector studies.

Various types of climate scenarios can be used for impacts and adaptation studies[4]. The objective of this project was to evaluate the economic consequences of potentially low flows into the Saint-Laurent River, and when possible, to identify and compare adaptation options. The scenarios used present various plausible futures.

3.1 THE GREAT LAKES/SAINT-LAURENT SYSTEM

Understanding and modeling the impacts of changing climate conditions response on the Great Lakes is a challenge for many reasons. It is difficult, for instance, to distinguish between the influences of climatic conditions and those of human interventions when examining observed records such as those associated with the construction of control structures, power-generating stations, locks and canals.

Another challenge is the understanding of the critical role played by evaporation and condensation. The five lakes cover an area of 244,000 km^2—approximately one-third of the total basin's (750,000 km^2). This large lake-to-land ratio makes all processes occurring at the air-water interface (evaporation, condensation, ice formation) much more important than in other watersheds. Moreover, evaporation acts somewhat counterintuitively; net-evaporation rates typically reach their minimum in June and their maximum in January (Ehsanzadeh et al., 2013). Indeed, other than Lake Erie, the lakes are so large and deep that their waters stay relatively cool in summer. When warm, moist air blow, some moisture condenses and falls, making up for evaporation losses during dry periods. Conversely, cold and dry air draws moisture out of the relatively warm lakes when there is no winter ice cover. Early hydrological models of the Great Lakes calculate evaporation using a simple approach based on air temperature. Applying these models to future scenarios that include warmer air temperatures generate higher evaporation rates and sometimes dramatically lower water levels. Recent studies taking into account energy transfers between air and lake-water paint a more moderate picture of evaporation losses due to higher temperatures (Lofgren et al., 2011).

These considerations result in significant uncertainties about future climate and hydrological conditions for the Great Lakes/Saint-Laurent River system. Instead of considering a wide ensemble of future climate conditions, this report uses two plausible what-if scenarios that could influence future water uses.

[3] The content in this section is taken mainly from the report *Étude économique régionale des impacts et de l'adaptation liés aux changements climatiques sur le fleuve Saint-Laurent: Description des scenarios climatiques,* prepared by Huard (2016)

[4] For more information, please refer to the full Huard (2016) report, as well as to the Guide for climate information and the FAQs at www.ouranos.ca.

3.2 CLIMATE SCENARIOS DESCRIBED

The two what-if climate scenarios created for this study explore hypothetical futures for the Saint-Laurent River.

What-if scenario 1 starts with the climate-model simulation from the Canadian Centre for Climate Modelling and Analysis Coupled Global Climate Model (CGCM2) over the period 2040−2069; simulated climatic variables were used to modify observed meteorological records from 1961 to 1990. These synthetic temperatures and precipitations series describing a warmer future were then fed into the Large Basin Runoff Model of the Great Lakes watershed to simulate runoff to and routing between the lakes, including flow-regulation rules. Flow changes in Saint-Laurent tributaries are estimated by transposing expected changes across the Great Lakes watershed to nearby regions.

What-if scenario 2 involves the analysis of an ensemble of Canadian Regional Climate Model (Music et al., 2015) simulations to determine expected changes in the net basin-supply across the Great Lakes. Monthly relative changes in net basin-supply were then transposed to monthly flows at Sorel, delayed by two weeks to accommodate the flow time between Lake Ontario and the Saint-Laurent River.

In the first scenario, average flows decrease over time, with high- and low water levels caused by natural fluctuations. In the second scenario, the defining feature is not average flow, which shows no long-term trend, but the annual cycle, which shows greater seasonal swings. More specifically, low flows during summer and fall become even lower, while winter flows increase.

Both scenarios span the period 2015−2064. In what-if scenario 1, flows gradually decrease and reach important low-flow conditions during the 2040s—similar to the low conditions of the 1960s—and recover only partially thereafter. The annual cycle during this period flattens; spring freshet comes earlier and weakens. In what-if scenario 2, flows decrease rapidly and reach their low point in the 2020s, before recovering to historically high levels and then gradually decreasing again. The annual cycle gradually amplifies over the 50-year period, with decreasing annual minima for the months of August and September. It is often these annual minima, rather than annual averages, that attract the most attention and drive the need for, and implementation of, adaptation measures.

These scenarios have significant implications for the economic analyses, since impacts that appear only at the end of the study period (50 years) result in significantly lower discounted potential costs. Figure 2 shows the annual average flow at Sorel for the historical period and the two what-if scenarios.

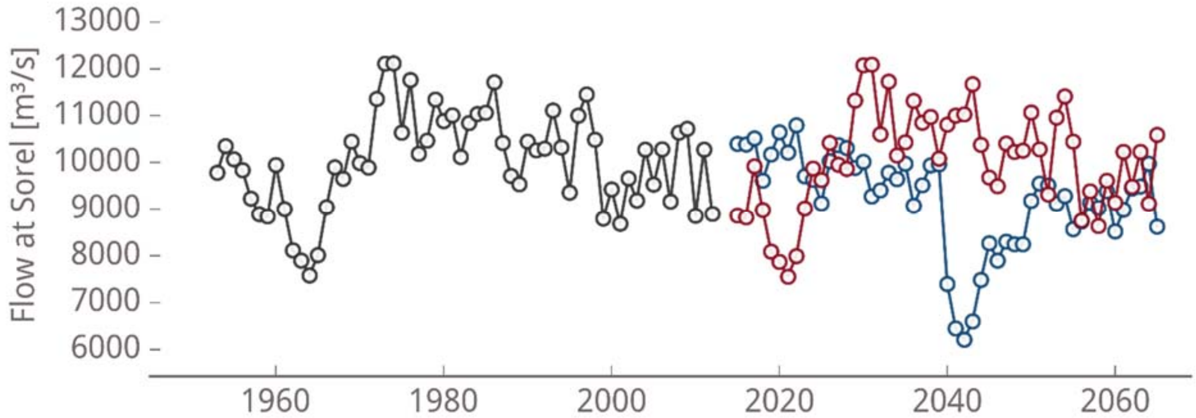

Figure 2. Annual average flow at Sorel for the historical period (black), and what-if scenarios 1 (blue) and 2 (red).

Figure 3 shows the mean annual hydrographs for the reference scenario added to the two what-if scenarios, illustrating the incremental increase in the annual cycle under what-if scenario 2.

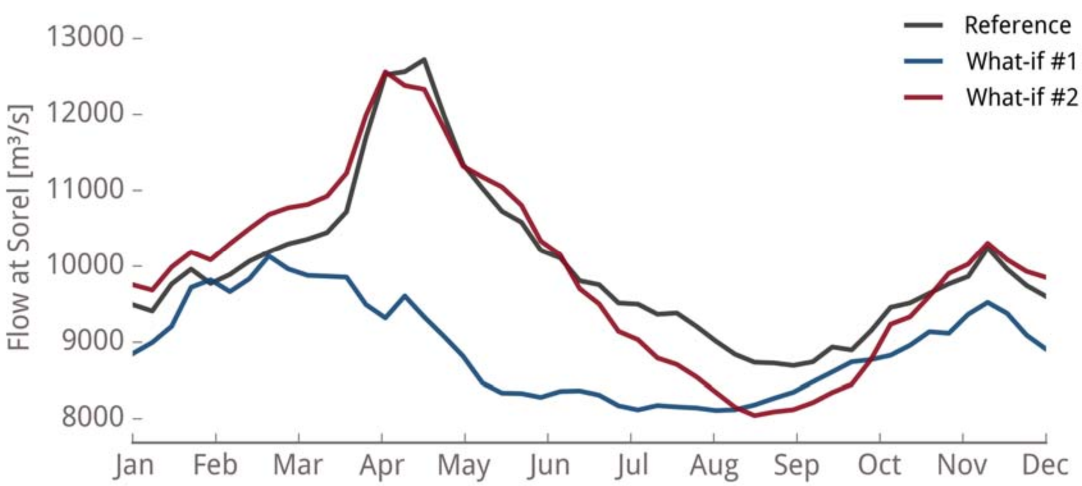

Figure 3. Mean annual cycles of what-if scenarios 1 (blue) and 2 (red) during the 20 last years of the period (2045–2065), compared with those of the reference scenario (grey) over the period 1990–2010.

Figure 4 shows the Saint-Laurent River flows at Sorel corresponding to the reference scenario (black/grey) and what-if scenarios 1 (blue) and 2 (red). What-if scenario 1 predicts severe low water levels during 2040–2045; what-if scenario 2 predicts low-water levels for 2020.

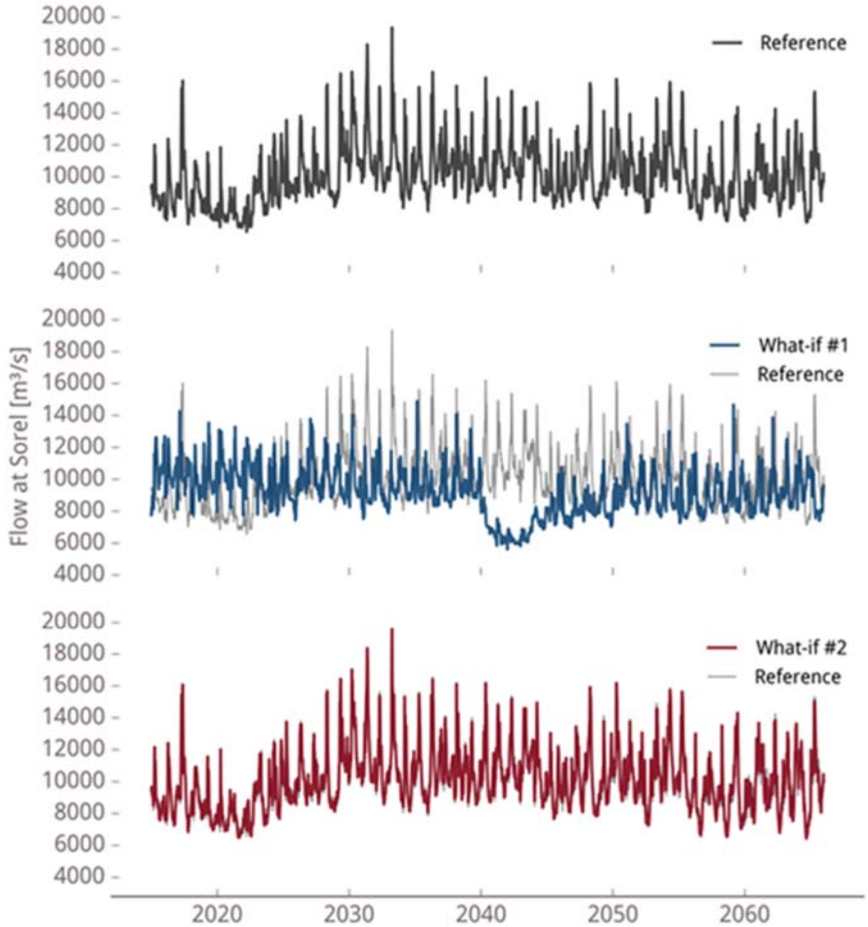

Figure 4. Saint-Laurent River flows at Sorel corresponding to reference (black/grey) and what-if scenarios 1 (blue) and 2 (red).

