WATER AVAILABILITY ISSUES FOR THE ST. LAWRENCE RIVER

An Environmental Synthesis

October 2006

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Foreword

Fluctuating flow and water levels in the St. Lawrence River, whether natural or human-induced, are of concern to the various stakeholders (government organizations, research scientists, industries and the general public) that have been involved for several years in managing water resources and their use, and in maintaining the physical chemical and biological integrity of the ecosystem. Such concerns are particularly justified in the current context of climate change, which is likely to significantly influence socio-economic and environmental policy decisions.

In recent years, Environment Canada research scientists have been studying the problem of fluctuating flows and water levels in the fluvial portion of the St. Lawrence. Much of their research has been carried out in the context of the work of the International Joint Commission and, more specifically, the International Lake Ontario–St. Lawrence River Study Board, which has a mandate to evaluate the procedures and criteria used to regulate outflows from Lake Ontario and manage water levels in Lake Ontario and the St. Lawrence River.

This document is the product of the work of several of the above-mentioned Environment Canada research scientists. It is a synthesis of the current state of knowledge and of certain recommendations relating to the possible impacts of fluctuating flows and water levels on various environmental and socio-economic factors. The following is a brief summary of each of the 13 chapters of the report.

Chapter 1 describes the issue of water availability for the St. Lawrence. The authors summarize the major changes that have occurred in the Great Lakes–St. Lawrence system and present the institutional framework applicable to fluctuating water levels in the St. Lawrence. They review the various laws, policies and federal-provincial agreements regarding water resources and flood control, wetland conservation, fish habitat management, species at risk, etc. They then provide a historical account of efforts to review the management of water levels in the St. Lawrence. The chapter ends with a discussion of the current challenges and issues relating to the sustainability of the St. Lawrence ecosystem.

Chapter 2 provides a synthesis of the current state of knowledge of the physiographic and hydrological characteristics of the fluvial section of the St. Lawrence downstream of Cornwall. It describes the various components (flow, inflows, anthropogenic features, the seaway, ice management, regulation, etc.) and the fluctuating flows (short-term, seasonal and long-term) and water levels.

Chapter 3 covers the dominant physical processes at play in the St. Lawrence River, the modelling of these processes and the integration of the resulting models in an ecosystem modelling system. On the basis of topometric information, bedrock and aquatic vegetation mapping and analysis of the fluvial hydrology, the authors present the steps involved in and results of the modelling of currents, waves, water masses and other physical variables that are important to the analysis and modelling of flora and fauna.

Chapter 4 deals with the modelling of the spatial distribution of and temporal changes in the aquatic vegetation of the St. Lawrence River. On the basis of information derived from physical changes as a function of flow and from a very large number of field observations, the authors show how modelling is used to understand changes in the aquatic vegetation and major wetland classes along the river's edge.

Chapter 5 studies the effects of the St. Lawrence River hydrological regime on plant diversity and productivity. The author presents in detail the characteristics of each of the primary producer compartments (phytoplankton, metaphyton, periphyton, and macrophytes) from the point of view of biodiversity, biomass and productivity. The author also discusses temporal variations as a function of water levels and threats to the integrity of organisms and their habitats posed by human activities (excavation of the river bed and basin tributaries, regulation and dams) and climate change.

Chapter 6 concentrates on the impacts of fluctuating water levels on reptiles and amphibians. The author reviews the direct and indirect effects of a decrease or increase in water levels on the various species of reptiles and amphibians that occur in the St. Lawrence Valley. The author also discusses the anticipated effects of climate change and gives an overview of the other environmental pressures on the herpetofauna of the St. Lawrence (i.e. habitat fragmentation, chemical pollution, infectious diseases, introduced species, etc.).

Chapter 7 focusses on fish communities in the lower St. Lawrence River. The authors analyze how the nature and the extent of hydrological variability influence fish dynamics and attempt to provide a prognosis in terms of the potential effects of regulation on ecosystem integrity and the dynamics of fish communities in the river.

Chapter 8 examines wetland birds. The authors provide a current picture of the bird species and habitats of the St. Lawrence and go on to analyze the role of fluvial dynamics on bird assemblages. One section is devoted specifically to species at risk. The chapter concludes with recommendations concerning the regulation of water levels for the benefit of bird species.

Chapter 9 presents a discussion of the muskrat, the only herbivorous mammal that has a direct impact on the dynamics of St. Lawrence wetlands. The authors cover certain aspects of the biology of this mammal and its interaction with wetlands before addressing the impacts of water-level fluctuations in winter and the ecological implications of regulating St. Lawrence River flows.

Chapter 10 looks specifically at species at risk. The author presents the current situation on the fluvial section of the St. Lawrence and the legislation protecting species at risk, followed by a section on species at risk whose survival depends on hydrological conditions. The author then discusses the performance of regulation plans from the perspective of various species and concludes with a number of recommendations aimed at improving our understanding and limiting the negative impacts of water-level fluctuations on these species.

Chapter 11 addresses St. Lawrence water use. The authors review the main water requirements for human activities (public supply, hydroelectric power generation, commercial shipping and recreational boating, etc.) and discuss the threats and issues associated with water availability. The authors conclude by evaluating the role of the adaptations to be considered to counteract human pressure on water resources.

Chapter 12 describes the concept of performance indicators and the various methods and approaches used to evaluate the regulation plans that have been proposed to replace the current plan. The chapter concludes with an overview of the research that remains to be done.

Chapter 13 presents the overall prospects for an integrated approach to the management of the waters of the St. Lawrence. The authors discuss the scientific base and the multiplicity of players and users as agents of integrated management. They conclude by providing a number of directions for the development of policy capacity and strategies based on comprehensive integration.

André Talbot, Ph.D.

Georges Costan, D.Sc.

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Glossary

The following definitions were drawn and adapted from the glossary of the International Lake Ontario–St. Lawrence River Study (http://www.losl.org/gloss/gloss-e.html), the glossary of the *Eighth Biennial Report Under the Great Lakes Water Quality Agreement of 1978 to the Governments of the United States and Canada and the State and Provincial Governments of the Great Lakes Basin* (http://www.ijc.org/php/publications/html/8bre.html), and the Fisheries and Oceans Canada glossary available at: http://www.waterlevels.gc.ca/english/Glossary.shtml.

Abiotic (*Abiotique*): Describes non-living physical or chemical variables in the environment, such as air, water, etc.

Accretion (*Accrétion*): An increase in beach area or wetland by natural growth or addition.

Algae (*Algue*): Microscopic aquatic organisms, classified as plants and capable of photosynthesis but having no roots, flowers or seeds (primary producers).

Anadromous (*Anadrome*): A species of fish that migrates upriver to reproduce and whose growth takes place mostly at sea.

Anthropogenic (*Anthropique*): Made by humans or resulting from human activities.

Areas of concern (*Secteur préoccupant*): Geographic areas that do not meet the General or Specific Objectives of the *Great Lakes Water Quality Agreement*, where such failure impairs or is likely to impair beneficial uses or the area's ability to support aquatic life. Such areas are designated in Annex 2 of the Agreement.

Areas of quality (*Secteur de qualité*): Geographic areas of high environmental quality that, because of their location and ecological significance, are identified as deserving special attention under antidegradation programs.

Basin, watershed (*Bassin versant, bassin hydrographique*): The region or area from which surface waters and groundwater ultimately drain into a particular course or body of water.

Benthic (*Benthique*): Pertaining to the bottom of a body of water, bottom sediment or bottom-dwelling organisms.

Best management practices (*Pratiques exemplaires de gestion*): Effective and technologically, economically and institutionally feasible conservation practices and land and water management measures that avoid or minimize adverse impacts to natural and cultural resources.

Biodiversity (*Biodiversité*): A measure of the number and variety of different organisms in an ecosystem, which may be used to identify the ecosystem's health.

Biosphere (*Biosphère*): The part of the earth and atmosphere inhabited by or affecting living organisms.

Biota (*Biote*): All plants and animals living in a given area.

Botulism (*Botulisme*): Botulism is a rare disease caused by a toxin produced by the spore-forming bacterium *Clostridium botulinum*. *C. botulinum* occurs naturally and can be found in soil, water, animals, contaminated food or agricultural products. The toxin produced by *C. botulinum* is the most potent toxin known and can affect humans, animals and even fish.

***Boundary Waters Treaty* (*Traité des eaux limitrophes*)**: A treaty concluded between the United States and Canada in 1909 to prevent and resolve disputes primarily concerning water quality and quantity along the boundary. The treaty established the International Joint Commission.

Chart datum (*Zéro des cartes*): The plane of vertical reference to which all charted depths and drying heights are related. In non-tidal waters, it is also the vertical datum for elevations and clearances. It is chosen to show the least depth of water found in any place under "normal" meteorological conditions, and is a plane so low that the water level will seldom fall below it. The CD surface will vary from place to place with the range of the tide or, in non-tidal waters, with the slope of the river at low stage. In non-tidal lakes, CD is normally a single level surface over the whole lake.

Climate (***Climat***): The prevalent weather conditions of a given region (temperature, precipitation, wind speed, atmospheric pressure, etc.) observed throughout the year and averaged over a number of years.

Climate change (***Changements climatiques***): Changes in global weather patterns, including predicted warmer average temperatures, caused by the buildup of gases in the atmosphere from human activity. These gases trap the sun's heat within the earth's atmosphere.

Diadromous (***Diadrome***): Refers to fishes that migrate between salt and fresh waters.

Discharge (***Débit***): See **Flow**.

Ecosystem (***Écosystème***): A biological community in interaction with its physical environment, and including the transfer and circulation of matter and energy. As used by the International Joint Commission, ecosystems include humans, their activities and institutions.

Environmental Technical Working Group (***Groupe de travail technique sur l'environnement***): A group of experts that is investigating impacts of water-level variations on fish, birds, plants and other wildlife in the Lake Ontario–St. Lawrence River system, with particular attention to ecological effects on wetlands.

Erosion (***Érosion***): The wearing away and accumulation processes that result from the action of water currents, rainfall, wind and waves. Erosion results naturally from weather or runoff, but human activity (urbanization, clearing of land for farming, logging, construction or road building) can intensify the process.

Eutrophication (***Eutrophisation***): The natural or artificial process of nutrient enrichment whereby a water body becomes filled with aquatic plants and its oxygen content is reduced. The low oxygen level is detrimental to fish.

Exotic species (***Espèces exotiques***): Species that are not native to an ecosystem and are usually introduced by purposeful or inadvertent human action.

Fetch (***Fetch***): The distance across water over which a wind blows with no obstructions.

Floodplain (***Plaine d'inondation***): The lowlands surrounding a watercourse or a standing body of water, which are subject to flooding.

Flow (***Débit*****):** Rate at which water travels through a given cross section**.** Amount of water flowing through the river.

Frasil ice (***Frasil***): Stream ice that has the consistency of slush and is formed when small ice crystals, developed in super-cooled stream water as air temperatures drop below freezing, join and are pressed together by newer crystals as they form.

Freshet (***Crue*****):** The sudden overflow or rise in level of a stream as a result of heavy rains or snowmelt.

Great Lakes–St. Lawrence Basin Ecosystem (***Écosystème du bassin des Grands Lacs et du Saint-Laurent***): The interacting components of air, land, water and living species, including humans, within the drainage basin of the Great Lakes and the St. Lawrence River, at or upstream from the point at which this river becomes the international boundary between the United States and Canada.

Great Lakes Water Quality Agreement (Accord relatif à la qualité de l'eau des Grands Lacs): An agreement signed between Canada and the United States in 1972, and amended in 1978 and 1987, to restore and maintain the chemical, physical and biological integrity of the waters of the Great Lakes–St. Lawrence Basin Ecosystem.

Groundwater recharge (***Alimentation des nappes souterraines***): Inflow of water from the surface to a groundwater reservoir. Infiltration of precipitation and its movement to the water table is one form of natural recharge.

Guild (***Guilde***): A group, not necessarily of the same species, that have similar breeding habits or depend on the same environmental resources.

Habitat (***Habitat***): The particular environment or place where a plant or an animal naturally lives and grows.

Hydrology and Hydraulics Modelling Technical Work Group (***Groupe de travail technique sur la modélisation hydrologique et hydraulique***): A group of experts that is developing models to predict water levels and flows in the Lake Ontario–St. Lawrence River system on the basis of various regulation plans and climate scenarios.

International Great Lakes Datum 1985 (IGLD 1985) (*Système de référence international des Grands Lacs de 1985*): A datum established by the Canada–USA Coordinating Committee on Great Lakes Basic Hydraulic and Hydrological Data, to provide a unified datum for use in hydraulic and hydrological studies on both sides of the border along the Great Lakes and St. Lawrence River.

International Joint Commission (*Commission mixte internationale*): An international federal government agency formed in 1909 by the United States and Canada as an application of the *Boundary Waters Treaty* to oversee the resolution and prevention of disputes with regard to all bodies of water shared by the two countries, and to provide recommendations on such water management issues as water quality and water levels.

International Lake Ontario–St. Lawrence River Study Board (*Groupe de travail international sur le lac Ontario et le fleuve Saint-Laurent*): A study board sponsored by the International Joint Commission to examine the effects of water level and flow variations on all users and interest groups and to determine if better regulation is possible using the existing installations controlling Lake Ontario outflows.

International St. Lawrence River Board of Control (*Conseil international de contrôle du fleuve Saint-Laurent*): Established by the International Joint Commission in its 1952 Order of Approval, the Board ensures that outflows from Lake Ontario meet the requirements of the Commission's order. The International St. Lawrence River Board of Control has ten members, five Canadian and five American. Outflows are set by the Board in accordance with the regulation plan in effect. It may deviate from plan flows under emergency conditions or winter operations. It may also make a change in the plan flow to provide benefits or relief to one or more interests without appreciably harming others, and without breaching the requirements of the Order. Additional information is available at: http://islrbc.org/new-Version/mandat.html.

Low water datum (*Niveau de référence des basses eaux*): An approximation of mean low water, used for harbour dredging purposes.

Monetized (*Monétisés*): The conversion of benefits or costs of an action into economic value, based on the measured impact and estimates of non-market values.

Net basin supply (*Apport net d'eau du bassin*): The net amount of water entering one of the Great Lakes, comprised as: (precipitation onto the lake + groundwater + runoff from its local basin) – (evaporation from the lake).

NOBOB (*Navires sans lest*): Vessels with no ballast on board.

Plan 1958D: A plan used by the International St. Lawrence River Study Board since April 1963 that specifies outflows from Lake Ontario in order to satisfy the existing set of criteria established by the IJC and related to interests on Lake Ontario and the St. Lawrence River.

Plan Formulation and Evaluation Group (*Groupe de formulation et d'évaluation du plan*): A group established as part of the Study Board to develop alternative water-level regulation plans, establish performance indicators for such plans and measure the effectiveness of such alternate criteria and operating plans.

Precaution (*Prudence*): A principle that involves taking an environmentally cautious and conservative approach where there are threats of serious or irreversible damage, to avoid and prevent pollution even with a lack of full scientific certainty.

Public Interest Advisory Group (*Groupe consultatif sur l'intérêt public*): A group of volunteers from the United States and Canada working to ensure effective communication between the public and the International Lake Ontario–St. Lawrence River Study Team.

Quarter-monthly mean water level (*Niveau d'eau moyen par quart de mois*): The average water level that would occur during a quarter-month period. A quarter-month is seven or eight days depending on the number of days in the month.

Recreational Boating and Tourism Technical Working Group (*Groupe de travail technique sur la navigation de plaisance et de tourisme*): A group of experts that investigate the impacts of water levels on individual boaters, marinas and boating-related tourism.

Remedial action plans – RAPs (*Plans de mesures correctives – PMC*): Plans to be developed to restore beneficial uses such as healthy aquatic life, and human activities, such as fishing, swimming and drinking water supply, to identified Areas of Concern.

Shared vision model (*Modèle de vision commune*): Decision-making tool used to develop a collective representation of the future a group aspires to create.

Socio-economic survey (*Étude socio-économique*): A survey measuring the basic characteristics of a community, from which statistics can be compiled.

Technical Working Group (*Groupe de travail technique*): A team of experts formed to study each of the following areas: shoreline zones, commercial navigation, common data needs, the environment, hydrological and hydraulic modelling, water uses, hydroelectric power generation and recreational boating and tourism for the International Lake Ontario–St. Lawrence River Study.

Water level (*Niveau d'eau*): The elevation of the surface of the water at a particular site on a water body or stream. The elevation is measured with respect to mean sea level.

Wetland (*Milieux humides*): An area characterized by wet soil and high biological productivity, providing an important habitat for waterfowl, amphibians, reptiles and mammals.

Chapter 1

WATER AVAILABILITY IN THE ST. LAWRENCE: INSTITUTIONAL CONTEXT AND MAJOR ISSUES

***Jean-François Bibeault*[1] *and Christiane Hudon*[2]**

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Introduction

The issue of water-level fluctuations brings forward the often-overlooked concerns regarding the key role played by hydrological factors in the changes in the various components of the St. Lawrence ecosystem. The impacts of water-level fluctuations combine with other known problems and major trends in the transformation of the Great Lakes and St. Lawrence. The issue also calls into question the scope of existing laws and policies, a number of which affect how such impacts are managed. Finally, it broadens the perspective to include other major issues and challenges for the future.

Major transformations in the Great Lakes–St. Lawrence system

The Great Lakes–St. Lawrence system has been under growing human pressure, particularly since the end of the Second World War. This pressure is linked to the major transformations that have driven the land use development and water use patterns seen today.

The main trends that reflect these changes can be summarized as follows:

- The **production capacity** of the watershed has increased considerably, necessitating more energy, more water, a more complex transportation network to serve the needs of business, and a growing workforce in proximity to industry.
- The **production and consumption profile** has also evolved towards products that feature a blend of materials and that rely increasingly on organic and inorganic synthetic products, one consequence of which has been the release of toxic substances into the environment.
- The **demand for energy** has resulted in an increase in the number of hydroelectric, nuclear and fossil fuel power plants. Stream flow regulation, in particular, was a major trend until the 1990s.
- **Water withdrawal and use** have been significant, particularly for food, cooling in thermal and nuclear power plants, and industrial washing and manufacturing.
- At the same time, water use for other purposes increased with the growth of **recreational needs** in the 1960s and 1970s. Requirements related to human health and quality of life also became increasingly important considerations.
- Growth in **national and international trade** required an increase in the number of transportation routes, specifically shipping routes and navigation channels. To achieve economies of scale, larger, deeper-draft ships were built, requiring increasingly more excavation to accommodate the passage of ships.
- The **population growth** that resulted from industrialization, improvement in sanitary conditions and immigration was particularly significant in the Great Lakes and St. Lawrence Basin, and has resulted in the human alteration of riparian ecosystems, among other impacts.
- **Urbanization, increased human alteration of land cover and shorelines** and strengthening of social interactions brought new concerns, including the environment, and new social players, such as environmental groups and groups promoting public participation; these factors also brought recognition of the cultural diversity of new Canadians and First Nations.

The combined effect of these major socio-economic and environmental changes was a proliferation of water-related needs and concerns. The more traditional uses of water for industrial, agricultural and municipal purposes were expanded to encompass various recreational uses, as well as ecological and aesthetic values (Maître and David 2000) and the cultural and identity-related values that are associated with bodies of water. Since the 1970s, the sustainability of ecosystems has also been a key sustainable development issue for the Great Lakes and the St. Lawrence River.

Water-level fluctuations and the measures implemented to manage them are one of the main challenges to the sustainable conservation of the St. Lawrence ecosystem. The environmental synthesis presented in the following chapters provides up-to-date knowledge and offers a more accurate picture of the vulnerability of ecosystem components to hydrological conditions—one that takes into account the geographic diversity of the river.

The Great Lakes–St. Lawrence Basin, including the marine portion in the Gulf, is one of Canada's and the world's major watersheds, both in terms of its size (Lasserre 1980) and the number of people who depend on it. In this respect, it has been the focus of sustained attention in recent years. The environmental synthesis that follows is the result of a variety of tasks undertaken in collaboration with the International Joint Commission as part of the review of the regulation plan for Lake Ontario and the St. Lawrence River, and helps identify the ecological boundaries of the freshwater portion of the St. Lawrence. In a broader context, the purpose of the synthesis is to improve the response to current and future issues and threats to water resource management at the watershed scale, which has been a source of problems not only in Canada (NWRI and MSC 2004) but in other countries as well (Richter et al. 2003).

To provide a clearer picture of the context of the work involved in the synthesis, it would be helpful to review the institutional framework guiding water and ecosystem protection in Canada, to provide greater detail on the framework for regulation of the St. Lawrence River and, finally, to identify the challenges posed by water use for the future of the river.

Evolution of the Canadian institutional context relevant to water-level fluctuations in the St. Lawrence

In hydrological terms, water-level fluctuations are caused by the combined effect of precipitation, inflows from upstream basins, water tables (and groundwater recharge), runoff, evaporation, water diversions into and out of the watershed, and the regulation of levels and flows (IJC 2000). This list of variables can be expanded to include modification of the stream cross-section and depth, increased impermeability of land surfaces (e.g. caused by paving in urban areas), transformation of plant cover (through agriculture and logging), climate and increased water withdrawals for various purposes.[1] These natural and human-based factors alter the quantity and availability of water and have impacts on the sustainability of ecosystems, habitats and species.

To address these impacts, a series of institutional measures have been developed to reduce pressure on the St. Lawrence resource and ecosystem. Notwithstanding the relative effectiveness of these measures, it is clear that they have increased in number since the early 1970s.[2] The main measures adopted to date, which are also relevant to the St. Lawrence ecosystem, are reviewed in chronological order.

Canada Water Act (1970)

The first significant measure adopted in this regard was the *Canada Water Act* (R.S., 1985, c. C-11). When it was first proclaimed in 1970, the Act encouraged federal-provincial freshwater management agreements, given that shared jurisdictions are usually involved. The Act also provided for integrated water resource planning and management based, among other things, on adequate monitoring of water quality and quantity data, targeted research and projects on the conservation, management and effective use of water resources (Section 5).[3]

Federal-provincial flood control agreement (1978)

The existence of the *Canada Water Act* and the record floods of 1974 and 1976 in Quebec prompted the adoption of a federal-provincial agreement on flood control followed by the mapping, beginning in 1978, of the flood risk areas of the St. Lawrence and its tributaries. This had the double advantage of raising awareness among shoreline residents about residential construction in flood risk areas and encouraging public authorities (particularly cities) to find other ways of developing shorelines, e.g., promoting green belts or creating riverside parks. The Archipelago Project, for example, begun in 1979 and revised in light of the "Archiparc" concept in 1985, also helped make cities more aware of less drastic possibilities for the development of riparian buffer strips.

Federal Water Policy (1987)

In connection with the Act and in response to the rising number of water-related concerns in the 1970s and the early 1980s, the first Federal Water Policy was developed in 1987. The policy presents general directions for management and specifically addresses problems of drought, floods, climate change and shoreline erosion, all of which are associated with water quantity. The policy, while relatively broad in scope, nevertheless highlighted certain ecological problems arising from water management, including loss of wetlands.

Federal Policy on Wetland Conservation (1991)

One of the indirect results of the Federal Water Policy was the development by the Canadian government, in 1991, of the first Federal Policy on Wetland Conservation. This policy puts forward the following principles to support wetland sustainability throughout Canada:

- maintenance of the ecological functions and values of wetlands;
- no net loss of wetland functions;
- enhancement and rehabilitation of wetland areas;
- recognition of wetland functions in planning, management and decision-making with regard to federal programs, policies and activities;
- securing of wetlands of significance to Canadians;
- recognition of sound, sustainable practices in sectors such as forestry and agriculture;
- utilization of wetlands in a manner that increases their productivity for future generations.

In the St. Lawrence, as in any other watershed, the application of these principles requires identification and evaluation of the wetlands, their significance, the risk of loss of surface area and possibilities for gains, monitoring of the wetlands and the development of methods for their restoration (p. 11). Chapter 5 addresses the issue of the effects of water-level fluctuations on wetlands and provides a more detailed analysis.

Policy for the Management of Fish Habitat (1986)

The *Fisheries Act* (R.S., 1985, c. F-14) presents the benefits of strengthening the link between habitat—of which water is a component—and fish communities. The Act protects habitat, in the very broad sense of the term, and requires that all interventions in aquatic environments have the authorization of the Minister; it also refers explicitly to habitat and water quality.[4] The Policy for the Management of Fish Habitat (1986)[5] was developed, in connection with this legislation, and parallel to the *Federal Water Policy*. It stipulates that fish habitats can be threatened "in ways both obvious and subtle, and by changes big and small (p. 7)."

The responsible Department "will strive to balance unavoidable habitat losses with habitat replacement on a project-by-project basis so that further reductions to Canada's fisheries resources due to habitat loss or damage may be prevented (p. 12)," and will do so on the basis of "professional judgement and common sense applied in an informed, cooperative environment by personnel experienced in habitat management, combined with supportive research (p. 12)."

More specifically, the policy sets out as its primary objective "the achievement of an overall net gain of the productive capacity of fish habitats (p. 10)." This objective implies an understanding of the actual or potential role of habitats in fisheries resource conservation and must also satisfy the requirement for no net loss of habitat productive capacity.

In this regard, an up-to-date knowledge of the constraints, including water-level fluctuations, on habitats becomes essential. In relation to the policy, Chapter 7 of this report deals with fish communities, their habitats and the effects of water-level fluctuations.

Wildlife Policy for Canada (1990) and Species at Risk Act (2002)

A *Wildlife Policy for Canada* was adopted in 1990 to conserve and restore ecological processes, biodiversity—ecosystems, species and genetic diversity—and the sustainable use of wildlife. In addition, the recent *Species at Risk Act* (which was passed by Parliament in 2002, but came into force in 2004) introduces a targeted approach favouring priority species and habitats in a context of urgency and the threat of irreversible loss.[6] This problem is addressed in Chapter 10 of this report.

With regard to birds, which are discussed in Chapter 8 of this report, some have historically been protected under the *Migratory Birds Convention Act* of 1917, and specifically the *Migratory Birds Convention Act, 1994* (1994, c. 22), which implements the Convention. Various measures have been introduced to support the Act: the North American Waterfowl Management Plan, flyway councils, a shorebird reserve network and wildlife sanctuaries.

Reptiles and amphibians (Chapter 6) and semi-aquatic mammals (Chapter 9) are not protected by any specific regulatory framework, except in the case of species that have been recognized as being at risk. The *Canadian Environmental Protection Act* (S.C. 1999, c. 33) provides general protection for such species, but actually applies to the discharge of contaminants and their impacts on all aquatic ecosystems.

Interest in the St. Lawrence has been marked in recent years by the implementation of successive federal-provincial action plans (1988 to 2004), and by the development and introduction of a provincial marine and inland water transportation policy (1998), Quebec's first provincial water policy (2002), emphasizing the integrated management of the St. Lawrence, and the recent sustainable navigation strategy (2005) for the St. Lawrence. Several hundred million dollars have been invested in the St. Lawrence in recent decades. But the fluvial ecosystem remains subject to numerous pressures, and its sustainability is at risk. In a context of increased scarcity of the water resource, attributable primarily to climate change, the continued existence of the St. Lawrence as we know it cannot be taken for granted.

Successive efforts to review management of water levels in the St. Lawrence

The hydrological regime of the St. Lawrence is distinctive in that it is subject to both natural factors and upstream control of flow. Efforts to control water levels and river flow date back to the early 20th century, against a background of international waters management — specifically the *International Boundary Waters Treaty* (1909) between Canada and the United States and the creation of the International Joint Commission in 1911 (Institute of the Environment and Clinton Edmonds and Associates Limited 2002). It was at this time that specific reference was made to an organization and an order of precedence among the various uses for the waters of the Great Lakes–St. Lawrence Basin (Article VIII of the Treaty). At the time, precedence was given first to uses for domestic and sanitary purposes, followed by uses for navigation,[7] including the service of canals for navigation, and then by uses for power and irrigation purposes.[8]

Almost 50 years later, the system for managing water levels and flows in the St. Lawrence was revisited (Figure 1.1) and the first water regulation plan (Plan 1958D) was introduced. As part of the construction of the international seaway, the plan proposed to balance priority uses (commercial shipping, hydroelectric power generation and flood protection) through operating standards and rules for the Moses-Saunders Dam. At that same time, the International St. Lawrence River Board of Control was established to ensure the application of the criteria and rules. After a number of adjustments, Plan 1958D went into effect in 1963.

Certain inadequacies in the plan, including the absence of environmental considerations, were later identified, obliging the International Board of Control to deviate on an ad hoc basis from the initial plan provisions almost half the time (Carpentier 2003). As early as 1964, a year of very low water levels, the plan proved to have several limitations. A sequence of periods of very low water levels (early 1960, late 1990) and very high water levels (mid-1970s) forced deviations to the plan. Chapter 2 on hydrology contains more detailed historical data on levels and flows in the St. Lawrence, while Chapter 3 describes the main physical characteristics of the system.

Because of the dissatisfaction with the regulation plan, the International Joint Commission made four successive attempts to review it.[9] The first was carried out in 1973 by the International Great Lakes Levels Board (IJC 1973), the second in 1991 by the IJC for the five Great Lakes, and the third by the International Board of Control in 1997. The last review, initiated in 1999, was intended specifically to respond more effectively to recreational boating and environmental requirements. At each attempt, it was very difficult to propose a plan that would be significantly better than Plan 1958D, which had been improved over the years by ad hoc modifications.

Figure 1.1 shows a cross-section of the system affected by the most recent regulation improvement exercise and shows the water-level increments between Lake Ontario and the St. Lawrence at Montréal.

Study of water levels in Lake Ontario and the St. Lawrence (2000–2005)

The most recent attempt involves the International Lake Ontario–St. Lawrence River Study Board,[10] established in 1999 and sponsored by the IJC to conduct a five-year study (2000–2005) of the criteria currently used to regulate water levels in Lake Ontario and the St. Lawrence River (IJC 1999).

This in-depth study, jointly funded by the United States and Canada, includes detailed technical analyses, an evaluation of impacts and alternative regulation measures. The study area comprises the 4350 km of shoreline between the western end of Lake Ontario (Niagara Falls, Ontario and New York) and Trois-Rivières, Quebec, where the impacts of the regulation of water-level fluctuations are felt (Figure 1.2). This five-year, C$30-million study was co-funded equally by the U.S. and Canadian governments. The objective was to improve the regulation plan by studying water-level fluctuations and, in particular, the effects attributable to regulation of Lake Ontario and St. Lawrence River levels and flows.

To achieve the objective, the effects of regulation plans were evaluated on the basis of a vision and a number of broad common principles[11] (see box). The result was presented in the report of the Study Board (International Lake Ontario–St. Lawrence River Study Board 2005).

The principles serve as guidelines for the Study Board in its comparative evaluation of the scope and frequency of the effects of various regulation plans developed to better meet the range of user and ecosystem requirements.

The work of the various technical groups provides the basis for the evaluation. A single group was responsible for producing the relevant indicators and studies for the environmental components.

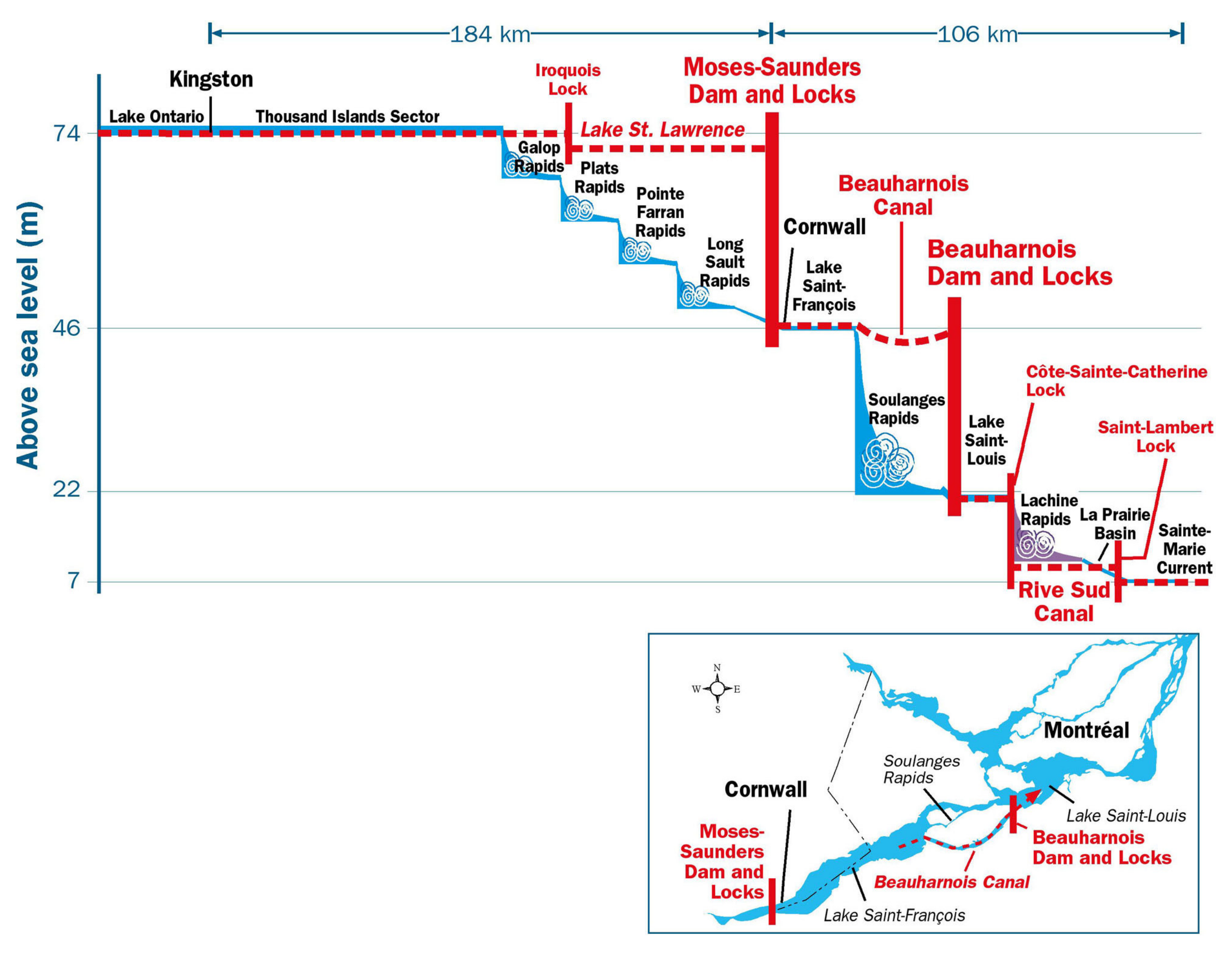

Figure 1.1 Profile of the drop in the St. Lawrence River between Lake Ontario and Montréal

Environmental Technical Working Group

The issue of ecosystem sustainability and integrity was specifically addressed by the Environmental Technical Working Group (ETWG). The ETWG was established to study and predict the response of certain environmental indicators to a variety of regulation scenarios, taking into consideration all components that could be affected by seasonal, annual and multi-year water-level fluctuations.

To guide its work, the ETWG first set two main goals for itself:

- To ensure that all types of native habitats (floodplain, forested and shrub swamps, wet meadows, shallow and deep marshes, submerged vegetation, mud flats, open water, and fast-flowing water) and shoreline features (barrier beaches, sand bars and sand dunes, gravel and cobble shores, and islands) were represented in an abundance that allows for the maintenance of ecosystem resilience and integrity across the seasons.
- To maintain hydraulic and spatial connectivity of habitats to ensure that fauna have access, temporally and spatially, to a sufficient surface area of all the types of habitats they need to complete their life cycles.

Vision, goal and guiding principles

Vision

To contribute to the economic, environmental and social sustainability of the Lake Ontario and St. Lawrence River system.

Goal

To identify flow regulation plans and criteria that best serve the range of affected interests, are widely accepted by all interests, and address climatic conditions in the basin.

Guiding principles

1. Criteria and regulation plans will contribute to the ecological integrity of the Lake Ontario–St. Lawrence River ecosystem.
2. Criteria and regulation plans will produce a net benefit to the Lake Ontario–St. Lawrence River system and its users and will not result in disproportionate loss to any particular interest or geographic area.
3. Criteria and regulation plans will be able to respond to unusual or unexpected conditions affecting the Lake Ontario–St. Lawrence River system.
4. Mitigation alternatives may be identified to limit damages when considered appropriate.
5. Regulation of Lake Ontario and St. Lawrence River levels and flows will be adaptable to the extent possible to accommodate the potential for changes in water supply as a result of climate change and stochastic variability.
6. Decision-making with respect to the development of the Lake Ontario–St. Lawrence River system governing criteria and plans will be transparent, involving and considering the full range of interests affected by any decisions with broad stakeholder and public input.
7. Criteria and regulation plans will incorporate current knowledge, state-of-the-art technology, and the flexibility to adapt to future advances in knowledge, science, and technology.

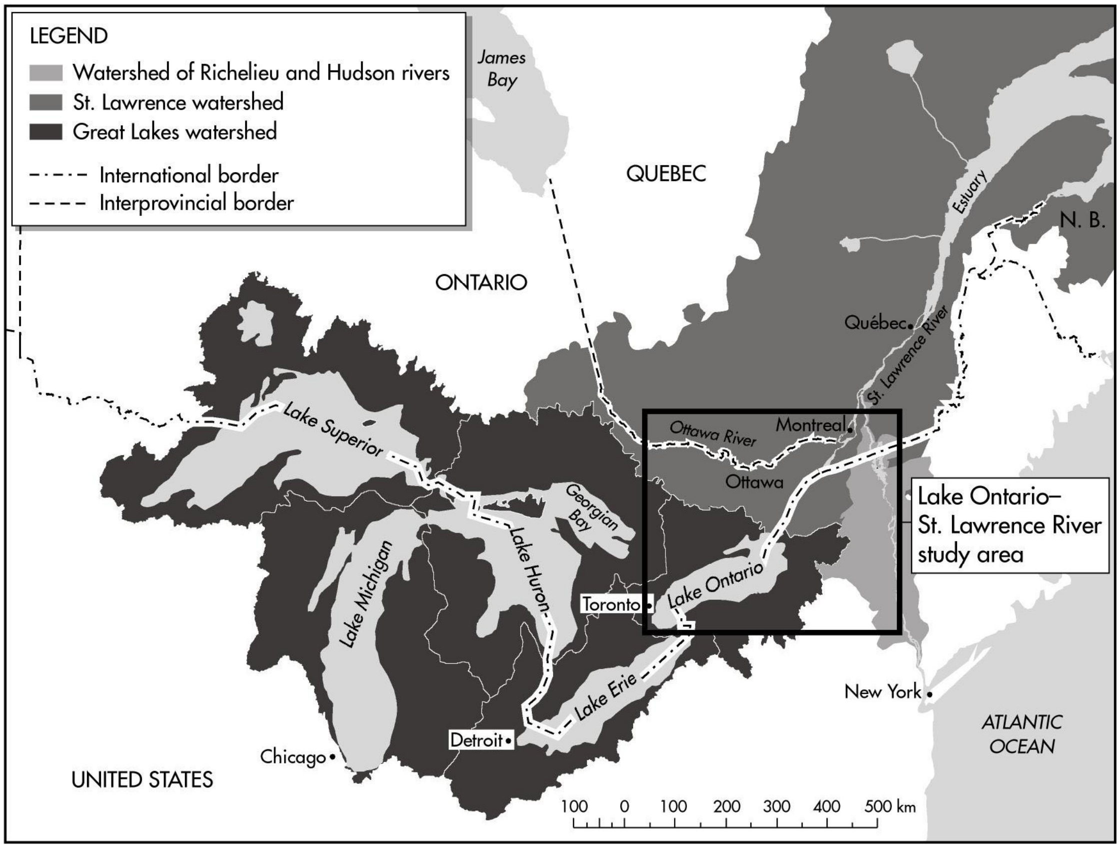

Figure 1.2 Study area affected by regulation of Lake Ontario and the St. Lawrence River

More specifically, after a thorough review of the literature and previous work, the ETWG established *performance indicators*, a set of measures used to evaluate the effects (*environmental performance*) of the water-level fluctuations caused by various regulation plans. As the following chapters will show, these effects can be direct, influencing the growth, survival or reproduction of plant and animal species, or indirect, affecting the accessibility (spatial or temporal) of certain critical habitats at various stages of the life cycles of plant or animal species. The response of organisms to water-level fluctuations can be measured at the scale of the species, guild, population or community, by their abundance, productivity or recruitment success. The following summary therefore focuses on key ecosystem indicators and the complementary information that provides a better understanding of the complexity of determining these effects.

In the case of the series of studies carried out between 2000 and 2005, several elements combined to result in plans that are more suitable than previous versions. First, the study mandate focussed on the link between Lake Ontario and the St. Lawrence. More studies targeted the environment, which led to new knowledge, and the historical data were evaluated more extensively. Updated climate projections were also considered. New tools were used: a spatially referenced system and a hydrodynamic model. For the St. Lawrence, this work was carried out in the context of the NIVODO program and the St. Lawrence Action Plan (Phase III), which served as an impetus for the work and provided a forum for scientific discussion of the results obtained. The environmental synthesis is one of the outcomes of this program and action plan.

Current Issues and Challenges for St. Lawrence Ecosystem Sustainability

Reviewing water-level regulation on a more ecologically sound basis is a daunting challenge for public decision-makers. In addition to regulation, other pressures exist—some obvious (e.g. the pressures imposed by major projects and diversions), and some more subtle (e.g. the cumulative changes to land use).

Large-scale water diversions and removals from the Great Lakes and St. Lawrence

The issue of Great Lakes water diversion is regularly in the headlines and is the subject of analyses focused primarily on the commercial aspects and water exports (Morin 2004). Indeed, this enormous body of water is undeniably attractive, and interest is likely to grow given the overwithdrawals of groundwater in many parts of the United States (Glennon 2002).

The International Joint Commission has acknowledged this issue,[12] and in 1981, the International Great Lakes Diversion and Consumptive Use Study Board, established by the IJC, conducted a preliminary evaluation of the impacts of diversion and consumptive use and concluded that rates of removal at the time could not be reduced in order to minimize low-level episodes. It also suggested monitoring of the potential impacts of new or increased diversions.

Almost 20 years later, in 1999, in response to various pressures and potential projects, the IJC produced an interim report on the same question,[13] while at the same time calling for the provinces and states to observe a moratorium on bulk removals of surface and groundwater and to exercise caution with regard to authorized removals.[14] In 2000, the final report[15] stressed the importance of considering the basin as a whole and the climate-related uncertainty that makes it all the more fragile. It also clearly indicated that, in terms of use of Great Lakes water, major outflows to the river must not be considered wasted because they serve an ecological function and help renew certain habitat types (page 46).

At the same time, the Canadian federal government approved an amendment to the *Boundary Waters Treaty*, prohibiting bulk water removals from the Great Lakes except for humanitarian purposes, fire-fighting and ballast water for ships.[16] A limit of 50 000 litres a day was also set for new removals, excluding the agri-food sector (products that contain water and bottled water).[17] It was also at that time (2001) that Annex 1 implementing the Great Lakes Charter (signed in 1985)[18] was released, providing for agreement among Quebec, Ontario, Wisconsin, Ohio, New York, Michigan, Indiana, Pennsylvania, Minnesota and Illinois. The discussions that followed were intended to provide each province and U.S. state bordering the Great Lakes with the right to withdraw a certain quantity of water. This right is set out as a common standard for the conservation and use of the resource.[19]

In 2004, the two Canadian provinces and eight U.S. states reached an agreement on removals and submitted it to public consultation. In December 2005, they concluded a formal agreement prohibiting large-scale diversions, except under certain conditions. The Agreement provides for an exceptional standard for a volume of 379 000 litres per day over any 90-day period and a regional review for 19 million litres per day or greater average volumes over any 90-day period (Article 201).[20] These limits remain subject to review by the parties. In its review of recommendations in 2000, the International Joint

Commission reported, however, that the states of Indiana, Ohio, Michigan and Wisconsin had not implemented water conservation programs. There are therefore grounds for concern that an approach based on the rationalization of water use may be more difficult for certain members of the Agreement. Such an eventuality also raises the question of the difficulty of not granting the same right to withdraw water to the other bordering states.

To date, in the case of projects with a potential to threaten the integrity of the basin, a number of which captured imaginations in the 1960s (e.g. the Grand Canal), actual withdrawals have been relatively modest. Quinn and Edstrom (2000) noted, for example, that diversions between basins had proven more beneficial to the Great Lakes than to other basins. The largest to date has been the Ogoki diversion, which redirected close to 113 m^3 of water per second from the James Bay watershed towards Lake Superior. In terms of transfers within a single basin, the largest was made in 1932, when 260 m^3 of water per second was transferred from Lake Erie to Lake Ontario via the Welland Canal. By way of comparison, in the 1990s, transfers were on the order of 0.11 m^3/s between basins (from Lake Michigan to the Mississippi, and from Lake Erie to the Ohio River) and 0.1 m^3/s within a single basin (from Lake Ontario to Lake Erie). Finally, with regard to bulk removals for export, the International Joint Commission (2002) pointed out that transportation costs were a major constraint on this type of development.

Major St. Lawrence River development projects: A potential threat to integrity

Again with respect to large-scale projects, the review of the role of the St. Lawrence Seaway (international and Quebec section), jointly initiated in 2003[21] in Canada by Transport Canada and in the United States by the Department of Transportation, could have an impact on water needs and habitats. Officially, projects intended to increase the capacity of the Seaway by deepening or widening locks are excluded.[22] Instead, the approach consists of evaluating options for optimizing existing infrastructure, thereby justifying any maintenance or improvements that might be required, depending on anticipated long-term needs.

Major navigation projects or projects that affect navigation conditions must comply with a body of legislation related to transportation safety (the *Navigable Waters Protection Act* [R.S., 1985, c. N-22] and associated regulations and the *International River Improvements Act* [R.S., 1985, c. I-20]), the control of environmental impacts (the *Canadian Environmental Protection Act* [R.S., 1985, c. 16]; the *Canadian Environmental Assessment Act* [R.S., 1992, c. 37]) and, finally, framework measures developed for the conservation of large areas of land (the *Act to Establish the Saguenay–St. Lawrence Marine Park* and the *Oceans Act* [1996, c. 31]).

Other development projects could emerge in the coming years, whether in relation to maintenance of navigation channels or development and redevelopment of shorelines and urban sectors (e.g. Cité du Havre in Montréal).

Integration of water quantity and quality issues: A necessary link to the health of Canadians

In 2001, in a survey[23] of heads or representatives of 65 organizations, the relationship between water quantity and quality emerged as the second most important issue after water diversions and exports. Although the *Great Lakes Water Quality Agreement* was signed in 1972 (revised in 1978 and strengthened by a protocol in 1987),[24] the links between these two aspects were not systematically developed. In the most recent version of the Federal Water Framework, quality and quantity are treated as two separate objectives,[25] an approach that does not enhance the synergy among research, monitoring and evaluation and decision making.

That said, there are several mechanisms that make it possible to regularly determine water quality, including the State of the Lakes Ecosystem Conference (SOLEC 2004), the series of U.S.–Canadian reports on the periodic monitoring of the application of the Agreement, and various monitoring programs, including the State of the St. Lawrence Monitoring Program, which addresses not only water quality, but also matters related to the state of the St. Lawrence ecosystem and uses of the St. Lawrence.[26]

Because new water quality problems arise periodically, however, a constant effort is required to update, integrate and disseminate information in order to effectively manage environmental risks.

Climate change: An impact accelerator

Water-level fluctuations are a natural consequence of climate variations. Biological communities have evolved to adapt to water levels and to the daily, seasonal and even annual changes in those levels. In fact, it is the type of water-level fluctuation that determines the diversity and the state of wetland plant communities and the habitats they provide for a variety of invertebrates, amphibians, reptiles, fish, birds and mammals.

High water levels can lead to the loss of many shrubs and invasion by upland plant species, cattails and other shallow water emergents. Low water levels may result in drying out of nearshore areas and the loss of submerged plant species, with certain emergent plants then growing from the exposed seed bank. Low water levels can also mean loss of access to fish spawning, feeding and nursery grounds and can restrict use of wetlands by muskrats. Several recent studies suggest that the climate in the Great Lakes–St. Lawrence region is in transition: winters are becoming shorter, the average annual temperature is rising, the duration of ice cover is decreasing and the frequency of intense rainfall events is increasing (Kling et al. 2003). In the future, the expected increase in the air temperature (approximately 2°C) and in the length of the growing and evaporation season (12–17%) should lead to a 0.2 to 0.7 m drop in average Great Lakes water levels (Lofgren et al. 2002). A recurring deficit in inflows to the Great Lakes basin could lead in turn to a 20–40% drop in outflows from Lake Ontario to the St. Lawrence, with a 1-m decrease in the average level of the river at Montréal (Mortsch and Quinn 1996). The most recent scenarios suggest that the decline in outflows from Lake Ontario could fluctuate between 4 and 24% (Crowley 2003).

In addition to direct effects on ecosystems (Mortsch 1998; Schindler 2001), long-term change in flows from Lake Ontario would have an impact on all Lake Ontario and St. Lawrence River interest groups (IJC 1999; NRC 2002). The climate factor introduces an uncertainty that is difficult to control and therefore demands a certain capacity to adapt.

The St. Lawrence ecosystem is already showing some response to the hydrological regime changes made in the past. However, the pace, scope and frequency of changes are capable of causing long-term disruption of the system as we know it. The climate factor, therefore, adds an increased risk over and above the other pressures. Monitoring this factor and its anticipated effects on the St. Lawrence will help develop a predictive capacity and a more rapid response, where required.