Although hypothetical, both scenarios are founded on sound climate science and refer to existing studies. The first scenario is based on flow scenarios created in 2004 as part of the International Joint Commission's large-scale study (Mortsch et al., 2005). Although the model and methodology may seem dated, they have been used for many environmental- and economic-impact studies that have contributed to the rich literature of recent years. This is one of the reasons that the scenario was selected for the present study.

The second scenario relies on regional climate simulations of future changes in the Great Lakes' net basin-supply, that is, the region's total water budget. Although there seems to be no consensus for changes in annual net water-supply among the simulations, they all suggest an amplification in the annual cycle, with more water during winter and less during summer.

The scenarios must be credible from the perspective of not only climate science, but also hydraulics. Indeed, some of the economic analyses in this study refer to water flows, while others refer to corresponding water levels. Moreover, the data for flows and levels are required for various locations along the Saint-Laurent (marinas, water-treatment plants, power stations, etc.). The relationship between flows and levels must be as realistic as possible, as well as spatially consistent. To meet this requirement, hydrodynamic simulations of the Saint-Laurent were used. Performed by the Meteorological Service of Canada using HYDROSIM (Leclerc et al., 1995), these simulations provide a static two-dimensional picture of water levels along segments of the Saint-Laurent River for specific flow conditions. These conditions include inflows from Lake Ontario, the Ottawa River, the Saint-Maurice River, the Saint-François River and other tributaries. With access to eight simulations spanning a range of flows from 5,000 to 20,500 m^3/s, it is possible to estimate levels corresponding to specific flows. As an example, Figure 5 shows simulated water depth corresponding to two of these eight hydrodynamic simulations.

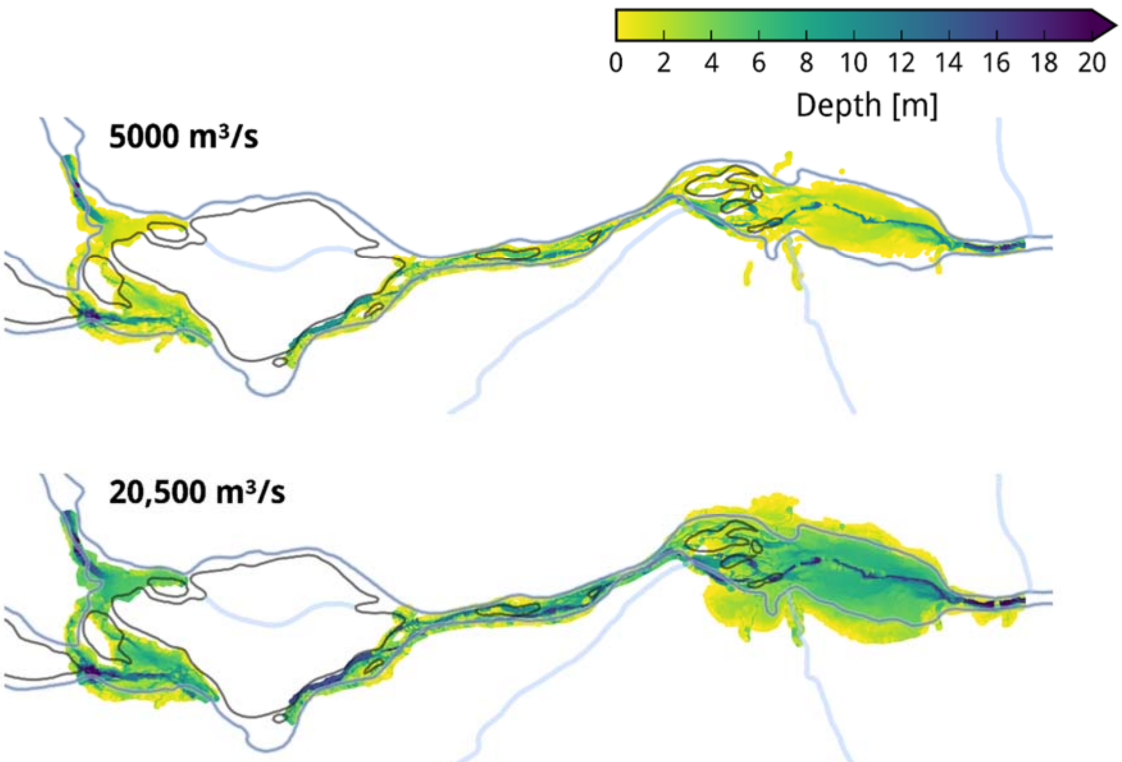

Figure 5. Simulated water depths for two of the eight hydrodynamic simulations. These simulations are used to link flow values at Sorel with water levels elsewhere. The domain covers the Saint-Laurent from Beauharnois to Trois-Rivières, except for the Lachine rapids.

4. SECTOR-SPECIFIC ECONOMIC STUDIES

The following section summarizes findings of studies of specific sectors: maritime transportation; municipal water supply and wastewater treatment; ecosystem services and fisheries; boating and related touristic activities; hydropower generation; and waterfront-property values.

4.1 MARITIME TRANSPORT[5]

Maritime transport and overall economic growth are closely linked. Global freight-distribution systems rely on maritime transport to move large volumes of goods over long distances at relatively low cost. The globalization of the industry is apparent through a set of routes that cover all oceans.

More than 75% of Quebec industries are located along or near the Saint-Laurent River; many use the river as a trade route.
Since 1970, the tonnage of world trade transport by sea has more than doubled. In 2012, more than 9 billion tons of goods were transported by sea (UNCTAD, 2013). Since the 90s, the growth rate in the volume of world merchandise exports exceeds that of world economic output. Clearly, port systems must adapt to the increase in traffic. In 2012, the consulting firm ADEC calculated that the maritime industry's direct, indirect and induced operating expenses and investments at Montreal alone contribute $ 751.8 million to Québec's gross domestic product (ADEC, 2012) each year. This figure does not include provincial and federal tax revenues through wages and various other para-fiscal charges (Employment Insurance, RRQ, CSST, etc.).

Climate change impacts could be important. Most forecasts project changes in the type, volume, seasonality and distribution of precipitation that will affect flows and water levels in navigable waterways, and consequently commercial shipping.

4.1.1 EXPECTED IMPACTS OF CLIMATE CHANGE

This study focuses on the impacts of low water levels below chart datum (the low-tide level listed on navigation charts) on the transport capacity of container ships travelling the Saint-Laurent. It assumes that lower levels would limit capacity. The standard measure of shipping capacity is a TEU (20-foot equivalent unit); the loss of a TEU translates into $373 worth of lost revenues for a ship. The economic impacts for the scenarios described in the study are measured using a discount rate of 4% per year.

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[5] The content in this section is taken mainly from the report *Étude économique régionale des impacts et de l'adaptation aux changements climatiques sur le fleuve Saint-Laurent : volet transport maritime,* prepared by Comtois et Slack (2016).

Based on the studies by D'Arcy et al. (2005) and the Institute of Water Resources, as well as the figures currently used by Transport Québec concerning the potential loss of cargo capacity due to decreased water depth, three different hypotheses were investigated.[6]

Hypothesis 1

- a loss of 3.8 containers per cm of water below chart datum

Hypothesis 2

- a loss of 6.0 containers per cm of water below chart datum

Hypothesis 3

- a loss of 11.5 containers per cm of water below chart datum

As with other sector-specific studies, three scenarios were used: one based on historical data and two what-if scenarios.

In the reference scenario, navigation in the Port of Montreal would be affected by low water levels for approximately 1,766 days during 2015–2064 (approximately 10% of the time). Based on the analysis of level variations, the frequency of levels below chart datum would be greatest during 2015–2024 and 2055–2064.

The following table summarizes estimated economic impact of each scenario.

Table 1. Monetary impacts of low water levels from 2015–2064 according to the different scenarios (4% discount rate; in dollars)

Hypothesis	Total cost (2015-2064)		
	Reference Scenario	What-if 1	What-if 2
H 1 (3,8 ETF)	29,087,890	69,975,299	38,715,802
H 2 (6 ETF)	45,928,247	110,487,315	61,130,215
H 3 (11,5 ETF)	88,029,141	211,767,354	117,166,245

According to the reference scenario, the estimated economic impacts over 50 years range from $29 million to $88 million. Under what-if scenario 1, low water levels would affect navigation at the Port of Montreal approximately 22% of the time—on approximately 4,040 days during 2015–2064. Water levels below chart datum would be more frequent during the second half of the period. The estimated economic impacts of what-if scenario 1 over the 50-year period ranges from $69 million to $ 211 million, as shown in Table 1. Under what-if scenario 2, low water levels would affect the Port of Montreal approximately 11% of the time (on 2,080 days), with levels below chart datum occurring more frequently during 2015–2025 and 2055–2064. The estimated economic impacts under what-if scenario 2 range from $38 million to $117 million.

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[6] See Comtois and Slack's (2016) full report for more information on these hypotheses.

All scenarios indicate periodic and temporary decreases below the chart datum at the Port of Montreal. A drop in water levels affects ship-loading capacity, traffic diversion, modal shifts and fluctuations in inventory volumes. These impacts highlight the importance of identifying and quantifying adaptation measures for commercial shipping.

4.1.2 POTENTIAL ADAPTATION MEASURES

The study identified four main adaptation measures for maritime roads, ports and fleets: 1) dredging 2) construction of structures 3) the partial transfer of port activities and 4) minimizing the under-keel clearance of ships[7]. The initial TOPSIS analysis[8] indicates that the two measures that rank the highest are minimizing under-keel clearance and dredging. The two other options are much more costly and have greater negative socio-economic and environmental externalities (D'Arcy et al., 2005). The criteria used in the TOPSIS analysis include:

- The ability of the adaptation option to respond to extended periods of water levels below chart datum;
- The costs required to implement measures to adapt to low water levels;
- The negative social and environmental externalities associated with implementing adaptation measures;
- The effect of the measure on competitive advantage for navigation and port activities during low-water-level episodes.

Table 2 presents a cost-benefit analysis for three options: dredging, minimizing under-keel clearance and a combination of both. The dredging option considered an increased depth of the 40 centimeters for the waterway. The second option examined optimizing under keel clearance by improving the monitoring and forecasting capacities for water levels. This measure, like the first one, allows increased ship capacity. Several costs-benefit analyses were also performed on investment costs, environmental costs, the number of containers lost per cm of water levels below chart datum, the discount rate applied and the depth of dredging required.

[7] Under-keel clearance refers to the minimum clearance between the deepest point of the vessel and the bottom in still water. This adaptation strategy involves improving monitoring and prediction of water levels to determine a higher resolution bathymetry to optimize navigational routes.

[8] TOPSIS is a multi-criteria analysis. See Comtois and Slack's (2016) full report for more details.

Table 2. Discounted costs and benefits associated with three adaptation strategies (in dollars)

Adaptation measure		Reference scenario	What-If scenario #1	What-If scenario #2
Dredging only	Total benefits (saved transportation costs and environmental benefits)	28,110,415	45,764,278	34,903,994
	Total costs (dredging, capital costs, maintenance, decontamination, habitat compensation)	8,764,544	8,764,544	8,764,544
	Net present value	**19,345,871**	**36,999,734**	**26,139,450**
	Cost-benefit ratio	**1:3**	**1:5**	**1:4**
Under keel clearance	Total benefits	2,0791,859	27,621,521	23,219,766
	Total costs	3,248,215	3,248,215	3,248,215
	Net present value	**17,543,644**	**24,373,306**	**19,971,551**
	Cost-benefit ratio	**1:6**	**1:9**	**1:7**
Combination of dredging and under keel clearance	Total benefits	28,952,058	58,367,216	38,246,762
	Total costs	12,012,756	12,012,756	12,012,756
	Net present value	**16,940,302**	**46,354,460**	**26,234,006**
	Cost-benefit ratio	**2:5**	**1:5**	**1:3**

Under what-if scenario 1, the greater net present value is associated with the combined solution (dredging and minimizing under-keel clearance). This option would save $46.4 million in transportation costs compared to $37.0 million for the dredging only option and $24.4 million for the under keel clearance option. Under what-if scenario 2, the highest net present value is again associated with the combined option, although only by a small margin compared to the dredging only solution (respectively 26.2 million and 26.1 million). In this case as well, the cost benefit ratio is better with the under keel clearance solution given its lower costs.

Sensitivity analyses that consider deeper dredging and higher under keel clearance costs change the results and the order of the preferred option. For instance, the higher cost for under keel clearance would make the dredging only option more interesting from an economic standpoint. It should be noted that these analyses may not include the full value of environmental impacts and do not take into account social impacts.

4.2 MUNICIPAL WATER SUPPLY AND WASTEWATER TREATMENT[9]

The Saint-Laurent River is the primary source of drinking water for nearly 2.5 million people; the river feeds 27 water supply treatment plants. Nine plants located upstream of Hydro-Québec's Beauharnois dam were excluded from the analysis[10] since they draw water from Saint-François Lake. Lake water levels are regulated to ensure navigability along the Saint-Laurent Seaway; they also ensure adequate water levels for the nine plants[11]. The study area also includes 28 plants that treat wastewater generated by approximately 2.5 million people and discharge the effluent into the Saint-Laurent River.

4.2.1 EXPECTED IMPACTS OF CLIMATE CHANGE

Decreases in water levels due to climate change could make it more difficult for plants to pump, treat and produce potable water.

Minimum water levels in the Saint-Laurent River are required to overcome head loss in intake structures connecting water-catchment areas and raw-water pumping wells. In this study, the impact of low water levels was evaluated based on the designed production capacity of water-treatment plants. Drinking water shortages may occur if levels fall below those required to maintain designed production capacity. Furthermore, minimum river levels are also required to ensure water intakes are submersed deep enough to prevent swirling, as well as clogging or jamming due to floating debris. Therefore, the magnitude of a water shortage was estimated based on the difference between a plant's designed production capacity and the level of production it can sustain at low water levels. Drinking water production capacity may also be reduced if minimum river water levels are not sufficient to ensure adequate submersion of intake structures.

This study estimated the minimum levels theoretically required to ensure the production capacity of each plant using technical data from a 2004 study by Carrière and Barbeau (2004); data collected from 18 of the water-treatment plants; head-loss calculations for intake structures using the Hazen-William Equation; and minimum submersion levels of one metre (Brière, 2000) or 1 to 1.5 times the diameter of the intake pipe (Knauss, 1987). These minimum levels were then compared with projected levels in the three hydroclimatic scenarios to determine whether any water production shortages would occur.

The analysis suggests that two drinking-water plants could experience water shortages during the timeframe considered, and six additional plants are vulnerable due to either reduced safety margins or lack redundancies for intake systems. While no water shortages were projected to

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[9] The content in this section is taken mainly drawn from the report *Étude économique régionale des impacts et de l'adaptation aux changements climatiques sur le fleuve Saint-Laurent : volet eaux municipales,* prepared by Chan et al. (2015).

[10] These plants are, from west to east, St.-Régis (N.Y.), St-Régis (QC), Saint-Zotique, Les Coteaux, Coteau-du-Lac, Grande-Île, Salaberry-de-Valleyfield, Pointe-des-Cascades and Beauharnois. Note that the 2-D hydraulic modelled used in this study does not cover Lake Saint-François.

[11] The 18 municipal drinking water treatment plants examined in this study are located in Bécancour, Berthierville, Candiac, Châteauguay, Contrecoeur, Dorval, Île Perrot, La Prairie, Lachine, Lavaltrie, Longueuil (local, regional and industrial plants), Montréal (Atwater and Des Baillets plants), Pointe-Claire, Régie de l'eau de l'ïle Perrot, Régie intermunicipale de l'eau potable de Varennes, Sainte-Julie et Saint-Amable (RIEP), Verchères.

occur for these six plants, operation under sub-optimal conditions reduces their ability to cope with other potential risks (e.g. accidents, equipment failure).

The main impact of low water levels is decreased water production capacity. Other impacts of low levels include degraded quality of source water and the resulting need to modify treatment procedures to ensure potable water. Potentially, all water plants considered in this study would be affected by reduced water quality in the Saint-Laurent due to decreased levels and flows. However, the study could not quantify these impacts because of a lack of data on the effects of climate change on the biophysical factors that influence water quality (for example, water temperature, turbidity, increased growth and decomposition of aquatic plants and algae).

The costs of impacts linked to water shortages were estimated by considering a proportional distribution/allocation between the different categories of users (e.g. residential, industrial and commercial) in the sectors covered by the two most vulnerable water plants. The volume of the estimated water shortage is multiplied by the value of water associated with each of these uses. Potable water can also serve other purposes, such as recreational activities (e.g. water parks, pools, etc.), but the quantities are generally less significant and are therefore not considered in this analysis.

Of the two plants expected to experience water shortages, the study estimated that one plant would experience a one-week water shortage only once during the 50-year timeframe. This would translate into a reduction of approximately 13% of the plant's production capacity. The cost of the shortage was estimated at approximately $3,100 ($2,700–3,600) in current values discounted at 4%. For the second plant, the frequency and intensity of water shortages are more significant: problems could occur 14 times during both summer and winter, and last up to several weeks. Its designed daily production would be reduced by up to 4%, with the total economic impact estimated at $53,700 ($46,200–63,200) in 2012 values discounted at 4%. Water shortages for both plants were projected to occur only under the driest of the three hydroclimatic scenarios under consideration.

For municipal wastewater treatment, a reduction in water levels could potentially affect the capacity of the river to adequately dilute effluent in addition to non-treated overflows. This could affect a number of uses downstream from wastewater-discharge points (e.g. water intake systems, swimming, fishing, etc.) and degrade ecosystems (e.g. quality of aquatic habitats, biodiversity).

However, a lack of data on the capacity of the Saint-Laurent River to adequately dilute wastewater effluent impeded a quantitative and economic analysis. In light of this, the study undertook a more qualitative evaluation of the performance impacts under the hydroclimatic scenarios. For most of the stations in the study area, it was hypothesized that future flow volumes would likely exceed the minimums required to ensure adequate dilution. This may be less true for some stations with larger volumes of effluent. Due to the qualitative hypothetical nature of these conclusions, it was not possible to estimate the cost of these impacts. Adaptation solutions were also not identified for these issues.