Water availability: An open question

Conservation of adequate water levels and flows in the St. Lawrence is rooted in several public policies adopted over the past 20 years. However, a clearer determination of the effects of such variables on the ecosystem and more specifically on the sector affected by the availability of water from the Great Lakes has been undermined by a lack of coordination of research efforts. This synthesis constitutes a first step towards improving this situation.

The ability to conserve ecosystem integrity requires the observation of environmental trends in the watershed, as well as research better illustrating the relative fragility of the ecosystem and modelling efforts that will make it possible to better anticipate future risks. Some of these risks have been briefly identified and described here. Although, for the present, it may be more relevant to talk about potential risks, some are very real (Lasserre 2005). These risks raise questions about modifications to future hydrological regimes and about the needs that will have to be taken into account—hence the usefulness of the data this synthesis provides on various ecosystem components and on the main uses of the system.

Finally, it would be appropriate to give more thought to the proposed technical solutions for stream management and to the economic choices associated with managing demand that could reduce pressure on water availability in the St. Lawrence.

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NOTES

1. In the case of the Great Lakes, by the early 1980s, it was estimated that 60% of municipal withdrawals were already being made in the Great Lakes–St. Lawrence Basin (Pearse et al. 1985).

2. The same year Environment Canada was established.

3. The question of federal and provincial jurisdictions seems more open to criticism in Part II of the Act, which deals with water quality (Pearse et al. 1985).

4. The latter consideration was the source of the first regulatory tools to limit water pollution.

5. In administrative terms, the management of habitat (physical aspects) is the responsibility of the Minister of Fisheries and Oceans, while pollution management (s. 36 to 42) comes under the jurisdiction of the Minister of Environment. Nevertheless, this division of roles implies an ongoing collaboration and coordination.

6. See the message from the Canadian government's ministers of the Environment, Fisheries and Oceans, and Canadian Heritage (2003). *Species at Risk Act: A Guide*. Quebec also has its own legislation governing threatened species.

7. Note that discussions concerning improvement of the waterway were first initiated with the United States around 1895, and that the International Waterways Commission was established in 1903.

8. International Joint Commission. 1988. *The International Joint Commission and the Boundary Waters Treaty of 1909.* September, 32 pp.

9. In 1973, the International Great Lakes Levels Board published *Regulation of Great Lakes Water Levels.* In 1993, the International Joint Commission tried a different approach with the *Levels of Reference Study.* In 1997, the International St. Lawrence River Board of Control published *An Updated Regulation Plan for the Lake Ontario–St. Lawrence River System.*

10. The Study Board is made up of experts from government, universities, Aboriginal communities and interest groups with geographic, scientific and social concerns related to the hydrographic network formed by Lake Ontario and the St. Lawrence River. It also has a mandate to seek public participation throughout the duration of the study by soliciting the opinions of citizens, analyzing their comments and ensuring that their concerns are taken into account in the scientific work of its technical working groups. Its objective is to make recommendations to the IJC concerning establishment of new criteria and updating of the regulation plan for water levels and flows. The five-year study evaluates the needs of all interest groups, but focuses particular attention on the interests of the environment, recreational boating and riparian property. Over 120 people work directly on the various activities related to the study, including representatives of interest groups and non-governmental organizations.

11. The vision and guiding principles were adopted at the Study Group's meeting in Buffalo, New York, on August 28, 2003.

12. The first major diversion was carried out in 1900 by the City of Chicago, which withdrew water from the Great Lakes to facilitate the flow of its wastewater toward the Mississippi.

13. International Joint Commission. 1999. *Protection of the Waters of the Great Lakes, Interim Report to the Governments of Canada and the United* States. August 10.

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26. A collection of fact sheets on the state of the St. Lawrence can be found at www.slv2000.qc.ca. The initial series of fact sheets was produced in 2003.

Chapter 2

ANTHROPOGENIC MODIFICATIONS AND HYDROLOGICAL REGIME IN THE FLUVIAL PORTION OF THE ST. LAWRENCE DOWNSTREAM FROM CORNWALL

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Introduction

In their natural state, large and small rivers are dynamic ecosystems characterized by annual and seasonal variations in the hydrological regime that determine the amplitude in their flows and levels. In turn, these hydrological variations, closely related to climatic conditions and therefore highly unpredictable, cause floods or droughts that are sometimes very unfavourable to the uses shoreline residents make of their watercourse. Works to regulate and control water flows and levels have been constructed on many rivers, whether for purposes of navigation, hydroelectric generation, flood control or agriculture. Unfortunately, these works have often been put in place without much concern for impacts on the aquatic ecosystem, reflecting a period when environmental awareness was not as acute as it is today. The result is that there are fewer and fewer "natural" rivers, and it is estimated that 59% of the world's large rivers (i.e. those whose mean annual flow exceeds 300 m^3/s), have been regulated to various degrees through construction of dams, levees or canals (Nilsson et al. 2005). In North America, 55% of large rivers, representing approximately 80% of the area of the continent's watersheds, are currently regulated, and requests for action are still being received.

The St. Lawrence River is no exception to the rule and its waters have been regulated since 1960, following construction of the Moses-Saunders Dam at Cornwall, Ontario, approximately 345 km above its mouth at Québec, and the control works in the watershed of the Ottawa River, the principal tributary of the St. Lawrence. Since the late 19th century, major works have been completed in the Great Lakes and St. Lawrence watershed. Dredging to depths of several metres has been carried out in the bed of the fluvial St. Lawrence (Morin and Côté 2003), and various regulation works have gradually altered its natural hydrological regime. These physical interventions, which have promoted economic development of the Great Lakes watershed, have also had an impact on its ecosystems. For example, the principal fish migration routes upstream from Montréal have been cut off by dams, the surface area of the St. Lawrence's riparian marshes has been reduced, and various habitats, both in slow- and fast-flowing waters, have seen losses associated with land development (such as embankments), stabilization of water levels in Lake Saint-François and channelization of the St. Lawrence (including construction of weirs in the channels of the Îles de Sorel).

This chapter addresses the physiographic and hydrological characteristics of the lower reach of the St. Lawrence (the fluvial section between Cornwall and Trois-Rivières), thus making it possible to determine the current and past status of St. Lawrence water availability. More specifically, the hydrological characteristics of the river are studied with regard to the physical developments that have adjusted and modified its flow and dynamics.

General Description of the System

Upstream, the Great Lakes–St. Lawrence system comprises a series of reservoirs (i.e. the Great Lakes), which drain a watershed larger than 770 000 km^2 through the outlet of Lake Ontario, which empties into the fluvial section of the system. Figure 2.1 shows the extent of the Great Lakes watershed affected by the current water regulation regime.

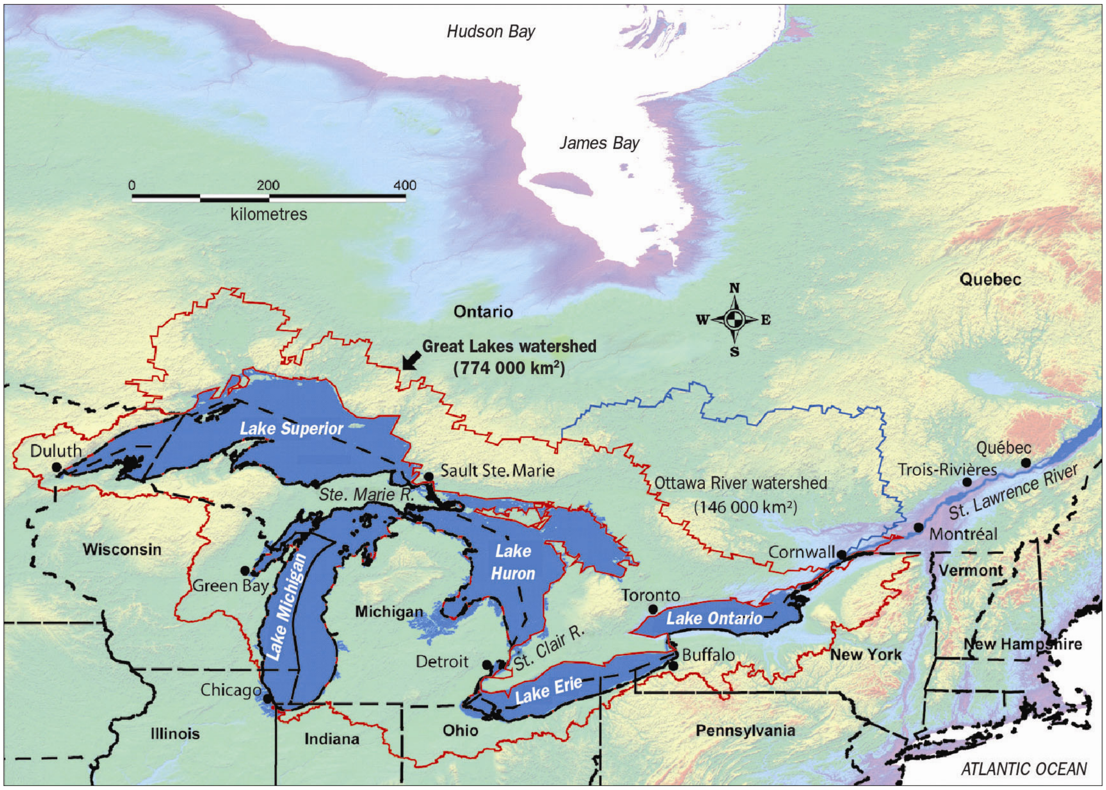


Figure 2.1 Great Lakes–St. Lawrence watershed

Hydrological characteristics

Physiography

The lower reach of the St. Lawrence affected by water regulation, extending for approximately 250 km, is bounded upstream by the Moses-Saunders Dam at Cornwall and downstream by the tidal phenomenon, whose effect increases at Pointe-du-Lac. The total elevation change along the reach is approximately 71 m (Figure 2.2). A succession of lentic and lotic zones are found here. In the upstream portion, the Moses-Saunders and Beauharnois-Les Cèdres hydroelectric facilities limit water-level fluctuations in Lake Saint-François to less than 15 cm annually. These waters then reach Lake Saint-Louis primarily through the Beauharnois-Les Cèdres hydroelectric complex. Approximately 84% of the flow entering Lake Saint-Louis passes through the Beauharnois Canal. The northern portion (Côteau basins at Pointe-des-Cascades and Soulanges Canal) receives the remaining 16% (Fortin et al. 1998).

Lake Saint-Louis is located at the confluence of the waters from the Great Lakes and the Ottawa River; the latter is the largest tributary of the St. Lawrence, draining a watershed of 143 000 km^2. The Ottawa River waters reach the St. Lawrence through Lac des Deux-Montagnes via the four channels that basically form the Montréal archipelago: the Rivière des Mille Îles and the Rivière des Prairies, which empty into the St. Lawrence at Repentigny, as well as the Sainte-Anne Canal and Vaudreuil Channel on either side of Île Perrot, which empty into Lake Saint-Louis. The Lachine Rapids between Lake Saint-Louis and the La Prairie Basin are marked by an elevation change of approximately 13 m. This is the downstreammost point of the river where traditional flow estimation methods can be applied. Downstream of this point, the flow is essentially of the fluvial type, and more complex methods must be used to estimate it, such as two-dimensional (2D) and one-dimensional (1D) numerical simulations, as well as estimates of inflows from tributaries and water transport times (water balance), in order to describe the flow type more accurately

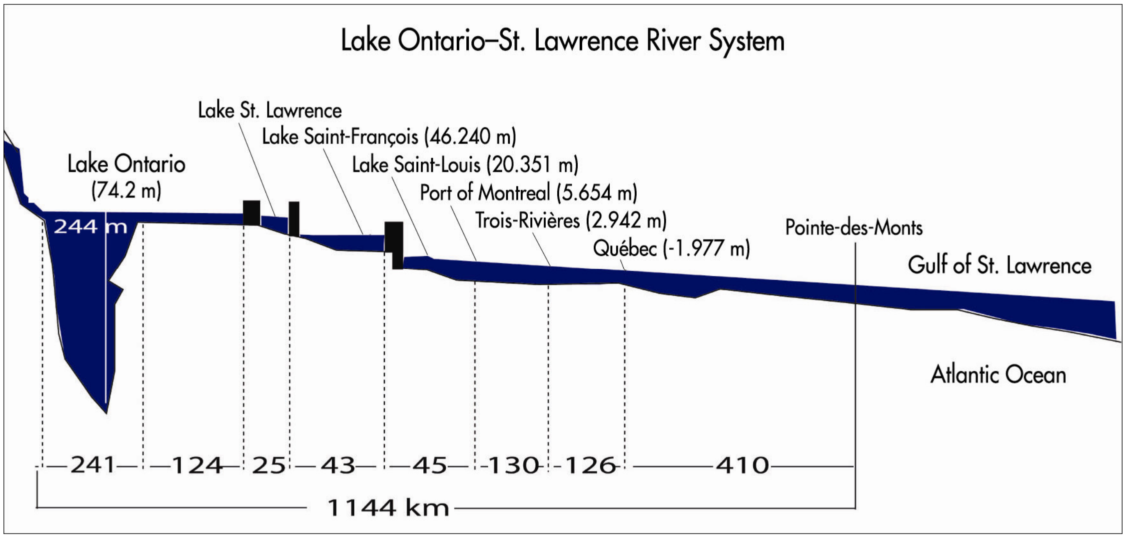


Figure 2.2 Longitudinal profile of the Lake Ontario–St. Lawrence River reach

Flow

In the reach between Cornwall and Trois-Rivières, the waters of the river present a non-permanent and non-uniform turbulent gravity flow of a generally fluvial nature, except in areas of pronounced slope such as the Lachine Rapids, where the flow is of the supercritical type. Flow here is essentially controlled by the discharge from Lake Ontario (partly regulated) and the tributaries, as well as by the slope of the bed. Downstream from Trois-Rivières, the progressive effect of the semi-diurnal tide becomes the factor controlling the flow (this is almost the total controlling factor at Québec and toward the Gulf).

Inflows

In addition to the Great Lakes watersheds at the level of the Moses-Saunders Dam (774 000 km^2) and the Ottawa River at the Carillon Dam (143 000 km^2), the watersheds of the tributaries emptying into the St. Lawrence River between Cornwall and Trois-Rivières total 67 559 km^2. More than two-thirds of these watersheds are gauged, in other words, data are available concerning their hydrological supply. These so-called “lateral” supplies to the lower reach of the St. Lawrence are calculated as daily means using a method adapted from Morse (1990) (Bouchard and Morin 2000). This method takes into account the principal gauged tributaries and non-gauged areas, allowing an estimate of flows (gauged and non-gauged watersheds). Finally, at the outflow from Lake Saint-Pierre, the total area drained by the Great Lakes–St. Lawrence system is approximately 1 000 000 km^2.

It should be noted that the distribution of flows and levels in the Montréal area is especially difficult because of the relatively large ungauged areas of approximately 15 000 km^2 for the Lake Saint-François and Montréal north shore sectors, and also because of the complexity of the flow in the area, the many constructed works and the regulation strategies adopted to accommodate various issues.

Anthropogenic developments

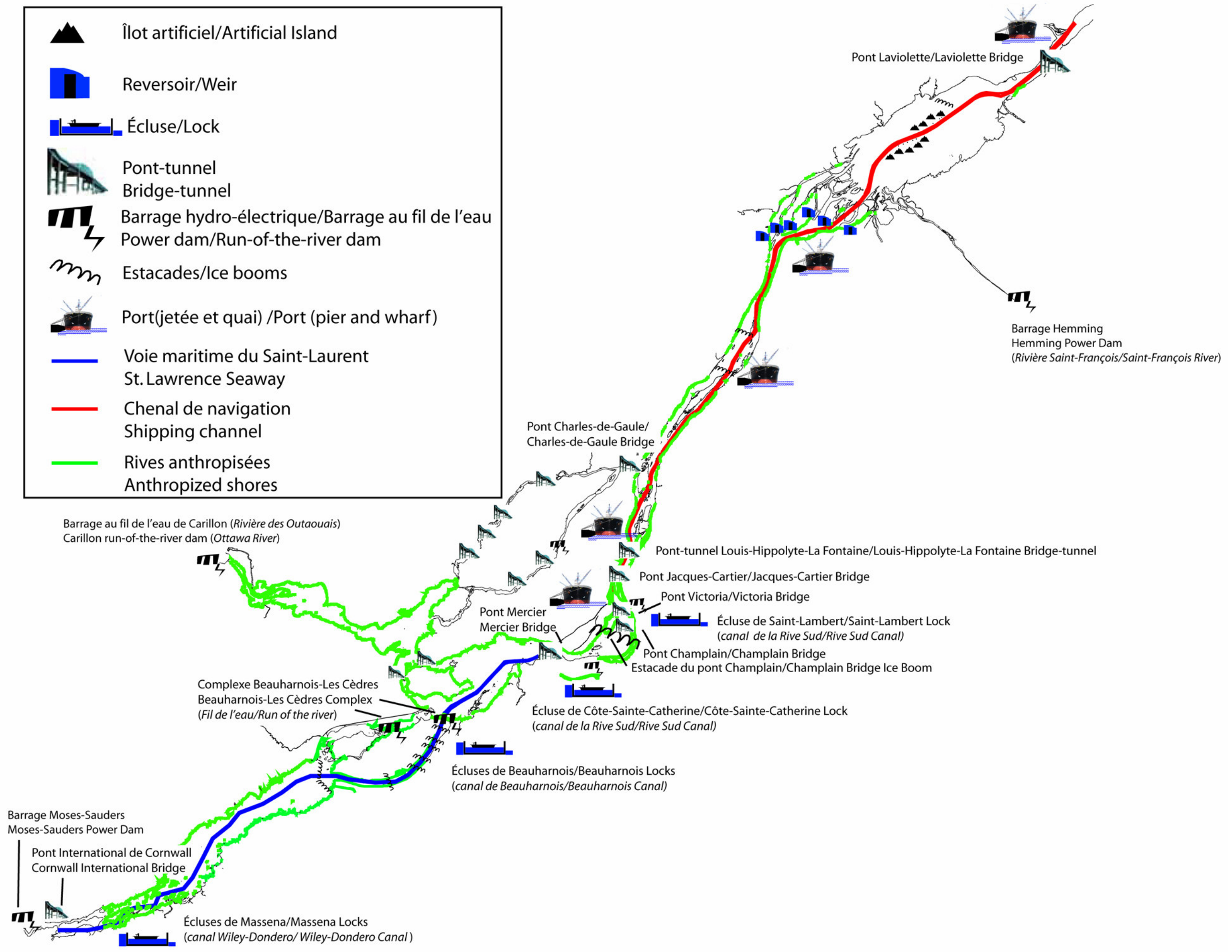
In support of economic development during the 20th century, various modifications have been made to the lower reach of the St. Lawrence: construction of a ship channel to allow passage of vessels from the Gulf to Montréal and beyond to the Great Lakes, development of major harbour facilities and construction of weirs to raise water levels, shoreline protection works to limit erosion caused by wave action from passing boats, ice management structures, canals and locks.

In addition to these modifications, hydroelectric facilities have been built to capture the energy potential of the St. Lawrence and certain of its tributaries, a large number of bridges have been constructed, islands have been created and modifications made to hundreds of kilometres of shoreline. Figure 2.3 provides an overview of the anthropogenic modifications made to the lower reach of the St. Lawrence, which are so major that it is becoming extremely difficult to draw historical comparisons of the flow before and after these interventions.

Hydroelectric development

In the area upstream from Cornwall, major development carried out between 1954 and 1959 has significantly modified the natural flow: two dams, several kilometres of ship channels, two locks, major dredging operations and several kilometres of embankments to contain the water reserve known as Lake St. Lawrence, upstream from the Moses-Saunders hydroelectric power station operated jointly by the New York Power Authority and Ontario Hydro.

Downstream from Cornwall, the first hydroelectric facilities were built in the Valleyfield sector between Lake Saint-François and Lake Saint-Louis to exploit the elevation change at the Soulanges Rapids, a 29-km section of the main channel consisting of four separate areas of rapids: the Coteau-du-Lac, Les Cèdres, Rocher Fendu and Les Cascades Rapids. The Les Cèdres Rapids were developed in 1914 to drive the Les Cèdres run-of-river power station, which is still operating with an elevation change of 12 m and an installed capacity of 135 MW. Further dams were built in 1932 on either side of Juillet Island, to concentrate the flow to the Les Cèdres power station (Morin et al. 1994).



Source: Environment Canada, Meteorological Service of Canada, Hydrology Section, Quebec Region.

Figure 2.3 Main anthropogenic developments on the St. Lawrence River

The Beauharnois Canal, built from 1929 to 1932, directs most (approximately 84%) of the St. Lawrence flow to the Beauharnois run-of-river power station, which was started up in three phases. In 1932, 2500 m^3/s were diverted for phase one, while phases two and three were completed respectively in 1952 with 4500 m^3/s, and in 1961 for the present turbinated flow of approximately 6500 m^3/s, representing an installed capacity of 1658 MW. With a difference in elevation of 24 m, this power station is twice as efficient as the Les Cèdres power station.

The Côteau reservoir structures, built between 1933 and 1942, serve to optimize the overall performance of the Beauharnois and Les Cèdres hydroelectric complex by controlling allocation of the flow between the two power stations in accordance with the following method: a minimum flow of 283 m^3/s is routed into the old Soulanges Rapids channel, except during the spawning season of certain fish species, when it is maintained at 450 m^3/s. Under normal operating conditions, priority is given to the turbines at the Beauharnois power station, which have a production coefficient of 0.2 $MW/m^3/s$ (Carter 2003), up to a maximum flow of 7200 m^3/s. Between 7200 m^3/s and 9400 m^3/s, the excess flow is turbinated at the Les Cèdres power station, with a production coefficient of 0.1 $MW/m^3/s$, up to the maximum flow capable of being turbinated by the Beauharnois and Les Cèdres development (9400 m^3/s). All additional flow is released at the Juillet Island dam without being turbinated.

The power required to operate the locks of the St. Lawrence Seaway in the Montréal area comes from the small Saint-Lambert and Côte-Sainte-Catherine 1, 2 and 3 power stations, whose installed capacities are 5.8 MW, 2.0 MW, 4.8 MW and 4.5 MW, respectively.

The Carillon run-of-river power station, built in 1962 on the Ottawa River upstream from Lac des Deux-Montagnes, has an elevation change of 17.99 m, yielding an installed capacity of 752 MW. Two more tributaries of the St. Lawrence River upstream from Trois-Rivières have hydroelectric power stations: the Rivière-des-Prairies run-of-river power station was started up in 1929 with an elevation change of 7.93 m and an installed capacity of 48 MW, while the Drummondville run-of-river power station on the Saint-François River was started up in 1910 with an elevation change of 8.23 m and an installed capacity of 16 MW.

St. Lawrence Seaway

The St. Lawrence Seaway makes navigation possible between the Atlantic Ocean and the Great Lakes. It currently consists of six canals, a number of diversion works and 15 locks 233.5 m long, 24.4 m wide and 91 m deep, thus enabling merchant vessels to navigate the 180-m elevation change between Montréal and Lake Superior. This enterprise, extending over a period of 300 years, was launched by the British following the conquest of New France, to support their war effort against the American colonies. It went through several phases before the current configuration was achieved in 1959. There are two groups of installations on the lower reach of the St. Lawrence, whose final construction was completed from 1954 to 1959: the Rive Sud Canal, with two locks (one at Saint-Lambert and the other at Côte-Sainte-Catherine) connecting the Port of Montréal with Lake Saint-Louis by enabling vessels to clear the Lachine Rapids, and the Beauharnois Canal, whose two locks make it possible for vessels to pass from Lake Saint-Louis into Lake Saint-François, clearing the Soulanges Rapids.

Ship channel

Between Trois-Rivières and Montréal, a number of works were completed from the mid-19th century onward for the purpose of promoting commercial navigation: successive dredging operations, construction of weirs in the Sorel sector and bank protection works along the ship channel. Table 2.1 sets out the sequence of dredging operations carried out in the St. Lawrence between Montréal and Québec.

Raising St. Lawrence River levels to facilitate commercial navigation has long been a goal. A study of water levels between Montréal and Lake Saint-Pierre (DMFC 1915) suggested that five weirs be constructed to limit the drop in water levels during periods of lower flows and concentrate the flow in the ship channel. These weirs were constructed from 1928 to 1931 between: 1) Île aux Barques and Île du Moine, 2) Île de Grâce and Ronde Island, 3) Ronde Island and Madame Island, 4) Saint-Ignace Island and Île aux Cochons, and 5) Île aux Cochons and Île du Milieu (Morin and Bouchard 2001).

These works were intended to increase water levels by approximately 0.12 m in the Port of Montréal and by 0.29 m at Sorel. The percentage of the flow in the ship channel apparently increased from 25% to 85%. However, this effectiveness, predicted in the design ratings, has been reduced over time because of erosion problems affecting the weirs in periods of high flows and the effect of ice (Dumont 1996). In addition, the ship channel creates an obstacle to mixing of water masses between Montréal and Sorel.

TABLE 2.1

Sequence of dredging in the St. Lawrence between Montréal and Québec

Years	Depth	Width	Location
Before 1844	3.2 m maximum	~	
1844–1847	4.2 m	45 m	Small section of Lake Saint-Pierre: unsuccessful attempt to construct a straight channel
1850–1851	4.2 m	45 m	Dredging mainly in the natural channel of Lake Saint-Pierre
1854–1856	4.8 m	45 m	Lake Saint-Pierre and other locations
1856–1865	6.1 m	75 m	Lake Saint-Pierre and other locations
1888	7.6 m		
	8.4 m	135 m	
1888–1907	9.0 m	135 m	
1912–1930	10.7 m	168 m	Montréal to Batiscan
1952–1954		245 m straight	Montréal to Québec
		457 m curve	
1954–1971			Local developments
1973–1974			Montréal-Nord anchorage
1992	11.0 m	245 m straight	Montréal to Québec
1998–1999	11.3 m	245 m straight	48 shoals between Montréal and Cap à la Roche

Ice management

Because of the massive ice presence in the St. Lawrence during winter, a number of ice-cover management measures are necessary to maintain the river’s hydropower capacity and prevent ice jams, which can interfere with production of hydroelectricity at Moses-Saunders and the Beauharnois-Les Cèdres complex, reduce keel clearance in the St. Lawrence waterway, obstruct the entrance to the Port of Montréal, affect municipal and industrial water intakes and make it difficult to control Lake Ontario water levels.

Since the production of frazil ice in turbulent flow zones in contact with cold air exceeds the production of ice in non-turbulent zones, such as bays and areas close to banks, by a factor of approximately 15 (Carter 2003), the Canadian Coast Guard implements an ice cover management strategy to reduce risks of flooding and facilitate commercial shipping into the Port of Montréal, by reducing the volume of drifting ice and increasing the capacity of the ship channel to drain ice. A number of facilities and equipment to promote establishment of ice cover have been installed since the mid-1960s.

Harbour developments and bank protection

Harbour developments on the St. Lawrence have modified the morphology of the banks; however, urban development of the shores is much more significant. Of the 1100 km of shoreline between Cornwall and Trois-Rivières, there are approximately 685 km on which structures to provide protection against wave action from passing boats and natural fluctuations have been developed. A detailed inventory of use of the banks, completed in 1994 by the Canadian Wildlife Service, established that approximately 47% of the banks of the St. Lawrence River between Cornwall and Trois-Rivières have been subject to anthropogenic disturbance (Villeneuve 2001).

The ports of Montréal, Sorel and Trois-Rivières occupy an area of approximately 450 ha. The Port of Montréal alone extends over 25 km of banks and comprises 100 berths distributed among 51 wharves (Villeneuve 2001). Port locations have also been subject to major recreational and tourism development since the early 1990s.

Regulation

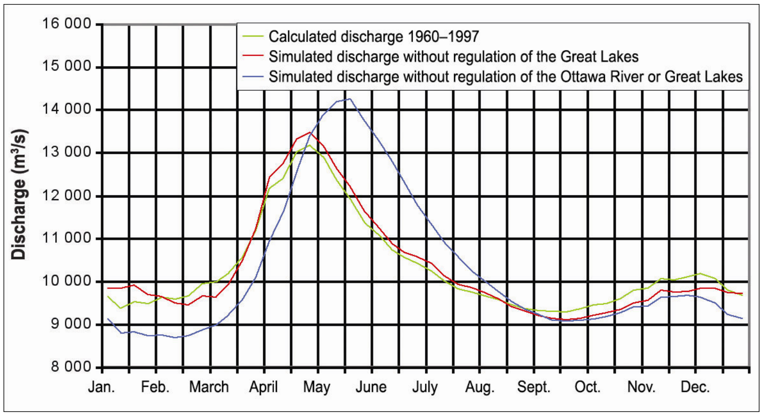
Discharge from the two main sources of inflow to the river, the Great Lakes and the Ottawa River, is regulated mainly in response to needs for hydroelectric production, commercial shipping and minimization of flood risks within the system. These needs were formalized in Regulation Plan 1958D, applicable to Lake Ontario and the St. Lawrence River. The effect of regulation is to reduce flow during spring, increase it in fall and winter, and stabilize flows to minimize extremes. Generally, the flows are reduced in spring by a maximum of around 2000 m^3/s and increased between September and March by between 300 and 900 m^3/s. It should be noted, however, that the flow is reduced in January to allow ice formation upstream from the Beauharnois and Moses-Saunders hydroelectric facilities.

To prevent flooding in the Montréal area, the outflow from Lake Ontario is managed as a function of the flood peak observed in the Ottawa River. The year 1998 provides an example of this management practice, when the freshet peak on the Ottawa River was high and occurred over a short time period. The International St. Lawrence River Board of Control reacted by reducing the volume of outflow from Lake Ontario. When the very high flows from the Ottawa River had passed, the flow at Cornwall was increased again to prevent flooding on Lake Ontario.

As shown by Figure 2.4, the impact of regulation of the Ottawa River on the flow at Sorel has been greater than regulation of the Great Lakes, especially in terms of reducing flood peaks, changing the times of occurrence of flood peaks in the year (earlier) and increasing winter flows (Morin and Bouchard 2001). Although this typical impact of regulation seems substantial, the actual manoeuvring room available to the Great Lakes–St. Lawrence Regulation Office in order to avoid extreme episodes is actually much more limited. For example, during long periods of low hydraulicity, the level of the Great Lakes becomes very low, with the result that it is very hard to compensate for the lack of water downstream without aggravating an already problematic situation upstream. The opposite is also true in terms of preventing flooding during episodes of high flows within the system.

St. Lawrence River Hydrological Regime

Flow fluctuations in the St. Lawrence River are mainly the result of inputs from its two main sources, Lake Ontario and the Ottawa River. While several major inflows downstream from these principal sources also contribute to these fluctuations, their impact is lessened because of their smaller size. On average, Lake Ontario supplies 6980 m^3/s per year to the St. Lawrence River, while the mean annual flow calculated at Sorel is 9868 m^3/s (Table 2.2). When the flow from Lake Ontario fluctuates by 5650 m^3/s and its level varies by 2.02 m, the flow and level fluctuations of the St. Lawrence at Sorel are 10 639 m^3/s and 3.62 m, respectively (monthly means). These larger fluctuations are mainly the result of greater variations in inflows from tributaries and the morphology of the fluvial environment.



Source: Morin and Bouchard 2001.

Figure 2.4 **Mean annual discharge at Sorel from 1960 to 1997: Calculated discharges, simulated discharges without the effect of regulation of the Great Lakes and the Ottawa River**

Nearly 3000 m^3/s, or about 30%, of the river flow at Sorel, therefore comes from the Ottawa River and other tributaries located in the sector between Cornwall and Sorel (Table 2.3). The percentages of the river flow from Lake Ontario and the other tributaries may vary over the year in accordance with the season, climatic conditions and the regulation strategy implemented.

Flow

Long-term fluctuations

The St. Lawrence is characterized by an extremely variable hydraulicity from one year to the next, depending mainly on the climate. The time series of St. Lawrence River flows at Sorel, shown in Figure 4.5, enables the reader to appreciate the extent of daily flow fluctuations, on the order of 14 000 m^3/s, and ranging from a minimum of 6000 m^3/s to a maximum of approximately 20 000 m^3/s. Extremely low flows were observed during the mid-1930s (6601 m^3/s), followed by high flows reaching 19 655 m^3/s in 1943. Extremely low flows were again observed in the mid-1960s (6093 m^3/s), followed by high flows (20 343 m^3/s) in 1976 and then, more recently in the late 1990s and the beginning of 2000, low flows once again (7014 m^3/s), with a recent increase since 2002.

It is also noted that the flows—and associated levels—recorded in the past during periods of very low water include more extreme values than those reached during the recent episode of low water in the summer of 2001. Although the values measured during that summer were very low, they are within the range of values measured over the last hundred years.

TABLE 2.2
Summary of Great Lakes and St. Lawrence River levels and flows

	Lake Ontario		St. Lawrence River at Sorel	
	Level (metres; IGLD 1985 value*)	Flow (m^3/s)	Level (metres; IGLD 1985 value*)	Flow (m^3/s)
Mean	74.8	6 980	4.96	9 868
Maximum	75.76	10 010	7.23	17 180
Minimum	73.74	4 360	3.61	6 541
Fluctuations	2.02	5 650	3.62	10 639

* International Great Lakes Datum 1985.

Note*:* Lake Ontario levels and flows are calculated from mean monthly data recorded at a group of stations for the period from 1918 to 2004. The daily and instantaneous water levels on a specific lake may be outside the maximum and minimum values indicated.

Source: Environment Canada, Great Lakes–St. Lawrence Regulation Office. St. Lawrence River levels and flows are calculated from the monthly means recorded at the Sorel station for the 1932–2004 period.
Source: Bouchard and Morin 2000.

TABLE 2.3
Summary of main water inputs to the St. Lawrence River as far as Trois-Rivières, compiled from mean daily flows for the 1932–2004 period

	Flow (m^3/s)		
	Minimum	Mean	Maximum
Lake Ontario at Cornwall	4 360	6 980	10 010
Inputs to Lake Saint-François	0.9	232	1 232
Châteauguay River watershed	1.3	42	1 847
Ungauged supply to Rive Sud Canal	0.1	5.4	248
Ottawa River at Carillon Dam	306	1 914	8 190
Montréal north shore (downstream from Carillon as far as L'Assomption, near Repentigny)	10.3	127	1 709
Richelieu River watershed	47	373	1473
Inputs to Lake Saint-Pierre	20	377	4 595

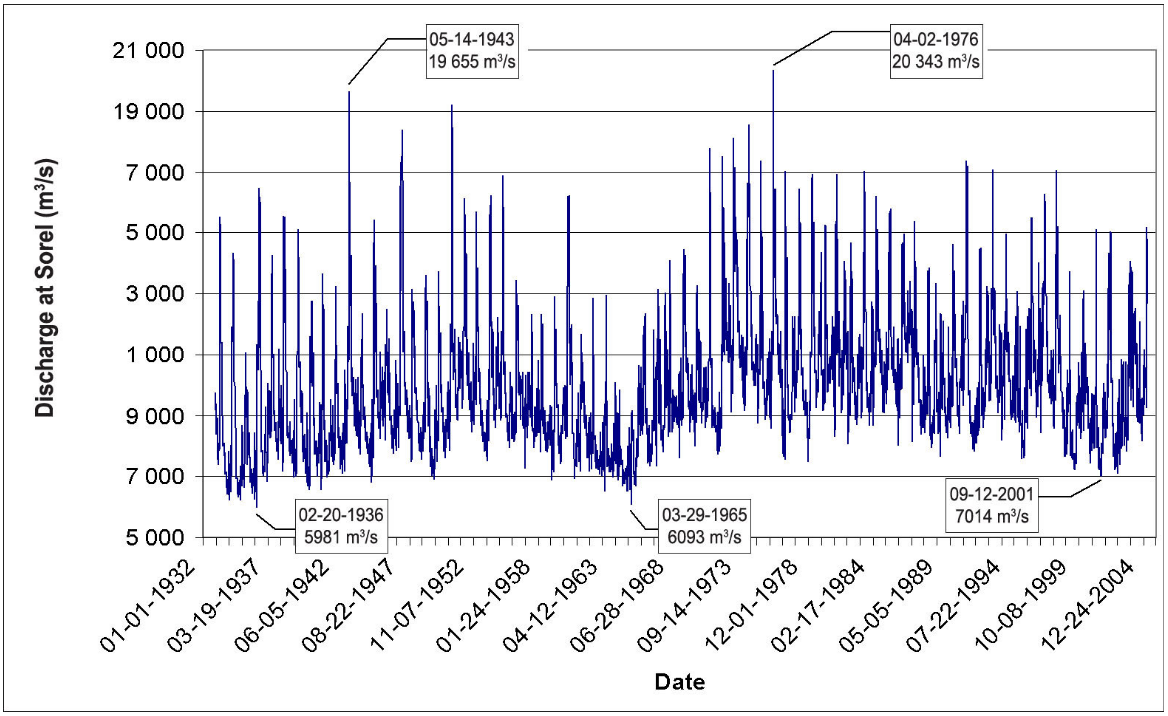


Figure 2.5 Daily mean discharge in the St. Lawrence, calculated at Sorel from 1932 to 2004

Seasonal and short-term fluctuations

St. Lawrence River flows can vary greatly, both seasonally and in the short term (daily, weekly). Many reasons explain this variability, including the volume of precipitation received by the watershed, evaporation, soil saturation, snow cover and regulation of the Great Lakes and the St. Lawrence River. In the latter case, this includes specific interventions under International Joint Commission (IJC) management plans to reduce flooding risks downstream or permit commercial shipping, for example, in the Port of Montréal.

Major flow variations at Sorel are caused mainly by freshets in tributaries, especially the Ottawa River. The flooding generally occurs in late April, with a flow of approximately 13 000 m^3/s, while the minimum flow occurs in late August and in January (approximately 9000 m^3/s). Peak spring flows may occur as early as mid-February (as in 1981), or may be delayed until late May (as in 1974).

Recent analysis of the mean daily discharge in the St. Lawrence, calculated at Sorel from 1997 to 2001, shows, for example, that 1999 and 2001 were very similar (years of low hydraulicity), and that stronger flows were recorded in 1997 and 1998. The year 2000 stands out: the freshet was very weak and there was a second late peak, with the remainder of the season resembling 1998. Great variability can be noted from one year to the next, both in the magnitude of the freshet and in the dates of its appearance. The same applies to the minimum flow.

Water levels

Each of the developments along the lower reach of the St. Lawrence River over a period of more than a century has had an impact on the distribution of levels. Whereas certain works, such as bridge piers, generate an impact that remains local, a number of major developments have changed the distribution of levels over major areas, particularly between Montréal and Trois-Rivières: repeated dredging of the ship channel (flow facilitation in the open channel), construction of weirs in the Sorel channels (to raise water levels), construction of Île Sainte-Hélène and the Louis-Hippolyte-Lafontaine bridge-tunnel (constriction of flow), ice management practices and bank protection structures (reduced formation of frazil ice and facilitation of ice draining). All of these developments have had major and sometimes variable impacts over time and space. For example, the

Sorel weirs alone caused a rise in the water level estimated to be 29 cm at Sorel and 12 cm at the Port of Montréal in 1930, followed by fluctuations associated with the deterioration and the many repairs made to these works. Finally, regulation of the discharge from the Ottawa River and, to a lesser extent, from Lake Ontario has also impacted on the distribution of St. Lawrence River water levels. In practice, it is therefore extremely difficult to isolate the effect of regulation of Lake Ontario from all other effects.

Figure 2.6 shows the time series of water levels recorded in the Port of Montréal from 1932 to 2005. The cumulative impact of the various initiatives on levels is clearly seen, mainly in the form of a major reduction in the very high levels associated with ice jams around the mid-1960s.

The interannual daily mean (IADM) levels from 1962 to 2005 at various stations in the Cornwall–Trois-Rivières sector can be used to calculate mean annual fluctuations of 0.1 m at Coteau-Landing on Lake Saint-François, 0.6 m at Pointe-Claire on Lake Saint-Louis and 1.5 m at Varennes. The IADM for the period from 1932 to 1958 indicates a lower hydraulicity. This situation, in addition to the effect of the various anthropogenic modifications in the reach, makes it difficult to perform a temporal and spatial analysis of water levels for most of the sites in the Cornwall–Trois-Rivières reach.

Furthermore, water levels in Lake Saint-François and Lake Saint-Louis have varied much less since regulation of the Great Lakes–St. Lawrence system began in the late 1950s. With regard to both freshet and minimum flows, the levels of these lakes have remained within a well-defined range. For example, the International St. Lawrence River Board of Control uses the following levels on Lake Saint-Louis at Pointe-Claire to guide its interventions: freshet level: 22.33 m; alarm level: 22.10 m; and minimum flow level: 20.60 m (all levels in International Great Lakes Datum 1985). These levels are associated with the damage to property and infrastructures caused by the floods of the 1970s.

Other factors affecting levels

Apart from the impact of water inflows from the Great Lakes, the Ottawa River and other sources, and the impact of the various anthropogenic developments and of regulation, water levels in the Cornwall–Trois-Rivières stretch also fluctuate as a result of factors such as friction caused by plants in summer and ice in winter, wind and the semi-diurnal tidal cycle.

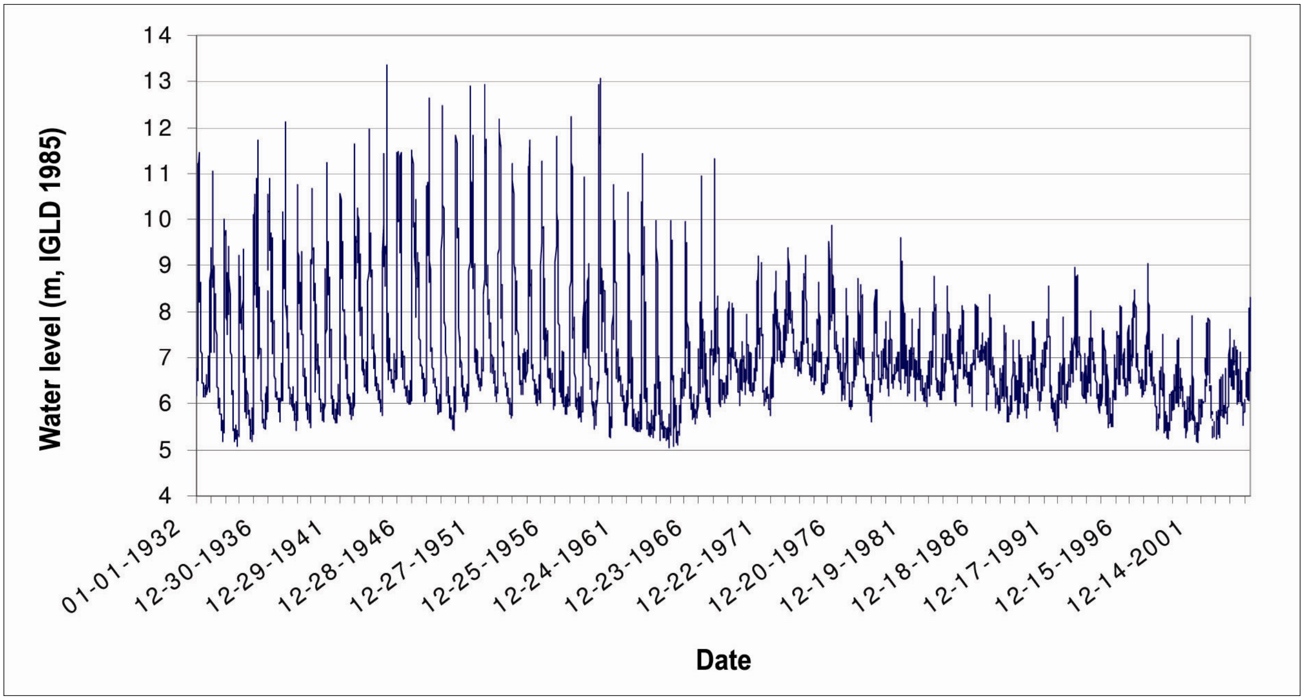


Figure 2.6 Water levels recorded in the Port of Montréal from 1932 to 2005

The effect of tides in the St. Lawrence River becomes appreciable at Trois-Rivières. The effect is less clear upstream of this point. Wind effect is considerable in lake sectors where the fetch is greater (Lake Saint-Pierre, Lake Saint-Louis, Lac des Deux Montagnes and Lake Saint-François). Wind is responsible for an increase in water levels on downwind shores and a decrease on the opposite side of the watercourse in question.

Flooding

Flow in the St. Lawrence River is regulated to a great extent through control of the outflow from Lake Ontario. The objective of the regulation strategy adopted by the IJC includes minimization of flooding by reducing flood discharge. However, control exercised during the freshet may be limited in a situation where the freshet is so large that the level of Lake Ontario reaches its maximum simultaneously with the freshet peak on the Ottawa River, thus reducing the manoeuvring room in terms of the application of mitigation measures. The impact of a freshet of this kind would be felt mainly in the area of Lake Saint-Pierre. A number of islands on the river would also be flooded should such an event occur.

Methodological limitations

Special attention must be given to analysis of water levels in the St. Lawrence River because of the impact of the many natural and anthropogenic factors affecting them. Certain practical issues must also be addressed. For example, because of anthropogenic modifications near the Port of Montréal, statisticians have been compiling historical data on the water level in this sector since 1967. The low levels recorded in the St. Lawrence River during the early 1930s and in 1964 and 1965 were not considered in this statistical database. Hence, these statistics cannot be compared with those calculated for the Great Lakes, which comprise a much longer period, dating back as far as 1918. In concrete terms, this situation led to a misinterpretation of the status of water levels in the river in 2001: according to the statistics, the Great Lakes would fall below their long-term mean level, while the Port of Montréal would experience record minimum levels. It is therefore vital to indicate the period being used to calculate water level statistics in the St. Lawrence River in any analysis of the status of flow in the Great Lakes–St. Lawrence system.

Another factor that must be taken into account when using water level as an indicator of the coefficient of flow in the Cornwall–Trois-Rivières stretch is the issue of vertical reference. The analysis of water levels presented here was prepared using the International Great Lakes Datum 1985. Several studies use the chart datum as their vertical reference, which causes serious reliability problems. Unlike the IGLD, which is a fixed reference, chart datum, developed for navigation purposes, is a sloped level that is variable in the longitudinal profile. Accordingly, its use as a reference level to study the impact of water levels on ecosystems is not always appropriate, since it is not spatially homogeneous (in other words, the chart datum does not correspond to a fixed return period along the length of the river). Use of mean sea level (MSL, a geodetic datum) or the IGLD as the reference is recommended.

Given all the natural and anthropogenic factors that can influence water level on a local scale, use of river flows (at Sorel for example) is more appropriate for gaining a view of the river's coefficient of flow, since this quantity integrates the many factors discussed above.

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Chapter 3

INTEGRATED MODELLING OF THE PHYSICAL PROCESSES AND HABITATS OF THE ST. LAWRENCE RIVER

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Introduction

The St. Lawrence is an immense fluvial system that stretches over more than 600 km between Lake Ontario and the estuary near Québec. A considerable spatial heterogeneity marks its course since it consists of narrow segments of swiftly flowing water and fluvial lakes where water flows slowly. This fluvial section is also characterized by over 2500 km of diverse wildlife habitats including wetlands, aquatic plant communities and lotic zones supporting considerable biodiversity.

The complex interactions between the riverbed and its floodplain, climate, hydrology, water quality in the river and its tributaries and type of substrate produce significant spatial and temporal changes in both the quantity and the quality of animal and plant habitats. Fluctuations in flow and water level modify the intensity and the spatial distribution of currents, waves and all other physical factors. The hydrodynamics, or pattern of flow (currents, water levels), is heavily influenced by the presence of submerged aquatic plants in summer, by ice in winter and by the substrate that covers the riverbed. In addition, during heavy flooding, the vegetation in the wetlands of the floodplain strongly affects the speed and the direction of flow.

Understanding and especially quantifying these interactions poses a serious challenge for scientific research and for the protection of these environments. High-resolution two-dimensional modelling (2D: distribution in geographic space) using mathematical models, in combination with GIS (geographic information systems), has become the preferred tool for quantifying and understanding ecosystems.

For several years, modellers have been working on the design and development of two-dimensional digital models for describing and predicting the fluvial dynamics of the St. Lawrence. The predictive capacity of the models would allow researchers to simulate a wide range of river flows, water levels, depths and currents, as well as hydrological events seldom, if ever, observed.

This chapter deals with recent developments in two-dimensional modelling of the physical characteristics of the fluvial environment as well as habitat models for fauna and flora. The modelling work has largely been done as part of the various phases of the St. Lawrence Action Plan and the Plan of Study for Regulation of Lake Ontario–St. Lawrence River Levels and Flows. A number of technological innovations have been brought together to lay the foundations for integrated modelling. The various information layers—digital terrain model, hydrodynamics and the other physical variables—are described in this chapter, along with data management and numerical methods used for geo-referenced databases (for further information, see Morin et al. 2005). Following a description of the techniques used to model the living habitat, fluvial modelling and its potential developments are looked at from an ecosystem perspective.

Fluvial modelling

Two-dimensional modelling of the St. Lawrence can be summed up as the process of integrating information and knowledge about the physical and biological aspects of the river into numerical models that simulate hydrodynamics (water level, flow, water depth), waves (height, direction, energy), distribution of aquatic vegetation (species), wildlife (species), etc. Modelling relies on the knowledge, experience and ability of researchers to reach a precision that is adapted to the answers required and working hypotheses. This is made possible by computers that are powerful enough to store and manage enormous amounts of data and then compare the data by means of different types of calculations. Because this modelling technique uses two and even three dimensions, it allows for powerful data visualization (maps) and for a very precise description of the study area.