4.2.2 POTENTIAL ADAPTATION MEASURES

For four of the eight plants presenting some vulnerability, adaptation options generally include modifying or replacing existing pumps with those capable of functioning at lower levels and increasing or reconfiguring intake systems to reduce the risks of head loss and hydraulic constraints. The study estimated the capital costs of these solutions and assumed that existing budgets would cover their operation.

For three of the eight water plants, no adaptation solutions were identified since their situation was not considered severe. This is due in part to the fact that during periods of low water levels, they could still operate safely at full production capacity, or that additional operational procedures could be put in place.

Benefits associated with these adaptation solutions are the savings linked to averted water shortages, as well as securing water-supply systems. The latter benefit is not quantified in this study since the method required to estimate this value (e.g. undertaking a willingness-to-pay study) was outside the scope of this study. Table 3 summarizes the costs and benefits of implementing the identified adaptation solutions.

Table 3. Summary of costs and benefits for adaptation solutions

Water treatment plant	Adaptation solutions	Approximate costs in $	Benefits
1	Modify or replace existing pumps	250,000	$8,930 and increased reliability of system
2	Replace existing pipes, install submersible pumps	5,250,000	$155,700 * and increased reliability of system
3	No measure anticipated based solely on hydraulic constraints	-	-
4	Insufficient information to identify appropriate adaptation measure	-	-
5	Modify valves in the pumping well; enlarge and lower main opening before grill of first intake	200,000	Increased reliability of system
6	No measure anticipated based solely on hydraulic constraints	-	-
7	No measure anticipated based solely on hydraulic constraints	-	-
8	Reinforce or enlarge intake pipe of first intake	3,000,000	Increased reliability of system

The following table summarizes the cost-benefit analysis during a 50-year timeframe for the two plants most susceptible to shortages, discounted at 4%.

Table 4. Summary of the cost-benefit analysis of the adaptation solutions (in dollars)

NPV 4 %, Horizon 50 years	Water plant 1	Water plant 2
Costs	109,710	2,303,880
Advantages: avoided water shortages (Scenario 1 only)	3,100	53,730
Net costs	**106,610**	**2,250,150**
C/B ratio	**35:1**	**42:1**

The analysis shows that the net costs of implementing the adaptation solutions are not economically efficient if only climate change impacts are considered. Indeed, if only the water shortages due to climate change are considered, the net costs are about $100,000 for water plant 1 (C:B ratio of 35:1) and more than $2.2 million for water plant 2 (C:B ratio of 42:1). Applying discount rates of 2% and 6% do not change these results significantly. It is important to note that the assessment of these net costs is based on the values of water established in this study for the various uses of potable water (i.e. residential, commercial and industrial). The values would have to be significantly higher to affect the cost-benefit ratio.

A sensitivity analysis was conducted based on an incident at a large water-treatment plant in the region that resulted in the total loss of supply for several days. In this case, the cost to supply residents with bottled water during the outage totalled approximately $745,000, or about $557/m^3 (in 2012 dollars). If this water value were applied to the projected shortages at the two plants under consideration, the net advantages would be around $19 million (C:B ratio of 9:1). Nonetheless, this example would be difficult to apply to the original analysis, because climate change impacts are projected to cause only partial rather than complete disruptions of water supplies. For this reason, the values used in the original analysis are considered to be more accurate.

Despite the fact that the costs of adaptation solutions seem prohibitively high compared to the costs of potential shortages, the proposed solutions would also help alleviate other issues, such as increases in demand, rehabilitation and renewal of infrastructure, as well as reliability improvements.

This study identified drinking-water plants that are vulnerable to low water levels in the Saint-Laurent River. It did not, however, assess biophysical factors that influence raw water quality (e.g. temperature, turbidity, algae, pollution, etc.) and that can block intake systems (e.g. frazil ice, debris). The potential costs of these impacts were therefore not calculated and adaptation solutions not identified. Consultations with operators and literature on the subject (Carrière & Barbeau, 2004; Hudon, 2011), however, underscore the importance of these factors in the production of drinking water. Future studies should focus on these factors and adaptation solutions.

4.3 ECOSYSTEM SERVICES AND FISHING[12]

This sector-specific study focusses on the Lake Saint Pierre area and the ecosystem services it provides. With a length of nearly 30 km and a width of 13 km, Lake Saint Pierre covers an area of approximately 500 km^2 and accounts for more than 40% of all wetlands found along the Saint-Laurent River (MDDEFP, 2013). The Sorel Islands form the largest archipelago in the Saint-Laurent with 103 islands (Municonsult, 2002). With an average depth of 3 metres, excluding the shipping channel dug through its centre, Lake Saint Pierre is the largest freshwater floodplain in Quebec (MDDEFP, 2013). The lake's unique ecosystem is characterized by a great diversity of wetlands that provide habitat for many plant and animal species, including 72% of the province's birds species (288 species) and 70% of Quebec's species of freshwater fish Quebec (79 species) (MDDEFP, 2013). Given its ecological importance, Lake Saint Pierre was designated a Ramsar site in 1998 and declared a UNESCO biosphere reserve in 2000.

Communities on Lake Saint Pierre and visitors to the area benefit from the lake's ecosystems through the provision of material goods, such as fish for consumption, and eco-regulating services, such as flood control and water purification. The lake's ecosystems also generate employment and income through the tourism sector.

In recent decades, the integrity of the lake's ecosystem has been deeply affected by human activities in its tributary watersheds and its floodplain, resulting in loss of fauna and flora (MDDEFP, 2013). Water quality also remains a concern in several areas, despite improvements brought about by government programs. During the past two decades, the population of species such as perch has declined so much that a fishing moratorium was introduced in 2012.

Climate change has the potential to affect the hydrological regime of the lake through earlier flooding and more severe droughts. Fish-mortality episodes linked to elevated water temperatures, such as those observed in 2001, may also occur more frequently. Conciliation between biodiversity conservation and maintaining or developing certain activities practiced on the lake, such as fishing, could be more difficult to achieve under changing climate conditions.

In recent years, and especially since the publication of the Millennium Ecosystem Assessment in 2005 (MEA, 2005), the concept of ecosystem services has been increasingly used to illustrate the benefits of biodiversity and ecosystems for human communities. Ecosystem services are essential to human well-being and, in many cases, cannot be replaced by human-made products (Daily 1997; De Groot, 2002; MEA, 2005).

From an economic standpoint, the findings of several studies published in the last decade show that the real contribution of ecosystems to human well-being is poorly evaluated, leading to the misuse of natural capital and to the deterioration of the environment (MEA, 2005; TEEB, 2010). One reason for this is the difficulty of evaluating the economic impacts of non-market ecosystem services. Consequently, ecosystem services are rarely expressed in economic terms and cannot be readily integrated into decision-making tools. To overcome this problem, tools and methods for economic evaluation of non-market ecosystem services have been developed in recent decades (Dupras et al. 2013).

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[12] The content of this section is taken mainly from the report *Étude économique régionale des impacts et de l'adaptation aux changements climatiques sur le fleuve Saint-Laurent : volet services écosystémiques,* prepared by He et al. (2016).

A cost-benefit analysis of climate change adaptation measures to preserve sport fishing and ecosystem services at Lake Saint-Pierre was conducted. An economic analysis to assess both the market and non-market benefits arising from sport fishing and other key ecosystem services associated with the lake was followed by a comparative analysis of the costs of implementing various adaptation strategies to maintain these services.

4.3.1 EXPECTED IMPACTS OF CLIMATE CHANGE

The natural heritage of Lake Saint-Pierre offers several ecosystem services. However, climate change could affect the ecosystems and the services they support.

Carignan (2004) showed that the future hydrological conditions of Lake Saint-Pierre could resemble those observed during the 1999–2004 period, with low spring floods and sudden winter and summer floods, and very dry years alternating with near-normal levels. These new conditions would decrease water levels and reduce the lake's floodplain. The partial drying of the lake would make its shores more accessible and thus more exposed to human activities. In summer, more pronounced droughts and lower water levels are expected (MDDEFP, 2013). The potential consequences on wildlife and their habitats could be important.

According to the what-if scenarios developed by Ouranos, it was assumed that similar water-level conditions could happen towards the second half of the study period or even earlier[13]. These conditions would amount to a sudden reduction of the Lake Saint-Pierre water level (between 30 to 40 centimeters on average) and a 10 to 13% decrease of its average 3 metre depth. These decreases would be combined with greater seasonal variations (both low and high water levels). The potential impacts associated with the what-if scenarios are qualitatively described in He et al. 2016 for the following aspects:

- wetlands and riparian vegetation
- water quality
- fish fauna
- avifauna
- reptiles and amphibians
- recreational and tourism services

4.3.2 POTENTIAL ADAPTATION MEASURES

To determine the economic benefits of adaptation strategies, two questionnaires were used to assess the market and non-market economic benefits that Quebecers assign to ecosystem services and goods, including sport fishing, on Lake Saint-Pierre. The questionnaires collected respondents' socio-economic information, and gauged their attitudes toward the environment, their knowledge of the lake, their expenses when visiting the area, and their willingness to pay for improvements to Lake Saint-Pierre conditions.

Six different adaptation measures (or strategies) were more thoroughly investigated.

[13] This team referred to the scenarios in a slightly different way, looking at specific periods within the 50-year time-frame. In one scenario (A), low water levels are projected for early in the period and in the second scenario (B), low water levels are projected only closer to mid-century. The scenarios are renamed to avoid any confusion with the two what-if scenarios used in the other studies.

1) Restore riparian areas around lake Saint Pierre to reduce encroachment by human activities.
2) Restore floodplains around lake Saint Pierre to reduce encroachment by human activities.
3) Change agricultural practices to improve water use and reconcile agricultural activities and wildlife protection.
4) Increase the efficiency and capacity of wastewater treatment by municipalities.
5) Protect and restore habitats for threatened or vulnerable species.
6) Educate and raise public awareness.