The modelling process applied to the St. Lawrence River can be summarized in four steps: data gathering in the field, organization (standardization in space and time) of field measurements through a mesh (computational platform), application of physical models (physical laws expressed in mathematical equations and, lastly, parameterization of the physical characteristics of faunal and floral habitats. Parameterization requires researchers to determine the statistical and causal relationships between the environmental variables (extracted from physical models) and available across the entire system, and the presence of various plant or animal species. This spatial and temporal interaction between physics and biota on a shared calculation grid is called integrated ecosystem modelling.

Geographic context

Two-dimensional (2D) physical models and habitat models have been applied to most of the fluvial section of the St. Lawrence (i.e. over more than 260 km). This area extends from the Moses-Saunders hydroelectric dam at Cornwall to the Port of Trois-Rivières upstream of the confluence of the St. Lawrence and Saint-Maurice rivers. A number of the complex segments of this stretch, such as those between Lake Saint-François and Lake Saint-Louis as well as the Lachine Rapids and the La Prairie Basin, have yet to be completed.

Reconstruction of the Physical Environment

Digital terrain model and two-dimensional physical models

A digital terrain model (DTM) is a digital representation of variables measured in the field (topometry, substrate, submerged and emergent vegetation, etc.) that generates calculated variables (velocity, level, current, etc.) and, subsequently, integrated models. The digital terrain model for the St. Lawrence is something like a smaller-scale model representing the river's physical characteristics. Since the digital terrain model provides the foundation for hydrodynamic simulations, it is the basis of numerical modelling. The digital elevation model, a major component of digital terrain modelling, is created in three dimensions and comprises a multitude of contextual data and information including bathymetry (surveys) and high-resolution topography. The digital terrain model involves the mapping of aquatic and emergent vegetation, substrate mapping and other terrain descriptive data (e.g. civil engineering structures).

Topometry of the riverbed, banks and floodplain

The digital elevation model developed assembles topographical data from several sources in a single geographical coordinate system (horizontal and vertical datum) providing unbroken coverage of the navigation channel, shallow areas near the banks and the floodplain (Figure 3.1). The digital elevation model generates a very faithful reconstruction because the data set has a vertical accuracy of approximately 15 cm and a horizontal accuracy of about 1 m.

Deep-water bathymetric data come mainly from the bathymetric surveys of the Canadian Hydrographic Service and the Canadian Coast Guard, which generally produce data at intervals of 20 to 50 m. The Canadian Hydrographic Service and the Coast Guard are responsible for mapping the deep waters of the river, where shipping activities are heaviest. However, bathymetric information on the shallow areas near the banks is inadequate. To make up for this deficiency, a number of measurement campaigns using high-precision instruments (echosounders) have been conducted in recent years in the shallow areas of the river.

Topographical data on the St. Lawrence floodplain have been gathered by using airborne laser technology (LIDAR: *light detection and ranging*) on the stretch of the St. Lawrence between Lake Saint-Louis and Trois-Rivières as a whole. A total of 30 292 geodetic control points distributed over the entire area were used to calibrate the LIDAR data. The measurements have a density of one point for every 2 m for a total of around 200 million points. The measurements were reduced to produce less cumbersome topographical datasets that use the most representative points (Fortin et al. 2002). A different approach was used for swamp and marsh areas in order to give a clearer picture of the topography of these more complex sectors (Ouellet et al. 2003).

Characterization of the St. Lawrence riverbed

The spatial distribution of grain size in the materials that form the riverbed—the substrate—must be determined for the entire study area, because the distribution of currents in the river is influenced by substrate-induced friction. The composition of the substrate is also a key factor in the selection of wildlife habitats by certain species (Mingelbier et al. 2005; Giguère et al. 2005). Substrate distribution has been mapped for purposes of hydrodynamic simulations.

The maps were produced with data from several organizations conducting research on the St. Lawrence. Specifically, the data were taken from sedimentological and grain-size studies and are based on samples of surface sediments, visual observations and underwater videos. The datasets were assembled in a geographic information system. The data were then interpreted to digitally reconstruct homogeneous substrate zones. Flow resistance caused by substrate friction was introduced in the model by means of Manning's friction coefficient.[1]

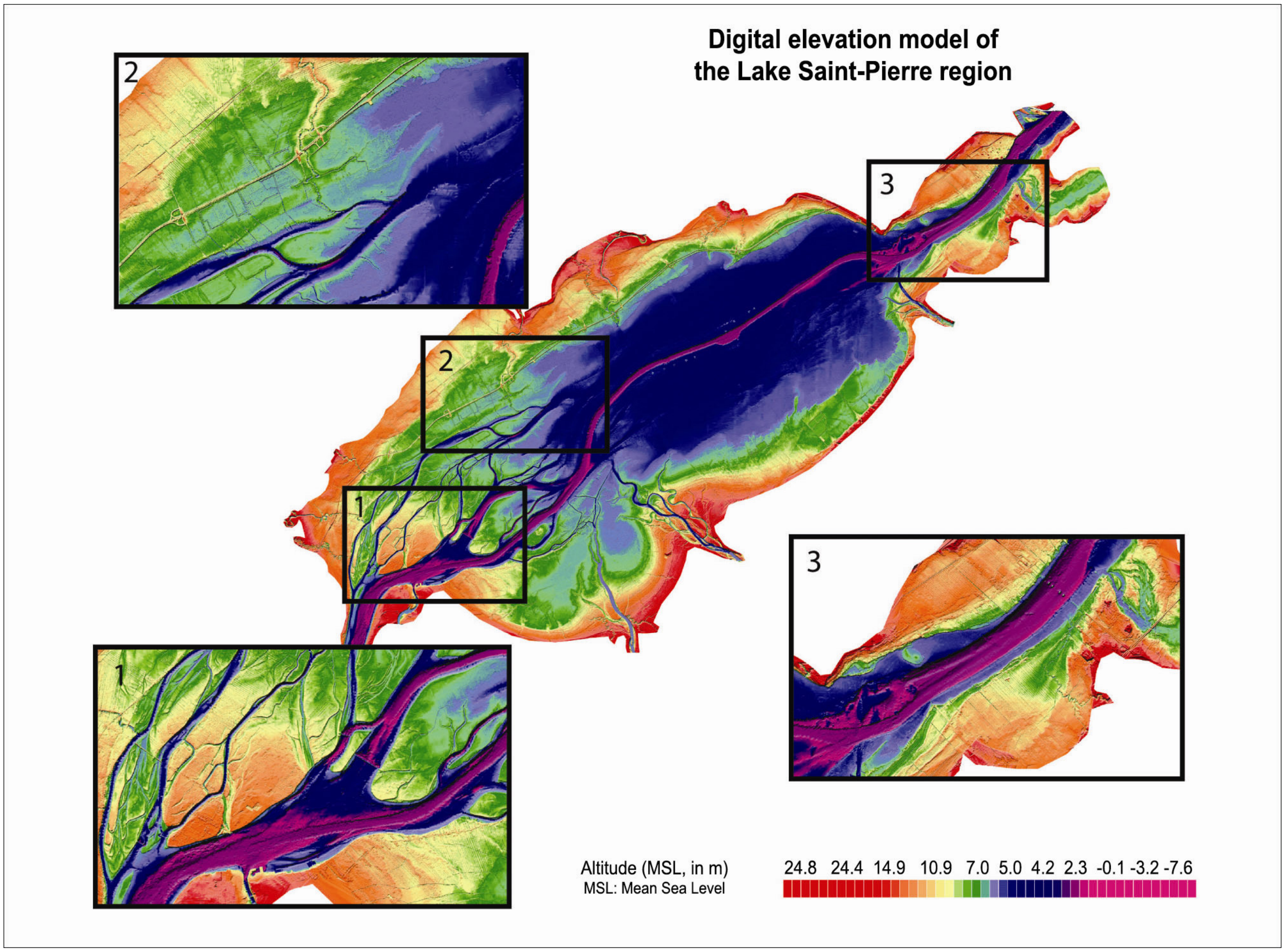


Figure 3.1 **Digital elevation model of the Lake Saint-Pierre region, showing a detailed view of (1) the Îles de Sorel, (2) Maskinongé Bay) and (3) the outlet of the lake**

Characterization of submerged vegetation

Submerged vegetation influences the spatial distribution of currents and water masses. Throughout the growing season, changes in the size and composition of aquatic plants affect water levels and control flow patterns. Boudreau et al. (1994), Morin et al. (2003b, 2000) and Morin (2001) have quantified the impact of aquatic plants on specific fluvial hydrodynamic parameters. In Lake Saint-Pierre, for example, riverbed vegetation causes upstream water levels to rise by 50 cm. In the same lake there are also preferential flow channels that structure the flow during the summer. These channels are created by the absence of vegetation. The impact on water levels is similar in intensity to the impact of friction caused by winter ice.

In the hydrodynamic model, flow resistance produced by aquatic vegetation is examined using a plant distribution map that covers the entire St. Lawrence River. The map was produced by combining echosounder data (transects) and direct observations obtained using an underwater video camera (Morin et al. 2003b; Côté 2003; Morin 2001). The level of friction is then estimated by converting local morphological data on species (height, stem density and percentage cover of each species) to Manning’s local friction coefficient (Morin et al. 2000).

Characterization of emergent vegetation

On the floodplain, flow resistance is mainly associated with wetland vegetation. The river’s floodplain is covered with large areas of forested or shrub swamps and shallow marshes. There are also deep marshes in which plant stems disappear for the most part during winter. The most accurate mapping of the St. Lawrence wetlands was done by Jacques (1986) and covers a total of 550 km of wetlands in the Lake Saint-Pierre region. The maps were digitized and validated by Falardeau and Morin (2000), who produced over 6000 polygons, in which the dominant and co-dominant plant species in the summer of 1985 were identified. The parameterization of the Manning's friction coefficient associated with emergent wetland vegetation was done using growth forms of dominant species. Maps from other studies have also been digitized to complete the database for the other sectors of the river.

Integrating the Hydrological Dimension

Reconstruction of river discharges

Modelling of the physical and biological aspects of the St. Lawrence requires the availability of data on river discharges. To analyze long-term changes in the system, river discharges were reconstructed for the years 1932 to 1998 (Morin and Bouchard 2000). Because the last hydrometric station is located at LaSalle, flows in the St. Lawrence are not measured downstream of Montréal. It was therefore necessary to reconstruct hydrological series from available measurements and the corrected discharges of tributaries. For example, the discharge at Sorel is composed of all major inflows upstream from Sorel: specifically, the sum of discharges measured at LaSalle, in the Rivière des Prairies and in the Rivière des Mille Îles and the corrected discharge for the Rivière L'Assomption. All of these data are available in real time.

In addition to discharges, wind direction and intensity and other meteorological parameters are considered when calculating the hydrodynamics in the St. Lawrence. Because engineering works also strongly influence flow hydraulics, an inventory of such works (dredging, overflow weirs, bridge piers, artificial islands) has also been prepared. The results of this analysis are available for the Montréal–Trois-Rivières section (Côté and Morin 2005a, 2005b; Morin and Bouchard 2000), for Lake Saint-Pierre (Morin and Côté 2003), for Lake Saint-François (Morin et al. 1994) and for Lake Saint-Louis (Morin et al. 2003b).

Hydrological scenarios

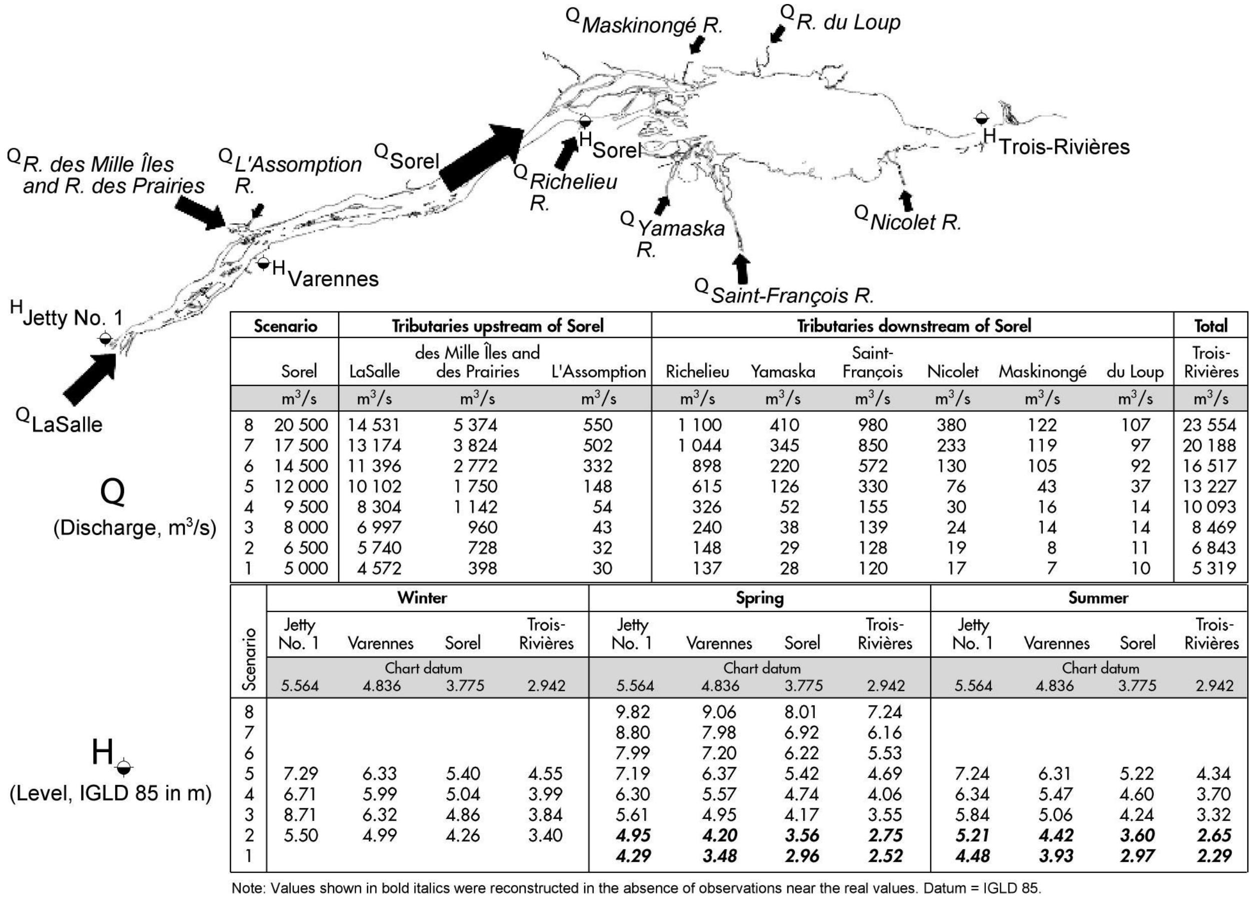
Hydrological scenarios, or "reference events," were created for the Montréal–Trois-Rivières section (Morin and Bouchard 2000) and were then extended to the whole of the fluvial portion of the St. Lawrence. The reference events represent a limited number of seasonal discharge and water-level conditions; they also cover the entire spectrum of the river's hydraulic conditions. Three hydraulic seasons are defined by the type of friction exerted on the flow of the river: (1) summer, with the presence of submerged aquatic vegetation; (2) winter, with ice; and (3) spring and autumn, with substrate friction as the only factor considered. In this way, after the statistical analysis of discharge frequencies (magnitude and season), eight spring/autumn reference events, five summer events and four winter events were identified. The scenarios represent discharge increments at Sorel varying from 1500 to 3000 m/s and corresponding to a variation of 0.6 to 1 m in water levels (Figure 3.2). The weekly average maximum and minimum flows recorded at Sorel since 1960 are, respectively, 20 500 m³/s (spring 1976) and 6500 m³/s (spring 1965). In the scenarios, an extremely small discharge was added to take into account the impact of climate change.

This 5000-m³/s event is based on a 20% reduction in the minimum observed value of 6500 m³/s, since it is estimated that the discharge of the St. Lawrence could decrease by 15–40% over the next 50 years, given the predicted warming of the climate (Environment Canada 1997).

Other input variables for physical models

Wind and waves

Wind-generated waves play a fundamental role on the river, particularly on fluvial lakes, where the process is often more important than currents in terms of energy dissipation. Data on winds are essential to their modelling. In order to reduce the total number of simulations and simplify data management, wind speeds were sub-divided into four classes of intensity: weak (0–9 km/h), moderate (10–24 km/h), strong (25–44 km/h) and extreme (45–60 km/h). Wind intensity frequencies in relation to direction and season were then used to estimate the seasonal means of wave-related variables such as energy dissipation and near-bed orbital velocity (Morin and Bouchard 2000; Morin et al. 1994).



Scenario	Sorel	LaSalle	des Mille Îles and des Prairies	L'Assomption	Richelieu	Yamaska	Saint-François	Nicolet	Maskinongé	du Loup	Trois-Rivières
	Tributaries upstream of Sorel				Tributaries downstream of Sorel						Total
	m^3/s	m^3/s	m^3/s	m^3/s	m^3/s	m^3/s	m^3/s	m^3/s	m^3/s	m^3/s	m^3/s
8	20 500	14 531	5 374	550	1 100	410	980	380	122	107	23 554
7	17 500	13 174	3 824	502	1 044	345	850	233	119	97	20 188
6	14 500	11 396	2 772	332	898	220	572	130	105	92	16 517
5	12 000	10 102	1 750	148	615	126	330	76	43	37	13 227
4	9 500	8 304	1 142	54	326	52	155	30	16	14	10 093
3	8 000	6 997	960	43	240	38	139	24	14	14	8 469
2	6 500	5 740	728	32	148	29	128	19	8	11	6 843
1	5 000	4 572	398	30	137	28	120	17	7	10	5 319

Scenario	Winter				Spring				Summer			
	Jetty No. 1	Varennes	Sorel	Trois-Rivières	Jetty No. 1	Varennes	Sorel	Trois-Rivières	Jetty No. 1	Varennes	Sorel	Trois-Rivières
Chart datum	5.564	4.836	3.775	2.942	5.564	4.836	3.775	2.942	5.564	4.836	3.775	2.942
8					9.82	9.06	8.01	7.24				
7					8.80	7.98	6.92	6.16				
6					7.99	7.20	6.22	5.53				
5	7.29	6.33	5.40	4.55	7.19	6.37	5.42	4.69	7.24	6.31	5.22	4.34
4	6.71	5.99	5.04	3.99	6.30	5.57	4.74	4.06	6.34	5.47	4.60	3.70
3	8.71	6.32	4.86	3.84	5.61	4.95	4.17	3.55	5.84	5.06	4.24	3.32
2	5.50	4.99	4.26	3.40	***4.95***	***4.20***	***3.56***	***2.75***	***5.21***	***4.42***	***3.60***	***2.65***
1					***4.29***	***3.48***	***2.96***	***2.52***	***4.48***	***3.93***	***2.97***	***2.29***

Note: Values shown in bold italics were reconstructed in the absence of observations near the real values. Datum = IGLD 85.

Figure 3.2 Hydrological scenarios for the section between the Port of Montréal and Trois-Rivières

Water masses

For most of its length, the St. Lawrence is characterized by the presence of several distinct water masses among which lateral mixing is very slow. The very distinct physical and chemical characteristics of these water masses influence the organisms living within them and the biophysical processes in different ways (Frenette et al. 2002). Because water masses are a necessary component of aquatic habitats, their positions must be considered in the physical and biological modelling process. The distribution of water masses is taken into account in transport-diffusion models, specifically through the integration of complex variables such as light penetration and sedimentation of fine particulate matter (Morin et al. 2003). For example, light penetration in different water masses strongly influences the predicted spatial distribution of plant and fish habitats (Mingelbier et al. 2005; Turgeon and Morin 2004; Bechara et al. 2003).

Physical Models

Operation of two-dimensional hydrodynamic models

Because today's high-performance computers remain limited in terms of computing capacity, the information contained in a digital terrain model cannot be fully exploited. To overcome this difficulty, topometric, substrate and aquatic plant data are located in a mesh that cleverly and efficiently reduces the amount of information required to effectively represent reality.

The HYDROSIM model (Heniche et al. 1999) was used to produce hydrodynamic simulations of the hydrological scenarios. This mathematical model solves the Saint-Venant equations on a triangular finite-element computational mesh.[2] The meshes comprise numerous elements, with computational nodes that hold the information on topography and local friction that is used in the calculations, as well as the results of the model (Figure 3.3). The meshes are also used to visualize the information.

In order to reduce computing time, the study area was divided into four sectors for which four separate meshes were produced: Lake Saint-François, Lake Saint-Louis, the Montréal–Lanoraie section and the Lanoraie–Lake Saint-Pierre section. In all, the number of computation points represents more than 400 000 nodes for which the topography and friction caused by substrates and aquatic vegetation are known.

The model generates results of critical importance for the study of the St. Lawrence: the *x* and *y* flow components as well as water levels. These values can be used to generate a multitude of hydraulic variables such as depth, shear velocity and specific discharge.[3] The results for velocity, depth and water level in the simulation area serve as input variables for the wave models.

Calibration and validation of hydrodynamic models

Calibration is a required step in the use of digital models, ensuring that specific model parameters can be altered to ensure an accurate representation of reality. The calibration process involves comparing simulated water levels with those measured at hydrometric stations for the same hydrological event. The hydrodynamic model was calibrated using hydrological events with water levels only and two with water levels and measured velocities, one representing conditions of weak hydraulicity (spring 1999), and the other representing conditions of strong hydraulicity (spring 1996). Calibration and validation with water levels ensures the integrity of the digital solution in relation to reality. Specifically, the calibration phase yielded a margin of error of less than 5 cm between the simulated and measured water levels over the entire study area for a wide range of flow conditions and aquatic plant growth stages. In short, the model effectively reproduces the slope of the water surface in the section.

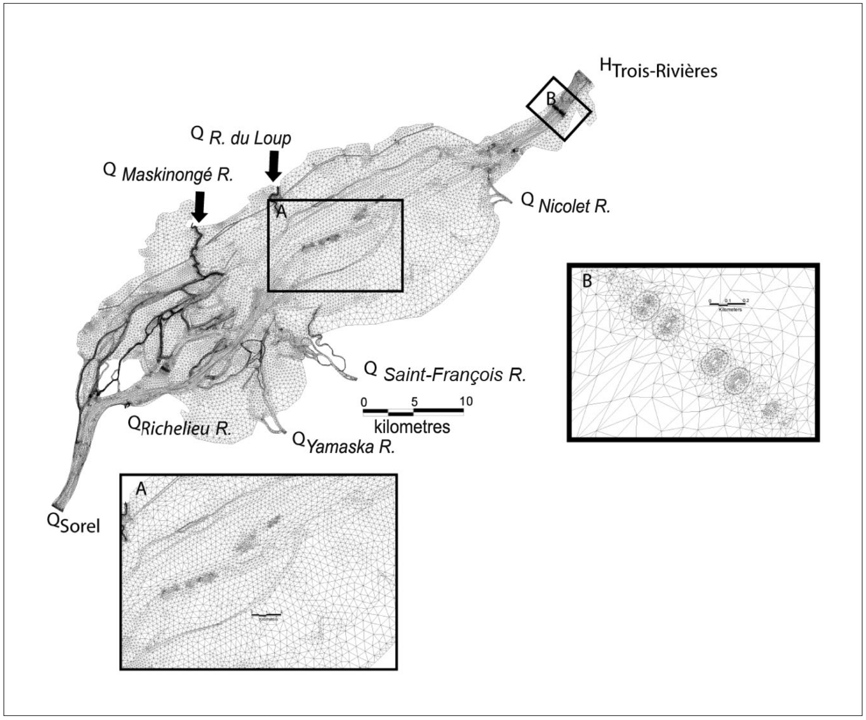


Figure 3.3 Triangular finite-element mesh for the digital terrain model of the St. Lawrence between Sorel and Trois-Rivières

Validating the hydrodynamic model by measuring velocity is as demanding as calibrating water levels. Precise velocity measurements were gathered in the spring of 1996 and 1999 using an acoustic Doppler current profiler (ADCP) to calculate the flows in one section of the river. On the whole, comparison between measured and simulated velocity yielded excellent results. The friction coefficients were slightly altered to either raise or lower velocities and thereby increase or reduce flow in certain zones. The apportionment of the flow on either side of the many islands in this section of the river was also verified so that the simulated and measured flows would be similar (variations were always below a 10% error rate). Figure 3.4 shows the hydrodynamic results (depth and current velocity) for Lake Saint-Pierre for extreme low, moderate and extreme high discharges.

Physical models of waves and transport-diffusion

The natural wave model for the St. Lawrence uses equations that describe the generation, propagation and spread of waves in relation to bottom topography, hydrodynamics and wind velocity and direction. For each computational node, the wave model simulates wave height, direction, frequency and period as well as near-bed orbital velocity.

Transport-diffusion models were used to produce the mean distribution of water masses for the eight hydrodynamic benchmark scenarios. Transport-diffusion models are used to propagate in a fluid—in this case water—substances or properties that persist over space and time, such as the colour of a water mass, as well as non-persistent substances or properties.

Another variable, the “fine material deposited on the bottom,” was produced using an advection-diffusion model. This variable, which is an indicator of seasonal, fine-particle deposition zones, was produced by joining the effects of waves and currents to generate a combined shear velocity measurement for the eight discharge scenarios (details in Morin et al. 2005). The concentrations of suspended material measured at the mouths of tributaries and upstream of the river are propagated according to water velocity and discharge (hydrodynamic fields). Then, depending on the local energy (combined shear velocity) produced by the waves and currents, the particles either settle to the bottom or remain suspended. The results of the model reveal the spatial distribution of sedimentation zones, which play a role in the presence of certain aquatic plant species and benthic organisms. Figure 3.6 shows the spatial distribution of several abiotic variables in Lake Saint-Pierre.

Summary of results

The two-dimensional approach of physical and integrated modelling makes it possible to produce distribution maps of physical variables quickly and efficiently (figures 3.4 and 3.5).

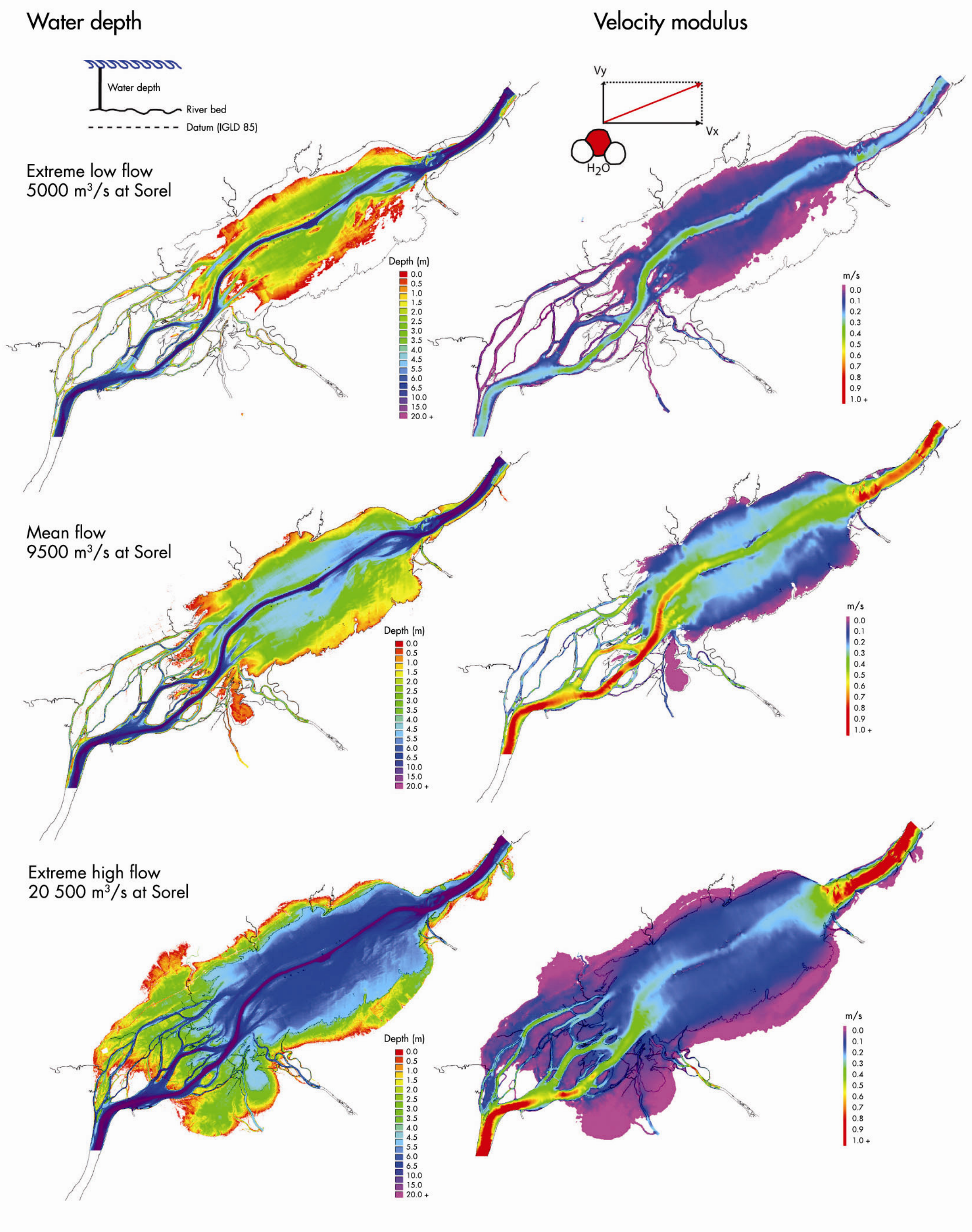
Habitat Modelling Techniques

For a number of years now, modellers have been incorporating the habitat dimension in their work in order to gain a better understanding of the interaction between living organisms and the physical characteristics of the river. The main objective of habitat modelling is to understand the distribution of a given species in the ecosystem and to use the knowledge acquired to predict future occurrences of the species in relation to changes in the river’s physical characteristics. Organisms in the St. Lawrence River are adapted to their environment. Their occurrence in specific sectors of the riverbed or floodplain is not random; it is due to the fact that certain environments or sectors meet their needs more effectively, whether in terms of water depth, current or ambient light. The physical characteristics of the habitat of a species or group of species can explain why they form a large proportion of the population in a given location (up to 95% success, in some cases).

A number of techniques can be used to establish connections between simulated abiotic variables and the presence of life forms. The choice of technique depends mainly on the quantity and quality of biological data and existing physical models. For an analysis of the impact of water-level fluctuations on the St. Lawrence ecosystem, two-dimensional habitat modelling is the tool preferred by most researchers. Models of this kind have been designed for submerged plants, wetlands, amphibians, fish, birds and the muskrat.

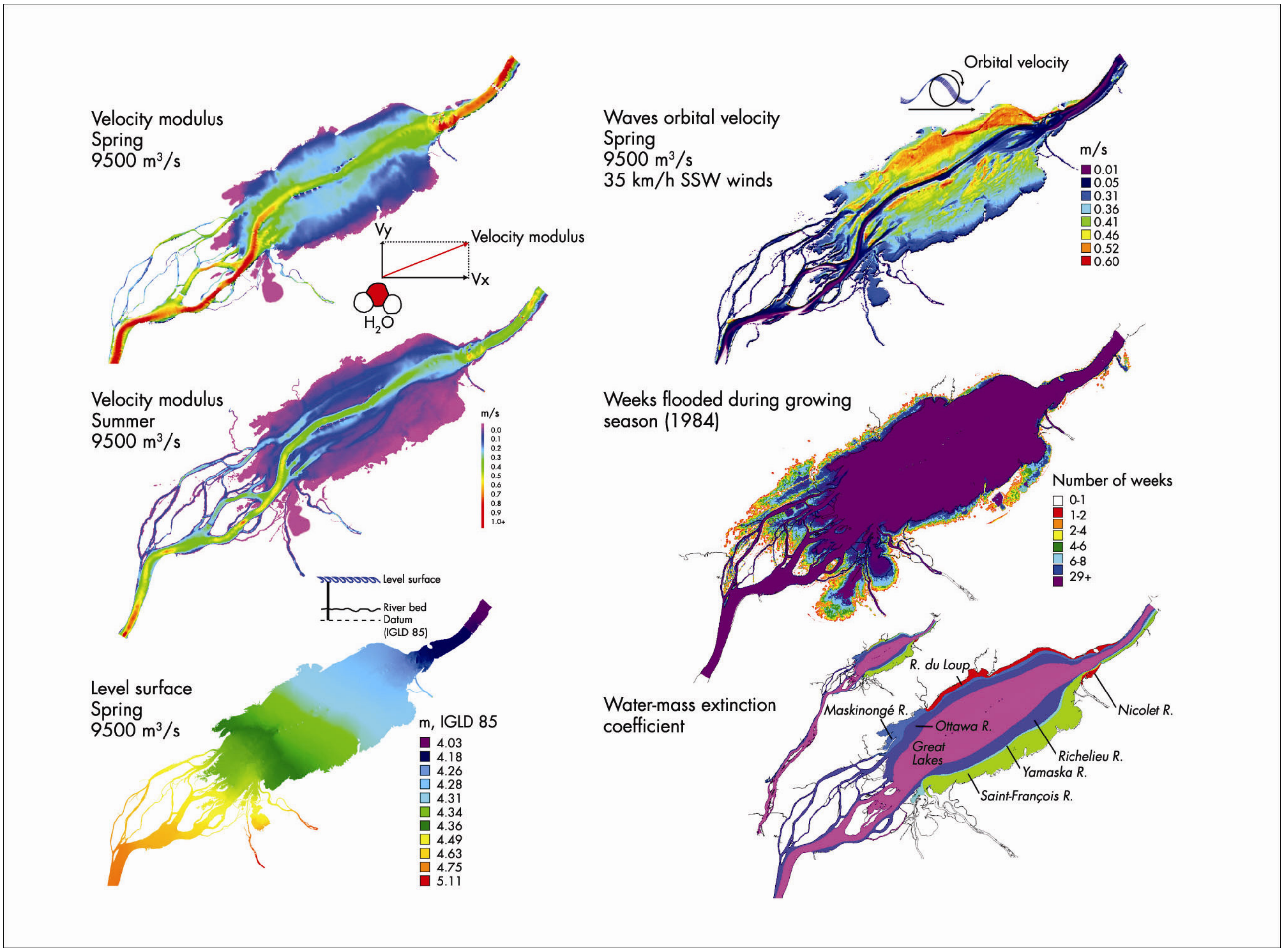
Habitat model

Habitat modelling techniques were first developed in the 1970s as a means of determining the minimum flow required to maintain fish stocks in harnessed rivers (Tennant 1976). This approach was structured in the Instream Flow Incremental Methodology, which combined one-dimensional hydraulic models with computer tools in a physical habitat simulation system (Bovee et al. 1998; Bovee 1982). These tools, which are now in widespread use for studies of small watercourses, combine data on water current velocity, depth and substrate dimensions to generate estimates of habitat quality for specific animal and plant species.



IGLD 85: International Great Lakes Datum 1985.

Figure 3.4 Comparison of depths and velocity modules in Lake Saint-Pierre (Sorel) for three discharge conditions: Extreme low flow (5000 m³/s), mean flow (9500 m³/s) and extreme high flow (20 000 m³/s)



Note: Modelling of variables was based on a discharge of 9500 m³/s at Sorel.

Figure 3.5 Spatial distribution of several abiotic variables in the Lake Saint-Pierre sector: Velocity modulus, surface level, wave orbital velocity, number of weeks of flooding during the growing season, and water-mass extinction coefficient

More recently, a number of researchers have adopted the two-dimensional hydrodynamic modelling technique, which provides for better representation of complex flows and visualization of data (Hardy 1998; Ghamen et al. 1996; Leclerc et al. 1995). This technique is now the preferred tool for studies of St. Lawrence habitats. In this context, two-dimensional hydraulic modelling is combined with various types of mathematical models that provide new key variables for analyzing factors related to aquatic life (Morin et al. 2003a).

Traditionally, mathematical relationships between the occurrence of species and the physical variables of habitat models have been based on habitat suitability indices (HSIs) (Bovee 1982). More recently, habitat probability indices (HPIs) (Guay et al. 2000) have been used to build much more robust and productive models. However, HPIs require a larger number of biotic samples. St-Hilaire et al. (2003) have compiled a list of articles on the present state of knowledge of aquatic habitat modelling.

Types of habitat models

In St. Lawrence River modelling projects, a number of combinations and modifications of the HSI and HPI approaches have been used with a high degree of flexibility, primarily on the basis of the available biological data and the complexity of the phenomena under study. The purpose of the models concerned is to take advantage of the significant relationships that exist between physical variables and the observed occurrence of species. The techniques used to generate habitat models can be divided into four groups: (1) the simplest approach, which could be called the "intersection model;" (2) the traditional HSI approach; (3) the HPI method; and (4) the combination of a probabilistic model and a time sequence model, referred to here as the "sequential habitat model."

Intersection models are very simple and are similar to HSIs. They are used when there is limited information on a species's preferences for specific habitat characteristics. This type of model has been used to study some at-risk or endangered species for which there were very few observations (Giguère et al. 2005). In such cases, expert opinion is required to determine the potential limits of a species's preferences in terms of key variables (current, waves, plants, etc.). The spatial intersection where all habitat conditions are "reasonable" is used to estimate available area as a function of flow.

Habitat models based on HSIs are developed using preference curves for key environmental variables. Developed from a number of observations, the curves represent the statistical distribution of physical variables measured at the time of site observations. HSIs are standardized between 0 and 1. Hence, an HSI of 1 represents a high probability of occurrence, while 0 represents a probability of absence. The advantage of this technique is that researchers can use the accumulation of knowledge and observations built up over many years and apply it directly to the environment under study. The disadvantage of the technique is that it is not very transferable from one calibration and validation area to another. In addition, it has built-in biases relating to the combined influence of several environmental variables. These models are validated by means of a portion of the observations, set aside in advance.

Probabilistic models have been used more often for St. Lawrence River modelling studies. They come into play when there are large quantities of high-quality data. Typically, researchers will set a portion (~ 10%) of the biological data aside for the purpose of validating the models. The known environmental variables for the area as a whole are interpolated on the sampling points. They are then used to explore significant relationships between the occurrence of a species and abiotic factors. A number of statistical tools are used: logistical and multivariate regressions, canonical analyses, principal component analyses (PCA), etc. Overall, logistic regression has been the method used most often in St. Lawrence River studies. It generates very powerful predictive statistical relationships. This approach is used to build a variety of habitat models, including those for aquatic plants, fish and wetlands.

The sequential habitat model has been used to simulate the effect of plant succession and the required response time for establishing or replacing wetlands as a function of various changes in the environmental variables. Based on logistic regressions, the model has been combined with a fairly complex system of preferential pathways that were predetermined and selected as a function of the environmental variables in play during the time simulation.

Two-dimensional habitat model variables

For the development of two-dimensional habitat models, three groups of variables are required. The first comprises the measured and observed data assembled in the digital terrain model. The group includes substrate maps, maps of aquatic plants, wetland maps and soil-use maps as well as all the other variables derived from the topography (local slope, slope derivative).

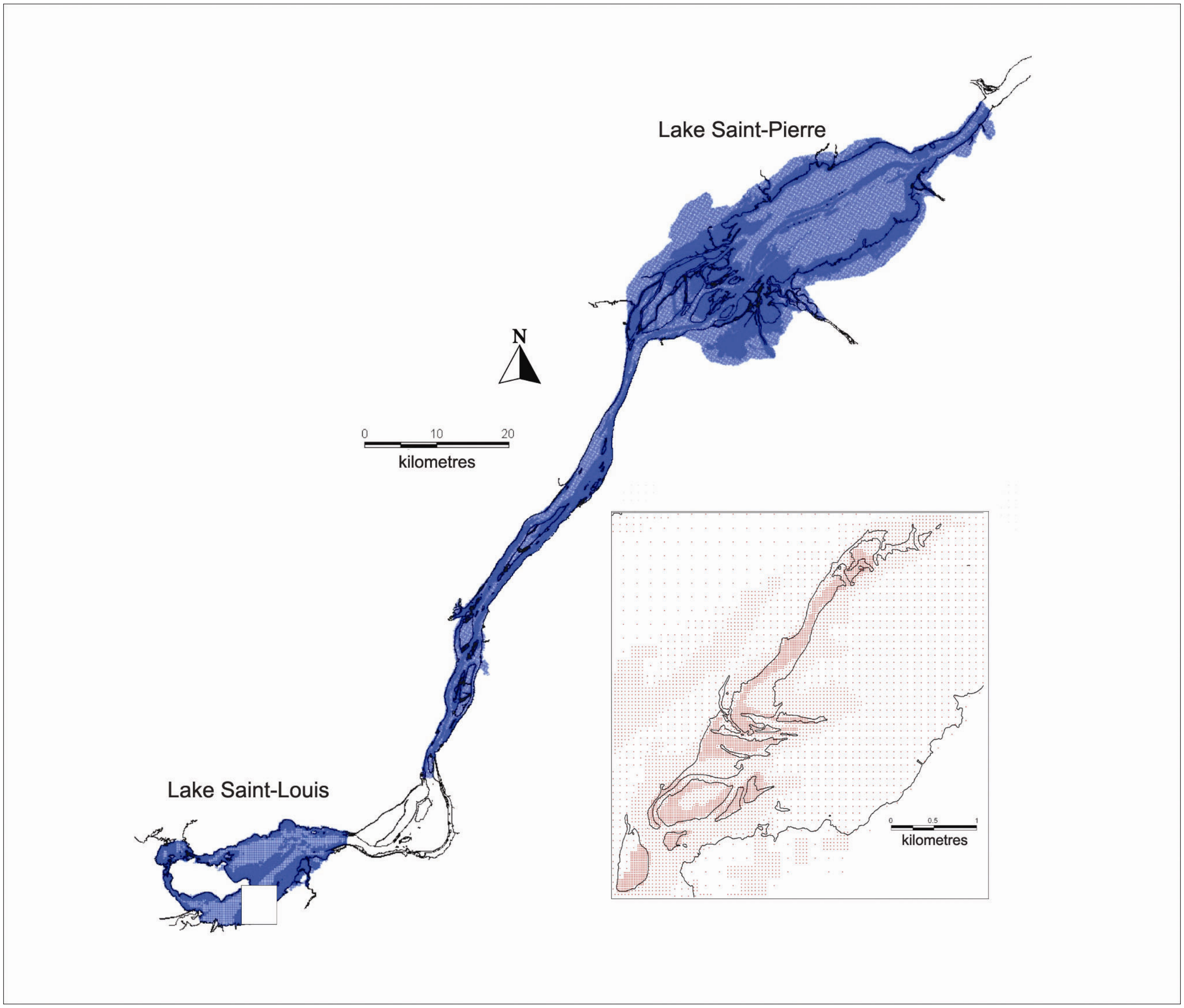
The second group of models handles the largest quantities of data and the most complex data. It covers natural wave and transport-diffusion variables produced by hydrodynamic models and includes data fields for current, water depth, orbital velocity, near-bed wave, shear velocity, and specific discharge. Included are more complex variables derived from the models, including bottom light, the index of fine particles deposited on the bottom, and nodal hydroperiod (Morin et al. 2005).

The third group includes variables derived from existing biological models, such as vegetation and wetland models. These variables are produced by habitat models, and they are used as explanatory variables in other habitat models. Modelled submerged plants serve as very significant explanatory variables in the spatial distribution of several fish species (Mingelbier et al. 2005).

Two-dimensional IERM Grid and Geodatabase

Predictive modelling of the habitat of a number of species for a broad range of flows requires a number of variables. In such a context, data management quickly becomes a daunting and complex operation. In the context of the study on the regulation of the St. Lawrence River, over 200 habitat models were developed and applied to time series for flows and water levels representing system inflows over the last 100 years. The series were constructed in months (quarter-monthly) and comprised a database of nearly 500 gigabytes (Morin et al. 2005).

Two-dimensional modelling of physical characteristics and habitats uses the node as the local point of input for information and results. The two-dimensional, node-based, Integrated Ecosystem Response Model (2D IERM) grid was integrated into a georeferenced database, known as the geodatabase. The geodatabase was constructed to manage all measured environmental data, simulated physical variables and integrated biological models. The spatial resolution of the grid was adjusted to reflect the degree of accuracy required for the habitat modelling, which itself is closely tied to topography. In the case of the St. Lawrence River floodplain, the grid resolution ranges from 20 to 80 m in shallow water and is 160 m in the main bed. For the area as a whole, from Beauharnois to Trois-Rivières (excluding the La Prairie Basin), the 2D IERM grid contains 124 121 nodes, for which all the physical and environmental variables are known at an appropriate spatial and temporal resolution (Figure 3.6).



Note: Inset map is an example of densification and distribution of points in a 2D IERM mesh for the Îles de la Paix on Lake Saint-Louis, Quebec.

Figure 3.6 Area covered by the 2D IERM mesh in the St. Lawrence River floodplain

Habitat models can be developed very effectively in a geodatabase environment as long as all the basic explanatory variables have been properly integrated. The biological models are produced as follows: the (geo-referenced) fish, plant and bird observation stations or sites used to calibrate the habitat models are incorporated into the geodatabase; the explanatory variables, which have already been identified with the help of experts, are assigned (measured variables) or simulated (modelled variables) for the period or condition corresponding to the observation period at each station. Statistical analyses are then conducted using specialized software to explore the relationships between the significant control variables and the occurrence or absence of a species or group of species.

In general, logistic regression is the tool of choice for generating predictive mathematical relationships. Single and multiple regressions, correspondence analyses and classification trees are also used. Predictive models are reintegrated into the geodatabase, habitat calculations are generated by the geodatabase functions and processes, and results are projected onto the 2D IERM grid. Commercial geographic information system software is used to query the geodatabase directly for display and analysis purposes. In this way, potential production problems can be identified quickly and new approaches tested. In addition, spatial integration (quantification) of estimated habitat values can easily be carried out for the whole river or a more limited portion of the study area.

With the geodatabase, factoring in the specific characteristics of the ecosystem is a relatively simple matter. For example, the St. Lawrence floodplain includes managed and natural residual marshes that are submerged during the freshet and retain water for some time as floodwaters recede. Specific processing is applied to these areas to calculate the local water level, which is actually a function of local management of a managed marsh or of evapotranspiration from a natural residual marsh beginning at the moment in the time series of its exposure. It is also possible to factor in complex hydroperiod variables and obligatory successions (e.g. plant succession), such as those used in modelling wetlands, and to model these complex systems accurately.

Ecosystem Outlook and Trends

Modelling is a powerful tool for gaining an understanding of the physical and biological dynamics of the St. Lawrence River. As a result of the progress that has been made in this field, these models can now be used to make predictions and obtain quantitative responses concerning phenomena about which little is known. That said, it is likely that digital models will become more accurate and complex over the next few years as they incorporate new variables and fields of knowledge.

Predictive use of modelling

Development of the various digital models, improvement in the quality of the basic data and the increased computational capacity of processors have led to the development of a number of operational physical and biological digital models that can now be used for predictive applications. By modelling the river's physical characteristics, it is possible to accurately predict variations in those characteristics for the entire river, under all possible flow conditions, including conditions that have never been observed; it is also possible to quantify the impacts of specific practices and activities. The capacity to predict results enhances knowledge and improves the decision-making process as it relates to management of the St. Lawrence River.

From a broader perspective, two-dimensional modelling serves to quantify the potential impacts of climate change on the river. Climate warming could cause the river flow at Montréal to decline by 15–40%, with a resulting drop in water levels there of as much as 1.3 m (Environment Canada 1997). In about 50 years, the St. Lawrence could look more like a series of lakes linked by a canal than the river that we know today.

Impacts of human activity

The predictive capacity of fluvial modelling can be harnessed to analyze the impact of human activity on the river environment. Such an analysis may focus on past, present or future changes. Once the numerical models have been developed, it is a simple matter to simulate a change in the riverbed (dredging operation, modification of the substrate) or new civil engineering structures (bridge piers, reconfiguration of wharfs and jetties) and then assess the impacts of the changes. The impact is quantified not only in terms of the river's physical variables (change in velocity pattern, water levels, shear stress, etc.), but also in terms of the habitats of animal and plant species, because a large part of those habitats is controlled by physical variables. Analysis may also be undertaken to gain an understanding of the impacts of past changes brought about by human activity. Potential retroactive impact studies include assessment of the impacts of development of Notre-Dame and Sainte-Hélène islands in the 1960s, the impacts of dredging on habitat over the last 150 years, and the impacts of industrial effluents discharged in the 1970s on aquatic animals then and now. Studies currently underway include an analysis of the impacts of dredging operations on St. Lawrence water levels since 1930. This type of work will show us which fundamental processes of the system were lost.

Improvements in habitat protection

Once in place, habitat models can help to improve and protect critically important habitats, quantify the impacts of flow regulation on specific types of habitat and assess the degree of vulnerability of a given species to changes caused by local human activities such as dredging, or to more large-scale transformations such as climate change.

Models have recently been developed for determining the habitat of a number of fish species. Once the preferred habitats of the walleye in Lake Saint-François had been characterized (Bechara et al. 2003), a number of organizations interested in the restoration of ecological functions were able to take measures to improve the species's habitat. The work of the Upper St. Lawrence ZIP (Priority Intervention Zone) committee in building underwater shelters to create areas of shade for the Lake Saint-François walleye is a practical illustration of how habitat modelling can be used to improve habitat.