4.3.3 THE ECONOMIC BENEFITS OF ADAPTATION STRATEGIES

Table 5 shows the costs of proposed adaptation measures. The various scenarios (optimistic, median and pessimistic) refer to a review of the literature and expert judgement on the range of costs for the implementation of those measures, multiplied by the extent of surface required to compensate the impact of climate change expressed in ghectars or kilometers.[14] For example, controlling common water reed over 5,000 ha is estimated to cost between $63 million and $126 million.

Table 5. Total cost of adaptation over 50 years (2016–2064) with an adjusted to 4% discount per year (in millions of 2012 dollars)

Adaptation measures	Optimistic scenario (M $)	Median scenario (M $)	Pessimistic scenario (M $)
Restoration of riparian zones	24.9	32.6	40.2
Restoration of the floodplain	89.6	129.6	150.9
Change agricultural practices	16.8	67.0	368.6
More efficient wastewater treatment	198.8	298.2	397.7
Protection and restoration of habitats	4.5	9.0	13.5
Education and awareness	11.2	22.3	33.5
Total cost	**345.8**	**558.7**	**1 004.4**

4.3.4 COST-BENEFIT ANALYSIS

Table 7 shows the current use-value of Lake Saint-Pierre, as well as the values if all adaptation measures actions are or are not implemented. Combining the results of direct economic benefits, access value and annual tourism fee for Lake Saint-Pierre, the total use-value would reach $419million per year. This figure mainly reflects the value assigned to avoiding any loss of use of the lake through proposed adaptations measures (preventing anticipated damages from

[14] See He et al's (2016) full report for more information about these scenarios.

occurring estimated at $300 million per year), as well as the gains in use value of the lake (the improvements that can be made by implementing the measures estimated at $119 million per year). For comparison purposes, the corresponding values for ice fishing are also included. Table 6 summarizes the benefits in terms of use value associated with the adaptation measures.

Table 6. Summary of use values of Lake Saint Pierre associated with adaptation measures (in millions of 2012 dollars)

Source values	General population ($/year)	Ice fishing
Losses avoided by use value	**300**	**41.6**
Economic consequences	75.8	3.9
Access value	224.2	37.7
Earnings measures use value	**119**	**3.6**
Economic consequences	24.4	2.6
Willingness to pay for the annual passes	94.7	1
Total gains in value use	**419**	**45.2**

The total gains presented in Table 7 are based on two scenarios that predict different periods of eight consecutive years of lower water levels during 2015–2023 (scenario B) and 2040–2048 (scenario A), discounted at 4%. It is assumed that in the rest of the 50-year period, there would be no additional economic consequences. The analysis is very sensitive to the discount rate applied, as shown with the scenario for low water levels occurring much later in the period, which significantly reduces the net present value of implementing the adaptation measures. Table 7 shows that all scenarios with interventions result in positive net total benefits. According to this analysis, the implementation of adaptation measures would be economically profitable, especially if low water levels occur earlier in the period.

Table 7. Cost-benefit analysis of climate change adaptation measures (in millions of 2012 dollars)

Discount rates	With interventions	Without interventions[1]
	4%	4%
Decreased water level in 2015-2023 (scenario B)		
Total benefits	3,271.14	-2341.70
Total costs (pessimistic scenario)	1,004.40	0
Net total benefits	**2,266.74**	**-2,341.70**
Decreased water level drop in 2040–2048 (scenario A)		
Total benefits	1,227.06	-878.44
Total costs (pessimistic scenario)	1,004.40	0
Net total benefits	**223.46**	**-878.44**

1. The “without intervention” scenarios measure potential changes in total earnings outcome of Lake Saint-Pierre’s ecosystem services using only the loss of earnings associated with the loss of ecosystem services and fisheries due to climate change.

4.4 RECREATIONAL BOATING AND TOURISM ACTIVITIES[15]

This sector-specific study focused on recreational boating, and inbound and international cruises.

The study was based on a literature review, consultations with experts, interviews with administrators and a survey of recreational boaters. The survey examined respondents' socio-economic characteristics, the types of boats used, the types of expenses made, their future boating intentions and the impacts of extreme low water levels on this activity. The survey also measured respondent's awareness of adaptation measures that had already been implemented.

Sixteen cruise operators are currently active in the study area. Very localized impacts were felt during low water level episodes (for example in 2012) on Montreal's south shore, in the port of Montreal, by limiting docking and passengers' access to boats. Impacts for infrastructure were also observed. International cruise ships, however, dock only at Trois-Rivières or Montreal ports. Low water levels to date have not significantly affected these activities since cruise operators have found it easy to implement solutions.

There are 48 marinas distributed over the study area, along with many public and private boat ramps. According to a 2006 estimate, Québec's recreational-boating industry generates an estimated $2.5 billion in annual revenues and more than 37,000 jobs. National figures for the same year estimate that 150,000 direct and indirect jobs were related to the boating industry (NMMA, 2012).

Data collected from marina operators and recreational boaters as part of this study indicate that most marinas reach maximum occupancy each season and can accommodate only a limited number of newcomers. This has been the case for at least the last five years. Without major facility upgrades, only a few marinas could maximize occupancy potential by adding 5 to 30 slips to commercial moorings or anchor facilities.

In 2014, Lefebvre estimated that 9,162 units (motor and sailboat) navigated the upper portion of the Saint-Laurent River. In addition, results from the survey reveal that 85% of boaters use existing marine facilities (yacht club, marina, port, etc.) and that 90% of recreational boaters intend to continue this activity in the coming years at least as often as they have in the past.

Managers anticipate that occupancy rates will remain similar and waiting lists will likely get longer if their marinas do not expand. As stated by the administrators interviewed for this study, the costs of rehabilitating marine infrastructure or modernizing installations often greatly exceed the revenues generated, making it more difficult to adapt to evolving hydroclimatic conditions.

4.4.1 EXPECTED IMPACTS OF CLIMATE CHANGE

While many factors influence the lucrative recreational-boating industry[16], low water levels and extreme events especially affect infrastructure that is sensitive to varying water levels. High

[15] The content in this section is taken mainly from the report *Étude économique régionale des impacts et de l'adaptation aux changements climatiques sur le fleuve Saint-Laurent : volet nautisme et de croisières-excursions,* prepared by Bleau et al. (2016).

levels can flood quays and wharves, for instance, while low levels dry out launch ramps and marinas, and make navigation more dangerous. To promote safety, marina operators would like depths of at least seven feet during navigation season; and they consider that the critical level is 5.5 feet atchart datum.

According to the Association maritime du Québec, many recreational boaters already feel the effects of low water levels, especially at the end of the summer and in autumn, but also at other times of the year. Some experts consider that the increasing number of deteriorating public and private marinas and boat ramps limits accessibility to watercourses and lakes. Large investments would be needed to improve infrastructure and equipment such as breakwaters, piers, quays, service docks, travel lifts, basins and hydraulic cradles to lower and lift boats. The capacity of a club or marina to implement such adaptation options depends largely on its membership and governance structure.

Low water levels would also affect the recreational-boating industry in other ways, such as the number of overnight visits, accommodation, services and accessibility to the water, damages to nautical equipment.. In terms of risk, comments from most managers and operators focused not only on the inability to guarantee user services and security, but also on damages to existing marine infrastructure. This has been associated in part with times when extremely low levels occur during peak season, or when boats are launched or hauled out. The total annual expenditures for boating for 2013–2014 season is evaluated at $4.2 million for motorboats and $ 450,000 for sailboats.

The number of slips at risk varies according to the area's specific characteristics and can represent up to 20% of all spaces for a given marina. This situation could worsen with changing climate conditions in the absence of adaptation measures. The most problematic zones appear to be in the secondary channels or the entrances to marinas because of continuous silting. It was difficult for marina operators consulted to estimate the potential financial losses and gains for the docks and related recreational-boating services.

According to survey results, the annual expenditures of individual boaters vary between an average of $8,400 for motorboats and $4,500 for sailboats. Motorboat users spend more than half of their total boating expenses on gasoline. Other significant costs include facilities such as launch ramps, food (17% of all expenses) as well as lodging and restaurants (12% of expenses). The same categories are particularly important for sailboats, with food representing a quarter of all expenses, and lodging and restaurants accounting for 16%. While these expenditures could be replaced by those from other tourism and recreational activities, they do represent losses for the boating industry when water levels are to low to navigate.

The analysis demonstrates that the impacts of future low water levels will affect three zones along the Saint-Laurent: the Montreal region (Pointe-Claire), the Boucherville islands and Contrecoeur (Sorel), and Lake Saint-Pierre. The number of days and magnitude of low water levels for the reference scenario, and the two what-if scenarios are translated into monetary impacts and discounted at 4%.

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[16] For example exchange rates, the quality of the equipment and installations, the number of slips available at marinas, storage space as well as costs and customer preferences

Potential economic impacts on users can be quantified by:

- the loss of potential days of boating, regardless of climate conditions (days of good or poor weather):
- the value that boaters grant to a boating day
- the additional expenses required to cope with the negative effects of low water levels (reparations and adaptations).

According to the study scenarios, there will be few years with significant decreases in the next 50 years. Conversely, during the years with low levels, there will be many days with low water levels.

The water level-impact relationship was calculated and focussed on two indicators:

1. The number of days lost per navigation zone based on the hydroclimatic scenarios for the 2064 horizon (with sensitivity analyses on potential levels);
2. The willingness to pay (consumer surplus) for boating based on the field survey.

The consumer surplus is the main indicator used in this study to calculate the monetary effects of a potential decrease in water levels. It can be derived from the willingness to pay: the surplus corresponding to the expenditure the consumer would have been willing to pay if low water levels had not forced them to cancel, reschedule or travel elsewhere. The expenses could be saved or made later on in the season. The surplus is estimated from the survey results and the user's willingness to pay.