Key variables to be developed: Temperature, light and waves

Water temperature

Water temperature is a fundamental variable for several fluvial ecosystem processes. It can vary over time and space with a high degree of complexity and hence is of limited use. However, incorporating a time variable, such as a weekly mean, makes it possible to reduce the number of simulations required. In a cooperative venture with INRS-ETE, the two-dimensional temperature model was used during its development phase to determine temperatures during the northern pike spawning season in the Îles de Boucherville (Morin et al. 2003c) and to model the same species's spawning grounds in the river (Mingelbier et al. 2005; Morin et al. 2004). Integrating this fundamental variable is an avenue well worth exploring over the coming years, given the significant contribution it could make to assessment of primary production and tracking of larval development.

Light

Light quality and intensity, which are influenced by water transparency and colour, are important physical factors affecting the structures of fish communities and submerged plants. Currently, the "bottom light" variable used in habitat models is derived from convection-diffusion models, which factor in the quantity of suspended particulate matter and light attenuation through the water column (Bechara et al. 2003). More simply put, these models propagate and diffuse mean extinction coefficients measured at the mouths of tributaries (Morin et al. 2004). In order to better quantify the relationships between light and the various fish species, it is important, over the medium term, to develop a light model that factors in the presence of phytoplankton, dissolved organic carbon and suspended particulate matter in general. These phenomena are complex and influenced by the presence of macrophytes, nutrients and ultraviolet rays (Martin et al. 2005; Frenette et al. 2002).

Waves

Natural wind waves are part of the various habitat models and are used to explain the distribution of many aquatic plants and wetland classes. Waves can also affect the distribution of fish spawning sites. On the basis of existing data, waves have been modelled for spring and fall conditions, when aquatic macrophytes are absent. In Lake Saint-Pierre, aquatic vegetation is particularly dense in summer, and wave action is very different because the fetch for wave formation is reduced, and dense aquatic plant communities absorb the wave energy. In addition, analysis of wind data over a long period of time shows that wind patterns are different in summer. This change is evidence that different parts of the lake are subject to wave action at different times of year. Simulation of summer wind waves requires a mathematical model that incorporates equations for the dissipation of wave energy by aquatic plants. Such a model was developed recently, but still requires parameterization and validation.

Improvements in knowledge of fluvial dynamics

In some areas of research on the St. Lawrence River, little progress has been made. Knowledge about the river's physical variables during winter is a case in point. Furthermore, there is no information at all about some sectors of the river, including the estuary from Trois-Rivières to Québec. Further research and future modelling projects will correct these shortcomings.

Winter

The St. Lawrence River is covered by a layer of ice from mid-December to mid-April. Only the ship channel and rapids remain ice-free, partly because of the currents but largely because of icebreakers. Very little knowledge has been acquired about the physical variables of the river during this period of the year. For example, current distribution, actual depths (frazil and ice) and distribution of water masses are still poorly understood.

It is vital to increase our knowledge of drift ice on the St. Lawrence in order to gain a better understanding of spring and fall processes. At present, only limited data are available on the impact of ice on emergent plants in spring, especially at the heads of bays in the Îles de Sorel (effect of stem shearing and clean-up of organic matter), or of the action of frazil ice generated on the weirs of the Îles de Sorel and built up on Lake Saint-Pierre. The action of frazil ice could be responsible for the presence in this fluvial lake of channels devoid of aquatic plants. Although site observations have been carried out and hypotheses developed, few conclusions can be drawn without new data for the period of ice cover. The understanding of the biological component of the ecosystem during winter is also very limited. There is virtually no information on the distribution of winter habitats, and yet they shelter species for much of the year.

Fluvial estuary

Very little is known about the physical and biological characteristics of the St. Lawrence estuary section, which stretches from Trois-Rivières to Québec. The section is unusual in that it is a freshwater estuary that is strongly influenced by semi-diurnal tides. In this area, the tides play an important role in determining the composition of plant communities, and the current inversion promotes the mixing of water masses. The section is characterized by a number of sites of interest, including the Gentilly mudflats, where a number of migratory bird species can be observed. The Richelieu rapids sector, across from the village of Deschambault, is interesting too, because it becomes a hydraulic threshold at low tide and the flow area is reduced by one third, causing very fast currents. Several other sites in the section have been identified as potential spawning grounds. The lack of information on these areas is surprising. For this section of the river to be adequately documented, a high-quality digital terrain model (covering topography, aquatic plants and substrate) should be developed; it would then be possible to perform hydrodynamic simulations that factor in semi-diurnal tides, wind wave simulations and transport-diffusion simulations. Once the digital models are ready, work on developing habitat models can start.

Conclusion

The two-dimensional modelling activities undertaken under the St. Lawrence Action Plan and the Plan of Study for Regulation of Lake Ontario–St. Lawrence River Levels and Flows have generated a number of tools for assessing the impact of various types of change on the St. Lawrence River ecosystem. This report presents the results of four years of scientific work—results that have made it possible to better quantitatively document and understand the dynamics of the river ecosystem. Many scientific and technological innovations have been introduced, including the integration of the data needed for a relational database, the spatial and temporal harmonization of data and the widespread use of numerical models to generate explanatory variables within habitat models. The various models are being updated and continually improved and will be increasingly used for monitoring the ecosystem and assessing the impacts of climate change and human activities such as dredging and other civil engineering projects.

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NOTES

1. The value of this coefficient is determined empirically on the basis of median grain-size distribution (D_{50}).

2. Saint-Venant equations are also known as shallow-water equations.

3. Specific discharge is defined as flow per unit area. This variable is very significant in many fish habitat models.

Chapter 4

MODELLING CHANGES IN AQUATIC PLANT COMMUNITIES AND WETLANDS OF THE ST. LAWRENCE RIVER

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Introduction

The St. Lawrence River between Lake Saint-Louis and Trois-Rivières represents an area of almost 1100 km^2 of faunal and floral habitats. Most of this territory is covered by wetlands and submerged aquatic plant communities. Swamp, marsh and wetland plants are key structural elements of the ecosystem. Maximum wildlife support capacity is determined by the resources and surface areas of wetlands and aquatic plant communities. Since these environments are dynamic in time and space, it is vital to be able to predict how they will evolve as a function of environmental variables, in order to be able to assess the impact of changes imposed on them.

The spatial distribution of submerged aquatic plant communities and major wetland classes varies mainly on the basis of such environmental factors as water levels and their short- and long-term fluctuations (hydroperiod), currents and waves. These variables are known at each node of the calculation grid for the entire study area (see Chapter 3). This makes it possible to establish the quantitative relationships between the distribution of a species or group of species and key variables, as explained in the section on habitat modelling approach or technique. The 2D Integrated Ecological Response Model (2D IERM) grid supports data from environmental variables and vegetation models. The latter, calculated on this grid, are used to analyze the impact of regulation or climate change on long-term change in vegetation. This is an integrated type of modelling, since the vegetation models are used as basic data for analysis and construction of wildlife models for species that use the vegetation found in wetlands and aquatic plant communities (such as fish, wetland birds, ducks, muskrat, etc).

This chapter will document the main environmental variables affecting riparian vegetation, describe and explain predictive spatial distribution models that take into account plant succession, and demonstrate how vegetation evolves as a function of discharge variations occurring in the St. Lawrence. For the purpose of integrated ecosystem modelling, the vegetation models were used specifically as input data for the wildlife models developed in the International Joint Commission's Plan of Study for Regulation of Lake Ontario–St. Lawrence River Levels and Flows. Lastly, we will address the ecosystem outlook associated with use of modelling and future wetland modelling trends and developments.

Submerged Aquatic Plant Communities

Submerged plants, or aquatic macrophytes, are found throughout the St. Lawrence River, principally in areas less than 5 m deep. They are extremely dense in fluvial lakes such as Lake Saint-Pierre, Lake Saint-Louis and Lake Saint-François. The St. Lawrence is characterized by water of great clarity, enabling light to penetrate at depth and support a large biomass of submerged plants. This is a rare situation in the case of large rivers, since their waters are generally loaded with suspended particulate matter.

The fluvial lakes are inhabited by submerged vegetation and hold great biodiversity. They are home to extensive invertebrate and fish communities, inevitably attracting more aquatic birds and mammals. Submerged plants provide a high-quality habitat (shelter, reproduction and food) for zooplankton and macroinvertebrates (Basu et al. 2000; Scheffer 1998; Timms and Moss 1984; Lorman and Magnuson 1978), fish communities (Weaver et al. 1997; Werner et al. 1983) and aquatic bird populations (Noordhuis et al. 2002; Lauridsen et al. 1993; Jupp and Spencer 1977).

When abundant, submerged plants can considerably alter the velocity of the current in a river system (Madsen et al. 2001; Morin et al. 2000; Chambers and Prepas 1994; Petticrew and Kalff 1992; Wilson and Keddy 1985), attenuate wave energy, thus limiting erosion (Kobayashi et al. 1993; Camfield 1977), filter suspended solids and reduce resuspension by currents and waves (Rooney et al. 2003; Madsen et al. 2001; Benoy and Kalff 1999; Sand-Jensen 1998; Petticrew and Kalff 1992).

Modelling submerged vegetation

Submerged plants create habitats suitable for many fish species. To determine available habitats for fish, one must be able to correctly predict the presence of submerged macrophyte species. The modelling of submerged plant habitats follows the methodology presented in Chapter 3: collection of biological data on the presence of species at several St. Lawrence stations, production of the physical variables corresponding to the conditions of the plant observation period, and production of statistical models that attempt to explain the presence of plants in terms of the physical variables characterizing their habitat. The models are then validated with an unused portion of the observations, in order to confirm their general applicability. When the models are considered valid, they can be used predictively for all possible conditions in the St. Lawrence River.

Acquisition of biological data

Submerged vegetation was sampled over a period of several years (from 1997 to 2002) in all sectors of the St. Lawrence River. Observations were made at a total of over 7855 stations. Every 50 m along the acoustic sounding transects, the presence, absence and identification of aquatic plant species were recorded by underwater videography. The location of sampling was measured using a differential global positioning system in real time, providing horizontal accuracy of 2 m. The underwater observations were validated by plant sampling. Field samples were then identified in cooperation with researchers from the Marie-Victorin Herbarium (Normand Dignard, Ministère des Ressources naturelles, de la Faune et des Parcs).

The assemblages of submerged plants consisted mainly of nine species: *Vallisneria americana* Michx., *Myriophyllum spicatum* L., *Potamogeton richardsonii* (Ar. Benn.) Rydb., *Potamogeton pectinatus* L., *Ceratophyllum demersum* L., *Elodea canadensis* Rich., *Heteranthera dubia* (Jacq.) MacMill., *Nitella* sp. and *Alisma gramineum* Lej. The observed assemblages were dominated by four species: *V. americana*, *P. richardsonii*, *Nitella* sp. and *M. spicatum*. The other species, such as *Lemna trisulca* L., *Chara* sp., and *Potamogeton crispus* L., were observed at a small number of stations.

Development of models

Physical variables

The habitat probabilistic models for submerged plants in Lake Saint-François were the first to be developed in connection with work on the St. Lawrence (Morin 2001). In the context of the International Joint Commission's Plan of Study, Turgeon and Morin (2005) produced habitat models of submerged plants for all sections of the river. In total, the habitats of eight aquatic plant species were modelled in three segments. The two-dimensional physical variables simulated or measured (i.e. slope of the bottom) for the acquisition periods of the calibration points and used in the statistical analyses are shown in Table 4.1. All the simulated and calculated two-dimensional physical variables used are presented in Chapter 3.

Statistical models

To identify the environmental gradients influencing the distribution of submerged plants, a canonical correspondence analysis was carried out from the calibration points of the various sectors of the river, using the CANOCO 4.5 software program (Jongman et al. 1995; Ter Braak 1987, 1986). Predictive equations were then produced using a logistic regression for the eight species present or absent. The models were calibrated using more than 7141 field observations. Validation was completed with 714 additional points not used in the calibration phase. Table 4.2 presents the performances of the various models.

Application of the models: Example of *Vallisneria americana*

Vallisneria americana is the most abundant submerged plant species in the St. Lawrence. In Lake Saint-Pierre, the habitat model for *Vallisneria* was calibrated using 315 occurrences and three physical variables: current velocity (simple and quadratic terms), intensity of light on the bottom (simple and quadratic terms), and bottom slope. In Lake Saint-Louis, the model was calibrated using 319 points and the logistic regression employed two variables: current velocity and bottom light (simple and quadratic terms). In the Îles de Sorel sector, the model was calibrated using 1528 points and two variables: intensity of light on the bottom and exposure to waves (spring waves with wind velocities of 17 km/h).

During calibration of the model, the correct classification rate of the *Vallisneria* models was very high, varying between 77.9% and 85.8% when using the optimal decision threshold. Cohen's kappa values were also high, falling between 0.517 and 0.689. These values indicate that the logistic regression models are robust and produce results different from those that might be expected at random. These results suggest that the logistic regression models for *Vallisneria* are very good for all sectors of the river, especially for the two fluvial lakes (Saint-Louis and Saint-Pierre). The same method was applied for the other abundant species in the St. Lawrence. Figure 4.1 shows the distribution of *Vallisneria* and the other dominant species in the section studied, for a mean summer flow of 9500 m^3/s.

TABLE 4.1

Mean and standard deviation of physical variables simulated at each study site for calibration points used to construct models of submerged plants

Variables	Lake Saint-Pierre	Lake Saint-Louis	Fluvial section
Depth (m)	4.707 ± 3.645	5.125 ± 3.723	5.019 ± 3.814
Velocity (m/s)	0.361 ± 0.139	0.243 ± 0.198	0.511 ± 0.236
Specific discharge (m^3/s)	2.011 ± 2.135	1.475 ± 1.697	3.219 ± 3.446
Bottom light penetration index (ratio)	0.131 ± 0.161	0.146 ± 0.246	0.162 ± 0.212
Slopes (degrees)	0.853 ± 1.496	1.250 ± 1.514	2.289 ± 2.368
Index of settled fine particulates (g/m^2)	0.010 ± 0.024	0.013 ± 0.012	0.003 ± 0.009
10 km/h waves, spring (m/s)	0.062 ± 0.053	0.037 ± 0.052	0.021 ± 0.028
17 km/h waves, spring (m/s)	0.139 ± 0.092	0.082 ± 0.084	0.055 ± 0.061
35 km/h waves, spring (m/s)	0.318 ± 0.145	0.200 ± 0.133	0.157 ± 0.124
45 km/h waves, spring (m/s)	0.407 ± 0.169	0.271 ± 0.153	0.220 ± 0.154
10 km/h waves, fall (m/s)	0.070 ± 0.064	0.037 ± 0.053	0.022 ± 0.031
17 km/h waves, fall (m/s)	0.144 ± 0.096	0.083 ± 0.085	0.058 ± 0.066
35 km/h waves, fall (m/s)	0.312 ± 0.145	0.202 ± 0.135	0.162 ± 0.129
45 km/h waves, fall (m/s)	0.394 ± 0.167	0.272 ± 0.161	0.205 ± 0.153
n (number of samples)	1135	979	5027

TABLE 4.2

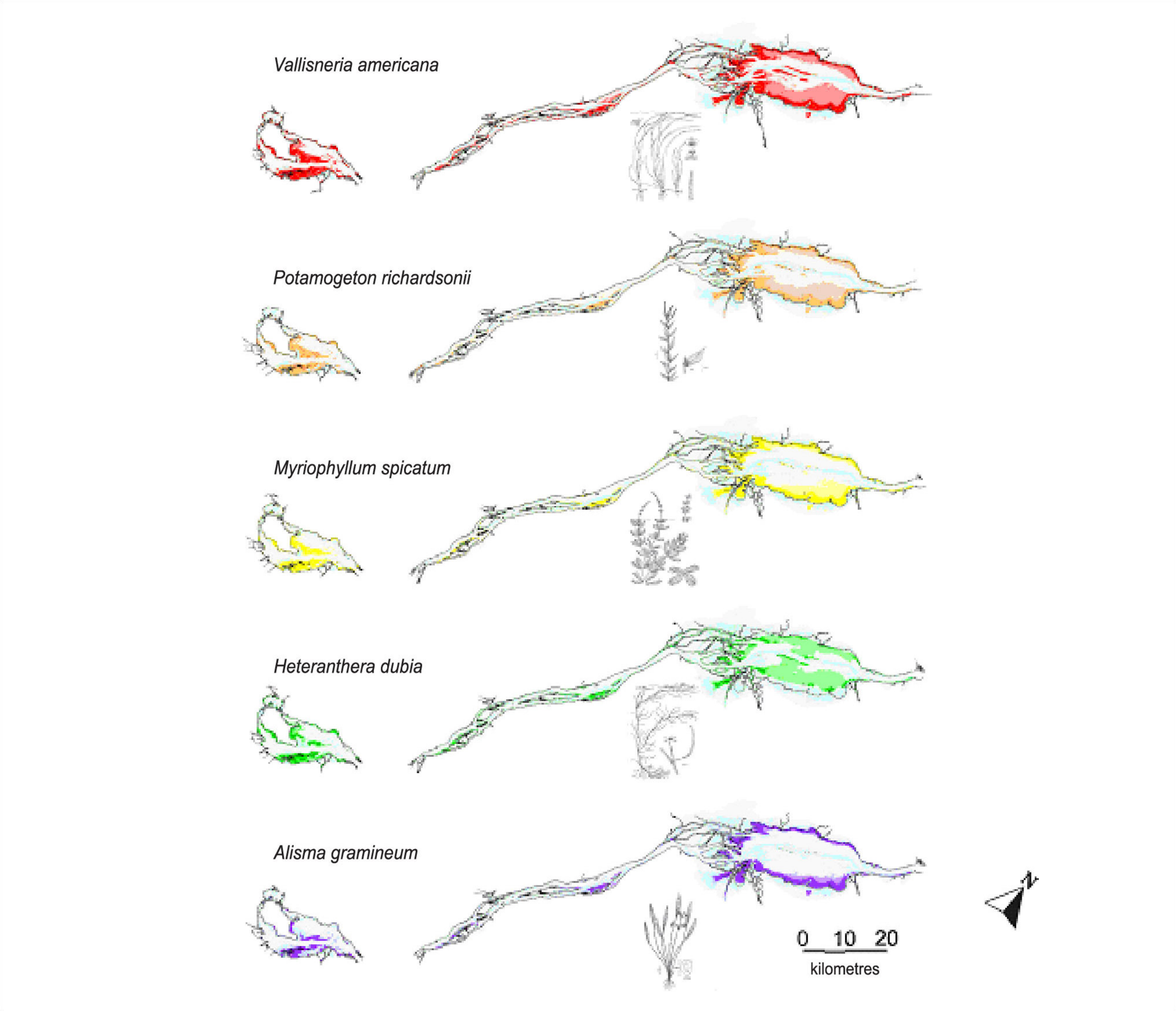
Performance of models by species and sector

	Sector		
Species	**Lake Saint-Pierre**	**Lake Saint-Louis**	**Îles de Sorel**
Alisma gramineum	95.3%	83.4%	80.7%
Ceratophyllum demersum	–	–	86.4%
Elodea canadensis	–	75.7%	84.0%
Heteranthera dubia	76.4%	80.3%	81.2%
Myriophyllum spicatum	86.3%	81.3%	84.9%
Potamogeton pectinatus	–	–	78.5%
Potamogeton richardsonii	87.8%	79.6%	78.1%
Vallisneria americana	86.6%	85.8%	77.9%

Note: Percentages were calculated by comparing the results of the models with values at observation points retained for validation purposes.

Changes as a function of water levels

Once calibrated and validated, the habitat models can be used predictively to estimate the effects of water levels on spatial distribution of plants. The predictive models can be applied to flows or levels that are common or close to the mean, or for events that are less frequent or have never been observed since the beginning of flow measurements. Figure 4.2 shows changes in the potential habitat of *Vallisneria* for all possible summer flows. The potential habitat areas vary from 39 800 ha to 30 180 ha for flows of 6500 m^3/s and 12 000 m³/s, respectively.



Note: Colour intensity indicates computational mesh density, not density of plants.

Figure 4.1 Spatial distribution of submerged plant species modelled for mean summer flow of 9500 m³/s throughout the study area

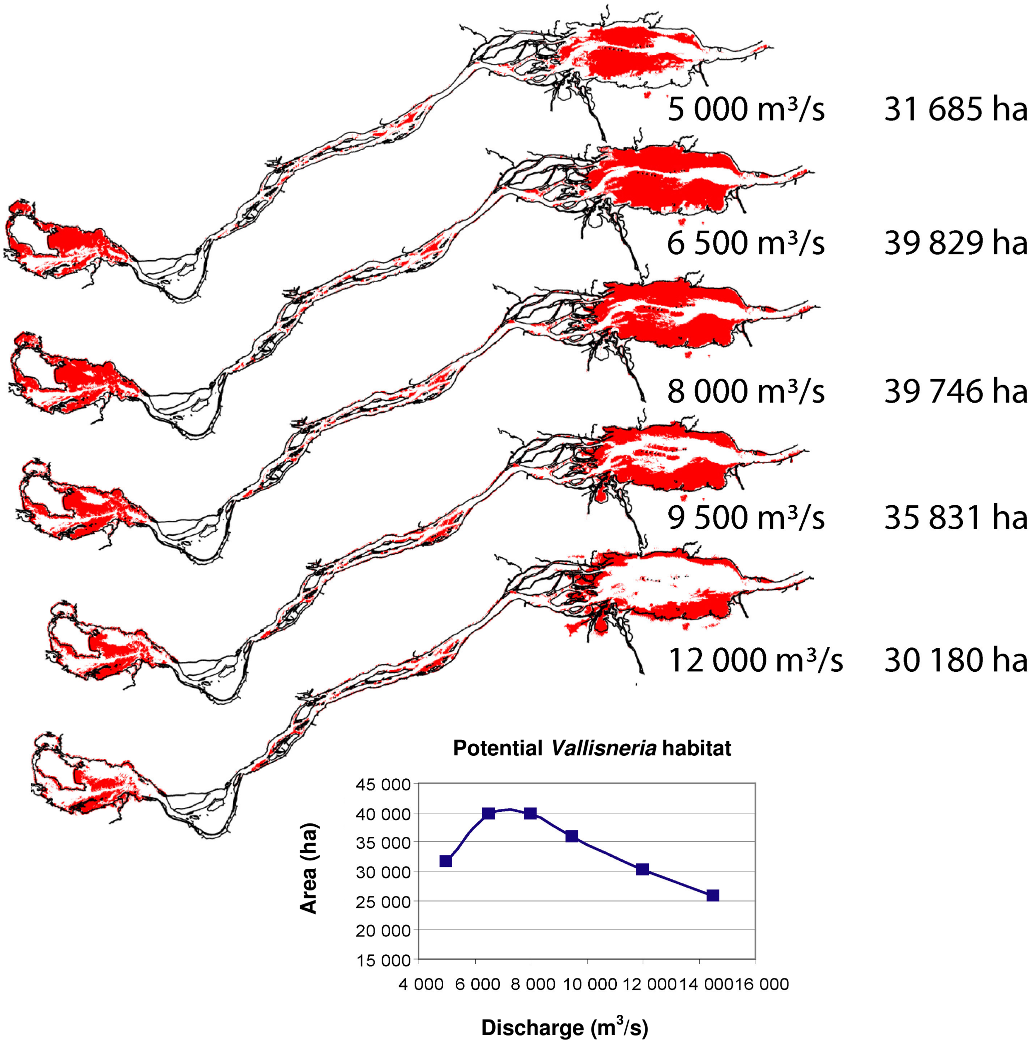


Figure 4.2 **Spatial distribution of *Vallisneria americana* and total potential habitat area for various summer flow scenarios, ranging from 5000 to 12 000 m³/s, at Sorel**

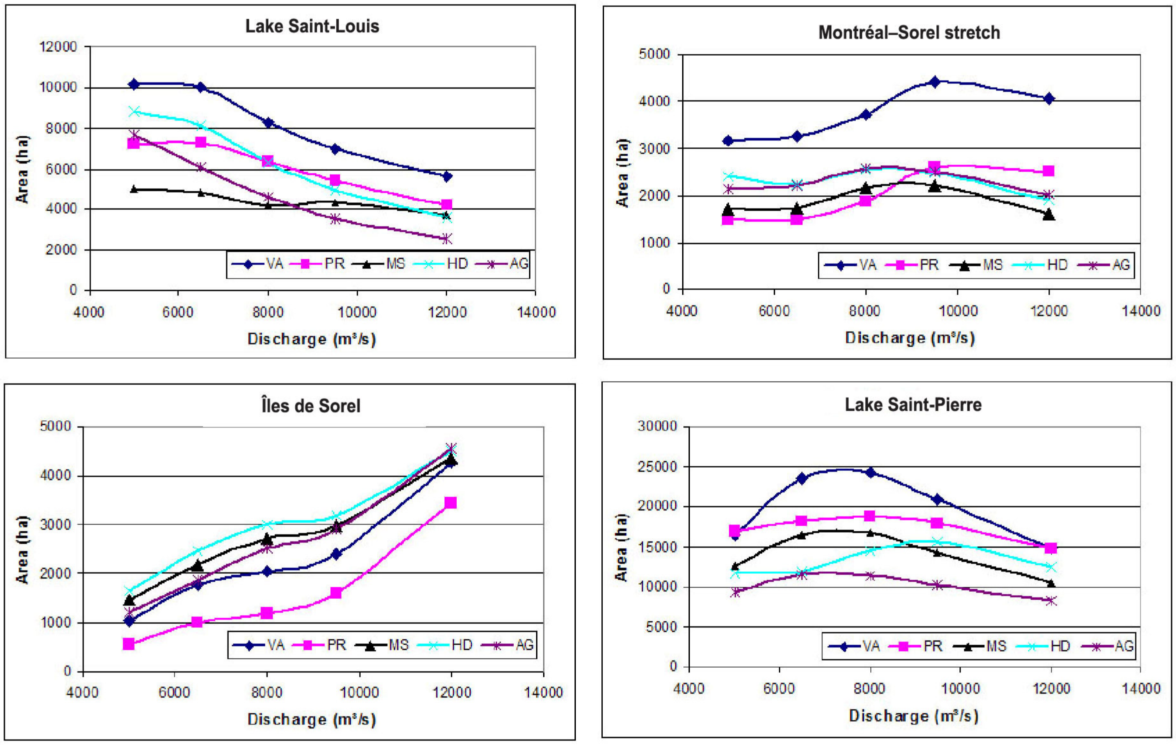
The simulated potential habitats in Figure 4.2 can be used to construct a simplified relationship between potential habitat area and flow, as shown by the graph at the bottom of the figure. For example, the potential habitat for *Vallisneria* throughout the river is at its maximum with discharges of approximately 7000 m³/s and decreases with higher or lower flows. The same type of graph can be produced for each species. Since this information is available for the entire river, this analysis can be performed for different sectors to describe local wetland dynamics.

Figure 4.3 shows the relationships between the area of potential habitat of submerged aquatic plants and discharge in four river sectors: Lake Saint-Louis, Montréal–Sorel, the Îles de Sorel, and Lake Saint-Pierre. This last sector differs from the others in terms of the large area of potential *Vallisneria* habitats—a maximum of approximately 25 000 ha—and the fact that the optimal area for all species is represented by a bell curve. It is notable that in this sector the relative areas of potential habitats for *Heteranthera dubia* and *Potamogeton richardsonii* increase with flow relative to the other species. These species remain relatively stable while the others are decreasing considerably. The Lake Saint-Louis sector behaves very differently, with areas of potential habitat of submerged plants reaching their maximum at very low flow levels and decreasing substantially as flows increase. In the Montréal–Sorel sector, areas of potential habitat increases with flow. In the case of the Îles de Sorel sector, a definite increase in the area of potential habitats is observed with flow in the case of all species considered. *Vallisneria* is the dominant species in most sectors except the Îles de Sorel.

All models demonstrate great sensitivity to flow and level fluctuations. However, when used to estimate the impacts of flow control at the outlet of Lake Ontario, they indicate that regulation would apparently have had only a limited effect on the distribution and density of submerged plants. This is related to the fact that regulation has very little impact on flows during the summer growing season; its impacts on spring and fall flows are greater.

The aquatic plant communities of the river change during the summer growing season. Submerged plants begin to grow when the water temperature reaches approximately 10°C, normally in May, and achieve their maximum growth in late summer, between mid-August and late September; thereafter they become senescent and disappear almost completely at the beginning of winter. Certain species of *Potamogeton* complete their life cycle very early in the season and become senescent in mid-July.

The spatial distribution models of submerged plant species presented here are based on the maximum growth period of the majority of species present in the river (from mid-August to late September). The water level and current variables used in the prediction models are mean values for the growing season.



Legend – VA: *Vallisneria americana*, PR: *Potamogeton richardsonii,* MS: *Myriophyllum spicatum*, HD: *Heteranthera dubia*, AG: *Alisma gramineum.*

Figure 4.3 Potential habitat areas as a function of flow for the dominant submerged plant species in different sections of the river

The submerged plant models are based on several years of observation, particularly the summers of 1999, 2000 and 2001. These seasons were characterized by discharges below the summer mean in 1999 and 2001 and discharges greater than the mean in 2000. The field observations carried out during these years show changes in species distribution in response to water levels during the growing season. This implies that species are resistant to fluctuations occurring over several years. At the present time, it is impossible to determine the response time of plants to a major change in flow occurring over several years in succession. Periodic monitoring of plant distribution could probably remedy this gap. Plant mapping for the seasons from 1999 to 2001 shows the existence of plant-free channels not connected to topographical channels. These plant-free areas could be the result of rapid currents in the preferred passages under winter conditions. To learn more about this phenomenon, mapping of frazil ice and ice cover, combined with monitoring of sub-ice velocities, should be considered.

Wetlands

Wetlands are components vital to balanced terrestrial ecosystems (see Chapter 5). They play a primary role in retention and purification of fresh water (Muscutt et al. 1993), recycling of carbon (Wetzel and Likens 1991), absorption of pollutants (De Snoo and De Wit 1998; Osborne and Kovacic 1993) and support of a large number of plant and animal species, several of which have been identified as threatened or vulnerable (Desgranges and Jobin 2003; Leck 2003). However, despite their usefulness, the area of these highly productive environments has been reduced by anthropogenic activities such as agriculture, logging and water-level regulation (Ellison and Bedford 1995; Jean et al. 1992; Lamoureux 1971). A better understanding of the processes governing distribution of emergent plants in wetlands would make it possible to more effectively evaluate the impacts of water-level fluctuations on plant and animal life and on losses or gains in certain wetlands.

Wetland modelling

Biotic data

The field observations used for modelling purposes are derived from Jacques (1986), who extensively characterized emergent plants along a total of 152 transects in the Lake Saint-Pierre wetlands during the 1985 growing season. This work was compiled in 23 maps of 1:10 000 scale, containing 6000 polygons and covering a total of 550 km^2 of the Lake Saint-Pierre floodplain. This database, which contains the description of the dominant and co-dominant plant species, has been digitized and validated (Falardeau and Morin 2000). From this database, 11 543 sampling points were selected at random from the 2D IERM grid. This node-based grid was integrated into a georeferenced database constructed to manage all measured environmental data, simulated physical variables and integrated biological models. The sampling points were used to determine the major wetland classes and model their distribution. The simulated physical variables for 1982, 1983 and 1984 were used to model the habitat of the emergent plants observed in 1985. These three years are characterized by relatively similar annual hydrographs. To define the lower and upper limits of the hydrosere, sampling points were added in open water and in areas dominated by terrestrial forest.

Determination of major wetland classes

A canonical correspondence analysis was carried out on all the points (calibration and validation) in order to identify the dominant species in the major wetland classes and determine the environmental gradients affecting vegetation distribution. This ordination technique represents direct environmental gradients and makes it possible to highlight the relationships between environmental variables and several plant species. The dominant and co-dominant species present at more than ten sites were retained in the analysis, minimizing the weight of rare species.

From the analysis, it was possible to produce eight major wetland classes and to determine that the local hydroperiod is a fundamental variable in terms of explaining the distribution of the various wetland classes. These classes are: deep marshes subject to the effect of waves (DM_W), deep marshes (DM), shallow marshes (SM) shrub swamps (SS), natural wet meadows (WM), forested swamps (FS), and two boundary environments used to define the edges of the hydrosere: open water (WATER) and terrestrial forests (FORESTS). For clarity, only the most abundant dominant species representative of the wetlands have been used in Figure 4.4. In order to prevent the loss of information, the boundaries of the area occupied by all emergent species in each wetland (coloured boxes) are identified.

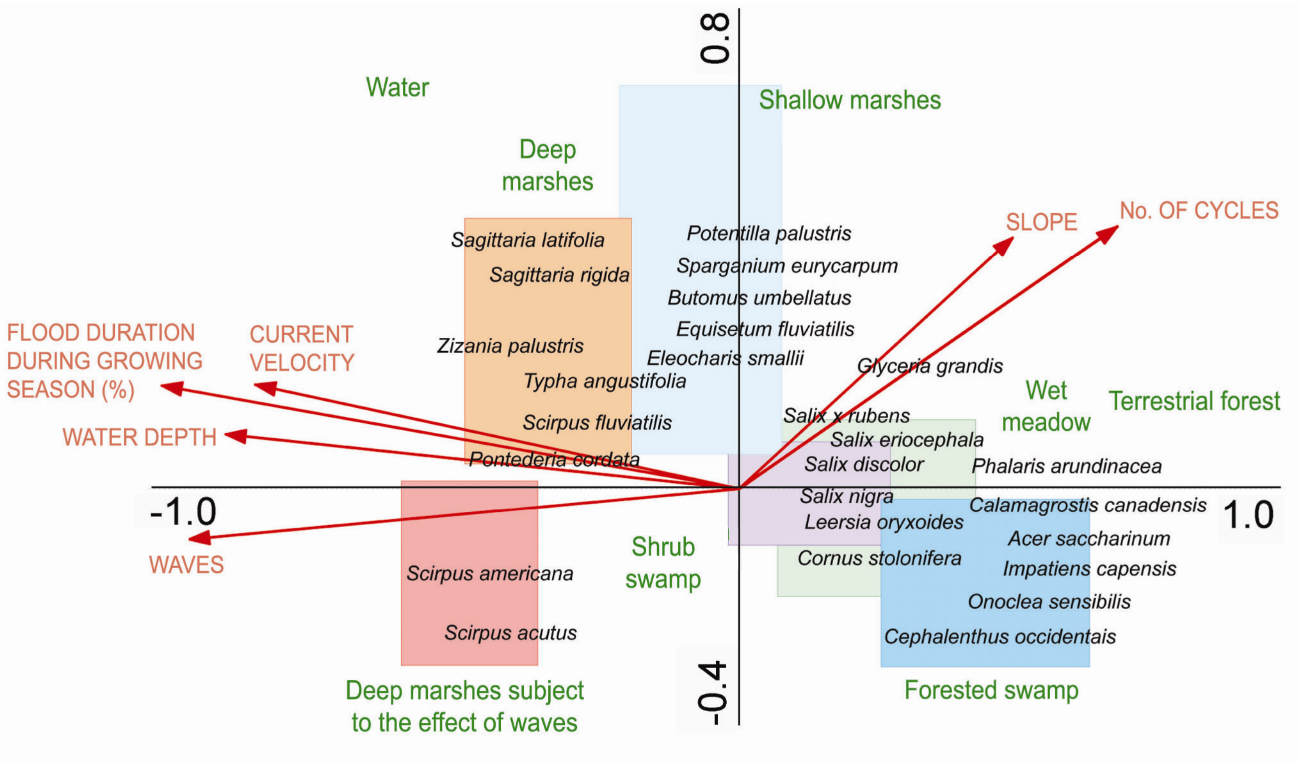
The results of the canonical correspondence analysis of the calibration points of the model suggest that the hydroperiod, represented by axis 1 of the ordination, explains a high proportion of the system variance (67.0%). Axis 2 of the ordination (16.3% of the variance) seems to be associated with a heterogeneity gradient involving the sites and characterized by cycles of flooding and exposure and the slope of the terrain. The centre of the ordination (mean of the environmental variables) allows effective differentiation between marsh plant species and swamp and wet meadow plant species.

Species capable of tolerating water depth and flooding duration above the mean are located on the left of the ordination and constitute the plant communities that characterize marshes. A clear difference is observable between the plant species that dominate deep marshes and those dominating deep marshes that are subject to the effect of waves. The difference between deep and shallow marshes is less clear. The emergent species present in marshes seem to adapt to variable conditions (tolerant of flooding and exposure cycles) over a relatively broad spectrum of environmental conditions. The shallow marsh (SM) species seem to be more strongly associated with the flooding and dewatering cycles.

Logistic regression model of wetland classes

Relationships between physical variables and wetlands were established by means of logistic regressions. To eliminate unnecessary co-linearity, all variables were standardized before calculating the products of the variables. A progressive (step-by-step) selection method with an acceptance threshold of $p = 0.10$ was used to determine which variables should be retained in the final models. The latter were then evaluated to detect multi-co-linearity among the predictive terms. Finally, the correct classification rate (or percentage of correctly predicted cases) was used to evaluate the predictive accuracy of the models.

The logistic regression models use six environmental variables (Figure 4.4) to explain the distribution of wetlands and the two environments, open water and terrestrial forests, that border the natural hydrosere. The variables that have the highest coefficients and seem to distinguish most effectively among the various wetlands are water depth and current velocity. These two variables are closely linked to axis 1 of the canonical correspondence analysis representing the local hydroperiod.



Note: The diagram (axis 1 and axis 2) explains 83.3% of the total variance in the presence of emergent plant species in the Lake Saint-Pierre floodplain.

Figure 4.4 Ordination diagram illustrating the presence of emergent species as a function of environmental variables (arrows)

The effectiveness (correct classification rate, sensitivity and specificity) of the calibrated models is high: 68% for natural wet meadows, 73% for shrub swamps, 76% for shallow marshes, 78% for deep marshes, 80% for forested swamps, 87% for deep marshes subject to the effect of waves, 91% for terrestrial forests and 92% for open water. The kappa value is also high (> 0.5) in the case of forested swamps, deep marshes subject to the effect of waves, open water and terrestrial forests. During validation of the models, the performance measurements remained high and were comparable to the values of the calibration trials. The uppermost diagram in Figure 4.5 shows the distribution of wetland classes predicted by the models for the Lake Saint-Pierre sector in 1985, the year in which the calibration data were measured.

Plant succession model

A complementary temporal model (plant succession model) was designed to use the predictive models over time and allow for the plant succession possible between wetland classes. The plant succession model was constructed using annual wetland types (wetland classes) that evolve through intermediate types of variable duration, in response to stimuli induced by changes in the physical environment (Turgeon et al. 2004). The logistic regressions provide a basis for evaluating the transformations brought about by the changing conditions of physical characteristics, mainly associated with the local hydroperiod. This method allows greater flexibility in how transitions are made between classes and successfully reproduces the phenomena that suggest extreme events are accelerating (prolonged submersion) or delaying (low water levels) the transition from one wetland class to another (Marie-Victorin 1995; Van Der Valk et al. 1994; Jean et al. 1992; Tessier and Caron 1981; Harris and Marshall 1963). Figure 4.5 shows the result of using the plant succession model on the series of measured river water levels. The “1967” portion shows the distribution of wetlands after several years of very low water levels. At that point, deep marshes occupied a major portion of Lake Saint-Pierre, and shallow marshes were well developed along the edge of the lake. In contrast, the “1977” portion shows a spatial distribution resulting from an extended period of very high water levels. At that time, marshes were restricted to a narrow band along the edge of the lake, and a substantial portion of forested swamps had disappeared following a long period of submersion. The “1985” portion shows that these swamps were still being re-established that year. The plant succession model imposes a vegetative stage on Baie de Lavallière and the other managed marshes of the river (that of 2002), since their hydrographs are practically independent of the river.

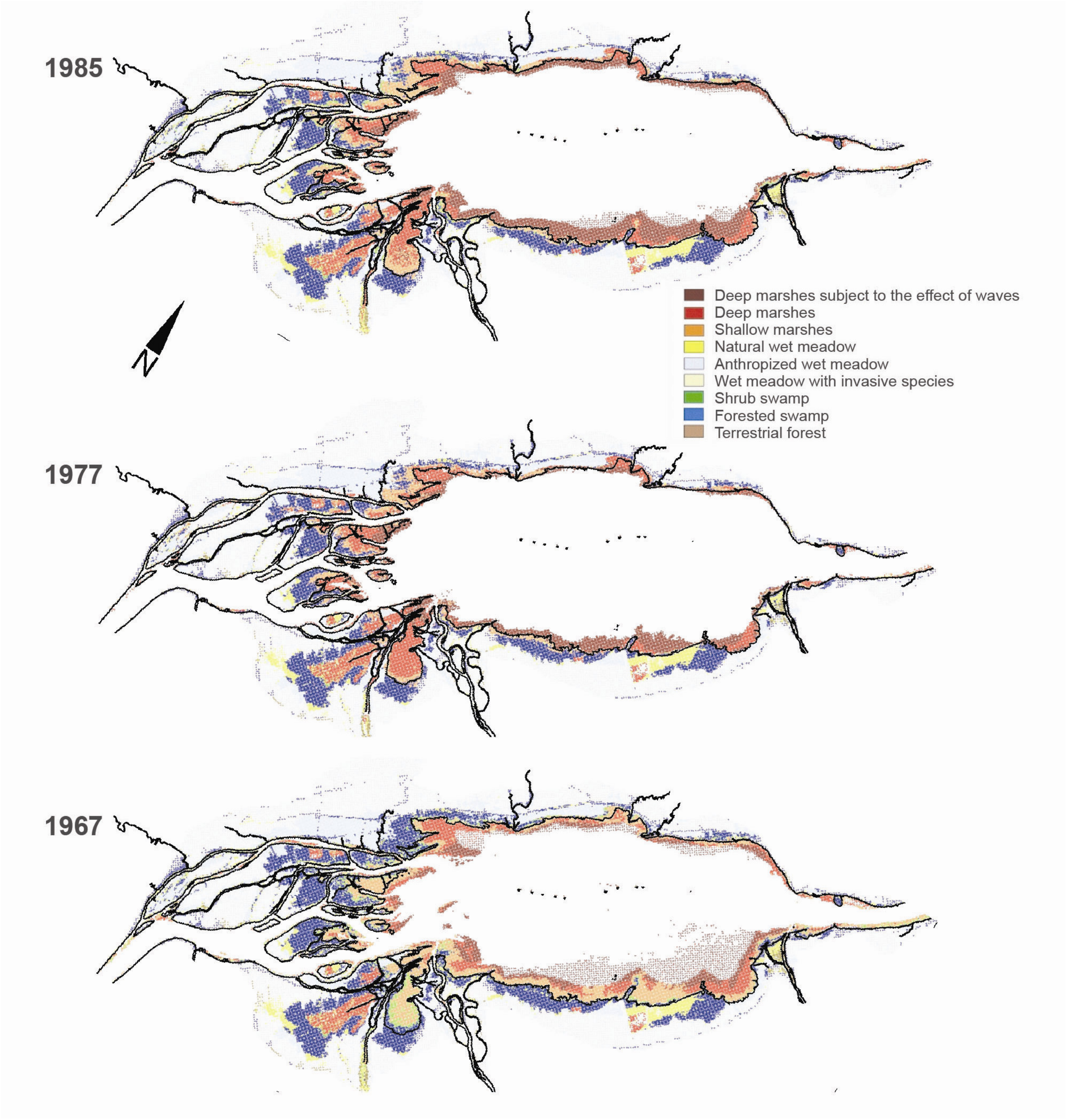
Spatial and temporal validation

The wetland predictive models were validated in three different ways. First, robustness of the wetland statistical models was spatially validated for the 1985 year, with performances varying between 67% and 92%, depending on class. Second, a spatial validation was conducted in the other sections of the St. Lawrence River floodplain where the terrain was well mapped: Contrecœur and Verchères islands (Jean et al. 2001; Pilon et al. 1980), Sainte-Thérèse, Varennes and Boucherville islands (Pilon et al. 1980) and Lake Saint-Louis (Jean et al. 1992). In this way, it was possible to validate the quality of the models for sectors of the river differing from the calibration sector, and for a period relatively similar to that selected by Jacques (1986). The agreement between the two data sets is excellent. Third, the wetland model and the temporal component were validated by evaluating the agreement between maps from remotely sensed data (IKONOS image, Létourneau 2005) and the predictions of the model for Lake Saint-Pierre in 2002.

There is good agreement between the wetlands predicted in 2002 and those identified from satellite images. Much of this agreement is attributable to the use of the plant succession model. Use of this model with the models that use logistic regression improves the performance of the models by approximately 20%, particularly for marshes, wet meadows and forested swamps. The correct classification rate and specificity of the models are better than 80% for all wetlands for the 2002 year.

Application of the model to time series

The predictive models for the major wetland classes successfully reproduce existing observations of the river. Because these models are applicable based on the time series of measured levels and can be used to calculate spatial control variables (velocity, depth, waves and hydroperiod) for each node of the simulated domain, it is possible to apply them to any time series. Under the Plan of Study for Regulation of Lake Ontario–St. Lawrence River Levels and Flows. prepared for the International Joint Commission, several time series were produced for the purpose of quantifying the impact of various regulation approaches or scenarios on the ecosystem. The measured series, known as 1958DD, had to be improved to coincide as far as possible with natural conditions (pre-project) and thus satisfy the members of the Environment Committee.



Note: The models were applied on the points of the 2D IERM grid (Lavallière Bay has imposed-stage vegetation).

Figure 4.5 **Distribution of wetlands in the Lake Saint-Pierre floodplain as predicted by the models using logistic regression and the plant succession model for 1985, 1977 and 1967**

Figure 4.6 shows the change over time, for both scenarios, of the surface area occupied by the wetland classes of the St. Lawrence in the Lake Saint-Louis–Trois-Rivières sector between 1960 and 2000. This figure also shows the area occupied by open water. It can be seen that few changes directly attributable to regulation occurred over a 40-year period. The greatest changes, specifically the disappearance of forested swamp areas, are the result of large water inflows during the 1970s and therefore do not entirely result from management of water levels. It should be noted that the models successfully reflect the major decrease in silver maple populations (dominant species in forested swamps) in the St. Lawrence River floodplain as a result of the very high water levels observed during the mid-1970s. According to these models, regulation was responsible for approximately 10% of the increase in forested swamp area losses and contributed to an increase in areas occupied by wet meadows. Figure 4.6 shows that wetland vegetation in the lower section of the hydrosere—deep marshes (DM and DM_W) and shallow marshes (SM)—reacts quickly to water-level fluctuations (two to three years). Temporal inertia and plant succession have little effect on distribution of these environments. However, in the upper part of the hydrosere, corresponding to wet meadows (WM) and swamps (FS and SS), emergent plants have greater temporal inertia (varying from five to 40 years).

Unlike Lake Ontario, where regulation has had a major negative impact on diversity, the wetlands of the St. Lawrence River have endured because of the major annual flow fluctuations observable in the river system. The St. Lawrence does not seem to have any wetland classes that are threatened by regulation in a manner similar to Lake Ontario's natural wet meadows, which have almost disappeared, replaced by cattail marshes.

Ecosystem Outlook and Modelling Trends

Plant habitat models as explanatory variables

In traditional habitat models, the explanatory variables used are normally physical variables measured in the field or simulated by numerical models (current, waves, etc.). Recent fluvial modelling works, especially development of predictive distribution models for submerged plants, have made it possible to integrate results as predictive variables for other habitat models. It has been shown that the modelled submerged plants constitute explanatory variables for the spatial distribution of several fish species (Mingelbier et al. 2005). Accordingly, the refinement of basic data and habitat modelling techniques opens the way to production of powerful two-dimensional habitat models that can be used in the same way as numerical models (i.e. as explanatory variables).

Similarly, the wildlife models (for birds, muskrats, frogs, fish, etc.) developed for the International Joint Commission used these results as input data, by integrating the results from the major wetland class models. In this way, a better understanding was obtained of the combined dynamics of wetlands and water levels with respect to habitat availability for several species or species groups, providing an initial version of a true integrated ecosystem model.

Development of a growth model for submerged plants

Water temperature is a fundamental variable in the river ecosystem. Observations made in Lake Saint-Pierre in 2003 indicate that local growth of aquatic plants is strongly influenced by water temperature at the observation station. The plants located on the south side of the lake, which are less exposed to the prevailing winds during spring and are therefore in a warmer environment, showed a much faster initial growth than the plants located in the centre and on the north side of Lake Saint-Pierre. This was observed for most plant species. Richardson's pondweed (*Potamogeton richardsonii*) specimens of approximately 50 to 75 cm in length were measured on the south side of the lake in late May 2003, while in the centre of the lake and on the north side, the first indications of aquatic plant growth were observed three weeks later, around mid-June. A growth model for aquatic plants that combines spatial distribution and water temperature models would offer the possibilities of making dynamic use of the impact of plants on flow and on the habitat of several other species, and simulating certain parts of the system more appropriately in real time.

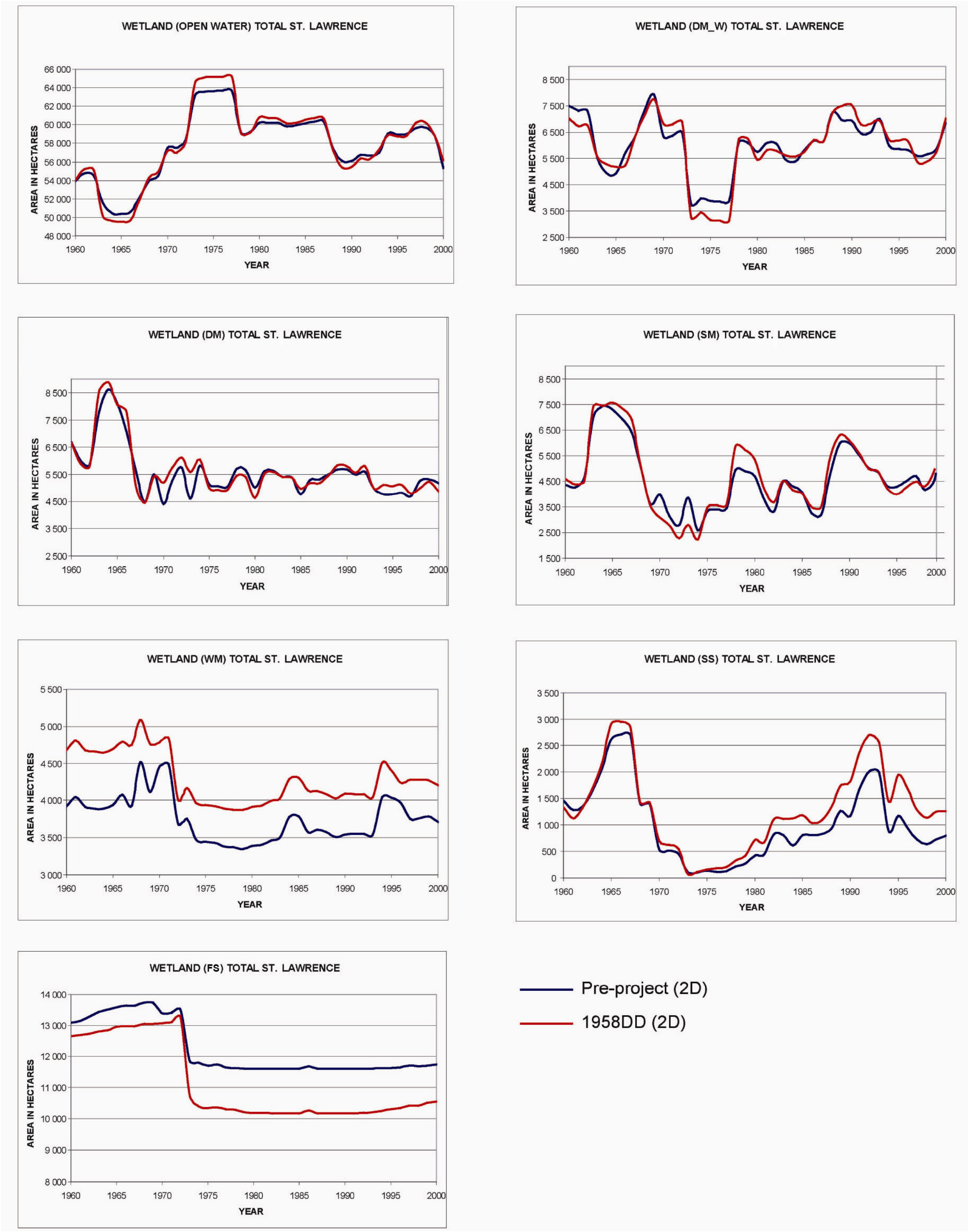


Figure 4.6 Changes over time in various wetland classes based on two St. Lawrence River regulation scenarios: A measured scenario (1958DD) and a scenario assuming no prior regulation of system conditions (pre-project)

Impact of agriculture and anthropogenic activities on wetland vegetation

Disturbances of anthropogenic origin, such as agriculture, grazing, logging and dredging may favour certain emergent species to the detriment of others (Odland and del Moral 2002; Toner and Keddy 1997; Langlais and Bégin 1993; Jean et al. 1992; Nilsson and Keddy 1988; Lamoureux 1971). As of the present date, 53 islands in the fluvial St. Lawrence are still being used for agriculture (De Koninck 2000; Bélanger 1991). These sites, which are located in the upper part of the toposequence, were probably dominated by forested swamps before agricultural lands were developed. The abandonment of some of these fields in recent decades has enabled invasive or highly competitive herbaceous species like *Phalaris arundinacea* and *Calamagrostis canadensis* to become established. This seems to have prevented return of the climax stage (i.e. forested swamps dominated by silver maple).

Some studies suggest that so-called “open” wetlands such as wet meadows and sparse forested swamps are a direct consequence of anthropogenic activities and are occupied by opportunistic species that quickly colonize abandoned sites (Foster and Motzkin 2003; Middleton 2003). A number of studies show that when *Phalaris arundinacea* becomes established it gradually eliminates indigenous plants (Lavoie et al. 2003; Green and Galatowitsch 2001; Keller 2000; Marks et al. 1994; Gaudet and Keddy 1988; Auclair et al. 1973). The main problem associated with rapid colonization by these pioneering species is the resulting impoverishment of vegetative diversity, and the minor possibility of the re-establishment of forested and shrub swamps and the wildlife associated with them. It would seem important to limit growth of these pioneering species experimentally, in order to restart “natural” plant succession. This would make it possible to restore wetlands, especially forested swamps, which seem to have greater vulnerability to disturbances.

Refinement of wetland models

The models that reproduce the spatial distribution of the major St. Lawrence River wetland classes are constructed from physical variables calculated on a weekly basis but compiled over the length of the growing season. Use of these models requires preservation of the river’s “natural” hydrograph (i.e. higher flows in spring and lower flows in summer in the scenarios analyzed). When these models are applied to sectors where the hydrograph is very different—for example, in stabilized environments like the managed marshes of Baie de Lavallière—predictive accuracy is not validated and apparently poorer, mainly because the calibration data are derived from the “natural” part of the wetlands and the dominant species are normally different. In addition, the major wetland classes are more or less approximate, since they represent a dominance of a type of growth over a species assemblage that may be highly varied.

In terms of prediction, in order to resolve the problem associated with possible major changes in the river’s hydrograph, or predict probable changes in wetlands in managed areas or the species that will be dominant in a specific environment, it is necessary to refine the time step and categories (species, genus or family of plants) of the predictive models. Reduction of the time step and improved determination of the categories of wetland classes used in the modelling would make it possible to take into account, at a local level, all the major stages in the life cycle of a species (germination, accumulation of reserves and seed production). Such an approach would make it possible to more accurately incorporate plant succession in managed areas in the models. Although this represents the enormous task of characterizing and managing information, work of this kind is necessary because it opens the way to substantial progress in the area of integrated habitat modelling.

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Chapter 5

EFFECTS OF THE HYDROLOGICAL REGIME ON PLANT DIVERSITY AND PRODUCTIVITY

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Introduction

The various types of aquatic plants (phytoplankton, periphyton, metaphyton, vascular plants) along the St. Lawrence form the basis of the carbon production that sustains the fluvial ecosystem. These plants also provide a physical structure for the aquatic faunal habitat. Each major plant type is typical of a specific axis of spatial and temporal variation that characterizes the pelagic and benthic compartments and the floodplain (Table 5.1). Hydrological factors play a major role, since flow conditions affect both longitudinal processes (current speed and residence time) and spatial heterogeneity (influence of tributaries), as well as transverse processes (overflow and exchanges with the floodplain and the terrestrial environment).

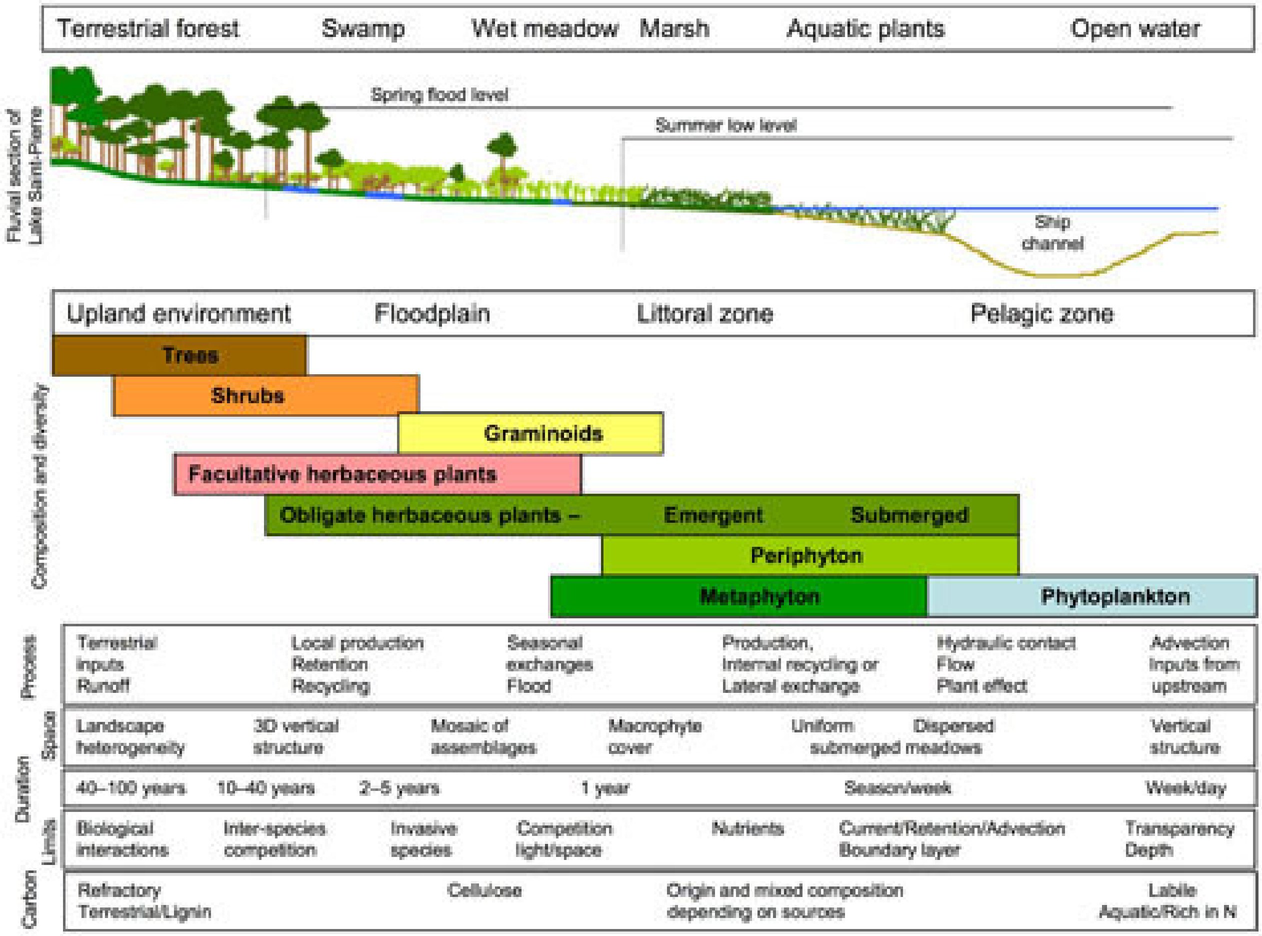
Figure 5.1 presents the main compartments of the primary producers of the St. Lawrence, along a theoretical section of a fluvial lake. Each of the major habitats is illustrated, from open water to the upper limit of the floodplain, along with their main associated plant communities. The types of primary producers described in this chapter are characteristic of specific types of habitats, although there is some overlap between zones. Depending on its position in the river section, each community is subject to different physical processes that determine its growth conditions and the retention or export of the biomass produced by the plants. These factors determine the spatial and temporal heterogeneity scales specific to each assemblage, the limits of biological production and the quality of the carbon produced in each environment.

From a theoretical viewpoint, it is essential to understand the major processes that control carbon production in the world’s major river systems, including the St. Lawrence. This knowledge should provide better guidance for management interventions (regulation of water level and flow, land and riverbank use, riverbed excavation) based on sustainable development.

TABLE 5.1

Summary of relations between the main axes of spatial and temporal variations and the main control mechanisms of the various types of fluvial plants

Main axes of variation	Compartments	Sources of carbon and types of plants	Physical mechanisms	Factors controlling plants
Upstream-downstream	Pelagic	Plankton, periphyton detached from its substrate, detrital organic particles	Drift, advection, residence time	Current, light intensity, nutrients
Spatial heterogeneity (longitudinal and transverse axis)	Benthic	Submerged vascular plants, periphyton and metaphyton	Thickness of the boundary layer, current friction and drag caused by plants	Space, light, current, nutrients, biological interactions: grazing, competition
Lateral and transverse	Terrestrial-aquatic transition, floodplain	Emergent macrophytes, organic detrital particles	Flooding, connectivity, fragmentation of the landscape, ice	Slope of the bank, erosion, waves, substrate, biological interactions: competition



Note*:* The diagram illustrates the composition of the main plant communities (*composition* and *diversity*), the physical processes (*process*), the spatial heterogeneity (*space*) and temporal response (*duration*) scales, the productivity limits (*limits*) and the quality of the carbon (*carbon*) produced by each community.

Figure 5.1 Diagram of a section of the St. Lawrence showing the elevation gradient between the terrestrial environment and the main channel

From a practical viewpoint, knowledge of the factors that determine carbon production in the St. Lawrence River is essential in order to identify the critical links that sustain animal productivity, including the populations of vertebrates (fish, waterfowl) subject to sport and commercial exploitation. An assessment of existing information on the primary producers of the St. Lawrence will enable us to take stock of the knowledge acquired. Finally, based on a summary of this information, it will be possible to identify the major management issues facing the St. Lawrence and the sectors on which future research should focus.

Current Knowledge

Upstream-downstream axis: Pelagic environment and plankton

Biodiversity

Among small species (2–20 µm in diameter), 363 planktonic, periphytic and ubiquitous algae have been identified in the St. Lawrence (Paquet et al. 1998; Table 5.2). This flora is dominated by some thirty taxa, mainly diatoms, Chlorophyceae and Cryptophyceae. With 208 taxa, the planktonic flora is by far the richest, reflecting the diverse origins of the water masses that make up the St. Lawrence.

TABLE 5.2

Number of species belonging to each family of algae identified in the St. Lawrence, depending on whether they live suspended in the water (plankton), attached to a substrate (periphyton) or in both environments (ubiquitous)

Group	Plankton	Ubiquitous	Periphyton	TOTAL
Chlorophyceae	94	29	16	139
Chrysophyceae	36	1	4	41
Cryptophyceae	11			11
Cyanophyceae	25	16	5	46
Diatoms	18	22	62	102
Dinophyceae	13			13
Euglenophyceae	10		1	11
TOTAL	207	68	88	363

Source: Paquet et al. 1998.

The species composition of the algae in the St. Lawrence reflects the diversity of habitats and the origin of the constituent water masses. Phytoplankton from Lake Ontario breaks down as it is drawn downstream and becomes enriched with species typical of the tributaries and the fluvial lakes. The lacustrine species are gradually replaced by species tolerant of the turbulent conditions, turbidity and decreased light intensity being prevalent in the ship channel (Basu et al. 2000a; Hudon et al. 1996). An assessment of the zooplankton reveals the same trends, with a rapid decline in microcrustaceans (copepods, cladocerans) typical of Lake Ontario and their replacement by rotifers in the fluvial section (Basu et al. 2000a). The comparative abundance of periphyton, particularly filamentous green algae, in the plankton of the fluvial lakes is a sign of the increased nutrients in these areas and the hydraulic isolation of the littoral zone, especially in the summer (Hudon et al. 1996). Depending on the season, the composition of the fluvial plankton is more homogeneous during high-flow periods and in the absence of aquatic macrophytes (e.g. in spring), emphasizing the importance of the hydrological regime (residence time and advection speed of water masses) as a control factor for this community (Basu et al. 2000b; Hudon et al. 1996).

Biomass

In the tributaries of the St. Lawrence, the biomass of phytoplankton and zooplankton is negatively related to the rate of water transport and positively related to levels of total phosphorous (for phytoplankton) and chlorophyll (for zooplankton) (Basu and Pick 1996). In the fluvial section, where water advection is strong, phytoplankton biomass is low (chlorophyll *a* < 1–4 µg/L), regardless of the water mass or the influence of urban effluent (Basu et al. 2000a, 2000b; Blais 2000; Hudon 2000; Hudon et al. 1996). This results from a combination of incident light intensity, the transparency of each water mass and its average depth.

Accordingly, phytoplankton biomass (chlorophyll *a*) in the Ottawa River, which is < 5 m deep, is greater than that of plankton in the waters originating from Lake Ontario, which circulate in the ship channel (> 11 m deep) (Hudon 2000; Blais 2000). For the biomass of phytoplankton, the effect of the difference in the average depth of the two water masses is greater than the difference in their turbidity.

The physical and chemical conditions in the littoral zones allow the growth and accumulation of larger biomasses of phytoplankton; the littoral zones are especially well developed in the fluvial lakes. Moreover, the littoral zones receive nonpoint-source inputs from several agricultural tributaries (Hudon and Sylvestre 1998; Basu and Pick 1996). In the southern portion of Lake Saint-Pierre, the combined effect of the slowing current, the shallow depth and the abundance of light and nutrients results in a ten-fold increase in phytoplankton biomass (10 to > 20 µg/L) in the plumes of the Richelieu, Saint-François and Yamaska rivers (Vis 2004; Basu et al. 2000b).

Productivity

The average values of photosynthetic efficiency and of maximum photosynthetic capacity obtained for the phytoplankton from the water masses from Lake Ontario and the Ottawa River approach the values reported in other studies on phytoplankton in temperate environments (Vis 2004; Blais 2000; Forget 2000). There is a positive link between the maximum photosynthetic capacity of the phytoplankton from these two water masses and the water temperature, which corroborates the well-known relationship between these two variables.

In the waters of the St. Lawrence, the light regime degrades further downstream, coinciding with a decrease in transparency, photic depth and average light intensity of the water column. This translates into a decrease in maximum photosynthetic capacity (factor of 1.25) and a drop in productivity per square metre (factor of 1.5), despite the increased phytoplankton biomass (factor of 2.4) further downstream. In the waters of the Ottawa River, luminosity is less favourable than in the waters from Lake Ontario, but does not change significantly further downstream; the photosynthetic parameters do not vary greatly, and productivity per square metre increases (factor of 1.5) with the increase in biomass (factor of 1.7) further downstream. At all measurement sites, biomass and productivity per square metre are highest in waters of agricultural tributaries because of shallow depths and despite significant turbidity.

Moreover, measurements of oxygen and CO_2 flow during the ice-free season reveal that the production-to-respiration (P:R) ratios are consistently > 1 in the waters from Lake Ontario, whereas this ratio is equal to 1 (annual average) in the waters from the Ottawa River (P:R < 1 when the levels are high and the water is turbid, and > 1 during the summer low-water period) (Blais 2000).

Temporal trends

In both the fluvial section and the fluvial lakes, seasonal and interannual variations in phytoplankton biomass are not very dramatic, showing only a slight increase in spring and fall. However, in low-level conditions, the biomass of filamentous algae (Vis 2004) and the proportion of algae species likely to cause an earthy taste and smell in drinking water (Hudon 2000) increase substantially. Given the greater frequency of low-level years in the last decade, it is difficult to determine whether the biomass of phytoplankton is displaying any temporal trends.

Spatial Heterogeneity of the Benthic Environment: Periphyton, Metaphyton and Vascular Macrophytes

Compared with the pelagic compartment, which is relatively homogeneous, the benthic compartment is highly heterogeneous, in both space and time. In increasing order of size and structural complexity, the benthic primary producers include attached microalgae (periphyton), filamentous algae (metaphyton) and submerged vascular plants (macrophytes). Although they share certain common ecophysiological traits, each plant type is discussed separately in the following paragraphs.

Periphyton

Biodiversity

To date, 98 typical periphyton species have been identified in the St. Lawrence, with diatoms being the most numerous (62 taxa, Table 5.2; Paquet et al. 1998). Moreover, 68 ubiquitous species can be found in the two types of environments (pelagic and benthic); these can be plankton species that settle on the bottom of calm sectors, or periphyton species detached from their substrates by waves or the current. The lower species richness of periphyton compared with plankton could be attributable to the fact that it is mainly produced locally, reflecting the traits of the environments in which it grows, rather than of algae produced elsewhere upstream and carried down by the current.

As in the case of phytoplankton (see previous section), the species composition of periphyton (particularly diatoms) reveals the characteristic signature of the different water masses that feed the St. Lawrence, particularly during the summer (Vis et al. 1998a). For example, the filamentous cyanobacteria *Plectonema notatum* can be used as an indicator of exposure to urban effluents downstream from Montréal (Vis et al. 1998b). In tributaries of the St. Lawrence that are subject to agricultural loading, periphyton communities are the most diversified when concentrations of total phosphorus are below 20 µg/L (Chételat et al. 1999). Unlike species composition, the Shannon-Weaver diversity index is little affected by differences between water masses and cannot be used to discern the positive effects of the decrease in total phosphorus between 1982 and 1994–1995 (Vis et al. 1998a).

Biomass and productivity

The strong spatial heterogeneity of periphyton in a natural environment is a well-known fact, and is one of the characteristics that complicates the quantitative evaluation and monitoring of this group of primary producers. In the St. Lawrence, the accumulation of periphyton biomass is positively influenced by light intensity and nutrient levels, and negatively influenced by the speed of the current (Gosselain et al. 2004; Vis et al. 1998a, 1998b). Accordingly, in a given water mass, the biomass will be greatest in waters that are clear, rich in phosphorus and have slow-to-moderate currents.

The microalgae, bacteria and detritus that comprise periphyton are an important food source for benthic invertebrates, which also benefit from the physical protection provided by the emergent plants, submerged plants and filamentous algae colonized by this microscopic community. Accordingly, in Lake Saint-Pierre, the biomass of periphyton growing on the stalks of emergent plants (60 ± 22 µg of chlorophyll *a* per gram of dry weight of plant) was clearly less than that growing on submerged plants (151 ± 25) or on filamentous algae

(264 ± 81) (Tessier 2003). The differences in available food types (periphyton biomass) and structural complexity (type of plant acting as support) corresponded to an increase in the biomass of invertebrates on the emergent plants (4 ± 1 mg of invertebrates per gram of dry weight of plant), submerged plants (43 ± 10) and filamentous algae (73 ± 5) (Tessier 2003). While the same trend may have persisted at all sites, there was a significant variation in the biomass of periphyton (factor of 8) and of invertebrates (factor of 2.5) between sites (water mass). However, the distribution of size classes of periphyton and microbenthos on navigation buoys was not a sufficiently sensitive indicator to differentiate the water masses or to reflect water quality in the Montréal area (Mercier et al. 1999).

A positive relationship exists between photosynthetic parameters and periphyton biomass ($r^2 = 0.33–0.72$), with an additional effect of temperature and in situ light intensity ($r^2 = 0.56–0.84$). The correlation between nocturnal respiration rate and photosynthetic parameters ($r^2 = 0.30–0.76$) also suggests that the degree of bacterial activity depends on the intensity of diurnal photosynthesis by the algae, which corroborates the coupling of autotrophic and heterotrophic processes in the periphyton matrix (Vis et al. 2006a). The photosynthetic parameters (measured per unit of biomass) of the periphyton in the St. Lawrence span the same range of values as in other types of aquatic environments (lakes and streams) and substrates (natural and artificial) (Vis et al. 2006a).

Metaphyton

Biodiversity

Metaphyton has a special place among benthic flora, because it comprises microscopic algae (individual cell size > 1000 μm^3) that form sufficiently large quantities of filaments to be visible to the naked eye. This group mainly comprises Chlorophyceae (green algae) belonging to the genera *Cladophora, Spirogyra, Hydrodictyon, Rhizoclonium, Oedogonium, Ulothrix* and *Zygnema* (Tessier 2003; Paquet et al. 1998), which form almost single-species masses during episodes of proliferation (Vis et al. 2006b). At total phosphorus concentrations greater than 20 µg/L, a decrease is observed in the diversity of periphyton, which is often dominated (> 70% of the total biomass) by filamentous algae such as *Cladophora* (Chlorophyceae), *Auduinella* (Rhodophyceae) and/or *Melosira* (Bacillariophyceae) (Chételat et al. 1999). Since 1995, filamentous algae of the genus *Enteromorpha,* usually associated with briny or highly mineralized waters, have been observed in the St. Lawrence (de Lafontaine and Costan 2002) with episodes of proliferation (Vis, personal communication). These algae have a mucous envelope that prevents the colonization of periphytic microalgae, altering their nutritional quality for grazers. In 2004–2005, filamentous (*Lyngbya* sp.) and colonial (*Gleotrichia* sp.) cyanobacteria were observed to be dominant over a surface area of approximately 20 km^2 in the southern portion of Lake Saint-Pierre. These potentially toxic algae are indicators of eutrophication as a result of excessive inputs of nutrients from the Richelieu, Yamaska and Saint-François rivers. This discovery raises several questions about the effects of nutrient loading on the fluvial ecosystem—to date considered local and minor.

Abundance and productivity

Filamentous algae proliferate mainly in environments enriched by nutrients, where their accumulation can occasionally lead to spectacular and unattractive biomasses. The dynamics of these algae are strongly influenced by the combination of hot and sunny weather conditions, alternating with windy periods, as well as low water levels and slow currents, occurring in a characteristic sequence. Initially, the filaments grow attached to the river bottom or to submerged plants, mainly in sheltered areas and relatively shallow water (< 2 m). During hot and sunny periods, intense photosynthesis produces oxygen bubbles that become trapped in the mesh of submerged filaments and detach them from their substrate, causing them to float to the surface. These floating masses of filaments form thick mats that monopolize all incident light and obscure the underlying water column. Depending on the environmental conditions, these floating mats disappear over subsequent days and weeks because they break down on site or are dispersed by the wind, or because of an increase in the water level (rain). The elimination of this layer of algae floating on the surface allows light to once again penetrate the water column, triggering the next cycle of biomass growth.

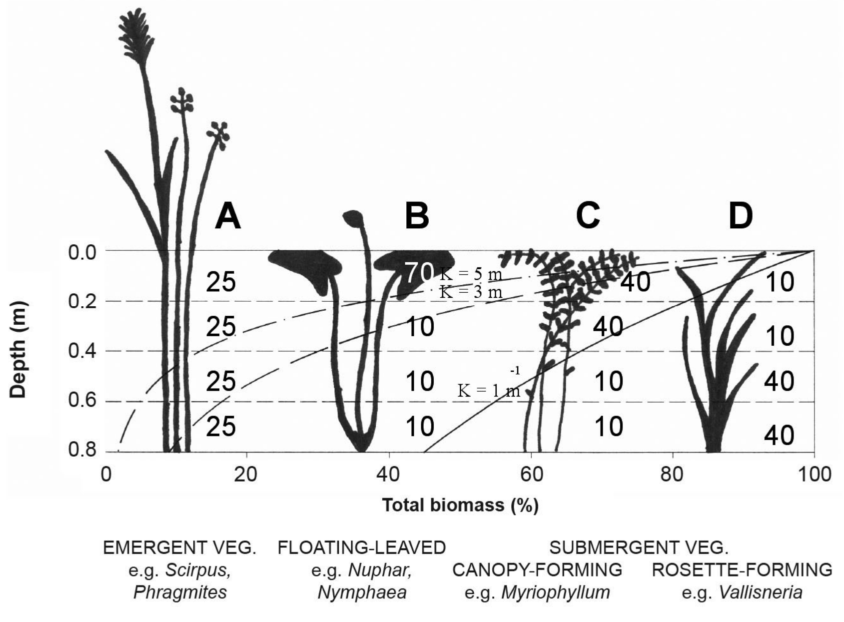
In Lake Saint-Pierre, the proliferation of filamentous algae appears to be particularly significant during summers with low water levels: large biomasses were observed in 1995, 1999 (Hudon, personal observation) and 2001, whereas they were virtually absent in 2000 (Vis 2004). Between 2000 and 2001, the biomass of filamentous algae increased from 0.04 to 1.26 g dry weight per square metre (Vis et al. 2006b). In 2001, the filamentous algae in Lake Saint-Pierre represented an average dry biomass of 74 g per square metre (min.-max., 1–201), i.e. 250 mg of chlorophyll *a* per square metre (min.-max., 16–1074), corresponding to production of approximately 1900 t C per year, or 6 g C per square metre per year (Vis 2004).

Submerged macrophytes

Biodiversity

The vascular plants commonly observed in the St. Lawrence include some twenty rooted submerged species (*Vallisneria americana*, *Potamogeton* spp., *Myriophyllum* spp., *Elodea* spp.) and some ten floating species, both rooted and not rooted (*Nymphæa* spp., *Nuphar* spp., *Lemna* spp., *Ceratophyllum demersum*) (Hudon et al. 2004). Moreover, certain algae belonging to the Characeae family (*Chara* spp. and *Nitella* spp.) are large enough to be evaluated with vascular plants. Apart from Characeae, which prefer the more mineralized waters originating from Lake Ontario, little specificity is seen in the composition of submerged plants in terms of the water masses present in the St. Lawrence.

The diversity in the growth forms of submerged plants adds to the heterogeneity of the community architecture and determines the three-dimensional structure of the habitats of aquatic fauna (Figure 5.2). The three types of growth forms of submerged plants differ from the architecture of emergent plants, whose biomass is evenly distributed with depth (Figure 5.2A). Certain submerged plants form linear rosettes of leaves that offer little resistance to the current and tolerate low light intensity (*Vallisneria americana*, submerged forms of *Butomus umbellatus* and *Alisma plantago-aquatica*); the bulk of the biomass of these plants is located near the river bottom (Figure 5.2D). Other taxa (*Myriophyllum* spp., *Elodea* spp., *Potamogeton* spp.) form a cover that rises above the plants mentioned above, thereby increasing the proportion of biomass near the surface and more effectively capturing the light (Figure 5.2C). Floating plants stretch this capacity a little further by extending their biomass up to the water's surface (Figure 5.2B). Because the latter two growth forms offer little resistance to the current, however, light is most effectively monopolized in sheltered conditions.



Source: Vis 2004.
Note*:* The light extinction coefficient (K per metre) resulting from shade cast by macrophyte biomass is also indicated.

Figure 5.2 Diagram showing the vertical distribution of green biomass (as a percentage of total biomass) for various types of submerged macrophytes in depth zones equivalent to 20 cm

Biomass and productivity

The dry biomass produced annually by submerged grass beds in the St. Lawrence, between Lake Saint-Louis and Lake Saint-Pierre, has been estimated at close to 108 000 t, 75% of which comes from Lake Saint-Pierre (Hudon 1997). The biomass produced is mainly influenced by exposure (fetch, exposure to waves and currents) and light intensity (turbidity, depth, light extinction coefficient), which affect the community architecture and the density of the plants, whose dry biomass ranges from 50 to > 500 g per square metre (Hudon et al. 2000b). The greatest biomasses (> 1 kg per square metre) have been observed on shoals located along the edges of the Seaway (at Boucherville and in the fluvial lakes), in waters originating from Lake Ontario; the greater clarity and moderate current of these waters have fostered the development of populations of *Myriophyllum* spp., *Stuckenia pectinata* or *Elodea* spp. dense enough to obscure a water column over 2 m deep.

In a fluvial environment, the development of submerged vascular plants associated with the river bottom (benthic) is determined by the combination of light, current and nutrient levels, which, in turn, are highly dependent on flow conditions (level and depth) (Hudon et al. 2004). Light intensity at the river bottom depends on the depth and clarity of the water and the plant biomass, which is a source of shade for existing plants. Several empirical models can be used to predict the distribution and the biomass of emergent and submerged plants based on physical variables, and their performance can be compared with methods that rely on remote sensing (emergent plants) and echo sounding (submerged plants) (Vis et al. 2000).

Various types of mathematical models (polynomial regressions, multiple regressions, binary hierarchical models) have been proposed to assess the biomass of grass beds in the St. Lawrence based on different combinations of physical factors (Vis 2004; Hudon 2003; Hudon et al. 2000a, 2000b; Hudon 1997). These models all converge on a small subset of physical variables, pointing to a decrease in biomass with exposure to wind and waves, and an increase with greater ambient light intensity.

Empirical studies using time series also indicate that hydrological conditions, specifically the level and flow conditions in the St. Lawrence, have an overriding influence on all environmental conditions that affect plant growth: average water level correlates positively with average depth and current speed, and negatively with turbidity, transparency and average water temperature (Hudon et al. 2003a). Accordingly, in low-level conditions, the productivity of submerged plants should be greater due to the decreased average depth, turbidity and current speed, and the increased water temperature and light intensity on the river bottom. Other factors, such as exposure, abrasion and/or freezing of roots, reduce the biomass of submerged plants over subsequent seasons (Hudon 2004a, 1997).

The transposition of these variables into a geographic information system reveals that the dry biomass of aquatic plants would increase from 56 g per square metre when average water-level conditions are high (over the long term) to 84 g per square metre under average low-level summer conditions (scenario 1) (factor of 1.50) in Lake Saint-Pierre (Vis 2004). These two scenarios correspond to total biomasses of 11 000–13 000 t produced annually (i.e. an increase of a factor of 1.15). Inclusion of the spatial distribution of the biomass of grass beds as a function of the decrease in the average water level in Lake Saint-Louis (Bibeault et al. 2004) and Lake Saint-Pierre (Vis 2004) also reveals that the total biomass of the grass beds varies with water level, according to a convex curve: the biomass is at its maximum at intermediate levels, and at its minimum when levels are very high (great depths) or very low (smaller wet surface area and change in distribution of water masses). When the water level drops, the increase in biomass per square metre is counterbalanced by the decrease in the wet surface area and the change in the distribution of water masses, resulting in a modest increase in total biomass (Vis 2004; Bibeault et al. 2004).

Submerged grass beds provide an important habitat for fauna, with dense grass beds sustaining a macrozooplankton biomass nine times greater (average of 180 µg/L) than sparse grass beds or open water (average of 20 µg/L) (Basu et al. 2000b). Depending on climatic and hydrological conditions, this littoral production either remains in place and is used locally in the fluvial lakes or is exported downstream (Basu et al. 2000b; Hudon et al. 1996).

Lateral-transverse axis: Riparian ecosystems and emergent macrophytes

The wetlands of the floodplain are located along the edge of the shore that forms the transition area between sectors that are constantly submerged (aquatic grass beds) and sectors that are constantly out of the water (upland areas), in a typical sequence of deep and shallow marshes, mudflats, wet meadows, shrub swamps and forested swamps. Seasonal variations in level (spring freshet) and shoreline relief (slope) and use (encroachment, human alteration) all influence the size of this area and its degree of connection to the main riverbed. The frequency, amplitude, seasonal cycle and duration of freshets determine the characteristics of the shoreline vegetation, which in turn determine the quality of habitats for aquatic and riparian fauna.

Biodiversity

The main plant communities that occur on the shores and floodplain of the St. Lawrence include over 300 species of herbaceous plants, some 40 species of shrubs and some 30 species of trees (Jean et al. 2002). The association of species in distinct assemblages, dominated by a small number of indicator species, reveals about 50 plant communities occupying the banks of the St. Lawrence, some 30 of which are located in the fluvial section between the aquatic grass beds and the wet meadows (Hudon et al. 2003; Jean et al. 2002). The presence of plant species found exclusively or only occasionally in wetlands provides a powerful diagnostic tool for defining the shoreline (Gratton et al. 1998) and the floodplain (Bouchard 2003). Following a progression from "permanently flooded" to "generally dry," the maximum species diversity is most often seen in water-saturated soils, just above the late-summer waterline (Hudon 2004a; Hudon et al. 2004).

At the landscape scale, the three-dimensional structure (height and coverage density of the herbaceous, shrub and tree zones), the presence of pools, and the heterogeneity of vegetation types on an intermediate scale (100 m) are important elements of structural (architectural) diversity that define the quality of habitats for bird life (Chapter 8) and mammals (Chapter 9). Depending on the size, mobility and spatial needs of each species of aquatic and marsh fauna, the elements of habitat structural diversity created by plants occur on different spatial scales.

Abundance and productivity

In 1990–1991, the wetlands of the St. Lawrence occupied a surface area of approximately 200 km^2, 76% of which was located around Lake Saint-Pierre (Jean et al. 2002, Table 5.3). Together, low marshes (44 km^2) and high marshes (109 km^2) (wet meadows) present 75% of the total surface area, with less significant representation by shrub swamps (14 km^2) and forested swamps (37 km^2); these latter habitats are particularly threatened by human activity, encroachment, deforestation and shoreline development.

Herbaceous plant communities demonstrate significant interannual plasticity, completely regenerating their green portions every year in response to environmental conditions. Water-level fluctuations in the current year and in the previous year exert major effects on plant communities (Hudon et al. 2005b): a drop in water level transforms a grass bed into a mudflat and a marsh into a wet meadow (Figure 5.3).

The presence of propagules (roots, rhizomes, seeds, turions, cuttings) dispersed over a very broad range of elevations in the littoral zone enables different species to express themselves or to remain dormant, depending on whether or not hydrological conditions (duration and depth of flooding) conducive to their germination occur in a given year (Hudon 1997). This plasticity is responsible for the variability in the landscape from year to year, resulting in the occurrence of different types of habitats on the same site, depending on hydrological conditions (Hudon et al. 2005b).

TABLE 5.3

Distribution and surface area of types of wetlands according to location, estimated on the basis of 1990–1991 mapping

	Surface area (ha)				
Location	**Low marsh**	**High marsh**	**Shrub swamp**	**Forested swamp**	**TOTAL**
Lake Saint-François	322.1	1 268.6	447.3	450.6	2 488.6
Lake Saint-Louis	117.0	488.0	61.0	184.0	850.0
Boucherville	8.1	343.2	38.5	17.1	406.9
Contrecœur	259.7	801.2	12.3	52.8	1 126.0
Lake Saint-Pierre	3 700.1	7 962.4	865.0	2 962.8	15 490.3
TOTAL	4 407.0	10 863.4	1 424.1	3 667.3	20 361.8

Source: Based on Jean et al. 2002.

Relative importance of the primary producers of the St. Lawrence, as a function of water-level variations

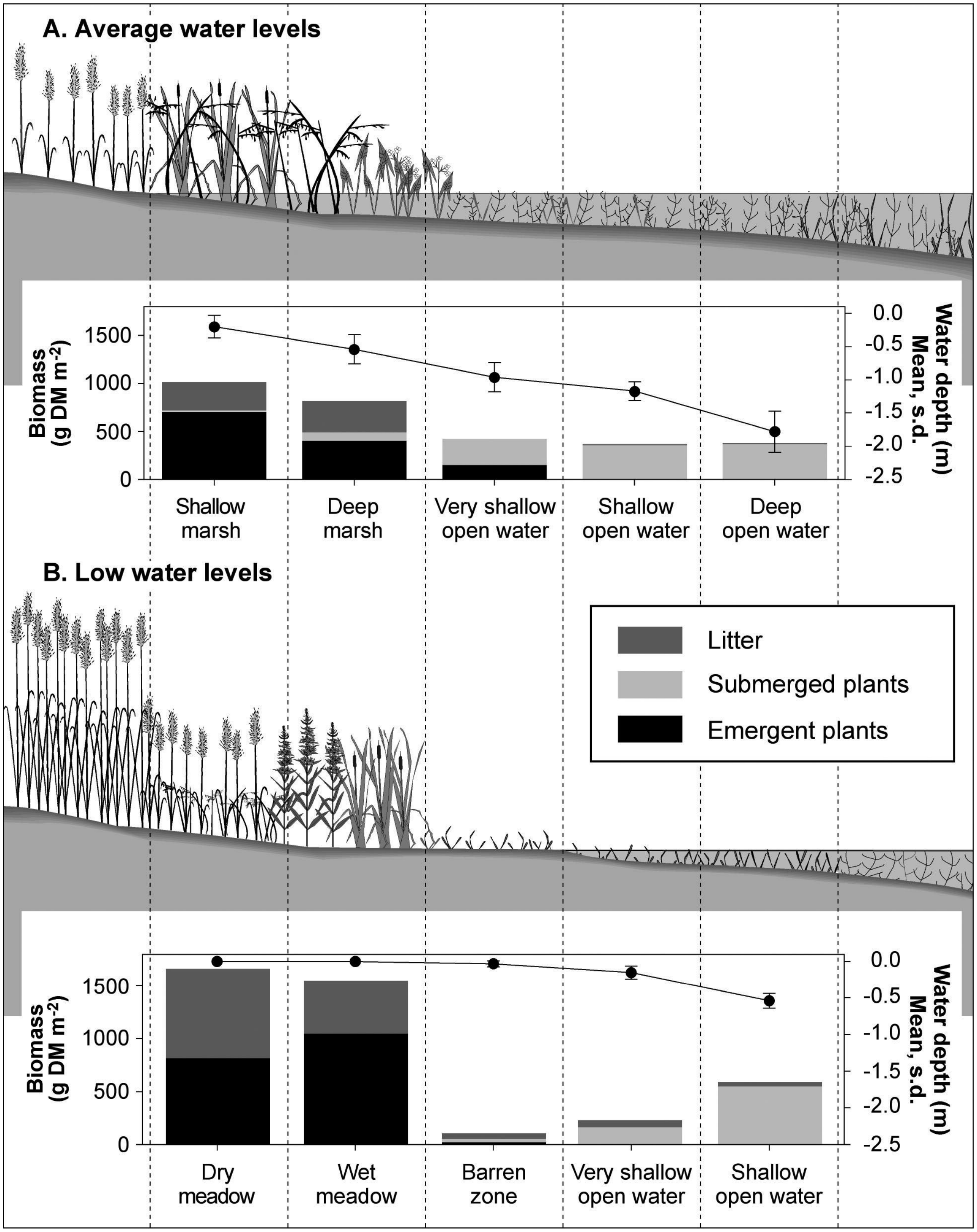
The primary production of macrophytes, epiphyton and phytoplankton was evaluated in Lake Saint-Pierre in 2000 and 2001. These two years correspond respectively to average level conditions (long-term) and low level conditions (drop of 0.6 m). Even though wetlands covered only about 15% of the total surface area, emergent macrophytes in this habitat accounted for approximately half of the total biomass, while algae represented less than 20% of the production. In the open water in the middle of the lake, the production of phytoplanktonic and periphytic algae was significant, with a lower contribution by submerged macrophytes (24–30%). In the lake as a whole, the annual average production in 2000 and 2001 respectively varied from 78–94 g C per square metre per year, including 32–35 g C per square metre per year for macrophytes, 16–18 g C per square metre per year for periphyton, and 28–43 g C per square metre per year for phytoplankton. The productivity of emergent macrophytes was influenced by water level, whereas exposure to wind and waves had more influence on the productivity of submerged plants. The productivity of epiphytic algae was mainly determined by the availability of macrophytes to which they could attach themselves, whereas the productivity of phytoplankton was determined by inflows from tributaries. A drop of 0.6 m in the mean annual level between 2000 and 2001 generated a 50% decrease in the surface area of marshes, a 60% increase in the production of phytoplankton in open water, and a 20% increase in total carbon production (approximately 5000 t) in Lake Saint-Pierre. However, between years, the relative size of the compartments changed less than 10%. This exercise demonstrates the complexity of the interactions in the physical environment and of the productivity of the various types of aquatic plants.

Source: Vis 2004.

Elevation relative to average July level, depth and duration of flooding as well as water-level variability are the main hydrological factors that affect populations of herbaceous plants (high and low marshes). The dry biomass from the aerial portion of a herbaceous community ranges from < 100 g per square metre (bare mudflat) to 200–700 g per square metre (low marsh) and 1000–2000 g per square metre (high marsh), depending on the position of the community on the littoral slope, its species composition and its density (Hudon 2004a, 2002; Hudon and Lalonde 1998; Hudon 1997). A decrease in level leads to an increase in the average biomass of marshes and shallow grass beds, but a decrease in the biomass of dewatered grass beds (Hudon 2004a). There is a close link between plant biomass, density of stems and percentage of coverage, which can be used to determine the value of the main plant communities as spawning grounds for pike (see Chapter 7).

In comparison, marsh communities, comprised of woody plants (trees and shrubs), respond more slowly to hydrological variations, with the delayed appearance (growth) or disappearance (decay) of shrubs (years) and trees (decades). For example, the decline of the forested swamps on the Îles de la Paix (Lake Saint-Louis) occurred after several consecutive years of flooding (period of high levels from 1972-1976), but was only noticeable several years later (Jean et al. 1992).

Swamps are particularly vulnerable to anthropogenic disturbances (backfilling, fire, cutting) because they are located at the upper limit of the wetlands gradient, near land. Moreover, swamps are subject to complex biological interactions (competition within and between species) (Jean and Bouchard 1991). As a result, on the Îles de la Paix, the swamps present in the 1970s were replaced in the 1990s by a wet meadow dominated by the invasive grass *Phalaris arundinacea*, which appears to be interfering with the recolonization of shrubs and trees in the area (Jean, personal communication).



Source: Hudon 2004a.

Note*:* The total biomass for each zone includes the green biomass of emergent plants (black), the submerged plants (light grey) and the dead litter (dark grey).

Figure 5.3 Diagram showing the zonation of littoral vegetation types and their biomass in conditions characterized by (a) mean levels and (b) an average 0.5-m drop in levels

Temporal trends

Temporal surface area variations in high and low marshes correspond closely to interannual variations in water levels because of the rapid response time (one to two years) resulting from annual regeneration of the aerial portions of these communities. An examination of aerial photographs and Landsat images (Lalonde and Létourneau 1996) taken over recent decades reveals an inverse relationship between the surface area of Baie du Febvre (Lake Saint-Pierre), occupied by marshes, and the average annual level during the growing season (Hudon 1997): the high and low marshes occupied almost 40% of the bay during low-level periods (1965), but less than 5% of the surface area during high-level years (1976). This relationship was confirmed for all of Lake Saint-Pierre by field data collected between 1999 and 2002 (Hudon et al. 2004) and by a predictive model of the distribution of high and low-marsh herbaceous communities (Hudon et al. 2005b). The hydrological conditions in the last 10 years favoured the growth of dense stands of emergents made up of robust and aggressive species, suggesting the gradual loss and drainage of the marshes. This same change has been noted in marshes near Boucherville (Hudon 2004a).

Swamp communities located at the upper limit of the floodplain are particularly vulnerable to human interventions (Jean and Bouchard 1991; Bouchard 2003). In the Greater Montréal area, close to 80% of the wetlands present 400 years ago have been lost because of human activity (Kessel-Taylor 1984). Moreover, a study of the surface areas of swamps around Lake Saint-Pierre (Sorel–Trois-Rivières) between 1931 and 1997 reveals localized drainage of the wetlands and their transformation into drier environments (Jean et al. 2002). For example, marshes have become swamps, and forested swamps have been colonized by species that tolerate drier conditions—two phenomena explained by the decreased amplitude and duration of freshets in Lake Saint-Pierre in recent decades.

Threats and Issues

Global biodiversity

Several processes modulate the biodiversity of the freshwater plant communities of the St. Lawrence, which are environments that are constantly changing. These processes include selection for stress-resistant species, introduction of non-native species, modification of natural distribution areas and invasion of the land by aggressive species (exotic or non-exotic).

Overall diversity is affected by natural changes in the distribution areas of species in neighbouring regions—changes that reflect the normal ecological process of the introduction (and disappearance) of species over several decades. Climate and its variations play a key role in the distribution of plant species. Species that grow in neighbouring basins, where the climate is more temperate than our own, specifically the Mississippi and Hudson basins, will therefore be more likely to colonize the banks of the St. Lawrence.

In more general terms, diversity is affected by ecosystem disturbances, such as the presence of ice, nutrient inputs and flooding. According to the intermediate disturbance hypothesis, the diversity of an ecosystem increases when it is periodically subjected to moderate disturbances. However, diversity is reduced if the disturbances are too intense, too frequent or unpredictable, in which case they lead to the elimination of sensitive species and benefit only resistant species. For example, forested swamps are commonly dominated by certain species of trees (silver maple, red ash) that tolerate flooding better than other, more upland species (sugar maple), but that will in turn be eliminated if the duration of flooding is too long. Several graminoids that are more resistant to dry conditions, such as reed canary grass and the common reed, have proliferated in the wet meadows of the St. Lawrence since the decrease in the amplitude of the spring freshets (Hudon et al. 2005a; Lavoie et al. 2003). The increased presence of certain submerged plant species, such as *Stuckenia pectinata* and *Potamogeton crispus* (which tolerate eutrophic conditions), to the detriment of other indigenous species, is another example of this type of selection.

Excavation of the riverbed and basin tributaries

Since European colonization and during the 20th century in particular, the riverbed has been changed considerably, to allow the passage of increasingly larger ships in the ship channel. Between 1854 and 2001, the depth of the ship channel in Lake Saint-Pierre more than doubled (4.9 to 11.3 m), and its width tripled (75 to 245 m), increasing by 750% the section of the river in which flow is concentrated. Historical changes are particularly significant in Lake Saint-Pierre, where cumulative changes over 150 years appear to have considerably altered water circulation, particularly along the shorelines (Morin and Côté 2003). With the advent of climate change, an increased frequency of low-level episodes could intensify the pressure to dredge the ship channel in order to preserve the depth needed for shipping, thus further reducing the amplitude of freshets and the circulation of water along the shorelines.