Table 8. Estimated economic impacts of each scenario, discounted at 4% (in millions of 2012 dollars)

Impacts	Reference scenario	What-if scenario 1	What-if scenario 2
Total in 2012 dollars[1]	65	129	142
Relative impact	**reference**	**129 - 65 = $ 64 M**	**142 - 65 = 77**

The economic impacts of the two climate change scenarios are $64 million and $77 million over the 50-year period (in 2012 dollars, discounted at 4%). The discount rate changes these results only slightly. While the amounts may seem insignificant over 50 years, stakeholder input suggests that repeatedly low water levels (decreases of 10 centimetres or more) could impede access to some facilities, diminish significantly the customer experience, and in some cases devastate business operations,. Consequently, the economic impacts on clubs and marinas associated with lower water levels should be considered in the future.

4.4.2 POTENTIAL ADAPTATION MEASURES

Adaptation solutions can be structural, organizational, political or communicational in nature. However, the stakeholders interviewed for this study (recreational and cruise sectors) seemed to largely favour technical solutions, as they provide long-term responses to recurrent low and fluctuating water levels. Among possible actions, dredging, revamping and modernizing marine facilities and installations, as well as protective structures (e.g. jetties, piers, breakwaters) are the most frequently named. Softer actions, such as improved navigation marking to facilitate access to docks and piers, and to prevent grounding are easier to plan and implement. Where these measures are insufficient or inadequate, docks can also be relocated or assigned to users according to required depths and boat features (e.g. draught). Moving decks could also be installed. Total or partial dredging of channels and marina basins are typically considered last-resort options.

From a recreational-boater's perspective (Bibeault et al., 2004), measures include navigating in areas less affected by low water levels, transferring memberships to nearby marine facilities, and modifying practices, itineraries and access areas (boat ramps, marinas, ports, yacht clubs). Other solutions include changing to a shallower draft, especially in problematic areas such as Îles de Boucherville and the north shore of Lac Saint-Louis, where a high concentration of water-use facilities such as private clubs, marinas, public boat launching ramps are more vulnerable to low water levels.

It was not possible to adequately quantify the costs of adaptation. The lack of data on implementing measures made it difficult to assess their costs and benefits. Moreover, many obstacles remain to implement adaptation measures such as financing capital costs, meeting regulatory requirements and competing interests for riverside properties.

4.5 HYDROPOWER GENERATION[17]

Along with transportation and boating, hydroelectric production is one of the main economic activities that relies on the water resources of the Great Lakes-Saint Laurent system. The huge hydroelectric potential of the system had a considerable impact on the industrialization of the whole region. Altogether, 15 major dams and power stations operate on the Great Lakes and along the Saint-Laurent River with a combined capacity of more than 9,000 megawatts (MW). Hydroelectricity accounts for about a seventh of the region's net power generation. It is a more prominent source of electricity in Ontario (25%), Quebec (98%) and the state of New York (19%).

Beauharnois, the second-largest hydro facility in the region, is a run-of-the-river plant comprised of 38 turbines capable of generating up to 1,903 MW. Built in three phases between 1929 and 1961, it was the third major hydroelectric plant owned and operated by Hydro Quebec. Well located to supply Montreal and southern Quebec, it is also close to markets in Ontario and the northeastern U.S. It operates in combination with nearby Les Cèdres (104 MW), which celebrated its 100th anniversary of operation in 2014. Hydroelectric generation is the most important source of energy in Quebec, accounting for close to 40% of total energy demand. As such, the Beauharnois-Les Cèdres complex is a significant contributor to the energy supply in Quebec. It accounts for up to 4% of Hydro-Quebec's total production of more than 200 TWh per year.

4.5.1 EXPECTED IMPACTS OF CLIMATE CHANGE

As previously mentioned, rising temperatures caused by increasing concentrations of greenhouse gases in the atmosphere might result in increased evaporation and evapotranspiration in the Great Lakes that would not be compensated by the expected increase

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[17] The content in this section is mainly from the report *L'impact économique des changements climatiques sur la production hydroélectrique du Saint-Laurent,* prepared by Desjarlais and Da Silva (2016).

in rainfall. The combination of rising temperatures and changes in precipitation would result in lower water flows and reduce the hydro-generation capacity of the Great Lakes and Saint-Laurent system. Based on the two what-if hydroclimatic scenarios, the study attempts to quantify the extent of the production reductions for Beauharnois and Les Cèdres attributable to climate change impacts on water levels and flows, and determine the associated costs for Hydro-Quebec and Québec society in general.

In scenario what-if 1, over the 50-year period, the estimated 6% decrease in water flows could correspond to a 3.3% loss of production. Under this scenario, an increase in production over the reference scenario (slightly less than 10%) is foreseen during 2015–2024 followed by a sharp decrease in production (averaging more than 15%) during 2040–2049. Under scenario what-if 2, the drop in production would be much smaller (0.3%) during the entire period. Small increases in winter-spring seasons and a decline during the summer season would result in an average production decrease of slightly less than 3%.

Several economic values can be used to assess the economic impact of production losses, such as the average cost per kWh to produce energy, and the market price paid during the period.

The first value assumes that the production loss must be offset to meet domestic demand. The value of the lost production is therefore its replacement cost and the average production cost or marginal cost can be used. The second value corresponds to the price of electricity purchased during the study period. The loss of production is valued at the market price on external markets.

Hydro-Québec mentions in its 2014 Annual Report a 2.01¢/kWh value for the average cost of production. When the cost of transportation at 1.73¢/kWh is added, the average cost of replacement is thus 3.74¢/kWh. Indeed, it can be assumed that the reduced production of Beauharnois-Les Cèdres would be offset by an increase in the production at all other Hydro-Québec power stations, spread over the entire province. Consequently, replacement cost for the energy produced near Montreal is the average cost of production and transportation from all of Hydro-Québec.

The second cost used in this study is the marginal cost of production. The cost of 7.5¢/kWh of the last hydroelectric complex soon to be in operation (La Romaine) is considered the marginal cost of production of Hydro-Québec. Adding the La Romaine complex should enable Hydro-Québec to meet its additional power needs for many years. It is therefore a good reference for the marginal replacement cost.

The third value used to quantify the economic value of production changes caused by climate change is the price on the export market. The study considered that for the periods in which Quebec will be in a situation of surplus, the loss of production will mainly result in a loss of export sales. The main export market for Quebec is New England, so the price used in this study is the average weekly rate charged from January 2010 to September 2015 as published by the International Hub ISO New England, in 2012 dollars.

Table 10 presents the value of the changes in production at Beauharnois-Les Cèdres over the period 2015–2064 in 2012 dollars under the three price assumptions and the two hydroclimatic scenarios. In what-if scenario 1, the value of this decreased production ranges from $44.6 million under the average replacement-cost of Hydro-Quebec to $89.5 million under a marginal replacement-cost assumption discounted at 4%. The choice of the discount rate has a major impact on these figures, since the low water levels are more critical towards the end of the study period.

In what-if scenario 2, which projects increased variability of seasonal flow and a relatively small decline in total flow rates (0.3%) throughout the period, the loss of production is much less important—$26.1 million over the period under the average replacement-cost assumption and $52.2 million under the marginal replacement-cost assumption.

Table 9. Total impact of production changes at Beauharnois-Les Cèdres (in millions of 2012 dollars)

Scenario What-if 1	undiscounted	4%
Average replacement cost	-742.6	-44.6
Marginal replacement costs	-1,489.1	-89.5
Export prices	-902.9	-30.5
Scenario What-If # 2	**undiscounted**	**4%**
Average replacement cost	-76.9	-26.1
Marginal replacement costs	-154.3	-52.2
Export prices	33.2	20.9

Under the export-price assumption with a discount rate of 4%, the value of lost production in what-if 1 falls to $31 million below the two previous values. In what-if scenario 2, a net gain of $21 million could be obtained due to the combination of higher prices and increased peak flows exceeding the value of losses during low water periods. Figure 6 shows the total change in output per quarter-month for what-if scenario2, as well as the average change in export price. In this figure, summer and autumn prices are much lower than those for the rest of the year. Also, the difference in production between what-if scenario 2 and the reference scenario in the first period (winter) is positive—as shown by the blue curve, while export prices are also relatively higher. Even if what-if scenario 2 projects a small overall decline in production over 50 years, the combination of flow variations in relation to the reference level and the change in export prices could produce monetary gains.

Figure 6. Evolution of average export prices by month and production difference per quarter-month between scenario what-If 2 and the reference scenario.

As mentioned, the choice of discount rate greatly influences the results, because depending on the timing of low water levels, monetary values of impacts may be greater. Indeed, if low water levels happen much earlier than the scenarios suggest, the costs would be much higher. In scenario what-if 1, which foresees production and economic gains in the first decade followed by production cuts from 2025 onwards and reaching their maximum level around 2040, the discount rate of 4% has the effect of reducing the value of lost production much more than the gains in production achieved in the early years.

In what-if scenario 2, discounting also reduces the total values, albeit less dramatically. This scenario projects a drop in production over the reference scenario. While the lost production value at the average replacement-cost, discounted at 4%, amounts to $26 million, the non-discounted value would be $77 million. With the marginal-cost method, the lost production value, discounted at 4%, would reach $52 million, while the non-discounted value would be $154 million.

This study of the economic impact of climate change on hydropower demonstrates that lower water levels in the Saint-Laurent caused by climate change could have a significant financial impact, even with limited reduced flows. The Beauharnois power station in particular, with a capacity of 1903 MW, is indeed a significant component of the production capacity of Hydro-Québec and any reduction in its water intake will result in significant production losses. Moreover, as the energy-replacement cost increases, the value of this loss is expected to grow over time.

4.5.2 POTENTIAL ADAPTATION MEASURES

As this is a run-of-water power station, few immediate adaptation measures are available. Adaptation measures are more a matter of managing the entire network of Hydro-Québec and include the construction of new hydroelectric capacity (reservoirs and plants) or windmill parks. Energy efficiency is also a good way to reduce the impacts of climate change on hydropower in Beauharnois, by postponing more costly investments.