The agricultural practice of realigning streams in the basins of several river tributaries also accentuates erosion and accelerates land drainage during periods of intense rainfall. The modification of the drainage network increases the amplitude, but reduces the duration of freshets at the time of the snowmelt or during episodes of intense rainfall, thereby modifying the surface area and the duration of shoreline flooding. The biological consequences of a shorter spring freshet include the decreased survival of fish eggs and larvae (see Chapter 7). In addition, a rapid rise in levels following an episode of intense rain risks drowning the nests of ground-nesting birds and leads to the loss of clutches, even if the duration of the rise is brief (see Chapter 8).

Regulation and dams

The outflow from Lake Ontario has been regulated since 1960 by Plan 1958D (with deviations), whose effect is to decrease the amplitude of freshets (to minimize flooding for shoreline residents) and increase the water level in the St. Lawrence during the minimum-flow period (to protect commercial shipping and the production of hydroelectricity) (Carpentier 2003). The International Joint Commission (IJC) recently completed a study aimed at revising the regulation plan to add the environment and recreational boating to the interests that have historically been considered (IJC 2005). Environmental studies show that for the St. Lawrence, as for other large rivers (Rosenberg et al. 1997; Prowse and Conly 1996; Dynesius and Nillson 1994), the health of wetlands and wildlife habitats requires the maintenance of a hydrological cycle whose seasonal and interannual variations (amplitude, duration, seasonality, frequency, change rate and interannual sequence) resemble natural conditions as closely as possible. However, should the chronic reduction in levels anticipated under climate change scenarios materialize, the increased pressure to store water in Lake Ontario in order to maintain flows during low-water periods would further stabilize water levels by reducing the range between the spring flood and summer low levels. Moreover, low-level periods are conducive to encroachment on the floodplain and riverbanks, which leads shoreline residents to call for greater control over freshets in order to prevent flooding once the water levels return to normal.

Climate change

There are numerous indications that the climate of the Great Lakes–St. Lawrence Basin is changing: winters are becoming shorter, the average annual temperature is rising, the duration of ice coverage is decreasing and episodes of intense rainfall are becoming more frequent (Kling et al. 2003). The climate is a key issue in the future of the St. Lawrence, since it determines the volume of water present in the Great Lakes–St. Lawrence Basin, where the average annual level is expected to drop by approximately 1.25 m at Montréal by 2030 (Mortsch et al. 2000). The increase in the average water temperature (Hudon et al. 2003b), the shorter winters and the changes in the amplitude, frequency and seasonality of freshets, low-water periods and extreme events will affect all the physical, chemical and biological processes that define the fluvial ecosystems (Bibeault et al. 2004). Moreover, human adaptation to climate change exerts numerous additional indirect effects, all of which have significant cumulative impacts on aquatic ecosystems (Schindler 2001), including the St. Lawrence (Hudon 2004b).

Cumulative impacts

All the human activities that have taken place since Europeans colonized the banks of the St. Lawrence have led to significant changes in the ecosystem.

An initial—physical—cumulative impact includes activities such as human alteration, shoreline encroachment and erosion, and dredging. All of these activities add up over the years and can be quantified by a comparison with historical conditions prior to colonization.

A second—biological—cumulative impact includes the continuing evolution of the species composition and productivity of aquatic ecosystems over time, in response to natural environmental conditions and/or human activity.

Finally, a third type of cumulative impact is the combination of physical and biological effects, with feedback effects between the various components. For example, the many structural changes to the riverbed and the shores of the river (channeling, weirs, dredged material disposal) concentrate the current in the main channel. Operations to regulate the water level and control the ice have reduced the amplitude and the duration of freshets. In conjunction with nutrient inputs along the shoreline, the slower current promotes the proliferation of submerged aquatic plants, which further hinder the current and promote increased sedimentation of particulate matter. All of these changes combined decrease the river's hydraulic power and reduce its ability to transport particles downstream. Over the long term, a feedback effect sets in among these elements, accentuating the hydrological isolation of littoral zones, which are less frequently flooded, more stagnant, more easily overrun by dense plants, and finally, less and less wet. For example, low water levels in 1995 enabled dense colonies of willows and water reeds to colonize the riverbed at the mouth of the Yamaska–Saint-François delta (southwest of Lake Saint-Pierre), on an emergent strip of land that extended the shoreline toward the middle of the lake by almost 2 km (C. Hudon, personal observation). We can reasonably anticipate that this change in configuration, by all appearances minor, will have significant effects on the future dynamics of sectors located directly downstream, which have become more stagnant because of the presence of this newly consolidated zone that is progressively drying up because of the vegetation that has appeared.

Ecosystem Outlook and Trends

Need for knowledge

Quality of riparian habitats for aquatic fauna

There is little quantitative information on the combination of critical factors that lead to the nocturnal hypoxia of the river habitats of the St. Lawrence—a harmful consequence of their excessive productivity. The conditions conducive to such problems are especially likely to occur when submerged plants and algae proliferate in littoral zones, when water levels are low and water temperatures high—all conditions associated with climate change. The size of habitats conducive to aquatic fauna could thus be severely reduced, leading to decreased growth and even mass mortalities of fish on occasion. A decrease in oxygen concentrations resulting from a rapid drop in the water level during a heat wave has been cited to explain the mass mortality of carp during their spawning period in the shallow grass beds of the St. Lawrence during the spring of 2001.

The harmful effects of the proliferation of certain emergent plant species (reed canary grass, common reed, purple loosestrife), submerged species (Eurasian water-milfoil, sago pondweed) and macroscopic algae (filamentous chlorophyceae and cyanobacteria) on the diversity of communities and the quality of bird and fish habitats are often cited in the literature, but remain poorly quantified. The proliferation of several of these species results from the overabundance of nutrients, which increases the ecosystem's vulnerability to invasion by new species such as the water chestnut (*Trapa natans*). A strict evaluation of the temporal dynamics of some of these assemblages would help determine their true impact on shoreline and aquatic ecosystems, and therefore to better tailor the measures designed to deal with the threat they pose.

The food web and carbon flow

The primary production of the St. Lawrence represents the basis of the food chain that supports the microfauna and aquatic vertebrates. However, very little is known about the aquatic fauna (benthos, microfauna, forage-fish) that consume the primary production in the St. Lawrence. The quantity and quality of the carbon produced locally and transported from the drainage basin are therefore key elements in the productivity of the higher levels of the food web (bottom-up effect). Selection will operate in favour of the different consumers likely to use the different sources of available carbon, depending on whether they are planktonic or benthic in origin, labile (low C:N ratio) or refractory, produced on-site or transported from upstream, detrital or anthropogenic in origin. Accordingly, carbon from human waste discharged into the Montréal Urban Community's municipal effluent supplies an extremely productive food web (identifiable by its $\delta^{15}N$ signature) that is separate from the food web supplied by local carbon sources (de Bruyn et al. 2003).

Effects of climate, specifically winter conditions

Climate is a factor that has a major influence on hydrology, and physical factors (temperature, sunshine) influence plant productivity. Given the major changes expected for the St. Lawrence by 2030, and the complexity of interactions documented to date, it appears crucial to continue tracking future ecosystem changes in order to assess the impacts. More specifically, winter floods have long been identified as events crucial to preserving the structure of wetlands (Prowse and Conly 1996), ensuring spatial heterogeneity by tearing up the plant cover, thereby enabling the formation of ponds and holes, and promoting the widespread dispersion and genetic mixing of populations of aquatic plants (Dansereau 1945). In the St. Lawrence, ice jams have been partially controlled since the early 20th century and virtually eliminated since 1960, which explains the decrease in maximum levels at Montréal and downstream. Climate change should increase the frequency of winter mild spells and episodes of rain-on-snow, two types of events that increase the risk of a winter flood, following the production of frazil ice, strong flow conditions and severe ice jams. Under such conditions, the wetlands of the St. Lawrence and their use (e.g. wildlife management activities) could change significantly from what they are today. However, there is very little quantitative information on the significance of winter processes, particularly given the major changes that have occurred in the past (control of ice and ice jams) and those to come (climate change).

Ecosystem links with Lake Ontario and the lower estuary

The fluvial section of the St. Lawrence is an important link in the large aquatic ecosystem connecting Lake Ontario to the Gulf of St. Lawrence. To date, studies have mainly focused on the transport of contaminants between Lake Ontario and the St. Lawrence River (Rondeau et al. 2005). Little is known about the ecosystem links between Lake Ontario, the river corridor and the Gulf of St. Lawrence. Recent studies (de Lafontaine and Costan 2002) suggest that Lake Ontario is a major source of non-native species for the St. Lawrence and that the probability of their transfer downstream is increasing over time. Moreover, several studies already indicate a relationship between freshwater flow in the river and the productivity of communities in the St. Lawrence Estuary and gulf (Therriault 1991). The importance of the species composition and the nutritive quality of fluvial plankton to food web conservation in the lower estuary has been demonstrated (Vincent and Dodson 1999). Accordingly, in the brackish transition zone of the lower estuary of the St. Lawrence (turbidity zone), exports of carbon from St. Lawrence phytoplankton have been estimated at 20-30% of the carbon flux produced locally by algae and bacteria in the period from May to July (Vincent et al. 1996). More recently, the harmful effect of nutrient and carbon inputs has been cited to explain part of the decrease in dissolved oxygen levels in the Laurentian Channel (Gilbert et al. 2005). These studies suggest the importance of these links, although much work is still required to assess the interdependence of the geographic regions between upstream and downstream areas, particularly in the context of climate change.

Conclusion

In summary, the St. Lawrence River continuum includes several physical and morphological characteristics that help explain its specific functioning and the wealth of primary producers that characterize this large river. Unlike other rivers that are similar in size, but much more turbid, the St. Lawrence is characterized by diverse and productive plant communities that sustain its metabolism. There are also complex physical and biological processes that act on the different communities, in the upstream-downstream axis (effect of the current in the pelagic zone), in the transverse axis (effect of flow and freshets on the floodplain) and in the littoral transition zone.

Lake Ontario acts both as an enormous basin for the sedimentation of inert particles and as a source of dissolved substances and planktonic organisms. The fluvial lakes reduce water transit time at the local level and allow production and internal recycling of organic matter, particularly in summer, thereby fostering the growth of submerged and emergent plants. The tributaries bring in mineral and organic particles and nutrients in a proportion far exceeding their flow, which makes a significant contribution to the feeding of plants and algae in the littoral zones, thereby modifying the quality of wildlife habitats. Finally, human activities modulate the flow regime and the physical framework (riverbed, shorelines) of these phenomena, causing significant changes that accumulate over time, reducing the area of the wetlands and the floodplain.

Far from being a simple conduit for emptying the waters of Lake Ontario into the ocean, the St. Lawrence is the point of convergence of all the waters that flow within its basin, where major processes produce and recycle the materials required to sustain vast, rich ecosystems. These characteristics make the St. Lawrence unique, a fact that is particularly obvious in the productivity of the different types of plants and the diversity of the wildlife habitats that it supports.

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Chapter 6

IMPACTS OF WATER-LEVEL FLUCTUATIONS ON REPTILES AND AMPHIBIANS

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Introduction

The herpetofauna of a region consists of two classes of cold-blooded vertebrates: amphibians and reptiles. Although amphibians were the first vertebrates to colonize land, they are still tied to aquatic environments. Most amphibian species still require aquatic habitats or wetlands for breeding, since their early life cycle stages (i.e. eggs and gilled larvae) occur in water. Once metamorphosis is complete, a number of species of amphibians remain near aquatic ecosystems (rivers, lakes, marshes), which provide food resources and protection against predators. For their part, reptiles do not require aquatic habitats for breeding, but remain closely associated with aquatic and semi-aquatic ecosystems for food and shelter.

At our more northern latitudes, amphibians and reptiles hibernate during the winter, either under water or in the soil below the frost line. Several species of Ranidae and Hylidae (Anura) have adapted to the winter conditions by producing cryoprotectants, which prevent biological tissue damage due to ice formation (Desroches and Rodrigue 2004; Pough et al. 2000).

Twenty-one amphibian species, of the orders Caudata (Urodela) (salamanders, newts and nectures) and Anura (frogs, tree frogs and toads), and 17 reptile species, of the orders Squamata (snakes) and Testudines (turtles), occur in the St. Lawrence Valley. Although these figures may seem low, considering that there are 4900 known amphibian species and 8950 known reptile species in the world (Pough et al. 2000), Quebec has the highest herpetological diversity in eastern Canada (Desroches and Rodrigue 2004). Several species of amphibians and reptiles are considered species at risk and are therefore protected under the *Species at Risk Act* (2002, c. 29) and the Quebec *Act respecting threatened or vulnerable species* (R.S.Q., c. E-12.01). They include ten species of reptiles and six species of amphibians that occur in Quebec (see Chapter 10 on species at risk).

Water-level fluctuations have many impacts that vary depending on the life cycle stage: breeding, hibernation or foraging. Their effects can be positive or negative. In this chapter, we will discuss the impact of water-level fluctuations on reptiles and amphibians. We will summarize the information on species of the orders Anura and Testudines as a function of St. Lawrence water-level fluctuations and climate change. Other stressors to reptile and amphibian species will be briefly discussed, namely habitat destruction and fragmentation, chemical pollution and infectious disease, introduced species and, finally, disturbance, illegal harvesting and deliberate destruction.

Possible Impacts of Water-level Fluctuations

Direct impacts

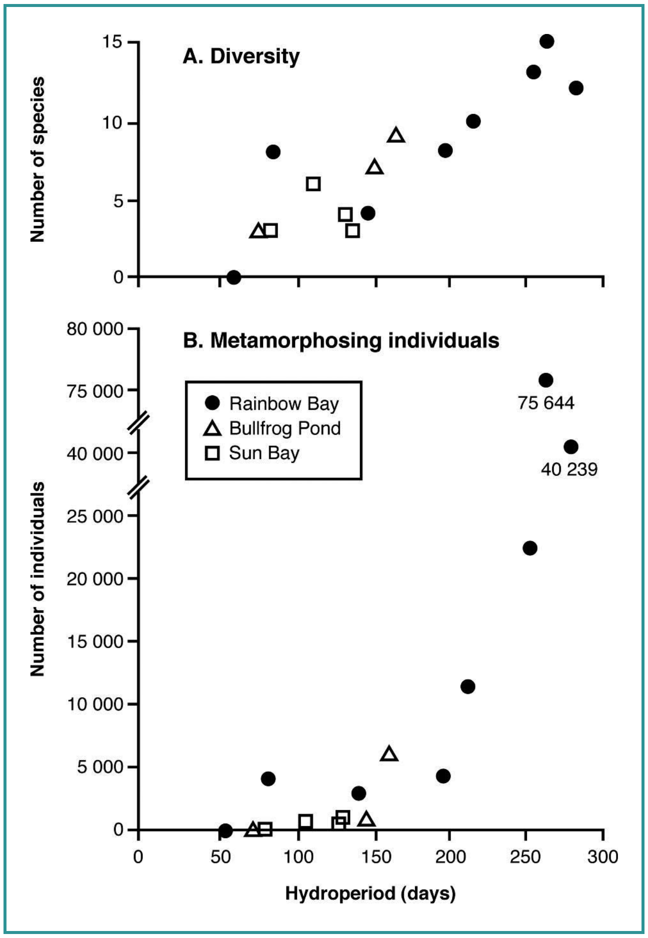
Anurans (frogs and toads)

The life cycle of most anurans consists of three distinct stages: egg, larva and adult. Egg masses are generally laid in aquatic habitats. The larvae emerge shortly after laying and metamorphose to the adult form in several weeks.[1] Laying in ponds and marshes is characteristic of the families Ranidae, Bufonidae and Hylidae, to which the species that occur in Quebec belong. After a period of incubation, which varies depending on the species and climate conditions, the larva or tadpole begins its growth leading to metamorphosis. The length of the larval stage depends, of course, on the species, but also on environmental conditions, such as temperature and availability of food resources (Pough et al. 2000).

In species that occur in Quebec, the larval stage can last from one month, in *Pseudacris triseriata*, to 36 months, in *Rana catesbeiana* (Desroches and Rodrigue 2004). During metamorphosis, anurans undergo dramatic morphological and physiological changes (formation of anterior and posterior limbs, modification of the digestive tract, development of lungs), as well as significant changes in preferred habitat, from an aquatic environment to a terrestrial forest or marsh environment. There are exceptions, however, such as *Rana clamitans melanota* and *R. catesbeiana*, which remain tied to aquatic environments (Desroches and Rodrigue 2004; Pough et al. 2000).

In anurans, reproduction and larval growth are therefore the life cycle stages that are particularly sensitive to hydrological and climatic factors that influence the continued availability of their habitats (Smith 1983). Herpetologists classify ponds and wetlands according to hydroperiod (i.e. the number of days a site contains water in a year) (Pechmann et al. 1989). In general, wetlands fall into one of the following classes: ephemeral, temporary, semi-permanent or permanent. Species richness and composition of larval amphibian assemblages, in both anurans and salamanders, reflect the requirements of each species relative to the hydroperiod (Hecnar 2004).

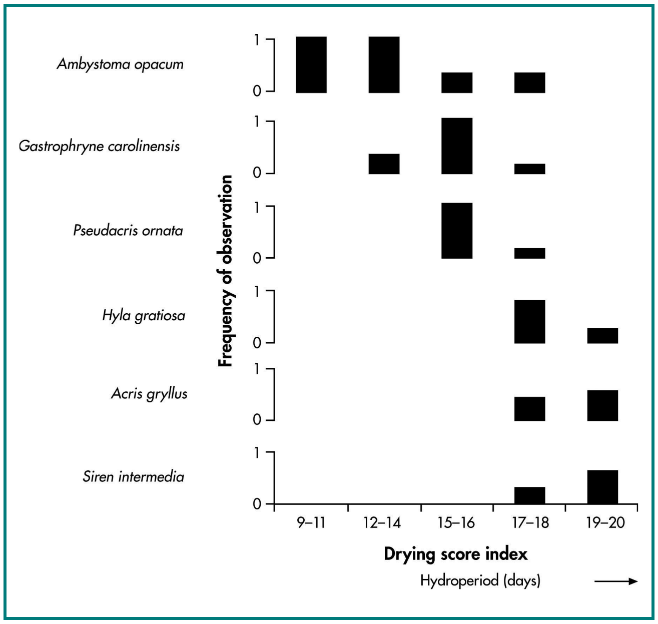
Both species diversity and abundance of amphibian larvae increase as a function of hydroperiod duration (Figure 6.1; Snodgrass et al. 2000).



Legend: A: number of species; B: total number of metamorphosing individuals.
Note: Each point represents one year of sampling.
Source: Based on Pechmann et al. 1989.

Figure 6.1 Relationship between anuran diversity and abundance and wetland hydroperiod

The renewal of amphibian species (i.e. the appearance and disappearance of certain species in the assemblage) affects both short-hydroperiod species and long-hydroperiod species. For example, *Ambystoma opacum*, a short-hydroperiod species, is disadvantaged when the drying score index increases. In contrast, *Siren intermedia*, a long-hydroperiod species, appears in the amphibian assemblage only when the drying score index is higher than 17 (Figure 6.2). Amphibian sensitivity to hydroperiod length is extremely high. In a study comparing two hydroperiods that differed by only 10 days, significant differences could be observed in the size of metamorphs and in the species diversity of an assemblage of salamanders (Phillips et al. 2002). However, it cannot be concluded that a long hydroperiod is necessarily favourable to anuran species diversity and abundance. This is because there are many predators associated with semi-permanent or permanent ponds, such as certain species of insects of the genus *Anax*, salamanders of the genus *Ambystoma*, and fish, such as *Lepomis gibbosus* or *Salvelinus fontinalis* that are known to exert sufficient predatory pressure to eliminate all species of amphibians from a pond.



Source: Based on Snodgrass et al. 2000.

Figure 6.2 Example of the renewal of amphibian species as a function of wetland hydroperiod

In the case of *P. triseriata* on Isle Royale, it has been observed that breeding does not occur in pools in which the hydroperiod allows for the presence of predators.

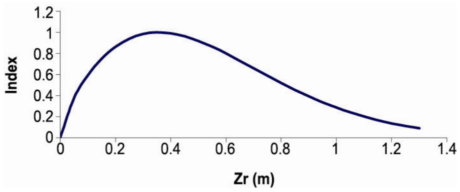
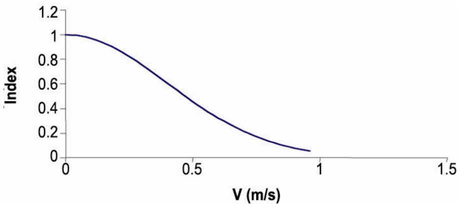
Smith (1983) concluded that populations of *P. triseriata* and other anurans were regulated by two factors: (a) the presence or absence of predators associated with the size of the pools; and (b) intraspecies competition, which plays an important role in larval growth and survival.

However, the importance of predation and intraspecies competition varies depending on the characteristics of the species in question. Intraspecies competition is a determining factor in the recruitment of species with short larval periods, because they have high energy requirements. Inversely, predation plays a critical role in species with long larval periods (Skelly 1999).

For anuran species that breed in rivers as opposed to lentic environments, hydrological conditions are just as important. For example, there is a direct relationship between discharge and current velocity and breeding success in *Rana boylii*, a species at risk in the western United States. This species produces sticky eggs, which are deposited in cracks and crevices in the shoreline near the surface. During low water-level conditions, there is a risk that the eggs will become exposed and subject to desiccation. Inversely, in high flow conditions, which are often associated with strong currents, the eggs may be scoured from the substrate and carried downstream (Kupferberg 1996). Due to the vulnerability of the eggs to hydrological conditions, *R. boylii* prefers wide, shallow channels—where changes in hydrological conditions are less abrupt—over deep, narrow channels where hydrological conditions are more variable.

In order to assess the impact of different St. Lawrence regulation scenarios, an anuran breeding habitat model was developed by Armellin and Plante (2004) and Morin et al. (2004). On the basis of a literature review, three breeding habitat characteristics were identified as critical to anuran breeding success: vegetation type, water level and current velocity (Table 6.1).

TABLE 6.1
Habitat suitability index of anurans in the St. Lawrence River

Attributes of turtle and frog breeding habitat	Benchmarks or descriptions of requirements	Variation of the index	
Depth (Zr), m Spring (frog reproduction) April to June	0.2 m ≤ Zr ≤ 1 m		
Plant diversity (Dv)	% vegetation cover Marsh dominated by emergent vegetation	Wet meadow Shallow marsh Deep marsh Grass bed Open water	HSI = 0.8 HSI = 1.0 HSI = 0.6 HSI = 0.2 HSI = 0.0
Current velocity (V), m/s	Low velocities, 0 > V > 1		

Source: Armellin and Plante 2004.

Anuran species are known to use vegetation associated with marshes and swamps, but they use emergent or submerged aquatic vegetation to a minor extent or not at all. The average water depth associated with breeding sites is 50 cm, whereas deep water sites, although rarely exposed, have the disadvantage of providing habitat for voracious predators of anuran eggs and larvae, such as fish and certain insects. Finally, breeding occurs at sites where the current is slow to non-existent. The potential of an environment to serve as anuran breeding habitat can be described by the following equation:

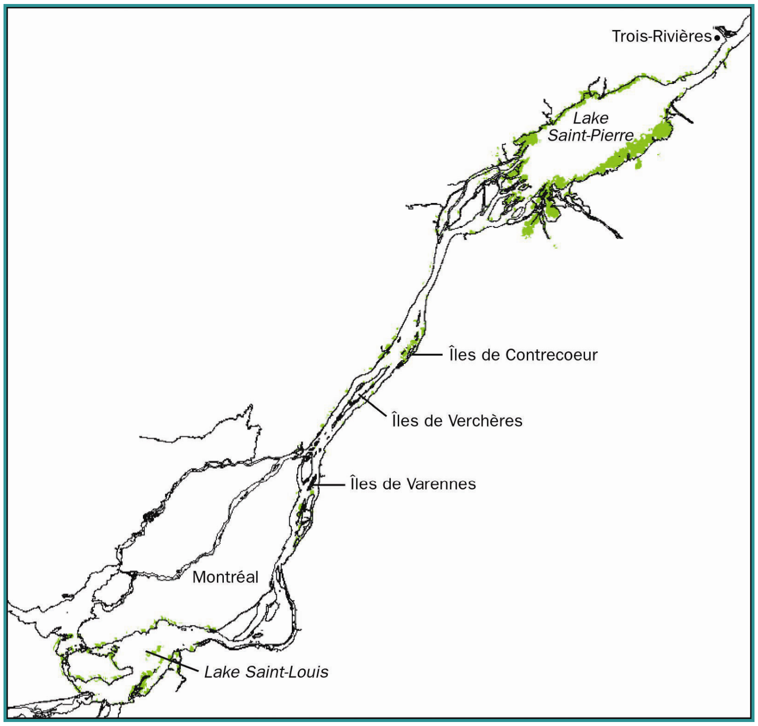
Potential breeding habitat = $(Zr * Dv * V)^{1/3}$

Under average spring flow conditions, most anuran breeding habitat between Lake Saint-Louis and Trois-Rivières is associated with the wetlands of Lake Saint-Louis and Lake Saint-Pierre. The fluvial section of the St. Lawrence between the Lachine and Sorel rapids has little potential as anuran breeding habitat due to the small area occupied by wetlands, which is largely the result of the high degree of shoreline alteration. However, the Boucherville, Varennes and Contrecœur islands still offer suitable sites for anuran breeding (Figure 6.3).

Habitat Suitability Indices (HSI)

Habitat suitability indices (HSI) are mathematical models that predict the potential of an environment to serve as habitat for a given species. The evaluation is based on the various physical, chemical and biological characteristics of an environment and on the response of the species or of a particular life stage (e.g. egg or juvenile) to one or more of the characteristics. The relationships between environmental characteristics and species responses are determined on the basis of data or expert opinion. HSIs are expressed as a ranking of between 0 and 1. A ranking of 0 indicates a habitat with no potential, and a ranking of 1 indicates a habitat with high potential.

It is important to bear in mind that the HSI is an indicator of potential only and does not necessarily reflect the density of organisms. It represents an environment's value as habitat for a given species. The HSI is very useful for comparing the impacts of different water-level regulation scenarios on habitat availability.



Note: Areas in green indicate anuran breeding habitats.
Source: Morin et al. 2004.

Figure 6.3 Modelling of potential anuran breeding habitats in the Montréal–Trois-Rivières section of the river with a discharge of 9500 m^3/s

In the evaluation of the St. Lawrence River regulation scenarios, habitat availability was considered essential to the maintenance and health of anuran populations (the fewer the habitats, the less favourable water-level regulation scenarios are to anuran conservation). The egg-laying period, which, for most species, extends from April to mid-June, and the larval development period, which extends from mid-June to the end of August, are both critical.

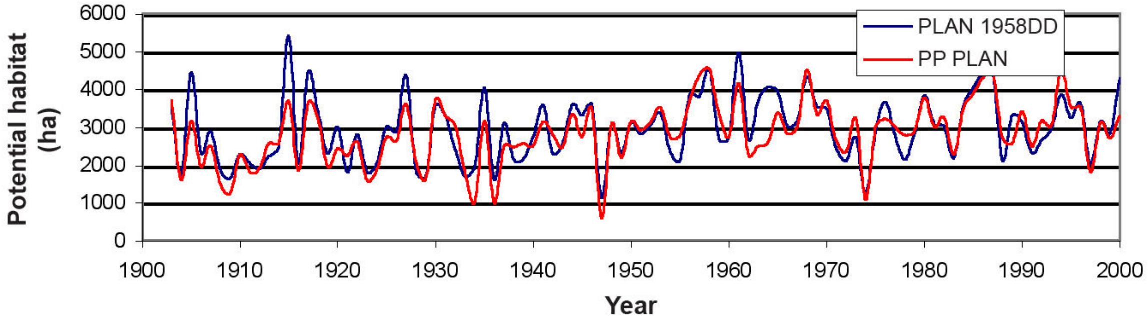
During these periods, desiccation of eggs and larvae may occur as a result of a sudden drop in water levels. Aquatic anuran species, such as bullfrogs and green frogs, are more sensitive to water-level fluctuations, particularly since, at our latitudes, their larval stage lasts two to three years. In general, there is little difference between the two St. Lawrence River regulation plans (Figure 6.4).

Turtles

Although aquatic turtles of the St. Lawrence do not breed in water, water-level fluctuations can have definite impacts on these reptiles. Aquatic turtles breed in riparian terrestrial habitats. The females lay their eggs in loose sand or clay soil devoid of vegetation near bodies of water. Some species, such as *Graptemys geographica* (Bonin 1998) and *Chelydra serpentina* (Loncke and Obbard 1977), exhibit nest site fidelity; in other species, such as *Chrysemys picta*, egg deposition is random (Christens and Bider 1987). Nest site fidelity was observed in close to 74% of *C. serpentina serpentina* females (Loncke and Obbard 1977) and close to 94% of *Emydoidea blandingii* females (Standing et al. 1999).

Nest sites are constructed a very short distance from the water. The average distance of nests from the water is 2.3 m in *Graptemys geographica*, 2.5 m in *Apalone spinifera* and 4.46 m in *E. blandingii* (Bodie 2001; Standing et al. 1999). The proximity of nests to the water increases the risk of nest flooding and, ultimately, death of the embryos. In addition to climate conditions and nest predation, nest flooding is a major factor in nesting success or failure in *E. blandingii* (Standing et al. 1999; Plummer 1976), a species at risk. In some years, close to 50% of *E. blandingii* nests are destroyed by flooding (Standing et al. 1999). In aquatic turtles, hatching success varies considerably from year to year, depending on hydrological and climatic conditions. It ranges from 2 to 49% in *Trionyx muticus muticus* and from 18 to 86.5% in *E. blandingii* (Standing et al. 1999; Plummer 1976).

Lower species diversity and abundance have been observed in turtle populations that use artificially modified shorelines. Frequent water-level fluctuations are particularly harmful to vulnerable species, such as *E. blandingii* or *A. spinifera* (Vandewalle and Christiansen 1996). However, the cause-and-effect relationships between artificially modified shorelines and the state of these populations are unclear. These losses could be due to nest flooding, as previously described.



1958DD: Current regulation plan; PP plan: pre-project plan (natural conditions).

Source: Morin et al. 2004.

Figure 6.4 Comparison of the effects of two St. Lawrence River regulation plans on potential anuran habitat

TABLE 6.2

Summary of the anticipated impacts of water-level fluctuations on the habitat characteristics of the herpetofauna of the St. Lawrence

Habitat variable	Drop in water level	Increase in water level	Decline in intensity of fluctuations	Phase shift in fluctuations and below-normal drop in level
Plant cover	Depending on the proportion of shallow marshes. The magnitude of the effect will depend on the morphology of the site: few gentle slopes, many steep slopes. Negative effect if the marshes transform into swamps.	Flooding of riparian forests and shrublands.	Negative effects, the magnitude of which will vary depending on site morphology: few gentle slopes, many steep slopes.	The magnitude of the negative effects will vary depending on the proportion of shallow marshes available for breeding.
Water temperature	Positive effect: shallow waters allow for a more rapid and more significant increase in temperature.	Negative effect: deep waters prevent a rapid increase in temperature.		Positive effects
Amphibian breeding site*	Negative effects, the magnitude of which will vary depending on the morphology associated with wet meadows or shallow marshes: few gentle slopes, many steep slopes.	Positive or negative effect, depending on the magnitude of the increase. Increased predation by fish and invertebrates when water levels are high.	Negative effect, the magnitude of which will vary depending on the morphology associated with wet meadows or shallow marshes: few gentle slopes, many steep slopes.	Negative effects
Turtle breeding sites		Negative effects: loss of breeding habitat.	Positive effects: better egg survival due to the reduction in the risk of nest flooding.	Negative effects: a late freshet can flood nests.
Presence of basking sites	Positive effects particularly for gently sloping shorelines.			Positive effects if decline is sudden. Adverse effects if the freshet is late.
Habitat fragmentation	Negative effects: loss of swamps and marshes and increase in the area of grass beds.		Negative effects: potential increase in residential development along shorelines.	Negative effects: certain species are more affected than others.

* Only amphibians breed in aquatic environments. Turtles lay their eggs outside the water in nests that are subject to flooding when water levels rise.

Indirect impacts

Disruption of hibernation

Hibernation in amphibians and reptiles involves a slowing down in activity. During the winter season, the animals enter a state of torpor and survive by drawing on fat reserves. However, they remain sensitive to their environment and can move short distances if disturbed (Cunjak 1986). In the St. Lawrence Valley, there are only four anurans that hibernate under water: *Rana catesbeiana*, *Rana clamitans*, *Rana pipiens* and *Rana palustris* (Hecnar 2004). The others, which produce cryoprotectants,[2] hibernate on land, burrowing into the soil litter. Little information is available on hibernation in anurans in aquatic habitats. They generally hibernate in shallow (< 1 m), slow moving (< 22.5 cm/s), well-oxygenated water (observed concentration of 7 ppm) (Cunjak 1986; Emery et al. 1972). *R. pipiens* hides under mounds of wood or rock, whereas *R. catesbeiana* looks for mud substrates (Desrochers and Rodrigue 2004; Emery et al. 1972).

For their part, aquatic turtles hibernate under water. The term "hibernaculum" designates the wintering habitat of reptiles and amphibians, both under water and on land. Aquatic reptile and amphibian species share the same hibernacula, and it is not uncommon to find several different species in the same hibernaculum (Pough et al. 1999). Reptiles and amphibians exhibit some degree of hibernaculum fidelity, and some individuals will travel distances of close to 15 km (Graham et al. 2000). These individuals look for specific environmental characteristics, such as well-oxygenated water, slow currents and soft substrates (Desroches and Rodrigue 2004). Depth does not appear to be critical to site selection, with species selecting sites on the basis of their tolerance to anoxia[3] (Reese et al. 2003, 2002). As a result, both shallow hibernacula in ponds (Brown and Brooks 1994) and very deep hibernacula (7 m in Lake Saint-Louis) (Graham et al. 2000) have been observed. However, juvenile *C. serpentina* and *C. picta* occur in shallower areas more frequently than adults (Congdon et al. 1992). Apart from the description of the phenomenon, little information is available on overwintering mortality and population dynamics of anurans and turtles.

In the St. Lawrence, environmental conditions associated with hibernation are seldom limiting; dissolved oxygen levels remain high and suitable substrates are present. The main limiting factors for anurans and turtles are climate and hydrology. High mortality rates are observed in winter when unusually cold temperatures combine with low water levels. Ice thickness also has an impact on the survival of hibernating anurans and turtles (Armellin and Plante 2004). Hibernation sites must be located at a greater depth than the thickness of the ice. Otherwise, contact with the ice would result in mortality due to freezing. In the St. Lawrence Valley, ice thickness varies on both a seasonal basis—with a maximum thickness in late winter—and an interannual basis—the ice thickness varies as a function of winter climate conditions. In Lake Saint-Pierre, the ice thickness ranges from 30 to 65 cm, for an average 49 cm (Armellin and Plante 2004). There is a risk that a decline in water levels during the winter could lead to a reduction in the size of hibernacula of anurans and aquatic turtles and to increased mortality.

Habitat modification

Water-level fluctuations modify the area of wetlands available for use by anurans and turtles as habitat (Barko et al. 1999). Because the size of marshes dominated by emergent vegetation is directly related to water levels, lower than average water levels would have adverse effects on suitable reptile and amphibian habitat, which would be reduced in size. Shoreline morphology also plays an important role in habitat loss. Habitat loss will depend on slope variation (Barko et al. 1999). Where shores have a gradual slope, marshes and grass beds are simply displaced, but if the slope is steep, the size of the area that can be colonized by plants declines.

In addition, for certain types of habitat, reduced water levels will not necessarily result in offshore displacement. For example, wetlands formed by islands or the bay they protect are subject to a greater loss of area than others. Similarly, there is no guarantee that the new vegetation will be similar to that which was affected by the water level reduction. To the contrary, there is a risk that reduced water levels would promote the establishment of pioneer or invasive species.

The prolonged high water levels of 1972 to 1975 resulted in the conversion of part of the swamps in the Îles de la Paix in Lake Saint-Louis to marshes (Jean et al. 1992). In the absence of water-level fluctuations, as in the case of Lake Saint-François, a conversion of swamps to forest area is observed (Jean and Bouchard 1991). Given the hydrological conditions at the time, these habitat modifications affected all riparian wetlands in the fluvial portion of the St. Lawrence between Repentigny and Trois-Rivières (Jean et al. 1992).

Climate Change

The main life cycle activities of amphibians and reptiles are closely associated with climate: a) mating in amphibians occurs primarily on rainy nights; b) in several species of turtle, sex is determined by temperature during incubation; c) embryonic and larval development occur in the presence of water; and d) wetlands that serve as refuge and foraging habitat owe their permanence to the presence of water. Because amphibians and reptiles are cold-blooded, they are particularly sensitive to changes in climate, such as an increase in average temperature, and extreme weather events, such as drought (Walther et al. 2002; Marcogliese 2001).

In amphibians, the start of spring calling in frogs and toads is directly related to temperature. In recent years, changes in the breeding phenology of anurans have been observed, with calling starting earlier. Through the monitoring of calling, it has been determined that breeding in four species of anurans in New York state occurs 10 days earlier than in 1990 (Gibbs and Breisch 2001). Also during the breeding season, movement of salamanders is positively correlated with precipitation and minimum air temperature. Similarly, the length of the larval period is inversely proportional to water temperature, with increased growth rates in warmer waters. Although this has the positive effect of reducing the risk of predation, it may also have a number of adverse effects: the larvae metamorphose at smaller sizes, and smaller adult body size may lead to reduced mating success in males (Galley 2004).

In several species of reptiles, sex is determined by incubation temperature. In *Emys orbicularis*, a European turtle of the family Emydidae, embryos develop male characteristics at temperatures below 28ºC and female characteristics at temperatures above 29.5ºC (Schneeweiss 2004). Despite the fact that temperatures rarely exceed 29.5°C under natural incubation conditions, females predominate in wild populations, which suggests that other factors, including genetics, control the sex ratio (Schneeweiss 2004). In most species of turtle in the St. Lawrence Valley, sex is determined by incubation temperature, with the exception of *A. spinifera* and *Glyptemys (Clemmys) insculpta* (Desroches and Rodrigue 2004). In *E. blandingii*, hatch time is directly related to temperature (Standing et al. 1999). Similarly, pipping[4] is exponentially related to temperature.

Reproductive success—expressed in terms of the number of nests producing young in a given year—depends on climatic conditions, particularly hours of sunshine, with nest temperature being related to sunlight. For incubation to be successful, a minimum number of degree-days is required (Schneeweiss 2004). The increase in incubation temperature also has an impact on the physical condition of juvenile reptiles. Genetics aside, size and weight at hatching are directly related to incubation temperature; the largest individuals are those that were incubated at the highest temperatures.

The anticipated impacts of climate change on aquatic or semi-aquatic ecosystems include alterations in water levels, currents, ice cover, eutrophication and acidification and increased ultraviolet (UV) radiation (Marcogliese 2001). However, it is difficult to assess their consequences for the herpetofauna of the St. Lawrence Valley. Several studies have attempted to establish a link between the disappearance of certain amphibian populations and climate change, but no direct causal link could be established (Carey and Alexander 2003). These changes can lead to increased competition between introduced and native species or to the spread of new diseases in native populations, which have very little or no immune resistance.

Other Pressures on the Herpetofauna of the St. Lawrence

We have considered the impact of water-level fluctuations and climate changes on the herpetofauna of the St. Lawrence. However, it is important to bear in mind that there are other stressors that affect these species, such as habitat fragmentation, chemical pollution, infectious diseases, introduced species, disturbance, illegal harvesting and deliberate destruction. The large urbanized and altered sectors of the river do not provide potential habitat for turtles or amphibians. In the Greater Montréal area, where two of the three study sites are located, the alteration of shorelines exceeds 85%. Only the islands still offer relatively unaltered riparian habitats (Armellin and Plante 2004). Because freshwater turtles and amphibians move very little once they find a favourable site, habitat fragmentation leads to isolation of populations (Bodie and Semlitsch 2000). For example, after a winter characterized by significant predation by otters, no increase was observed in the number of eggs or nests of *C. serpentina* in Algonquin Park. This suggests a lack of immigration, which, combined with an overly small population, was such that the population was unable to maintain itself (Brooks et al. 1991). In studies on amphibians, habitat fragmentation has been shown to have a negative effect on anuran species richness (Kolozsvary and Swihart 1999). Sensitivity to physical changes in habitat varies depending on the species. *G. geographica*, *A. spinifera* and *E. blandingi* are particularly sensitive to habitat changes (Vandewalle and Christiansen 1996).

Little is known about the diseases that affect amphibians and reptiles in natural environments. Certain diseases are suspected to be the cause of the population declines in some amphibians, such as *R. pipiens* in Western Canada (Wagner 2003). Infections are aggravated by the presence of pollutants, such as pesticides, which lead to immune system suppression (Gendron et al. 2000) or by an increase in the number of intermediary hosts, such as molluscs, as reflected by a higher prevalence in a given population when there is increased eutrophication (Johnson and Chase 2004). The impacts of contaminants are of particular concern because they are widespread in the environment—although significant regional variations are observed—and because, in some cases, the contaminants can reach concentrations that are known to affect embryo development and hatching success (de Solla et al. 2001).

The introduction of exotic species, whether fish, invertebrates or other amphibians, has direct and irreversible impacts on anuran populations. For example, the introduction of *R. catesbeiana*, a species that is harvested for its prized frog legs, led to the disappearance of several populations of *R. pipiens*, *R. aurora* and *R. boylii* (Wagner 2003). Competition for basking sites has been observed between the European pond turtle (*E. orbicularis*), an endangered species, and the red-eared slider (*Trachemys scripta elegans*), an exotic species that can be readily purchased in pet stores (Desrochers and Rodrigue 2004). It is important to bear in mind that exposure to sunlight enables reptiles to modulate their metabolism, and that competition between species for basking sites can therefore compromise the survival of *E. orbicularis* (Cadi and Joly 2003). At the current rate of species introductions into the St. Lawrence Valley (i.e. one species a year), and given the precarious situation of several species of amphibians and reptiles in this region, concerns about the survival of these species are justified.

Disturbances are interruptions or disruptions of the normal behaviour of animals by human activity, such as hunting, fishing or boating. The effects of disturbances on aquatic freshwater turtles are not extensively documented. However, the disturbance of nest sites by vehicles, livestock or vacationers can compromise the survival of both eggs and juveniles (Bonin 1997). Similarly, the disturbance of hibernating animals can reduce their chances of survival (Bonin 1997).

The commercial harvesting of frogs for teaching, research, fishing or human consumption places considerable pressure on anuran populations, particularly since it is recognized that they undergo major fluctuations in number. In some years, as many as 93 000 individuals have been captured in Lake Saint-Pierre for personal or commercial purposes. It is estimated that commercial harvesting, combined with habitat loss, pesticide use and mortality due to road traffic, has resulted in a decline in anuran populations (Langlois et al. 1992).

Research Avenues

The decline in reptile and amphibian populations was first observed in the 1970s, and although a number of causes have been identified, it is important to establish and maintain monitoring programs, since little is known about the dynamics of amphibian and reptile populations. In addition, anurans and reptiles are considered indicators of ecological integrity. Immediate action should therefore be taken in the following areas:

- establishing and maintaining monitoring programs;
- identifying national and regional areas of biodiversity;
- studying life cycles, conducting surveys and carrying out long-term monitoring;
- conducting research on emerging infectious diseases;
- studying the impacts of agricultural practices—pesticide and fertilizer use, cultural methods and agricultural landscape—on amphibians and reptiles;
- conducting research on the impact of the introduction of exotic species of reptiles and amphibians;
- studying the effects of climate change on the modification of range, breeding success, behaviour, physiology of the various life cycle stages, population dynamics.

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NOTES

1. In some anuran species, breeding takes several forms. Tree frogs, for example, lay their eggs in vegetation overhanging streams. The tadpoles hatch and drop directly into the water. In some species, development is direct (i.e. there is no larval stage).

2. These are complex glycoproteins that prevent the formation of ice in cells. The ice crystals destroy the cell membranes and lead to necrosis of the tissues and death of the animal.

3. Absence or significant reduction in the quantity of oxygen in the tissues.

4. In the egg incubation stage, pipping is the phase immediately prior to hatching, when the hatchling begins to crack the shell.

Chapter 7

IMPACTS OF THE HYDROLOGICAL REGIME ON ST. LAWRENCE RIVER FISH COMMUNITIES AND THEIR HABITATS

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Introduction

From time immemorial, rivers have been preferred sites for human settlement. This was due in part to abundant fish stocks, which were a direct source of food. In many watercourses, fish stocks proved to be highly variable in time and space and heavily dependent on cyclical fluctuations in water levels, which often forced fishers to relocate. Researchers have documented the influence of the hydrological regimes of large rivers on fish since the early twentieth century. Antipa, for example, showed that fishery production on the Danube was directly proportional to the amplitude and duration of the spring freshet (Botnariuc 1968). The effects of natural and anthropogenic hydrological fluctuations on the fish communities of lotic systems have been the subject of many studies over the past several decades, and it has been clearly established that changes in the hydrological regime have repercussions on fish at various levels of biological organization. However, the impacts vary from one watercourse to the next, and it is impossible to predict exactly what will happen without factoring in the physiography and hydrology of the system under study. The most obvious major changes are undoubtedly the ones resulting from the construction of dams and regulation structures, which usually have an impact on species richness and the diversity, abundance and biomass of fish (Kœl and Sparks 2002; Holcik and Macura 2001; Lopez-Lopez and Paulo-Maya 2001; Lusk 1995; Poff and Allan 1995; Neves and Angermeier 1990; Bain et al. 1988). In spite of the fact that the close connection between aquatic environment and fish communities has been proven for decades, human beings continue to change the hydrological regimes of major rivers in support of economic development and to the detriment of aquatic communities. If the socio-economic and environmental uses of fluvial systems are to be maintained, it is vital to gain an understanding of the mechanisms that control nature's response to changes in hydrological regimes, thereby ensuring informed management of aquatic ecosystems.

Although the St. Lawrence is one of the largest rivers in the world (its drainage basin is the thirteenth largest) and it has 87 freshwater fish species and 18 diadromous species (SLC 1996), very few studies have been carried out on the effects of flow and water-level fluctuations on the river's fish communities. The earliest evidence was produced by marine environment studies that established empirical relationships between interannual fluctuations in the river's freshwater flows and the abundance of commercial fish species in the Gulf of St. Lawrence (Runge et al. 1999; de Lafontaine et al. 1991; Sutcliffe 1973). Significant empirical relationships have also been established between fluctuations in the hydrological regime and the abundance of two anadromous species in the St. Lawrence estuary—the Atlantic tomcod (*Microgadus tomcod*; Fortin et al. 1990) and the rainbow smelt (*Osmerus mordax*; Mingelbier et al. 2001a). In the case of purely freshwater species, an empirical model developed by Nilo et al. (1997) suggests that the annual recruitment and year-class strength of the lake sturgeon (*Acipenser fulvescens*) is partly attributable to the range of flows and the water temperature in early summer and during the spawning and larval drift stages. Apart from these studies on the handful of commercial fish species referred to above, little work has been done to document and gain an understanding of the influence of the hydrological regime on fish assemblages in the fluvial section and on the other components of the St. Lawrence ecosystem. Taking the scientific literature and recent studies for the International Joint Commission as its starting point, this chapter examines the influence of the type and extent of hydrological fluctuations on fish dynamics in the Lower St. Lawrence River. The findings will serve to predict potential effects of regulation on the integrity of the ecosystem and the dynamics of the river's fish communities.

The St. Lawrence Hydrological Regime and Fish Communities

Unlike headwater rivers, the St. Lawrence is not subject to sudden fluctuations or flash floods (Welcomme 1979). This is attributable to the fact that it is well downstream in the drainage basin, and also to the natural buffering capacity of the Great Lakes, the partial regulation of outflows from Lake Ontario, and the tight regulation of the Ottawa River since 1912 (Morin and Bouchard 2000). Even though the daily discharge rate can vary from 9000 to 26 000 m^3/s at the mouth of the river (SLC 1996), fluctuations in its hydrological regime are relatively limited. Its hydrological cycle is relatively well buffered and is largely dominated by major spring flooding between late February and mid-May caused by runoff from precipitation throughout the basin. The water retention capacity of the Great Lakes is six months at most, so annual flow fluctuations in the St. Lawrence are determined primarily by the amount of precipitation and the climate.

Flow fluctuations inevitably influence the physico-chemical conditions of the water and available habitats, and in particular water temperature, the amount of dissolved oxygen and desiccation, which are all considered vital to fish. These effects vary with local topography and are usually more pronounced and noticeable in lentic habitats because they are shallow and currents are slow. The St. Lawrence alternates between narrow corridors (Montréal–Sorel section), where flooding is localized along a narrow strip laterally to the main channel, and lentic areas (lakes Saint-Louis and Saint-Pierre), where the freshet extends over an alluvial plain where a number of smaller tributaries also empty. This topographical variability underlies a web of hydrologically complex conditions and habitats, which according to Pearsons et al. (1992) should foster a wider variety of fish assemblages and greater resistance to hydrological disturbances. In some cases, fish may change their behaviour to adjust to variations in physical conditions or move to more conducive habitats (Northcote 1998). In others, the extreme physical and/or chemical conditions in some watercourses may generate special adaptations in fish (Welcomme 1979).

In the St. Lawrence, the water temperature in the main channel where there is no thermal stratification can reach 26°C in summer. The average summer temperature correlates positively with seasonal flow ($r = 0.61$, $p = 0.009$; de Lafontaine et al. 2006), suggesting that years of low hydraulicity are often associated with higher water temperatures. For example, water levels in the St. Lawrence dropped gradually by about 35% between 1975 and 2003, and during the same period, a significant 1.5°C increase was seen in the summer water temperature (de Lafontaine et al. 2006). The correlation between the two opposite trends is very significant ($r = -0.685$). The water temperature along the shoreline fluctuates more than in the main channel, quite often exceeding 30°C (de Lafontaine et al. 2003) and even reaching 34°C in shallow grass beds during periods of low water levels and high temperatures (Mingelbier et al. 2001b). A number of St. Lawrence fish communities are considered coldwater or intermediate species that have trouble tolerating such high temperatures and would have to move to the cooler waters of the main channel. Little research has been conducted on the relationship between water-level fluctuations and the thermal conditions of the water in littoral areas of the St. Lawrence, and more extensive analyses should be carried out.

Shortage of oxygen is one of the factors that place the highest stress on fish, and it may be a determining factor in the spatial and temporal distribution of fish in the floodplains of rivers (Welcomme 1985). There are no documented cases of hypoxia (dissolved oxygen < 1 mg/L) in the St. Lawrence, where deep waters are very well oxygenated. It is therefore unlikely that the dissolved oxygen levels would place stress on fish in the lotic area of the river. However, the situation may be different in areas of dense vegetation (riparian plant communities), where eutrophication can cause significant declines in oxygen levels. The degree of deoxygenation of water underneath plant cover will depend on current, water exchange and the oxygen requirements of decaying organic matter. Slavik and Bartos (2001) elegantly demonstrated how the partial regulation of specific sections of a river can cause nocturnal deficits in dissolved oxygen (3–4 mg/L), resulting in a simultaneous drop in fish richness and abundance. However, the same phenomenon was not observed in unregulated areas. Major daily fluctuations in levels of dissolved oxygen, with typical nocturnal minimums of 2–3 mg/L, have also been observed in the grass beds of Lake Saint-Pierre in late August (Hudon 2005), but their impact on fish communities has yet to be studied.

Very few fish species have adapted to survive desiccation, and enormous numbers of fish can perish after being trapped in temporary ponds on the floodplains of rivers (Lusk et al. 1996; Welcomme 1985). The long-term exposure of shallow habitats in the St. Lawrence, and especially in Lake Saint-Pierre, has been observed during years with very low water levels (the summers of 1963 and 1964 in particular). However, these desiccation events did not cause very high mortality rates in adult fish.

It is therefore clear that the study of the impacts of the hydrological regime on fish assemblages is complicated by the need to take into consideration and, where possible, to differentiate between the direct and indirect effects of water level and flow fluctuations on fish. Direct effects involve a causal relationship between flow or level and a biological response in fish. Indirect effects involve a cause that is not level or flow as such but that changes in response to fluctuations in level or flow. For example, a rapid drop in the water level in riparian grass beds may lead to an increase in water temperature, a drop in the level of dissolved oxygen in stagnant water and possibly even the production of excessive amounts of hydrogen sulphide, thus forcing fish to leave the area. If the fish cannot move out, abnormally high mortality rates will ensue. Such a scenario could explain a recently documented case of high mortality in carp (*Cyprinus carpio*). The case occurred in late June 2001, just after an episode of very low water levels, when a number of factors seem to have contributed to weakening the fish in the post-reproductive phase (Mingelbier et al. 2001b). It is vital to gain a better understanding of the links between hydrology and the physicochemical environment of littoral areas, which are frequented by most fish species during the juvenile stages; achieving this understanding will be one of the challenges for future research on the St. Lawrence.

Fish response to hydrological fluctuations

Fluctuations in the hydrological regime may be considered a disturbance factor to which organisms can adapt by developing behavioural, morphological, physiological or ecological characteristics to minimize the effects of such variations or turn them to their advantage. The spring flooding that typically takes place over several weeks at the same time of year (season) may be considered a "predictable disturbance." The fact that fish use the floodplain and riparian areas to protect themselves from being transported downstream is often given as an example of adaptation (Lucas and Baras 2001; Welcomme 1985). Fish response to flood events differs from one species to another, and Meffe (1984) has shown that these behavioural differences have a genetic component and are transmissible. On the other hand, few studies have been conducted on the effects of an unpredictable disturbance, associated with a hydrological event outside the frequency or intensity range of predicted measurements, the only exception being research on the effects of dam construction. For example, the exceptionally heavy flooding of the Mississippi in 1993 produced impacts varying from beneficial to minimal on a number of faunal populations but had no significant effect on the trophic structure of ecosystems in the floodplain (Delong et al. 2001). This type of event has never been documented for the St. Lawrence ecosystem.

Hydrological fluctuations can affect fish at various temporal and spatial scales. Over the short term (intra-annual), flow and level fluctuations may modify the local and seasonal distribution and the migratory patterns of species. Water flow and level are migration triggers for a variety of freshwater species (Lucas and Baras 2001). Fluctuations in the migratory pattern and seasonal distribution of fish will exert a direct effect on catches of sport and commercial fish because they change fish availability in specific fishing areas. Such fluctuations can also alter the reproductive behaviour of adult fish by modifying access to spawning grounds or sheltered areas in rivers. Over the long term, fluctuations in the hydrological regime can influence the dynamics of fish populations by acting on reproductive and recruitment processes and thereby changing the relative abundance of a given species (Schlosser 1998). Flow can also affect drift in the early stages of life of fish along a watercourse (Humphries and Lake 2000) or the growth and survival of juvenile fish in nurseries (Moses 2001). By acting on year-class strength, the hydrological regime may modify the relative abundance of the various species and ultimately alter the composition and structure of fish assemblages in the river. Because of the age structure of the fish, it follows that the stress-response relationship between hydrological fluctuations and the characteristics of a fish community can only be determined in the fishing sector after some time has elapsed. Therefore, an analysis of this type should preferably be based on time series of sufficient length (Bjornstad and Grenfell 2001, Jackson et al. 2001).

The next section reviews the degree to which fluctuations in the St. Lawrence hydrological regime influence fish at various organizational levels, including the following: (1) migratory behaviour and seasonal distribution of species, (2) availability of fish habitats, (3) reproduction and recruitment pattern of populations, and (4) diversity and integrity of assemblages. The first subject covered will be the observed responses to permanent disturbances caused by dam construction. This will be followed by consideration of disturbances associated with hydrological fluctuations in the St. Lawrence.

Permanent disruptions: Dams

The building of hydroelectric dams along the St. Lawrence (Rivière-des-Prairies in 1930–31, Beauharnois in 1932 and Moses-Saunders at Cornwall in 1959) caused permanent disturbances to the hydrological regime upstream and downstream from the dams and created barriers to fish movement upstream from Montréal. Annual water-level fluctuations for the Lake St. Lawrence reservoir, created immediately upstream from the Moses-Saunders Dam, are about 2 m. Downstream, however, the water level of Lake Saint-

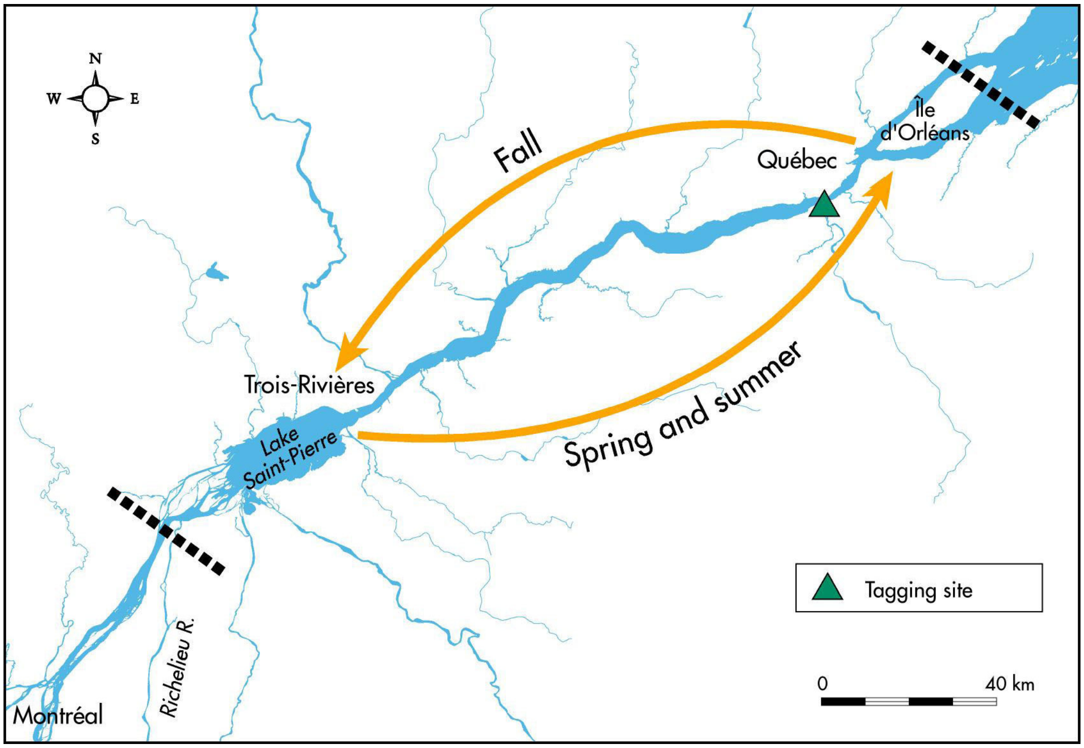
François, which functions as a reservoir and is wedged between the Moses-Saunders and Beauharnois dams, has risen 40 cm above its natural level, but fluctuates no more than 20 cm annually (Morin 2001). The fish assemblage that develops in a reservoir created by the construction of a dam basically depends on the assemblage that was previously living in the watercourse, unless new species are introduced (Lopez-Lopez and Paulo-Maya 2001). The effect of such a disturbance is usually determined by comparing assemblages sampled before and after dam startup.

Ribey (1997) observed that littoral fish communities upstream from the Moses-Saunders Dam were significantly less diverse and abundant than those downstream. This was attributed to greater fluctuations in water levels (effect of peaking and ponding operations) or to the more limited range of habitats and smaller amounts of vegetation upstream than downstream. Relatively constant water levels foster diversity and abundance of littoral fish (Kinsolving and Bain 1993). At the same time, habitat diversity can generate greater specialization in feeding patterns and, accordingly, a greater diversity of fish (Tonn and Magnuson 1982). The upstream-downstream differences noted by Ribey (1997) were primarily associated with fish in the chub family: there were virtually no banded killifish (*Fundulus diaphanus*), golden shiner (*Notropis crysoleucas*) or mimic shiner (*Notropis volucellus*) upstream from the Moses-Saunders Dam, even though they were plentiful downstream. These three species need a habitat with sub-aquatic macrophytes to reproduce and hide from predators, and this type of habitat is much more abundant downstream. The sparseness of the plant habitats in the upstream sector is attributable to the relatively recent creation of flooded habitats, 37 years before Ribey's study, and major fluctuations in water levels, draining water from llittoral areas normally used by fish. Comparing his results with data collected in 1930 for the upstream sector, Ribey noted the disappearance of at least six fish species as a result of the destruction of habitats caused by construction of the dam.

In conclusion, the lack of adequate (areas with macrophytes), diversified habitats caused by the flooding of the upstream sector and perpetuated by major fluctuations (~ 2 m) in water levels seems to provide an explanation for the difference in the degree of diversity and abundance of fish between areas upstream and downstream from the dam. However, it is difficult to estimate how much time would be required for habitats in the flooded sectors to recover. The lack of vegetation in the upstream sector more than 37 years after flooding suggests that it could be difficult for vegetation to establish itself there. The results produced by the Fish Monitoring Network, which was operational between 1995 and 1997, showed that the fish communities in Lake Saint-François included 27 species and that their degree of richness was much lower than that of communities surveyed downstream in Lake Saint-Louis and Lake Saint-Pierre, which comprised 40 species (La Violette 2004). Comparison of the results of the 1996 survey with a 1968 inventory of Lake Saint-François, in which 43 species were caught, suggests that 16 species were lost over a period of about 30 years, including several rare species of minnow (*Cyprinidae*) that were probably sensitive to the disturbances. Here too, the lower degree of diversity of fish habitats caused by the raising and stabilization of water levels is cited to explain the lower degree of fish diversity in Lake Saint-François in comparison with the typically fluvial and hydrologically more variable sectors downstream from Beauharnois (La Violette et al. 2003).

Migratory behaviour and seasonal distribution

Contrary to the fairly widespread perception that freshwater fish are fairly sedentary and spend most of their lives in a small area, several fluvial species travel laterally or longitudinally in response to environmental conditions and habitat use requirements (Lucas and Baras 2001; Northcote 1998). With the exception of some sport and commercial fish species, our knowledge of the migration patterns of freshwater fish in the St. Lawrence is still fairly limited. Results to date suggest, however, that migratory behaviour is relatively variable, depending on the study area. For example, yellow perch (*Perca flavescens*) populations in the Lake Saint-Louis sector upstream from Montréal are relatively sedentary, with limited transfer between the north and south shores of the lake, and their movements are largely confined to each shoreline (Dumont 1996). The copper redhorse (*Moxostoma hubbsi*), a rare and endangered species of the St. Lawrence, migrates from the Îles de Contrecœur in the Montréal–Sorel fluvial section to reproduce in the Richelieu River (Dumas 2005). A tagging study conducted from 1999 to 2001 in the Québec sector highlighted a fine example of potamodromy (migration in freshwater only) in the case of more than 20 freshwater fish species in the St. Lawrence (de Lafontaine et al. 2002). These species, including the yellow perch (*Perca flavescens*), the walleye (*Sander vitreus*), the sauger (*Sander canadensis*), the channel catfish (*Ictalurus punctatus*), the white sucker (*Catostomus commersoni*), the northern sucker (*Catostomus catostomus*) and the white perch (*Morone americana*), move seasonally over a distance of approximately 200 km along the fluvial portion between the Îles de Sorel, in the far western end of Lake Saint-Pierre, and the easterly tip of Ile d'Orléans (Figure 7.1).



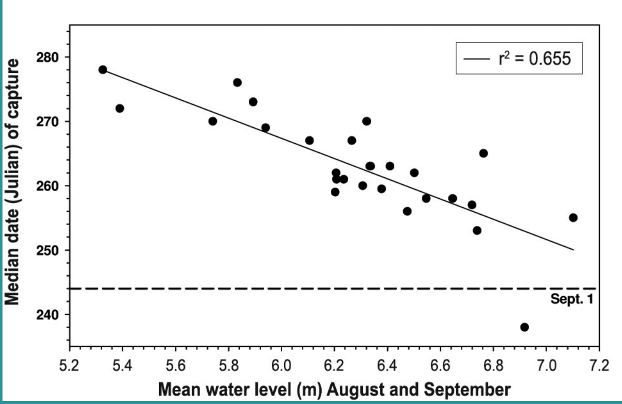
Note: The species identified are the yellow perch, the walleye, the sauger, the channel catfish, the white sucker, the northern sucker and the white perch.
The crossbars mark the extent of the main area of migratory movement.
Potamodromy: Seasonal migration pattern and occupied area.

Figure 7.1 Seasonal migration patterns and distribution area of a number of fish species in the Lower St. Lawrence, based on data from a tagging study conducted at Saint-Nicolas, from 1999 to 2001

The most mobile species is the walleye, with seasonal movements from Québec to Montréal (~ 240 km). The seasonal migration of the yellow perch over a distance of approximately 175 km along the St. Lawrence had never been described previously, and it is one of the relatively few cases of long-distance migration of this particular species, which is generally considered sedentary and non-migratory (Scott and Crossman 1973). If we also take into consideration the many anadromous species in the St. Lawrence (e.g. lake whitefish (*Coregonus clupeaformis*), rainbow smelt (*Osmerus mordax*), Atlantic tomcod (*Microgadus tomcod*), lamprey (*Petromyzon marinus*) American shad (*Alosa sapidissima*) and Atlantic sturgeon (*Acipenser oxyrhynchus*), which are also known to migrate in the fresh waters of the river in order to reproduce (Bernatchez and Giroux 2000), we can conclude that a high proportion of fish species in the St. Lawrence use and depend on a variety of habitats scattered over a wide area in order to complete their life cycles.

This pattern of seasonal migration upstream in fall and downstream in spring, which has been observed in a number of St. Lawrence species, does not seem to be connected with imminent needs associated with reproduction, which for most of the river's freshwater species occurs in the spring. Instead, it would seem to be controlled by seasonal fluctuations in habitat accessibility, as has been documented for other northern rivers (Lucas 2000; Nikolsky 1963). The assumption is that upstream migration in the fall enables the fish to avoid the effects of ice on coastal habitats in the fluvial portion and take shelter in the lacustral habitats of Lake Saint-Pierre in preparation for spring spawning (de Lafontaine et al. 2002). Migration to upstream spawning grounds is a very widespread phenomenon among river fish and is apparently a form of adaptation that minimizes losses of spawning products and fosters the drift of juvenile fish to productive downstream habitats (Humphries and Lake 2000; Schlosser 1998).

Using daily fish catch data recorded at the Saint-Nicolas experimental fishery between 1975 and 2002, Marchand and de Lafontaine (2004) showed that the median date of migration and the duration of seasonal migration of 20 fish species in the downstream section of the St. Lawrence (out of a total of 38 cases analyzed) varied considerably from year to year and that the variation was attributable to fluctuations in the hydrological regime. Downstream spring migration was delayed in years of heavy flooding. Conversely, upstream fall migration was delayed in years when water levels in late summer and early fall were higher. In most cases, water level was a stronger predictor than water temperature. One of the most convincing cases is that of the American eel (*Anguilla rostrata*): the fall migration of this species is closely related to the amplitude of water levels in the St. Lawrence (de Lafontaine et al. 2006) (Figure 7.2).



Note: The numbers represent the last two figures of the observation years.

Figure 7.2 Relationship between fall migration time of the American eel in the St. Lawrence at Québec and the mean St. Lawrence water level at Pier No. 1, Montréal

Based on data covering the period 1944–2002, the analysis shows that the eel's migratory behaviour has not changed over the last 60 years, in spite of changes in the hydrological regime since 1960. While the potential effect of other variables (temperature, luminosity, availability of food) on fish migration is not dismissed (Jonsson 1991), the significant relationships between water levels and migration dynamics for about half the fish species suggest that the spatial and temporal distribution of fish in the St. Lawrence is directly connected to hydrological fluctuations that determine the accessibility of adequate habitats. These findings seem to support the hypothesis that migratory behaviour responds adaptively to interannual fluctuations in the hydrological regime, which function as a stimulus for migratory movement. The assumption is that over-regulation of flow and levels could therefore cause a loss of variability in the migratory function. However, the consequences of a change in the migration patterns of fish in the St. Lawrence and most of the world's major rivers are still unknown. Agostinho et al. (2002) demonstrated that fluctuations in flow had a greater impact on the dynamics of populations of migratory species than on non-migratory species in the Paraná River. Moreover, studies of marine fish suggest that there may be impacts on the long-term dynamics of fish populations (Comeau et al. 2002).

Fish/habitat relationships

Fish have developed a broad range of morphologies and living strategies to adapt to highly heterogeneous habitat conditions (Souchon et al. 1989; Bovee 1982; Stalnaker 1979). They choose environments that are compatible with their requirements, and their presence in such locations is not accidental (Payne and Lapointe 1997; Greenberg et al. 1996; Morantz et al. 1987; deGraaf and Bain 1986; Mathur et al. 1983). In addition, their spatial distribution in the fluvial portion of the St. Lawrence reflects the spatial and temporal heterogeneity of habitats. These differences are related to fluctuations in flow, complex topography, water masses with distinct characteristics (turbidity, conductivity) in the various tributaries, exposure to currents and waves, the presence and density of plant species, and the substrate of the fluvial ecosystem (La Violette et al. 2003; Lessard 1991). Habitat preferences and spatial models are being increasingly used to evaluate potential habitats for a number of fish species to spawn, grow and feed (Hardy and Addley 2003; Parasievicz 2003; Leclerc et al. 1995). According to Boisclair (2001):

[Translation]

> The value of explicit spatial models lies in their capacity to generate a detailed representation of key habitats requiring protection. In light of ever-increasing pressure caused by the exploitation of fish populations and the local and global destruction of fish habitats, this is a significant asset.

Information on the habitat preferences of fish in the St. Lawrence was first documented in the early 1980s in a feasibility study conducted as part of the Montréal region water management project. A comprehensive, extensive, habitat-by-habitat approach was recommended for identifying the main factors limiting the presence of fish and the impacts of construction of a hydroelectric plant (Bureau and Gravel 1981). Habitat potential keys and rates of use by species representative of the fish communities were developed at that time for purposes of an overall assessment of the potential of the area under study (Leclerc 1984; Gravel and Dubé 1983; Leclerc and Vallières 1983). The approach was applied again recently in a study by the International Joint Commission to determine the impact of regulation of outflows from Lake Ontario on the habitats of fish in the river (Mingelbier et al. 2005). The study was made possible by an improvement in high-spatial-resolution models of the physical variables of the fluvial portion of the St. Lawrence (Morin et al. 2003). The terrain model currently covers a very large area stretching from Cornwall to Trois-Rivières. It incorporates a very accurate description of the topography and makes it possible to predict habitat variables that are key to fish, such as current velocity, depth, waves, temperature, substrate type and emergent and submerged vegetation (Turgeon et al. 2004). It also estimates habitat losses attributable to flow fluctuations. A model of this kind had never before been developed for a hydrographic system as large as the St. Lawrence. Most digital habitat models had been developed for watercourses with relatively low flows or for specific sectors (Guay et al. 2000; Lamouroux et al. 1998; Leclerc et al. 1996).

Regulation has a significant effect on flow in the spring (decrease) and late summer (increase) (Morin and Bouchard 2000). Accordingly, only these two periods of the year were documented for several key fish species for the International Joint Commission study. Habitat availability was estimated in terms of area conducive to northern pike reproduction in the spring and feeding by ten species of adult fish in late summer. The study was restricted to the river corridor between Cornwall and Trois-Rivières because water-level fluctuations attributable to flow regulation can only be measured in a nontidal freshwater area.

Northern pike spawning grounds

Access to the various types of marshes and the floodwater drawdown pattern play a very important role in the dynamics of the St. Lawrence fish community. Successful reproduction by the northern pike, a predator in the food chain, is fostered by high, stable water levels during spring spawning.

A habitat suitability index (HSI) was developed from empirical data and documentation to estimate the impact of flow on the northern pike's reproductive habits. The index incorporates water temperature, type of wetland and current velocity in order to assign a quality rating to areas accessible to fish. The HSI was combined with a two-dimensional digital model that very accurately calculates the area of potential habitats on the basis of a number of realistic flow scenarios ranging from 5000 m^3/s to 20 500 m^3/s. It was found that flows in the St. Lawrence had a positive impact on the availability of potential habitats for the northern pike to lay eggs and on the area of higher-quality potential habitats (Figure 7.3). The year-over-year differences observed in hydrological conditions clearly illustrate the effect of flow on the area of potential habitats. For example, such habitats were twice as large in 1998 (discharge of 14 453 m^3/s resulting in 7136 ha of potential habitats) than in 2000 (discharge of 9582 m^3/s resulting in 3664 ha of potential habitat). A region-by-region analysis shows that the effect of flow differs considerably from one region to the next and that the habitats of the Lake Saint-Pierre archipelago are the ones most affected by flow (Figure 7.3). The regions concerned include most of the northern pike breeding grounds in the system, and they require a higher flow rate ($\geq$ 14 500 m^3/s) than Lake Saint-Louis or the Montréal-Sorel section in order for habitat areas to exceed 70% of regional potential. These regional differences could be attributable to local topography, current velocity and water temperature at high flow rates, and the surface area and elevation of wetlands in the floodplain.

Flows in the St. Lawrence can cause fish mortality if the floodwater recedes and the spawning grounds dry up during the egg incubation period or the first few days of growth, when the larvae have yet to acquire the swimming skills needed to leave the spawning grounds. According to Armellin (2004), exposure is one of the causes of mortality during the early stages of development. In order to evaluate the effect of water-level fluctuations on habitat availability, the surface areas of exposed spawning grounds have been calculated annually since 1960 (Mingelbier et al. 2005). A recurrence analysis shows that habitat losses attributable to floodwater recession occurred in two years out of every three. The average proportion of lost habitats is 25% ± 20% (1 to 56%) for the St. Lawrence as a whole. The Îles de Sorel area is the most vulnerable to flow fluctuations, with habitat losses reaching as high as 78% and averaging 39% ± 27%. A historical analysis (Mingelbier et al. 2005) shows that reductions in water levels during the critical period have been more stable since flow has been regulated at Cornwall, and that this is probably due to other factors, such as climate, tides and regulation of the Ottawa River. Availability of reproductive habitats is therefore relative, depending on both the area available at the time of egg deposition and the area lost when floodwaters recede too early.

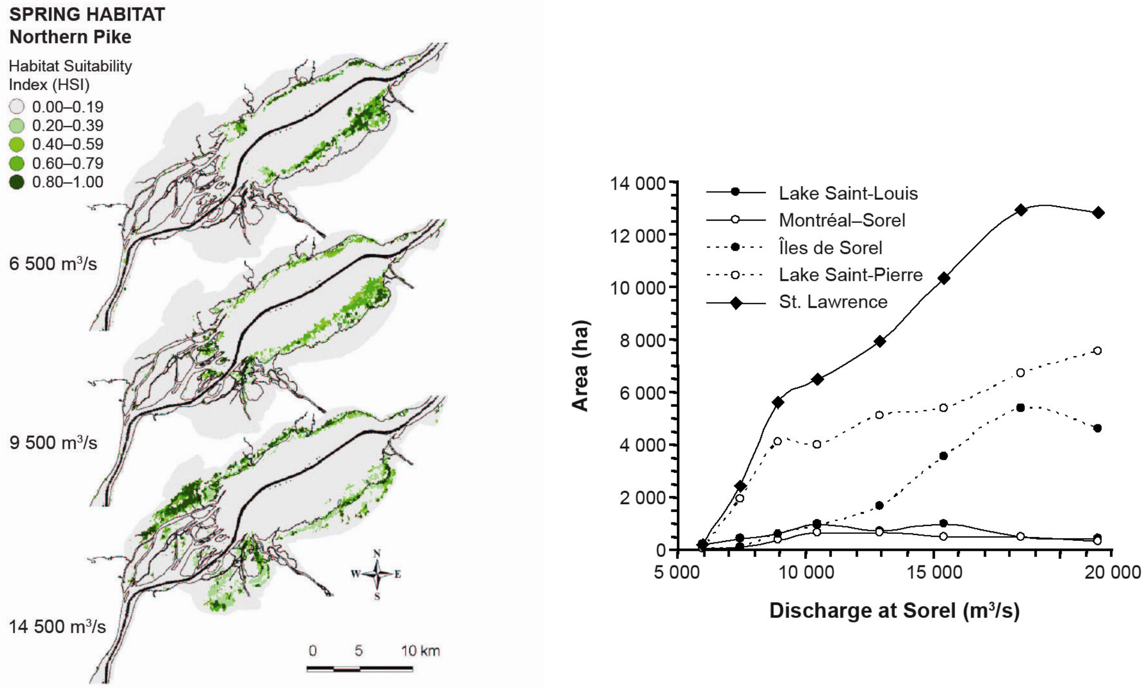


Figure 7.3 Area of potential northern pike spawning grounds in the St. Lawrence based on a discharge at Sorel ranging from 5000 m^3/s to 20 500 m^3/s

If floodwaters recede very quickly, even when the young-of-year (YOY) have already developed strong swimming skills, large numbers of fish can be cut off in natural depressions in the floodplain (Dumont and Fortin 1977). YOY are then trapped and subjected to extreme temperature, oxygen and predation conditions. A historical analysis of levels measured at Sorel between May 17 and June 30 during the period 1917–2002 shows an increase in the speed of recessions since system regulation was introduced at Cornwall (~ 1 cm/d) (Mingelbier et al. 2005). Prior to regulation, average recession rates in the St. Lawrence were 3 cm/d; this was comparable to rates for the Richelieu River, which were on the order of 1 to 2 cm/d (Dumont and Fortin 1977).

To evaluate the impact of regulation on spring habitats, a comparison was made between two reconstructed river flow series for the period 1960–2000: the series preceding regulation (natural flow) and the 1958DD series (regulated flow) (Morin et al. 2005). Using a model based on empirical data and documentation, air temperature was factored in as well to make yearly predictions of the chronology of reproduction and thereby pinpoint the exact time when habitats were used (Mingelbier et al. 2005). By lowering the flood crest almost two years out of every three, regulation has caused annual reductions of 5–10% in the area of potential habitats throughout the St. Lawrence (Figure 7.4). Once again, the Îles de Sorel area is the one most strongly affected by the flow, and it is here that, because of regulation, the largest (54%) and most frequent (one year out of every two) decreases are registered. These decreases reduced the availability of habitats even further during periods of low natural hydraulicity (as much as 28%), and they also occurred several years in a row (1962–1965). It is precisely in conditions such as these that the impact of regulation is likely to damage fish populations the most and that the system must be managed with particular care. The frequency of the decreases may well increase as future water inflows drop because of climate change (Mortsch and Quinn 1996), unless action is taken to modify the approach to managing water levels.

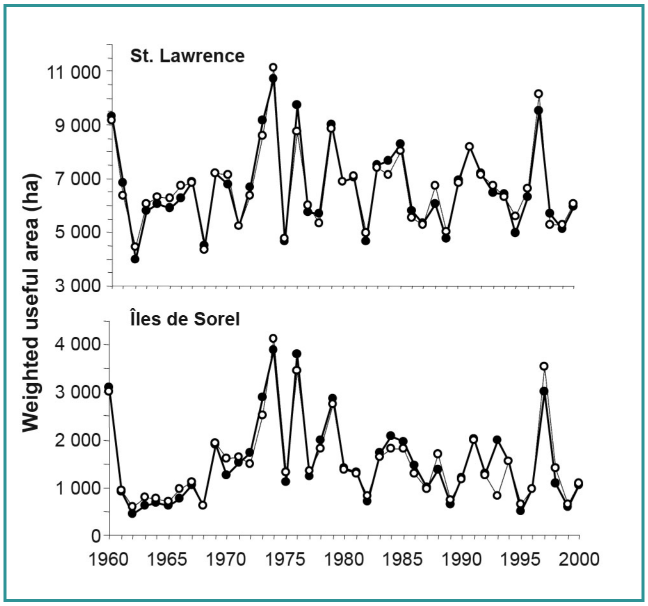


Figure 7.4 Potential areas available for northern pike spawning with (solid line) and without (dotted line) flow regulation based on Plan 1958DD

A telemetric study of northern pike in the Montréal region, which found that seasonal movements were shorter than 1 km in 92% of the cases tracked, suggests that the species is sedentary (Leclerc 1984). The findings show that unfavourable conditions can have major local impacts on fish populations. A decrease in potential habitats for several years in a row could have repercussions on the local ecological balance. The findings also show that, in making management choices relating to the system, it would be more advisable to identify parts of the river where habitats are more limited than to consider the total area of the system. In practice, it is hard to accurately estimate the impact on northern pike populations of decreases in surface area caused by regulation, particularly given the fact that this species behaves opportunistically in selecting spawning sites. At the very least, it can be assumed that regulation has had adverse repercussions on the abundance of the northern pike in specific locations and at specific times, since variations in the year-class strength in the Boucherville region are attributed to the high proportion of available spawning grounds (61%).

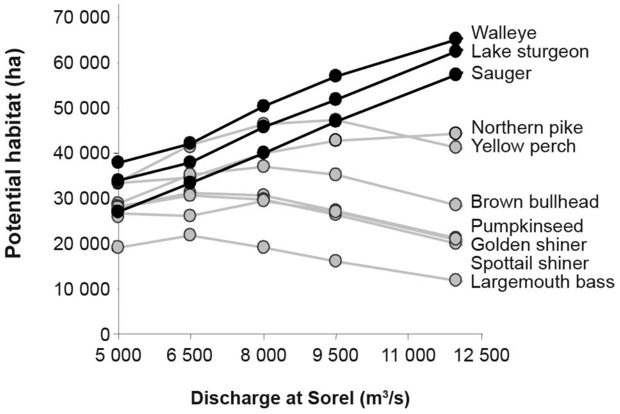
Interannual flow fluctuations at Cornwall are attributable to climate. Since regulation influences flow in the current year, not flow in the following year, the impacts of management decisions and procedures are less significant than those of climate. Even though the impacts of regulation at Cornwall seem minor, they must be taken into consideration and reduced as much as possible to limit the various types of pressure that are already exerting a cumulative effect on fish populations (exploitation, habitat loss, interruption of migration routes, etc.). At the same time, efforts must continue in order to protect and restore habitats in the floodplain, which are too often sacrificed to farming and urban interests. These habitats are vital to maintaining the fish populations of this major river (Welcomme 1979), hence the importance of restoring them.

Growth and feeding habitats of adult fish

Summer habitats play an overriding role in feeding. They provide fish with a very productive living environment and shelter to protect themselves (1) from predators in areas covered with vegetation (Verret and Savignac 1985), (2) from intense light in turbid waters, and (3) from high deepwater temperatures. Summer is a strong period of growth, a key stage during which food availability and temperature are decisive factors. The size reached by the young fish and the adults at the end of the season and the food reserves stored up in their bodies are crucial for winter survival (Guénette et al. 1994). Flow influences the accessibility of rearing and feeding habitats, their physical characteristics and their spatial distribution. The complex topography of the St. Lawrence, the great variety of characteristics of the water masses, the density and composition of vegetation, and the substrate cause conditions that differ markedly over space and time (Morin et al. 2003). The complexity is reflected in the highly heterogeneous spatial distribution of fish in the fluvial portion of the St. Lawrence (La Violette et al. 2003; Lessard 1990; Verret and Savignac 1985).

Mingelbier et al. (2005) estimated the impact of regulating the flow of the St. Lawrence on the availability of potential summer rearing and feeding habitats for fish species about which information is available. Out of the 50 species examined, 10 were selected for the purpose of illustrating fish diversity. Five hydrological scenarios were tested, covering a broad range of summer flow measurements. Ten multivariate habitat models (habitat probability indexes generated from logistic regressions) were developed with data from three intensive Fish Monitoring Network sampling surveys conducted by Faune Québec in the fluvial portion of the St. Lawrence at the end of the summers of 2001, 2002 and 2003 (La Violette et al. 2003). The habitat models were combined with the two-dimensional digital model of the river to predict useful habitat areas as a function of flow. The same work was carried out separately for the four other regions of the St. Lawrence with a view to evaluating the areas most sensitive to hydrological fluctuations.

The habitat simulations reflect the biological characteristics and preferences of the 10 species under study (Mingelbier and Morin 2005). Overall, the simulations highlight a dichotomy between species associated with lentic environments (northern pike, largemouth bass, brown bullhead, golden shiner, spottail shiner, yellow perch and pumpkinseed) and those associated with lotic environments (lake sturgeon, sauger and walleye) (Figure 7.5).



Note*:* Black curves indicate positive linear relationships and grey parabolic curves indicate a loss of habitat starting at a discharge of 9500 m^3/s and negative relationships at higher flows.

Figure 7.5 Relationships between potential habitats and discharge

Some species prefer calm, shallow water and a fine-grained substrate with vegetation (pumpkinseed and yellow perch). In general, the area of their potential habitats reaches its maximum value when flow is relatively low, and it even exhibits a negative relationship when flows exceed 9500 m^3/s (Figure 7.5). Other species prefer a fast current and often frequent shallow areas that have less exposure to light, no vegetation in many cases, and a medium-to-coarse-grained substrate. The overall area of their potential habitats in the fluvial portion of the St. Lawrence shows a strong relationship with flow. These results show that the habitat of lentic species is much more vulnerable to fluctuations in flow than the habitat of lotic species, which seems to be less restricted.

The study of the four regions of the St. Lawrence reveals the extent to which impacts vary from one location to another and that flows must be regulated on the basis of the areas with limited potential habitats, especially in the floodplain, not on the basis of the system as a whole, in order to maintain balance within fish communities.

The example of the golden shiner, a common forage fish of the Cyprinidae family, shows that, at a low summer discharge of about 6000 m^3/s at Sorel, the number of potential habitats in Lake Saint-Pierre reaches a maximum, whereas there are virtually no potential habitats between Montréal and Sorel or in the Îles de Sorel. At a very high summer discharge of about 11 000 m^3/s, the habitat area becomes very limited throughout the St. Lawrence system. Lake Saint-Pierre exerts a strong influence on the absolute area of potential habitats available along the river. If just the system as a whole is considered, the habitat of the Cyprinidae family is likely to disappear in the section between Montréal and the Îles de Sorel and to flourish in Lake Saint-Pierre. The ecological (trophic) balance could suffer from the shortage of forage fish as important as the Cyprinidae in a specific region, were summer discharges to be too extreme (too low or too high) or to fluctuate faster than the growth of plant communities.

To test the effect of regulation, the relationship between potential habitat area and discharge (Figure 7.5) was used to reconstruct a historical series (1960–2000) for habitat areas based on regulated flows as measured and natural flow rates as they would have been measured had regulation not been introduced. For purposes of illustration, the habitat of the walleye was chosen to represent that of lotic species, and the habitat of the golden shiner that of lentic species (Figure 7.6).

Note that the area values used are solely illustrative and are intended to facilitate comparison of several regulation plans. They are assigned to the habitat of a species considered in isolation from the fish community and from an ecological context that is also changing over time. The fact remains, however, that the weakness of the hydrological regime in the 1960s and its strength in the 1970s generated different potential habitats that likely had an influence on fish abundance. A number of comparable trends have been observed in the fluvial estuary (see de Lafontaine and Marchand 2004).

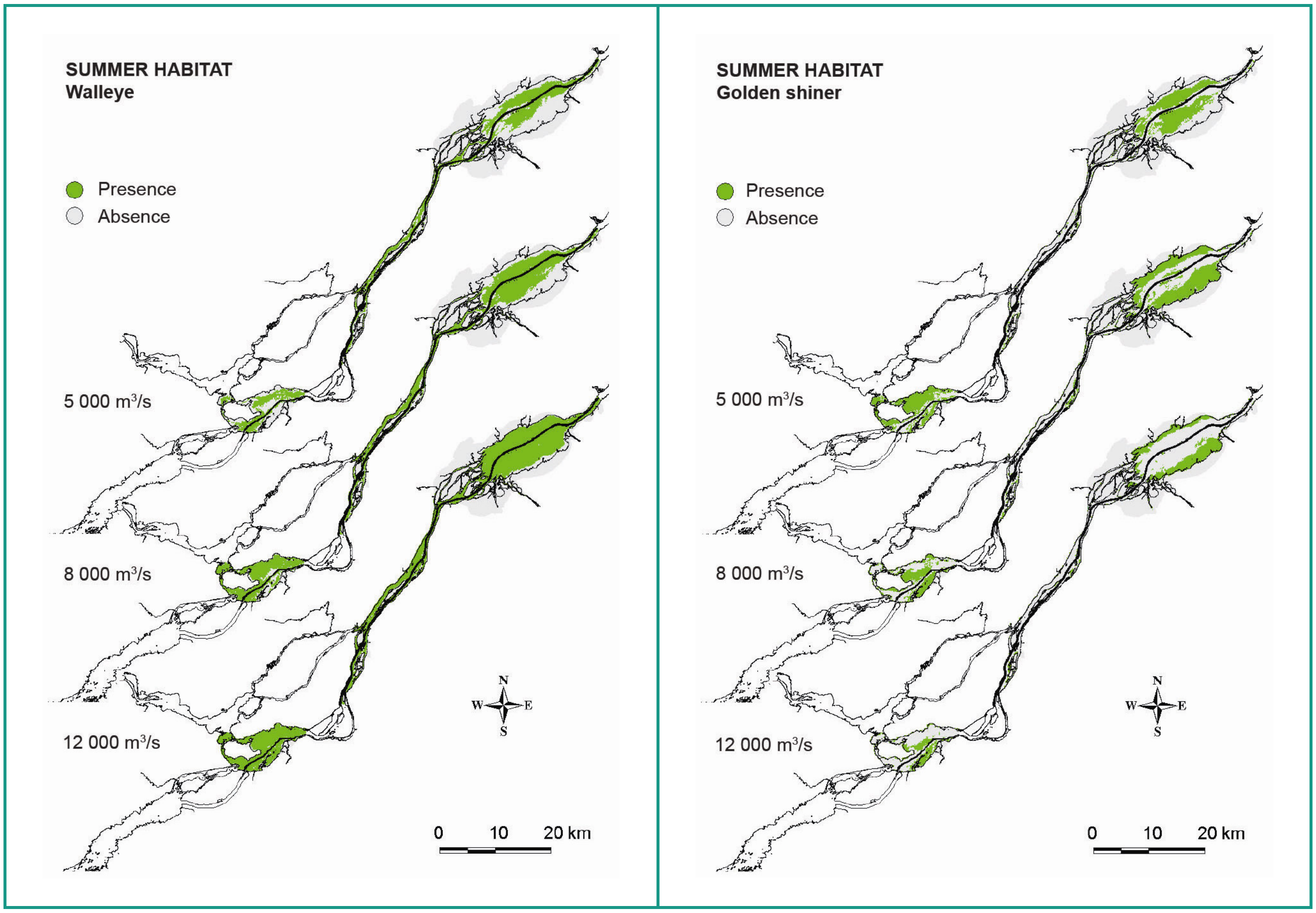
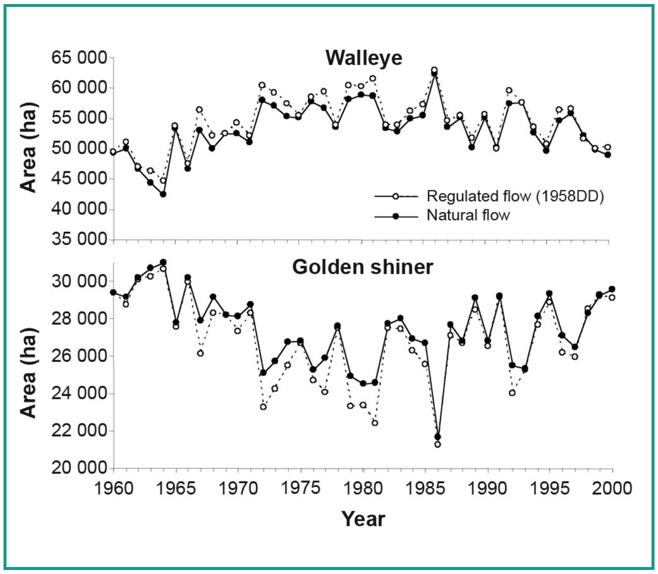


Figure 7.6 Simulations of potential summer habitats for walleye and golden shiner, based on three discharge scenarios at Sorel

Managed habitats along the St. Lawrence

Wetlands play an important ecological role and are essential for maintaining the health of the St. Lawrence River's aquatic ecosystems. These environments are under constant pressure from human activity (land development and management, agriculture, commercial shipping), and their surface areas are steadily shrinking. Nearly 80% of the wetlands that existed in the Montréal region at the beginning of the colonial period has disappeared (SLC 1996). Since the 1980s, many managed marshes have been created along the St. Lawrence and Ottawa rivers for fish and waterfowl as a means of offsetting the loss of habitats. In Lake Saint-Pierre alone, the managed area accessible to fish covers 1326 ha of protected zones, or about 10% of the floodplain (Mingelbier and Douguet 1999). The managed marshes are like large basins surrounded by dikes, with structures for partial control of water levels.

The managed marshes provide fish with multi-species habitats frequented by 37 species. They function as productive spawning and fry-rearing sites, especially for early spawning species like the northern pike and the yellow perch (Brodeur et al. 2004). The spring growth of yellow perch YOY is stronger in managed than in natural habitats—a fact that could increase the species's reproduction and survival rates (Tardif et al. 2005). Managed marshes extend the period of spring flooding, which had been about three weeks shorter since regulation of the Ottawa River was introduced in 1912 (Morin and Bouchard 2000), and they serve to raise the water temperature more quickly at the start of the growing season (Mingelbier et al. 2005; Tardif et al. 2005; Lepage and Lalumière 2003). They provide high water levels during a critical period, giving fish access to the best spawning grounds and thus preventing the high mortality rates caused by the drying up of eggs and larvae. Management of water levels in the marshes is adapted to the ecology of the species that frequent them and restores a part of the St. Lawrence's natural hydrological cycle.



Note*:* The figure presents the areas of potential summer habitats for walleye and golden shiner in the St. Lawrence as a whole.

Figure 7.7 Historical reconstruction of potential habitats (1960–2000), based on a non-regulated mean discharge (solid line) and a Plan 1958DD-regulated mean discharge (dotted line) at Sorel in September

The water stage, duration and timing of the spring freshet have repercussions on the ecology of marshes (Brodeur et al. 2004) and on fish access to them for reproduction. As part of the International Joint Commission study, Mingelbier et al. (2005) assessed the impact of interannual hydrological variations since 1960 on access to managed marshes in Lake Saint-Pierre. The authors also made recommendations to protect the marshes, which are already helping to make up for the loss of natural habitats. The study shows that, from 1960 to 2003, spring access to managed marshes was influenced by interannual changes in the river's water levels and varied considerably, from 0 to 125 days (average of 43 ± 36 days), with an available area of 0 to 1326 ha (Figure 7.8). The mid-1960s were characterized by short periods of access and a decrease in the area of available potential habitats; in fact, contact between the marshes and fish was completely broken in 1965 and 2003. From the early 1970s to the mid-1980s, there was an increase in the length of the access period and in available habitat area. Since 1975, the average duration of access has dropped by 1.3 days per year ($p < 0.01$). Even though the hydrological regime of the Great Lakes–St. Lawrence Basin has a cycle of about 30 years (Morin and Leclerc 1998), a drop in water inflows in the near future as a result of climate change (Mortsch and Quinn 1996), as well as marked changes in the St. Lawrence ecosystem (Vincent and Dodson 1999), are to be expected. The effect of these changes on managed marshes could take the form of a loss of species diversity and a drop in total abundance of spawners (Brodeur et al. 2004).

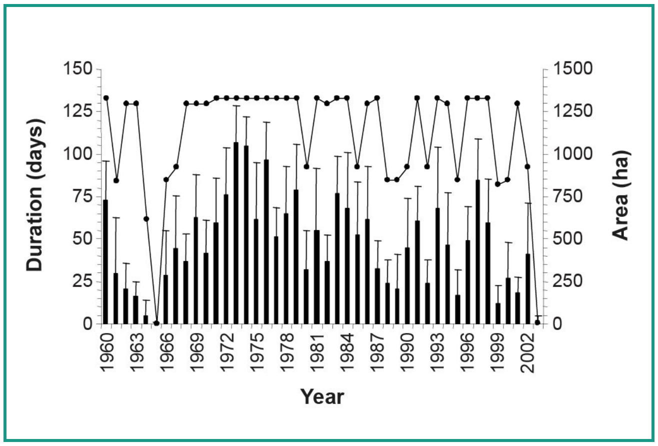


Figure 7.8 Average duration of spring access to managed marshes (histogram) and available area (line) had managed marshes been accessible since 1960

To a large extent, it is the synchronicity between the freshet and water temperature that determines the composition of the fish community in managed marshes (Mingelbier et al. 2005). In April, species diversity in Lake Saint-Pierre reaches a maximum after the accumulation of 75–100 degree-days (~ 20 days of flooding). The multimodal distribution of species richness of the migrating community over time also shows that species migrate to the floodplain in stages, depending on photoperiod, temperature (Dabrawski et al. 1996) and water level (Rioux and Morin 2001). An early, short period of flooding is therefore likely to favour coldwater-spawning species, while a late period of flooding is likely to favour warmwater-spawning species. Interannual fluctuations in fish diversity within managed sites may be attributable to the water level reached during the freshet, and a positive relationship exists between the number of species in the marshes and the water level of the river ($p < 0.001$). Even though there is no causal relationship between the two variables, the above finding suggests that water level could act as a stimulus to fish migration toward the floodplain. In addition, in combination with the spring tides, the spring freshet affects not only habitat accessibility but also the intensity of fish movement toward the floodplain. In fact, a number of studies conducted on the St. Lawrence have highlighted the significance of water-level fluctuations as a major determinant in the migration of the northern pike to its spawning grounds (Brodeur et al. 2004, Rioux and Morin 2001, Massé et al. 1991). The duration of the access period and the height of floodwaters are therefore of critical importance in ensuring optimal species richness in managed marshes.

Research on managed marshes indicates that hydrological fluctuations in the St. Lawrence have a significant impact on fish access to managed marshes, on the area available and on duration of access. The duration, stage and timing of the spring freshet may well influence fish abundance, species richness and intensity of fish movement to managed sites. The fish access period, which is influenced by the stage and duration of the spring freshet, must be synchronized with the migration of the various species to ensure access to the marshes. A low water level (< 5.6 m at Sorel) during migration and reproduction cuts off access to high-quality habitats and prevents the managed marshes from offsetting the loss of habitats on the floodplain and protecting key sites.