4.6 LAND VALUES OF WATERFRONT PROPERTIES[18]

Properties along the water's edge are generally valuable because of advantages such as pleasant views, direct access to boating and swimming opportunities, as well as the attractive environment. Compared with other properties of the same structural quality (size, type of building and amenities, quality construction) built further from the water, those on the water tend to sell at a significant premium.

Added value for view and access vary by region and country, and in particular according to the relative scarcity of available waterfront properties , but it generally remains very significant. In the Montreal region, the average difference in prices for properties with a view compared to those without view are estimated to be 42.6%. Moreover, sales records suggest that properties in the region with water access can obtain an additional 124% over those with a view only.

Changing hydro-climatic conditions such as lower water levels may affect the view from waterfront properties and their access to water. Waterfront views can lose some of their aesthetic value when beaches are eroded or low water levels uncover mud and rocks, or give rise to marshes and aquatic plants such as algae (Brutzman, 2012). Low water levels can also result in reduce access to water for swimming or recreational boating, or generate costs associated with the lengthening of wharves. Consequently, owners who have invested in these lands for their location advantages could face a reduction in the value of their properties.

The sensitivity to lower water level varies from place to place. With regard to the impacts of low water levels, Kashian et al. (2006) found that, compared to other lakes with five centimetres less water, the property values at Koshkonong and Beaver lakes that benefit from the regulated level of the hydro-electric dams had their premiums increase between 79% and 90%. Another study in Tennessee by Murray et al. (2003) suggests that lower water levels translate into a 1 to 5% reduction in property values. These losses tend to rise if the low water levels continue over the year and, on the contrary, to diminish when water levels return to normal. Hanson and Hatch (2001) found that a permanent reduction of 30 cm of water can reduce property values between 4 to 15%.

4.6.1 EXPECTED IMPACTS OF CLIMATE CHANGE

The study attempts to assess the likely decrease in property values due to lower water levels along the Saint-Laurent River between the Ontario border and Trois-Rivières. It is based on the change in water flows of the scenario what-if 1, described in Section 3. The scenario projects an average 6% reduction in water flows over the 50-year period, compared to the reference scenario. The scenario foresees increases in flow rates during the first decade followed by significant decreases after 2040.

The assessment used a multi-linear regression model where the value of property is a function of a set of its structural and location characteristics, including view and water access.

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[18] The content in this section is mainly from the report *Étude économique régionale des impacts et de l'adaptation liés aux changements climatiques sur le fleuve Saint-Laurent : volet valeurs foncières,* prepared by Özdilek and Revéret (2015).

The data for most of the variables were obtained from sales and municipal-property assessments between 2000 and 2015, and positioned through GIS to localise properties with water view or access. The following table presents the values obtained from these two datasets. Detailed data on changes in water flow rates were obtained from the Centre d'expertise hydrique du Quebec (CEHQ) and Ouranos, also in digital format and geocoded.

Table 10. Estimated values(2012-2014) and observed sales price (2000-2012) of properties in the Montreal region.

ESTIMATED VALUES (in 2012 dollars)						
	Average value	Number of units	Median	Min	Max	Total
No effect	250,972	136,088	231,090	36,600	5,100,000	34,154,234,439
View	346,391	9,893	265,930	50,000	6,090,000	3,426,842,870
Access	817,306	4,291	593,010	67,000	9,570,000	3,507,058,608
	471,556	**150,272**	**395,000**	**36,000**	**9,570,000**	**41,088,135,917**
OBSERVED SALES PRICES						
	Average price	**Number of units**	**Median**	**Min**	**Max**	**Total**
No effect	266,991	52,367	235,750	50,000	4,900,000	13,981,525,681
View	380,649	802	297,500	50,000	1,900,000	305,280,566
Access	851,360	652	650,000	50,000	1,900,000	555,086,764
	499,667	**53,821**	**410,000**	**50,000**	**5,000,000**	**14,841,893,011**

In this table, one can notice a mean difference of about $95,000 in estimated average values between properties with a view and those with no view (no effect), or about 38% more according to data from the municipal property-assessments. Concerning the properties with access, the difference in value relative to those with only a view averages $471,000 (136%) and $566,000 (226%) in comparison with those with neither a view nor an access.

The study used a multi-linear regression model to assess the contribution of each characteristic to the value of properties. The multilinear regression model achieved in general good results and was able to provide a good degree of explanation of the variation in prices. In particular, the model indicates that the market depreciates property values when the water flow-rates are lowerat sale time. All things being equal, when a property on a riverbank is sold, it tends to involve a premium of around $15.2 per m^3/s of additional water flow. This result suggests that the sale of a water-access property can obtain an additional premium when water flows are high, compared to the sale of an identical property with lower water flows,. However, there is probably a limit to this trend if we take into account, at the other extreme, the risks of damage that could be associated to high flows and weaterlevels in sectors vulnerable to erosion or flooding. Note also that the the model does not suggest a similar correlation between water flow and properties with a view but without access. We can thus infer with confidence that the impact of low water level would be felt only on waterfront properties with water access.

The model results linking water flows and properties values was then used to assess the economic impact of the lower water levels of what-if scenario 1 on the 4,291 properties on the Saint-Laurent waterfront between the Ontario frontier and Trois-Rivières. Using this linear model, and a discount rate of 4%, the economic impact for all of 4,291 properties on the waterfront of the Saint-Laurent would be a $72.5 million decrease. This represents a -2 % negative impact in the total value of these properties. Sensitivity analyses with discount rates of 2% and 6% translate to potential losses of $102 million and $53 million, respectively, showing the significant impact of the choice of the discount rate.

It should be noted here that this economic impact ignores the potential increase due to the number of properties or renovations.

4.6.2 POTENTIAL ADAPTATION MEASURES

The Saint-Laurent River is an important waterway and it is difficult to assume the establishment of new structures such as sills, weirs or dams to regulate water levels. Without the ability to maintain water levels in areas with waterfront properties, there are few adaptation measures that can be implemented. In these circumstances, the study did not conduct a cost-benefit analysis of potential adaptation measures.

5. DISCUSSION

The sector-specific studies reveal that low water levels due to climate change in the Saint-Laurent could cause negative impacts on all six sectors assessed in the study during 2015–2064. For the some sectors of activity, economically advantageous options could contribute to significantly reduce the impacts. A summary of the main results for each sector study is provided below, along with a discussion of the limits of these analyses.

5.1.1 SUMMARY OF RESULTS

Considering the six sector studies, the greatest economic impacts of low water levels in the Saint-Laurent would be associated to the loss of ecosystem services. In particular, reduced water levels would significantly affect the Lake Saint Pierre environment—the largest freshwater floodplain in Quebec. The lake’s unique ecosystem is characterized by a great diversity of wetlands that provide habitat for many plant and animal species. Many recreational and tourism activities, such as fishing, bird watching and boating, take place on the lake and along its shores. The estimated economic value of the impacts, discounted at 4%, would be between $878 million and $2.3 billion. Since this study focused solely on Lake Saint Pierre ecosystems, complementary research on other sectors would likely reveal larger total impacts over the whole study area.

Adaptation measures could reduce these impacts to a large extent and possibly improve the current health of the ecosystem. In this sector study, six adaptation strategies were considered: 1) restore riparian areas; 2) restore floodplains;; 3) change agricultural practices; 4) increase the efficiency and capacity of wastewater treatment by municipalities; 5) protect and restore habitats for threatened or vulnerable species; and 6) educate and raise awareness in the general public. The cost to implement all six adaptation strategies was estimated to be $346 million–$1 billion. Estimates of the total resulting benefits vary from $1.2 to $3.3 billion, while estimated net benefits, discounted at 4% and using the highest estimated adaptation cost, range from $216 million to $2.3 billion. The adaptation measures could equally prove to be useful for other climate-change related impacts, such as water-quality issues. Some measures also constitute no-regret options and could be advantageous regardless of the magnitude of changes in climate. The values assigned to non-market goods and services in the ecosystem services and recreational fishing sector study are based on revealed preferences and willingness-to-pay approaches. This methodology differs from the market-based evaluation used in the other sector-specific studies. This must be taken into consideration when comparing the relatively higher benefits associated with ecosystem services.

The analysis of economic impacts on the maritime-transportation sector focused on the effects of water levels below chart datum as provided by the hydro-climatic scenarios. The study considers that decreased water levels in the Saint-Laurent would limit shipload capacity. Using a discount rate of 4% per year and an assumption of 3.8 ETF container loss per centimetre of water, the value of impacts varies between $38 million for what-if scenario 2 to close to $70 million for what-if scenario 1 during the 50-year period. These results are, however, sensitive to the assumed number of containers lost per centimetre decrease in water level[19].

Following a Topsis multi-criteria analysis,, two adaptation measures were investigated through a cost-benefit analysis: dredging and minimizing under-keel clearance. The estimated value of the benefits associated with the combination of the two measures, discounted at 4%, ranges from $58 million dollars under what-if scenario 1 to $38 million under what-if scenario 2. The total cost of the measures is approximately $12 million. An analysis using net present values of a combination of both adaptation measures reveals that the benefits outweigh the costs by $46 million and $26 million under both scenarios, with benefit:cost ratios of 5:1 and 3:1, respectively. These assessments may not consider all the potential environmental and social impacts associated with the measures.

Recreational boating will also be affected by low water levels in the Saint-Laurent. The total economic impact of varying water levels, discounted at 4% over 50 years, is estimated at $64–$77 million, according to the two what-if scenarios. These impacts are based on the value given to boating days, but do not include the potential costs of adapting equipment or infrastructure at marinas and nautical clubs. Adaptations options for recreational boating have been identified but not quantified, since they consist mostly of management and operational changes.

Reduced water flows and levels would also affect hydroelectric production at the Beauharnois-Les Cèdres power station. The expected reduction in hydroelectric production at this power station would translate into important monetary losses from reduced sales in domestic and export markets. The lost production at a marginal replacement cost would amount to $52 million under what-if scenario 2 and $89 million under what-if scenario 1. These results are, however, sensitive to the discount rate applied. Given the type of production (run-of-the-river) for the Beauharnois-Les Cèdres power station, where there is no reservoir to manage, adapting to climate change could require solutions involving either improved energy efficiency or increased production from other watersheds or other sources of energy. The economic costs and benefits of these solutions have not been assessed.

Lower water levels could also affect the value of properties with an access to the river. The economic impact of sustained lower water levels under what-if scenario 1 for the close to 4,300 properties located along the Saint-Laurent River between the Québec-Ontario boundary and Trois-Rivières could amount to $72.5 million during the 50-year period. This represents an estimated loss of 2% of the total value of these properties. Adaptation options were not identified for this sector. Further studies of the impacts of climate change on riverside property values should also examine flooding issues and possible options for adapting to fluctuating water levels.

Reduced water levels and flows in the Saint-Laurent due to climate change could cause problems for the plants that capture, treat and produce potable water. To ensure the designed production capacity of water-treatment plants, the water level in the Saint-Laurent River must be enough to overcome pressure loss in the intake pipes between water-catchment areas and the supply lines. Based on the scenarios used, two of the 18 treatment plants assessed in this study would face water shortages during the period. The total estimated economic impact would be

[19] See Slack and Comtois (2016) report for more information on the sensitivity of the results to the number of containers lost per centimetre decrease in water level.

between $48,900 and $66,800 discounted at 4% over the period. These impacts remain relatively low when compared to the cost of adaptation options.:.

These adaptation options considered include modifying or replacing existing pumps with equipment that functions at lower water levels, for example increasing the size of, and/or reconfiguring, water-intake systems to reduce the risk of pressure loss and hydraulic constraints associated with lower water levels. The benefits associated with these adaptation options are the savings created by averting water shortages, as well as a more secure water supply. A cost-benefit analysis was conducted for the two water plants that could face water shortages. Results from this analysis over a 50-year period and discounted at 4% show that implementing these measures is not economically efficient when considering climate change impacts only. Indeed, the analysis shows a net cost of about $100,000 for one of the water plants (cost-benefit ratio of 35:1) and more than $2.2 million dollars for the other one (cost-benefit ratio of 42:1). However, the analysis also demonstrated that implementing these measures as part of construction or rehabilitation work increases costs only marginally, while making the systems more robust.

5.1.2 STUDY LIMITS

Hydroclimatic scenarios

The hydroclimatic what-if scenarios developed are founded on the state of knowledge on the Great-Lakes and Saint-Laurent River watershed and they represent plausible future conditions. However, no probability is associated to them and they thus remain hypothetic. The development of probabilistic scenarios and the use of more various scenarios would allow the analysis of potential impacts associated to a greater diversity of possible futures.

Time horizon and discount rate

Because of the application of a discount rate (4%), the time of critical low water levels on the time horizon has an big influence on the economic value associated to the impacts. For instance, what-if scenario 1 suggests a sharp decrease in water levels towards the end of the period (2040–2049). The value associated to the economic impact of this low water level episode would be lower if it occurred later and, conversely, it would be higher if the episode occurred sooner, as it is the case in scenario 2. The sensitivity analysis with discount rates of 2% and 6% also show this, notably in the hydroelectric production study.

Socioeconomic status quo assumption

The assumption to maintain the current social and economic status quo is also important to keep in mind. In reality, demographic growth, economic development, technical changes and other factors will combine with climate change over the next decades and influence the magnitude of the impacts as well as the adaption measures to be considered. For example, if investments were needed to increase the production capacity of a water supply treatment plant in order to respond to demographic growth, it could become advantageous to take the opportunity to adapt the infrastructure to low water levels.

Study area

The study area covers the Saint-Laurent River between the Québec-Ontario border and Trois-Rivières. Ecosystems and economic activities out of this area can also be significantly impacted by climate change and water-level fluctuations. For example, the water supplies of Québec City and Lévis could be vulnerable. Further studies should be conducted to assess the potential impacts and adaptation options for other areas along the Saint-Laurent River.

Sector-specific adaptation

Only sector-specific adaptation options were examined. Although it was initially considered, no major structural adaptation measures, such as building water level regulation structures in the Saint-Laurent, were evaluated using a cost-benefit analysis. According to the initial multi-criteria analysis conducted in the maritime-transportation study[20], the economic returns as well as the social and technical feasibility of such measures appeared too low to consider implementation. As well, interviews and consultations with users suggested sector-specific adaptations. No cross-sectoral or structural watershed-scale adaptation measure was considered for this study. Nevertheless, the evaluation of the lac Ontario and Saint-Laurent River regulation plan and the adaptive management approach put forth by the International Joint Commission represent important adaptation tools for the management of water levels.

Consideration of non-market ecosystem goods and services

One interesting aspect of the study was the challenge of quantifying the economic value of ecosystem goods and services. While this was not done systematically in all sector-specific studies, the analyses that did take these into consideration demonstrated that they greatly influence the results. While the importance of valuing these non-market goods is increasingly recognized, more work needs to be done to overcome the methodological challenges associated with including them in cost-benefit analyses.

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[20] See : *Étude économique régionale des impacts et de l'adaptation aux changements climatiques sur le fleuve Saint-Laurent : volet transport maritime,* prepared by Comtois et Slack (2016).

6. CONCLUSION

This regional study represents a first step to investigate the economics of adaptation to low water levels on the Saint-Laurent due to climate change. The study deepens our understanding of the sensitivity of key activities and ecosystem services to these impacts.

The study suggests that episodes of low water levels presented in the hydroclimatic scenarios could lead to impacts on all six sectors. For all sectors, the impacts calculated for what-if scenario 1 are slightly higher than those for what-if scenario 2, even if the most critical low water levels occur lately in scenario 1 and thus the value of impacts are largely reduced by the discount rate.

The greatest economic costs of future low water levels are associated with ecosystem services and fishing. Considering the contingent approach used to assess these costs, this result reflects a high willingness-to-pay to protect Lake Saint Pierre's ecosystem services among the populations surveyed. Of the six sectors studied, municipal water supply was projected to experience the smallest economic impacts, as most of the water plants can already cope with most fluctuations of water levels.

Considering that the hydroclimatic scenario databases have been analyzed using various approaches for the different sector-specific issues, it is difficult to compare the economic impacts identified for the different sectors of activity. While there was some common assumptions and guidelines for all sectors, the methodologies applied to assess the costs differed from sector to sector based on the nature of the impacts and the types of adaptation measures considered. For maritime transport and municipal water-supply, market-based approaches were used, whereas the study on ecosystem services had to use contingent approaches to estimate the value of non-market goods and services. Different results would likely have been obtained if the impacts on municipal water-supply had also been assessed by measuring the willingness to pay for potable water. The values of impacts remain therefore sensitive to the methodologies used and are difficult to compare.

The study contributed to the collection of new data and application of methodologies to support the planning of climate change adaptation strategies. In most of the sector-specific studies, stakeholders were consulted to better understand the issues of low water levels and to identify potential adaptation options. Sector-specific adaptation measures were identified and quantified for maritime transport, municipal water-supply and ecosystem services. The cost-benefit analyses suggest that some adaptation options could be economically beneficial for maritime transport and ecosystem services.

The studies also show that some no-regret or low-regret options could be considered. These options are measures that are of interest regardless of the magnitude or timing of climate change impacts; they could even help cope with current climate variability. They include, for instance, actions to protect or restore habitat refuges, to raise awareness, or to improve signage around marinas. Also, considering the lifecycle of infrastructure and equipment, some adaptation measures could be integrated in infrastructure investment plans and help achieve other objectives. This could be the case for adaptation of municipal-water production, for instance, since the marginal cost of adapting to climate change could represent only a fraction of the investments planned to increase the plant's production capacity in order to respond to demographic growth.

Considering the uncertainty of future climate conditions and the complexity of the Great Lakes and Saint-Laurent system, it remains an important challenge to assess the economic impacts of low water levels and of adaption options for the next 50 years. This study nevertheless makes a significant contribution to understand the issues and to their economic analysis. More efforts and research will be needed to paint a clearer picture of the future hydro-climatic conditions of the Great Lakes and Saint-Laurent along with potential impacts and adaptation solutions. Different institutions and experts are already working on hydrologic and hydraulic modelling to produce more probabilistic scenarios. More transdisciplinary collaborations will be needed also to connect economic and hydroclimatic expertiss and with other relevant fields to address water-level issues in various sectors of activity.

Updating this kind of global assessment in the future to account for new scientific knowledge will be necessary to plan and implement appropriate adaptation strategies. Technical studies will also be needed in some cases to assess the feasibility and the potential costs and benefits of specific adaptation options.

The focus on this study was on the potential impacts of future low water levels, but climate change could raise many other issues on the Saint Laurent. Flooding might occur in some vulnerable areas. Erosion is an important issue mainly along the Saint-Laurent estuary and Gulf but it also affects different areas of the fluvial portion. Intense precipitation events in the future could also raise water-quality problems in some parts of the river. It will be important to plan applied scientific research and collaboration with all concerned stakeholders to support adaptation to low water levels and to other impacts of climate change.

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Ouranos was born from the shared vision of the Government of Quebec, Hydro-Québec and Environment Canada, with financial support of Valorisation-Recherche Québec in 2001. Incorporating a network of some 450 scientists and professionals from various disciplines, the consortium focuses on two main themes: climate science and vulnerabilities, impacts and adaptation. Its mission is the acquisition and the development of knowledge on climate change and its impacts, as well as socio-economic and environmental vulnerabilities, in order to inform policy makers about climate change and advise them on how to identify, evaluate, promote and implement local and regional adaptation strategies.