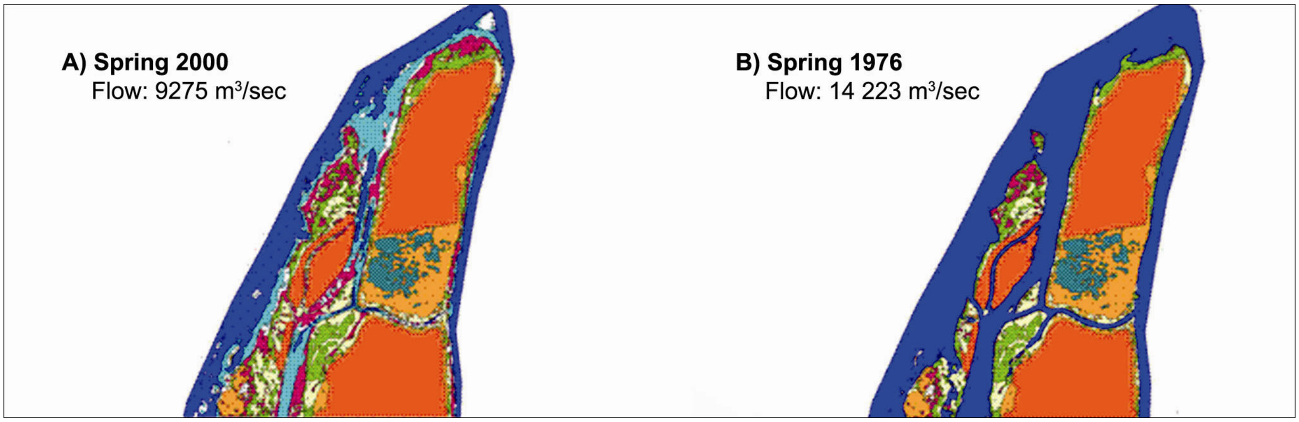
Variations in northern pike year-classes

Although the relationship between the quantity of potential habitats (essentially based on the presence or absence of species) and fish abundance is generally assumed to be positive, it is important to verify this premise in order to accurately assess the potential impacts of fluctuations in the hydrological regime on fish populations in a given watercourse. Angermeier and Schlosser (1989) showed that the best predictive variable of diversity was fish abundance at a site, and that the complexity level of habitats had no predictive (explanatory) force. In fact, the very close relationship between species richness and fish abundance in habitats seems to be explained by sampling effort. Angermeier and Schlosser (1989) assumed that variations in the diversity of fish assemblages in the different habitats are primarily a function of the reproductive success of each species and that this success is strongly influenced by interannual fluctuations in flow and water temperature. This section summarizes the results of the study of this hypothesis with reference to the northern pike in the St. Lawrence.

The availability of habitats that can be used by the northern pike is a direct function of the water level of rivers. The decline in the northern pike population in the Gulf of Finland has been attributed to changes in the plant cover in spawning and nursery habitats, and especially to the disappearance of *Fucus vesiculosus* (Lehtonen 1986). Although the northern pike acts opportunistically in selecting egg-laying sites, it seems that certain types of vegetation favour the survival of the eggs and larvae of the species (Vaillancourt et al. 1992). For example, a wet meadow dominated by graminoids is an ideal habitat for reproduction. The species composition and surface area of the wetlands in Lake Saint-Pierre vary with hydrological conditions (Hudon 1997). Specifically, high water levels give spawners access to the best spawning grounds. Stability of water levels is an equally crucial factor in egg and larva survival. If the floodwaters recede too quickly, eggs may be exposed to the open air and die from desiccation. Similarly, larvae attached to vegetation may suffer the same fate if the water level drops significantly.

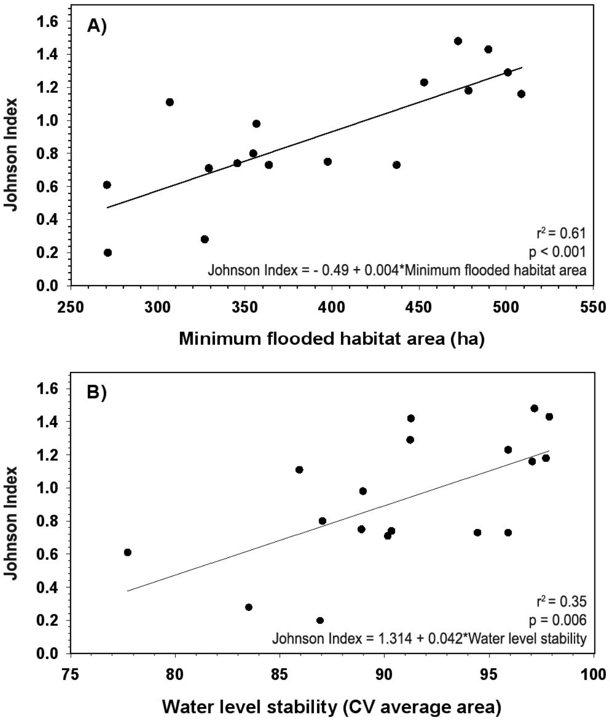
The results of the two-dimensional model (Rioux and Morin 2001) have been used to determine the area of available potential habitats for northern pike reproduction in the Îles de Boucherville (across from Montréal) (Armellin 2004) for a range of hydrological conditions in the river. In the spring of 1976, which was a record year for hydraulicity, discharge was about 14 223 m^3/s, and as a result, 565.3 ha of floodplain in the northern part of the Îles de Boucherville were under water (Figure 7.9B). In 2000, spring discharge was about 9275 m^3/s, so only 326.4 ha were flooded in the same area (Figure 7.9A). Based on these figures, a relative increase of 53% in flow between the two years resulted in a 73% increase in spawning ground accessibility.

Using the age structure of this particular northern pike population, which was inventoried over a period of several years, Armellin (2004) demonstrated a positive linear relationship between a relative year-class index (Johnson 1957) and spawning ground accessibility (Figure 7.10A). The area of flooded habitats explained 61% of the observed variance in the year-classes of the northern pike of the St. Lawrence. Based on the fact that speed of floodwater recession is another key factor in the survival of eggs and fry, it was possible to establish a positive relationship between that factor—expressed as the spring water level variation coefficient—and the year-class strength of the northern pike (Figure 7.10B) (Armellin 2004; Armellin and Méthot 2004).



Source: Armellin et al. 2003.

Figure 7.9 Satellite images classified by vegetation showing extent of flooding under two different types of hydrological conditions



Source: Armellin 2004.

Figure 7.10 Linear relationship between northern pike year-class strength index (Johnson index), flooded area of spawning grounds and stability of spring water levels in the St. Lawrence

Water temperature is one of the main environmental factors controlling the reproduction, development, growth and metabolic activity of the northern pike (Casselman 2002). If temperatures are too low during the reproductive period, fatal congenital malformations, direct mortality or atresia of eggs in the gonads of female fish may ensue (Casselman 2002; Fortin et al. 1982). In a study conducted on the Richelieu River, Fortin et al. (1982) identified the average air temperature in June as a determining factor in the year-class strength of the northern pike. Similarly, Massé et al. (1991) reported that air temperature had a significant influence on the species's year-class strength in the St. Lawrence. Hence, the years with high rates of increase or high water temperature variation coefficients appear to correspond to the years of highest seasonal temperatures, which foster the growth of young fish to a size required for them to survive the winter (Frost and Kipling 1967). This is in fact the case for the population in the St. Lawrence, where the daily rate of temperature increase in June and July and the coefficient of variation of average degree-days from April to September show positive correlations with the relative year-class strength index (Armellin 2004; Armellin and Méthot 2004).

All these abiotic factors affect northern pike recruitment dynamics simultaneously. The results of a multiple regression model showed that the availability of reproductive habitats and the maximum water temperature during the reproductive period explain 73% (adjusted $r^2 = 0.73$) of the interannual variability of northern pike year-class strength in the St. Lawrence (Armellin and Méthot 2004). Even considering the fact that several biological phenomena, such as adult biomass, female fertility (Craig and Kipling 1983), predation and cannibalism (Fortin et al. 1982), may influence the dynamics of northern pike populations, it is the abiotic and climatic factors that seem to play an overriding role in determining the accessibility of habitats recognized as essential for controlling recruitment and abundance of the species in the St. Lawrence.

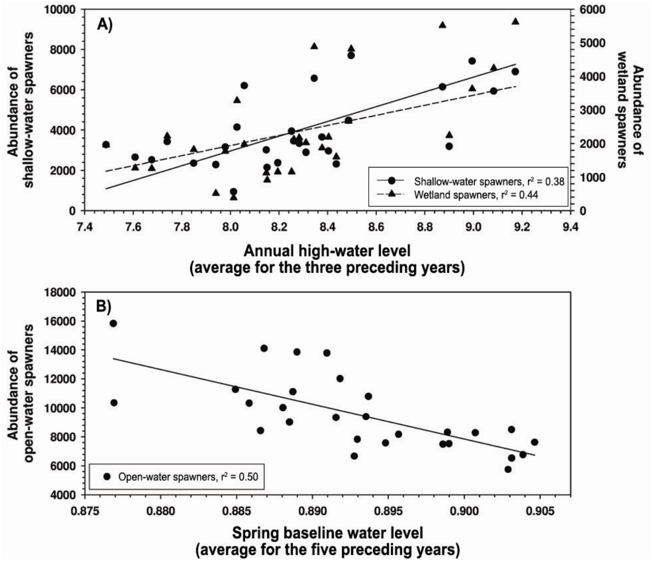
Variations in relative abundance and diversity of assemblages

On the basis of annual catches at the Saint-Nicolas experimental trap fishery from 1975 to 2002, de Lafontaine and Marchand (2004) tested the hypothesis that the annual abundance of fish varied according to hydrological conditions prevailing during the years prior to catch, which corresponded to the recruitment period for the various species. The study focused on a total of 40 different fish species and 13 functional fish groups. The functional groups comprised a subset of species with similar ecological characteristics and habitat requirements, and group abundance corresponded to the total numerical strength of each species.

The results showed that interannual changes in the abundance of 12 species were related significantly to fluctuations in water level; water temperature was not a factor. Interannual variability in the abundance of 14 other species was attributed to a combination of parameters associated with water levels and water temperature. The time interval between the catch year and the year of the environmental variable generating the best predictive model corresponded fairly closely to the modal age of the fish caught. As Welcomme (2000) has stated, the existence of significant relationships between fish abundance and environmental variables associated with time intervals that correspond to the number of years between egg deposition and catch year suggests that fish productivity and abundance are determined by processes operating during the reproductive phase of the various species.

Similarly, an analysis of functional groups showed that the prevalence of fish spawning in shallow water and the prevalence of fish spawning in wetlands correlated positively with St. Lawrence water levels during the three years preceding catch (Figure 7.11A). Furthermore, the prevalence of fish spawning in open water was inversely related to the spring base level, showing that a small freshet has a negative effect on the abundance of species in this group (Figure 7.11B). Abundances varied by a factor of 2 to 5, depending on the functional group. Overall, significant relationships between group abundance and various water-level parameters were observed for 8 of the 13 functional groups under study, whereas the interannual variation in abundance of five other functional groups was more effectively explained by a combination of water-level and water-temperature parameters. It is found, therefore, that interannual fluctuations in the St. Lawrence hydrological regime have a significant impact on the recruitment and abundance of fish in the river.

Between 1975 and 2002, the species richness of the fish community inventoried at the Saint-Nicolas fishery remained stable (average of 42 species per year), while total annual catches varied by a factor of 3, declining from 19 466 individuals in 1976 to 6124 in 1989. Annual abundance of the entire fish assemblage (40 species) caught at the experimental fishery appeared to be strongly and inversely correlated (regression cœfficient $r^2 = 0.74$) with the average spring base level ratio for the St. Lawrence measured over the five years prior to catch. The base level ratio is inversely related to the amplitude of the spring freshet. It can therefore be inferred that the abundance of the fish community in the Lower St. Lawrence, between Lake Saint-Pierre and Île d'Orléans, is highly dependent on the strength of the spring flood. This suggests that fish productivity is greater in years when spring flooding is heavy and prolonged. In general, fish abundance was not very sensitive to hydrological conditions during other seasons of the year.



Source: de Lafontaine and Marchand 2004.

Figure 7.11 Annual abundance of various functional groups of fish based on level parameters in the St. Lawrence

The impact of spring flooding—amplitude, timing and duration—on river fish recruitment and productivity has been documented many times in a host of other studies (Galat and Zweimüller 2001; Welcomme 2000). Given the key role of climate in interannual fluctuations in the river's hydrological regime, the empirical relationships between fluctuations in that regime and abundance and productivity of fish are primarily interpreted as the fluvial ecosystem's dynamic response to the climatic signal that influences the hydrology of the Lower St. Lawrence.

The St. Lawrence: Ecosystem or Canal?

According to the criteria and terminology used by Welcomme (1979), the Lower St. Lawrence has reached a "slightly modified" stage in its evolution. Over the years, the St. Lawrence has been excavated to channel its flow and facilitate water retention for navigation purposes. However, the timing and duration of freshets have changed relatively little. The floodplain is being increasingly stripped of trees and subject to extensive farming, with various areas devoted to livestock or specific local uses. Urban sprawl stretches along the shorelines. Changes in the hydrological regime remain slight, but they reflect a significant trend over the past 100 years toward the "channelization" of the river, while amplitude variations in water levels have become less pronounced since the regulation facilities were built.

Despite all the pressures exerted by human activity, the river's hydrological regime still depends to a large extent on variations in the climate, which controls fluctuations in flow and water levels in the section downstream from Montréal. In fact, interannual variations in the hydrological regime are in the 40% range and remain much higher than variations associated with regulation (~ 5%). These hydro-climatic fluctuations have tangible, measurable effects on the freshwater fish in the St. Lawrence. Over the short term, flow rates and water levels influence the migration patterns and spatial and temporal distribution of fish by ensuring the availability and accessibility of breeding and feeding habitats. Over the long term, water-level fluctuations play a role in determining the annual recruitment strength and dynamics of populations of several species and, by extension, the productivity of the fish community as a whole. As observations in other rivers have shown (Pusey et al. 2000; Loneragan and Bunn 1999; Wanzenböck and Keresztessy 1995), the impacts of hydrological fluctuations on the habitats and dynamics of fish in the St. Lawrence vary by species. A higher water level may be beneficial to one group of species and harmful to another. The species richness of fish in the St. Lawrence has remained stable, and in spite of the precarious situation of a number of species, only the striped bass (*Morone saxatilis*) may be considered to have disappeared completely from the river (Robitaille 2004). The construction of hydroelectric dams in the upstream sectors of the river has had adverse effects on the diversity and structure of fish communities, causing a loss of species in artificial reservoirs upstream from the dams.

It can therefore be said that interannual fluctuations in the hydrological regime of the Lower St. Lawrence help maintain the diversity and dynamics of the entire fish community both locally and regionally. Increasing regulation to reduce these hydrological variations still further will have adverse effects on the life cycle and production of the fish. Therefore, short of restoring the integrity of the river to a state comparable to its original, pre-regulation condition, it appears essential to consider a "naturalization" alternative, whereby the hydrological characteristics of a regulated system can resemble those of a natural one (Kœl and Sparks 2002). If efforts are focused on reducing human control of flows and water levels to a minimum, the hydrological regime will then be controlled by climatic forces, potentially resulting in fluctuations in the river's water levels over a long-term cycle of approximately 30 years (Chanut et al. 1988). Given the importance of spring flooding to various aspects of fish ecology in the St. Lawrence, the integrity of the flood cycle must be preserved in order to maintain a highly diversified and resistant fish community. Controlling flooding and/or regulating flows and water levels in order to deal with the cases of individual species are not recommended approaches, because if they are repeated over several years, there are bound to be effects on the other components of the ecosystem. It would be more appropriate to act on the real causes of disturbance to a species of interest, instead of using regulation of the hydrological regime to rectify a situation. At the same time, priority must be given to protecting and, if possible, restoring shoreline areas and floodplains, which are essential to the maintenance of fish populations. The worst-case scenario would be stabilization of the floodplain biocenosis, because fish species adapted to this variable, temporary environment do not tolerate stabilization. There are few fish in areas where there is no floodplain (Welcomme 1979). Given the current state of the river, a "naturalization" approach to management of the hydrological regime would seem necessary to avoid turning the St. Lawrence River ecosystem into a canal.

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Chapter 8

WETLAND BIRDS: A GROUP VULNERABLE TO HYDROLOGICAL CONDITIONS IN THE ST. LAWRENCE WETLANDS

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Seasonal and annual variations in water levels and flows in the St. Lawrence River have a considerable impact on natural ecosystems. Variations in water level influence the areal extent, productivity and diversity of wetlands (peat bogs, marshland, swamp, wet meadows, aquatic grass beds), which provide habitat and food sources for a wide range of animals, including many bird species.

The progressive decline in precipitation and anticipated rise in temperatures projected in the climate change scenarios for the Great Lakes–St. Lawrence Basin point to a significant drop in the quantity of water flowing from Lake Ontario into the St. Lawrence. In view of the predicted repercussions of climate change on the Great Lakes–St. Lawrence Basin, the International Joint Commission (IJC) undertook to reassess the existing regulation criteria to take account of environmental factors. Fortunately, recently developed hydrodynamic modelling tools make it possible to evaluate the effects of various water-level scenarios on the fauna and flora of the entire fluvial (freshwater) section. This chapter describes the main characteristics of the avian fauna and the effects of water-level regulation on aquatic and wetland-dependent birds along the St. Lawrence River.

Present State of Avian Fauna

Wetlands: Conditions conducive to a high diversity of bird life

The term *wetland* designates the varied mosaic of habitats found where land meets water, wherever the ground is waterlogged or flooded long enough to influence soils or vegetation. All these ecosystems are of great value, given their contribution to biological diversity and productivity, their filtering capacity and their role in the life cycles of many plant and animal species. The floodplain plays a key part in the functioning of the river ecosystem; it is where many fish species spend part of their life cycles in spring, and large flocks of geese and ducks gather during migration.

Regulation of water levels in Lake Ontario affects first and foremost the flood-prone areas in the freshwater stretch of the St. Lawrence River, especially the wetland habitats of the fluvial lakes and low-lying islands in the fluvial section. This is why studies of the impact on bird life have been limited to riverine species, those that customarily nest in shoreline and aquatic habitats associated with this watercourse. Of the 370 or so bird species that nest in the fluvial section of the St. Lawrence, 81 depend directly on resources associated with the river itself (DesGranges and Jobin 2003; DesGranges and Tardif 1995), and 72 wetland species have been observed nesting in wetland habitats along the river.

Major wetland bird groups

The species that make up the nesting avian fauna of the St. Lawrence can be broken down into a variety of groups on the basis of their anatomy or their specific ecological requirements. With half of all species, the passerines are five times as abundant as most other groups, such as colonial birds, waterfowl and raptors. The groups vary in both number of species and relative abundance along the whole length of the St. Lawrence, reflecting the availability and quality of the successive ecological zones. Roughly 41% of the species nesting along the St. Lawrence show a preference for aquatic habitats, 36% for woodland, and 23% for farmland or urban environments (DesGranges and Jobin 2000). The St. Lawrence Lowlands are the sector richest in breeding species with a predilection for freshwater habitat. Though many sections of the shoreline are not particularly rich in breeding species, they are nonetheless very important for the nesting of waterfowl and certain kinds of colonial birds on the islands in Lake Saint-Pierre and along the freshwater corridor. The freshwater portion of the river and its floodplain are home to nearly 50% of the entire breeding population of dabbling ducks in the St. Lawrence (Lehoux et al. 2003, 1995).

Use of wetlands

The freshwater corridor of the St. Lawrence is of great importance to birds that nest there or stop over during migration. The area is particularly remarkable for the waterfowl that gather there in spring. Generally, the first migrants arrive in late March, and the birds leave again en masse in mid-May. Spring staging of waterfowl thus lasts for nearly a month and a half, with the migration usually peaking in about the third week of April.

In early May, most resident ducks leave the floodplain and settle their broods in marshy habitats along the shores, especially around islands. The breeding season for dabbling ducks in the fluvial section under study essentially lasts some 150 days, from mid-April to mid-September (Figure 8.1) (Lehoux et al. 2003). The period from early April until mid-September is therefore the crucial time when the water levels in the freshwater portion of the river are likely to impinge upon both migration and the various phases of breeding (egg-laying, incubation and rearing).

May is when most wetland birds return from the south, and most species are busy rearing their broods from mid-May to mid-July. Waterfowl and wetland species rely largely on aquatic resources (invertebrates, small fish and the seeds of water plants) for food and nesting, while the majority of colonial species customarily nest in multi-species colonies for reasons of safety.

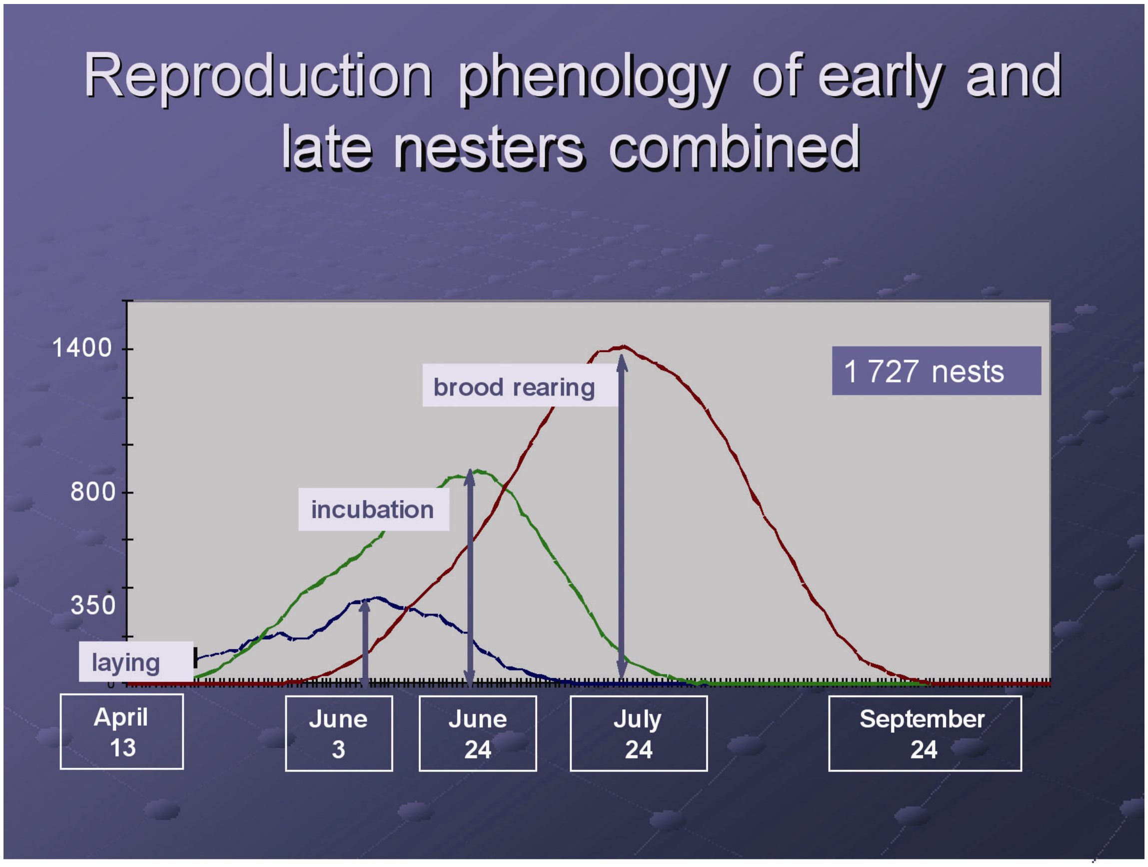

Reproduction phenology of early and late nesters combined

Figure 8.1 **Breeding season of dabbling ducks in the freshwater corridor of the St. Lawrence**

The marsh environments on 171 islands in the Lake Saint-Louis–Lake Saint-Pierre stretch of the river have an annual production capacity of nearly 2500 dabbling duck nests (Lehoux et al. 2003). Gadwall, mallard and pintail are the dominant breeding species in the region, in that order, with 35%, 23% and 19% respectively of nests found. Aggregate average nesting density on islands is estimated at 0.23 nests per hectare. Almost three-quarters of the nests observed in the various surveys conducted by Bélanger (1989) in our study area in the 1970s and 1980s were located in tall grass (average nest density: 0.7 per ha).

Bird distribution and specialization by vegetation zone

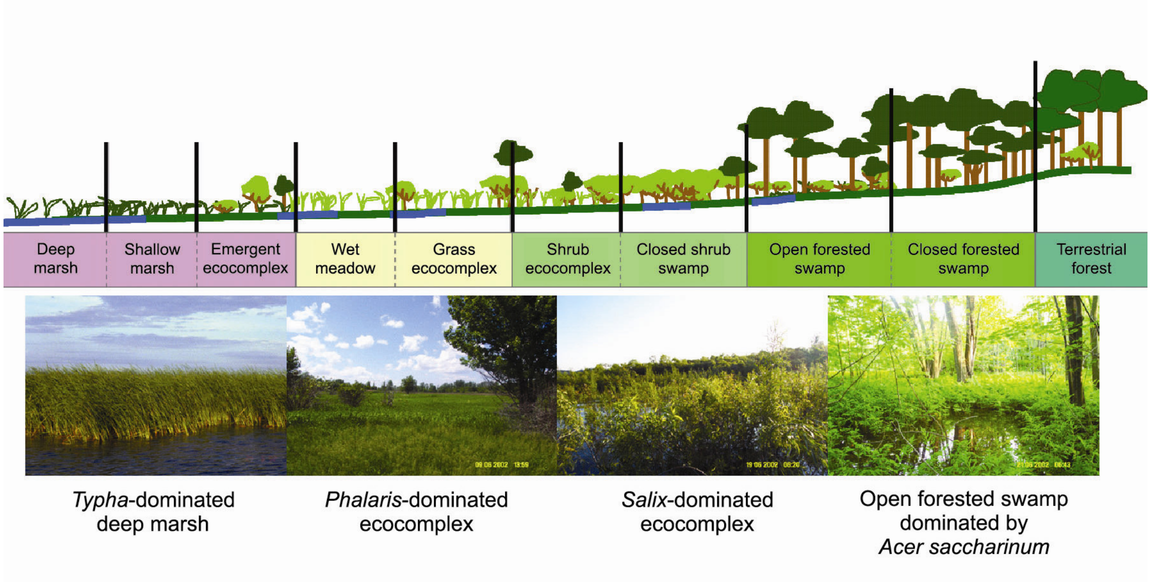
The territories defended by breeding birds normally comprise several different habitat types. A method better suited to the study of birds has therefore been developed to evaluate the vegetation and landscape characteristics of wetland habitats used by various bird species (DesGranges et al. 2005). Since birds are particularly sensitive to the landscape characteristics of the habitats surrounding their breeding territory, the environment has been characterized up to a distance of 350 m from the centre of the sampling sites (areas of 38.5 ha). Characterization of the landscapes was done by using classified remote sensing images (MEIS 2000 and IKONOS 2002).

Some 80 species of wetland birds nest in the various wetland habitats along the Lower St. Lawrence. These habitats comprise various plant communities including many plant composition and structure combinations. These habitats number ten and are represented throughout the riverine toposequence (Figure 8.2) of the Lake Ontario–St. Lawrence freshwater hydrosystem.

The wettest part of the gradient (in mauve), flooded throughout most of the breeding season, takes in deep marsh, shallow marsh and the emergent plant ecocomplex.

Deep marsh is a homogeneous herbaceous habitat devoid of trees and shrubs. The dominant plant species that colonize it are emergent plants such as bulrushes (*Scirpus lacustris* and *S. fluviatilis*), swamp spike-rush and cattails. This habitat is in constant interaction with moving water, and water levels are usually high (nearly 1 m).

Shallow marsh has the same characteristics as deep marsh; it is a homogeneous herbaceous habitat with no trees or shrubs, but the water level is much lower (averaging less than 50 cm). The dominant species are cattails (*Typha*), flowering rush, broad-fruited bur-reed, sweet flag and river bulrush (*S. fluviatilis*).



Typha-dominated deep marsh

Phalaris-dominated ecocomplex

Salix-dominated ecocomplex

Open forested swamp dominated by *Acer saccharinum*

Illustration: Caroline Savage, Environment Canada.

Figure 8.2 Bird habitats forming the riverine toposequence of the freshwater portion of the St. Lawrence

The emergent plant ecocomplex is a heterogeneous herbaceous environment, which may contain close to 30% shrubs and 10% trees. This type of marsh is often found in places where dikes have been built, where soils are more heterogeneous and the microtopography and water levels more variable. The dominant emergent plants are cattails, flowering rush and horsetail, while the shrub stratum is dominated by willows, sweet gale, speckled alder, buttonbush and red-osier dogwood.

The second group of habitats along the gradient (in yellow) is flooded in spring, but remains above water for most of the season. This group includes wet meadows and grass/shrub ecocomplexes. Wet meadows constitute a homogeneous herbaceous environment with no trees or shrubs, dominated by grasses such as reed canary-grass or blue-joint or by other non-emergent herbaceous species such as sedges. Grass/shrub ecocomplexes contain less than 30% bushes and up to 20% trees. The dominant species are reed canary-grass, blue-joint and other grasses. The codominant shrubs are willows, red-osier dogwood, broadleaf spirea and speckled alder. This type of habitat is found chiefly on islands that have previously been farmed. The grass/shrub ecocomplex then forms brushland with an especially rich diversity of both plant and animal life.

Next come the shrub ecocomplex and closed shrub swamp (pale green). These groups are subject to variable hydrological conditions, depending on whether the habitat is diked or not. The shrub ecocomplex has 30–60% shrub cover and may contain up to 30% trees. The dominant shrubs are speckled alder, willows and broadleaf spirea. It is an environment with many openings, colonized chiefly by grasses like blue-joint and sedges and emergent plants like cattails. Closed shrub swamp is more homogeneous and has 60% shrub cover. The dominant species are speckled alder, willows, red-osier dogwood and buttonbush. Willow swamp is found mainly along riverbanks on sandy deposits. Alder swamp is characteristic of diked areas, where it grows abundantly on organic deposits, as does buttonbush, which is found in the same kind of conditions or in permanently flooded habitats.

At the top of the gradient are the last two groups, dominated by trees (shown in darker green). Swamp is distinguished from terrestrial forest by its palustrine components, attributable to spring flooding. The boundary between terrestrial forest and closed forested swamp is indirectly drawn by hydrological factors, since the less frequent and shorter periods of flooding in terrestrial forests allow a larger number of terrestrial plant species to become established. The degree of opening in the canopy is what distinguishes open and closed forested swamps. Open forested swamps have a cover of 30–80% and thus have many openings that are colonized by herbaceous species or shrubs. These swamps are characterized by a greater number of tree and shrub strata. Closed forested swamp has a cover exceeding 80%. The dominant tree species in swamps are silver maple, red ash, arborescent willows, cottonwood, red maple and American elm. Terrestrial forests are closed treed environments with over 80% cover and with more terrestrial components, especially among the codominant tree species (e.g. bitter hickory) or herbaceous plants in the ground cover. The dominant trees are species with a wide ecological amplitude, such as red ash and cottonwood.

Importance of River Dynamics for Bird Life

Wetland bird abundance and diversity are largely determined by the diversity of wetland vegetation and the complexity of its spatial distribution in the landscape (Gibbs et al. 1991). Any ecological process tending to simplify wetland habitats or make them more homogeneous is therefore detrimental to bird life. All the plant communities along the shores of Lake Ontario and the St. Lawrence River include one or more bird habitats in which water depth and duration of flooding are decisive (DesGranges et al. 2006). The most crucial factor is seasonal and annual variation in water levels (see Chapter 2), which determine the extent and physiognomy of the wetland habitat and the risk of nest destruction through flooding or dewatering (Steen and Gibbs 2002; Gilbert 2001; Mowbray 1997; Leonard and Pickman 1987; Griese et al. 1980; Robertson 1971; Weller 1961; Glover 1953).

The floodplain

The Lake Saint-Pierre floodplain, including the sector adjoining the Berthier–Sorel islands, presents a mosaic of habitats consisting of swamp, natural grassland and, especially, farmland. Only the flooded farmland is routinely frequented by waterfowl in spring for feeding and resting. The floodplain farmland (apart from the sectors managed by Ducks Unlimited, 10% of which is shielded from high water to better serve the needs of wildlife) starts to flood when the water level reaches 4.5 m. When the river reaches the two-year recurrence level (attained once every two years; 6.2 m at Sorel), flooding covers nearly 2500 ha of cropland, and when the 100-year recurrence level is reached (8.0 m at Sorel), the habitat available to waterfowl increases to some 10 000 ha.

The various surveys of Lake Saint-Pierre done since the 1980s have confirmed that between 15 000 and 20 000 dabbling ducks, 50 000 to 100 000 or more Canada geese and up to 550 000 snow geese use the Lake Saint-Pierre floodplain at the peak of spring migration (Dombrowski et al. 2000). However, most of the waterfowl frequenting Lake Saint-Pierre congregate in the sectors managed by Ducks Unlimited; indeed, almost all the snow geese (97%), some 50% of the Canada geese and nearly 30% of the dabbling ducks seek refuge there. The farmland directly affected by water levels attracts very few aquatic birds: about 15% of the migrating Canada geese and 30% of the dabbling ducks, amounting to some 15 000 to 20 000 birds. Those sectors less affected by water levels, including the larger bays, the midstream waters and the shoreline of the lake, share the remainder of the migrating waterfowl population.

Wetland habitats

Data from several years of bird counts make it possible to study wetland habitats under differing flooding, water-level and water-level fluctuation conditions (DesGranges et al. 2006). The indicator species were chosen on the basis of their affinity for one or other of the four main wetland ecosystems (marshland, wet meadows, shrub swamp and forested swamp), their sensitivity to hydrological conditions (surface water depth or height of the water table and fluctuations in water levels) (Weller 1999), and their nesting strategy (on the ground near the shoreline, in floating vegetation, in emergent vegetation or in terrestrial vegetation) (Steen and Gibbs 2002; Gibbs et al. 1991).

For marshland, the following indicator species have been selected on the basis of the statistically significant biological impact that hydrological conditions have on them:

- the black tern, which generally builds a rudimentary nest on a raft of dead water plants (Dunn and Agro 1995);
- the common gallinule, which anchors its large, sturdy nest to emergent water plants (Bannor and Kiviat 2002);
- the Virginia rail, which builds its nest of plant material among emergent vegetation in waterlogged or slightly submerged habitats (Conway 1995);
- the least bittern, currently considered a species at risk in the study area, which builds a nest of leaves among rank emergent vegetation, generally 20 cm to 80 cm above the water (Giguère et al. 2005; Gibbs et al. 1992a). Since observation data for this species are insufficient to establish a statistical link between nesting density and hydrological variables, a breeding index has been modelled on the basis of habitat suitability indices (see Giguère et al. 2005);
- the marsh wren, whose nest, also of leaves, is built in rank emergent vegetation, generally more than 60 cm above the water, in wetlands of varying depth (Kroodsma and Verner 1997);
- the American bittern, which nests on the ground, usually very close to the water (< 15 cm), on the shoreline or an islet (Gibbs et al. 1992b).

With the exception of the American bittern, all these species show a curvilinear relationship between nesting density and water depth (DesGranges et al. 2006, 2005). The black tern's nesting density increases with water depth, whereas the other species display a preference for shallow water (optimum depth: 0.3 to 0.8 m). According to predictive data, marshland that is dewatered during the breeding season is unsuited to at least four of the six indicator species. The data for the other two species, the least bittern and the American bittern, are insufficient to make a determination on this score. However, the known preferences of the least bittern and the published data on this species's nesting habits lead us to believe that the least bittern's nesting density is also lower on dewatered marshland.

We have confirmed a negative correlation between nesting density and water level for five of the marshland indicator species (DesGranges et al. 2006, 2005).

Forecasts point to a sharp drop in density with an increase in water level of 0.2 m or more between two periods of seven to eight days. The Virginia rail is the only species for which both falling and rising water levels affect nesting density. These results clearly demonstrate that wetland birds react strongly to hydrological conditions in their nesting habitat, probably because they build their nests either on floating vegetation or slightly above water in emergent vegetation. If the water level rises, nests are likely to be flooded; if it drops, nest sites may dry out, exposing them to land predators, and they may be abandoned (Post 1998; Weller 1961).

As indicators for habitats flooded only during spring freshets at the start of the breeding season, we have chosen two species that nest mostly in trees or shrubs, more rarely on the ground: they are the song sparrow for shrub swamp (Arcese 2002) and the veery for forested swamp (Moskoff 1995). Both species usually choose nest sites in places where the water table is close to the soil surface. They show a preference for environments that are just wet rather than regularly submerged.

The veery is generally more sensitive to flooding than the song sparrow, but nest density for both species drops sharply as water levels rise. No significant correlation has been established between hydrological variables and nesting density for the indicator species associated with wet meadows (DesGranges et al. 2006, 2005).

Threats and Issues

Flow regulation and bird habitats

The most important ecological factor for the conservation of wetland diversity, and hence the biodiversity they support, is the daily, seasonal and annual variation in water levels and flows. Biological communities are adapted to the natural fluctuations in water levels. However, disturbance of natural regimes, whether by human action or as a result of climate change, may alter the areal extent, composition and distribution of the various types of wetland (Morin et al. 2005; Wilcox et al. 2005). Such alterations may have serious repercussions on the capacity of the wetlands of the Lake Ontario–St. Lawrence River basin to fulfill their function as habitat for hundreds of bird species, especially during the breeding season. All the wetlands of the Lake Ontario–St. Lawrence River basin consist of several habitat sequences subject to the effects of flooding associated with the hydrological regime. The main variables are the duration of flooding, which determines the total area of wetland and the presence of surface water in swamps, and water depth, which determines the physiognomy of the landscape (Morin et al. 2005; Wilcox et al. 2005). The wetlands of the Great Lakes–St Lawrence Basin are subject to both short and longer cycles of flooding and drought (IJC 1993).

Long-term flooding, extending over one or two vegetation seasons, is necessary to prevent trees and shrubs from becoming established and to allow herbaceous plants to complete their life cycles. Herbaceous plants thus have time to complete one or more reproductive cycles, ensuring they persist in the local seed bank (Keddy and Reznicek 1986). If there is no flooding, trees and shrubs invade the marsh, unless it is artificially maintained by annual burning, as was done on Lake Saint-François until 1978 (Jean and Bouchard 1991).

Depending on the plant species present and their spatial distribution, a diversity of environments develop serving as habitat for the various animal species frequenting them in lesser or greater numbers. Avian assemblages of various types frequenting the freshwater environments of Lake Ontario and the St. Lawrence River have been identified, including some species at risk.

Importance of flow regulation for riverine birds

Avian assemblages

The freshwater stretch of the river is very uniform in terms of avian assemblages on a local scale, reflecting the continuity of a varied mosaic of habitats along this sector of the St. Lawrence. The ecocomplex described in the *Atlas of the Breeding Birds of Québec* are located in the freshwater stretch and shelter an average of 45 riverine species, or 56% of this sector's riverine species (DesGranges and Tardif 1995). The wetland avian assemblages consist mainly of common freshwater species associated with southerly latitudes. Though abundance is essentially the same from one type of wetland habitat to another (roughly one individual per hectare), the same cannot be said for avian biomass, which is substantially higher in marshes. With a "bird mass" of over 1.25 kg per hectare, the biomass in marshes is practically four times what is found in the other three types of wetland. This is attributable to the fact that the water birds frequenting marshes weigh an average of 11.5 g, compared to about 2.5 g to 3.5 g for the species that nest in the other types of wetland habitat.

The links between birds and their habitats (vegetation characteristics and hydrological conditions) have been detailed by means of cluster analyses; this has made it possible to classify habitats by type according to the hierarchy of those criteria that seem to be the most significant for the species (DesGranges et al. 2006, 2005). This approach has brought to light three categories of environmental variables of particular importance for nest site selection in wetland birds: 1) tree cover and the degree of opening in the canopy; 2) hydrological conditions, and 3) the degree of heterogeneity of the riparian landscape. The various combinations of these categories of variables allow us to identify ten types of avian assemblage (Figure 8.3).

The first assemblage (Figure 8.3, top right corner) is associated with treeless wetlands (less than 10% cover): deep marsh, shallow marsh and emergent plant ecocomplexes. These habitats are flooded for a good part of the breeding season. The marsh wren is particularly abundant in the most heavily flooded sites, whereas the black tern seems to be more common in habitats less prone to water-level fluctuations. Depending on local microtopography, these areas, dominated by herbaceous plants, may present a more or less heterogeneous spatial structure.

The American coot, the common gallinule, the sora, the Virginia rail, the least bittern and the American bittern are the most common species in habitats where pools persist throughout the summer.

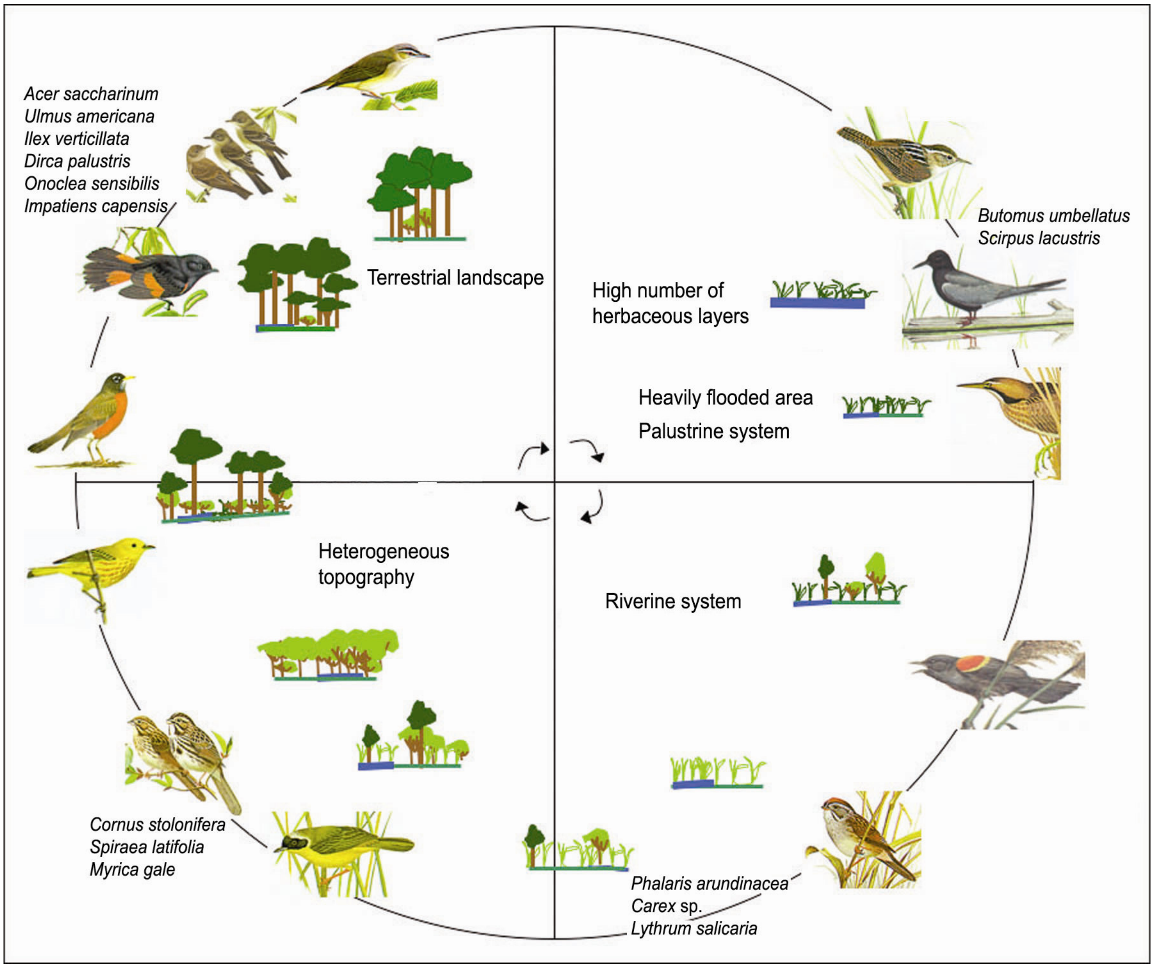


Illustration: Caroline Savage, Environment Canada.

Figure 8.3 Factorial analysis (RDA) showing the environmental variables most closely associated with species abundance in the various types of bird habitat

The second assemblage (Figure 8.3, lower right corner) consists chiefly of the red-winged blackbird and the swamp sparrow, species customarily associated with semi-open habitats such as wet meadows and grass/shrub ecocomplexes.

The third assemblage (Figure 8.3, lower left corner) is found in shrub ecocomplexes and closed shrub swamp. Among the species most frequently seen in forest-edge thickets are the yellow warbler and the song sparrow. This type of landscape is a highly heterogeneous mosaic of habitats, sometimes including permanent ponds which attract dabbling ducks (e.g. the American wigeon, shoveller and mallard), the green heron and the common yellowthroat.

The fourth assemblage (Figure 8.3, upper left corner) is found in wooded wetlands: open forested swamp, closed forested swamp and terrestrial forest, all of which may be more or less covered and more or less subject to spring flooding. At the bottom of this sequence, trees are more sparse, and pools often form in spring. This is the preferred habitat of the wood duck and the tree swallow. In some places, structures have been erected to retain water and form deeper ponds, surrounded by dead trees and shrubs. Such arrangements attract wood duck, tree swallows, alder flycatchers and willow flycatchers. In habitats where the forest canopy is more closed, species such as the veery, the warbling vireo and the northern oriole are more common. At the upper end of the sequence flooding is less frequent and of shorter duration, and the bird life is more characteristic of deciduous forests. Forest species such as the white-breasted nuthatch, the eastern wood-pewee, the red-eyed vireo and the American redstart are well represented in this ecotone between forested swamp and dry deciduous woodland.

The stability of summer water levels in the ponds managed by Ducks Unlimited along the shores of the riverine lakes seems to be attracting many other kinds of birds as well as waterfowl. Larger numbers of water-loving birds such as bitterns, rails, gallinules and Wilson's snipe have been observed there. This finding clearly shows how important residual perched marshes must have been in the floodplain in earlier times. Before the recent extensive draining for farming and the rapid urban development of land along the river, these natural ponds must certainly have harboured a significant proportion of the water bird populations of the St. Lawrence Lowlands (DesGranges and Jobin 2003).

Waterfowl on migration

Water levels are the chief factor governing use by and distribution of waterfowl in the unmanaged sectors of Lake Saint-Pierre during spring migration. When the water level at Sorel fails to reach the minimum level of 4.4 m, unmanaged sectors dry out and are completely abandoned by dabbling ducks and Canada geese. It is high water levels, exceeding the 6.0 m mark at Sorel, which provide for the best distribution of migrating aquatic birds in the Lake Saint-Pierre floodplain between April 10 and the first week of May.

If high water levels are not regularly maintained in the Lake Saint-Pierre floodplain, we can expect to see significant impact on the waterfowl population that uses it. Nearly 15 000 birds would have to move and congregate more densely in managed marshland, which is already intensively used by waterfowl. This could have the effect of increasing inter- and intra-specific stress. The managed habitats are often occupied largely by snow geese, leaving little room for other species. Since Canada geese do not get on well with snow geese, the former may be forced to move into less suitable habitats.

High concentrations of birds in one sector may also lead to rapid exhaustion of food resources. When spring freshets were small, Lacroix and Bélanger (2000) observed a larger proportion of dabbling ducks foraging, suggesting that the available food resources were somewhat limited. Poor diet during the migratory staging period may entail poor physiological condition, potentially resulting in lower breeding success later. However, it remains difficult to make a qualitative assessment of the impact of small spring freshets on reproduction.

The situation could become even more serious if managed areas should ever cease to fulfill their function adequately, for instance as a result of large-scale failure of control structures (dikes, shutters, pumps, etc). In such a case, the various activities (feeding, resting or breeding) of over half a million water birds (500 000 snow geese, 50 000 Canada geese and 10 000 dabbling ducks) would be disrupted, not to mention the ensuing economic repercussions. Indeed, it has been estimated that springtime observation of water birds in the neighbourhood of Baie du Febvre alone, on the south shore of Lake Saint-Pierre, generates annual revenues of $1.5 million.

Breeding waterfowl

Water levels may sometimes limit the area available for waterfowl nesting and rearing, especially when these levels are high, as they were, for instance, in the early 1970s, when they broke records. However, it is hard to assess the impact of such situations on bird life with any accuracy. More limited habitat is not necessarily indicative of compromised breeding. In lean years, birds may change their behaviour and adapt to the prevailing, more restricted conditions. They may, for example, nest and rear their broods in greater densities. They may even take to habitats that they would otherwise tend to eschew, such as farmland, an environment less often flooded, even in wet years. Broods may also feed more often in submerged marshland, which is more abundant when water levels remain especially high during the growing season. Recourse to submerged marshland may then induce broods to forage at different times of day to evade predators or disturbance, since submerged marsh offers little protective cover.

Yet water levels may influence waterfowl productivity. Productivity seems to be optimum in years when average water levels during the growing season remain high and to drop in years when these levels are kept very low. This phenomenon may be explained by the fact that, at particularly low levels, island habitat, where the bulk of waterfowl production in the study area occurs, is more accessible to terrestrial predators, the latter being one of the greatest limiting factors on waterfowl reproduction in the study area. In the Berthier–Sorel islands, for example, breeding success in some years is no more than 25%, most losses being attributable to such predators as racoons and skunks.

Low water levels will dry out emergent marshes to a large extent, thereby depriving broods of access to protective cover and quality foraging grounds. Such levels also leave a lot of stagnant water, which may be conducive to the development of botulism, a problem that has already occurred several times in the freshwater portion of the St. Lawrence, specifically in 2005 and 2001, when mean July and August water levels at Sorel were 3.8 m and 3.9 m, respectively.

However, it is within the bounds of possibility that very high water levels (> 5.5 m at Sorel) may also have an adverse impact on productivity. At such levels, the area of emergent marshland available for rearing broods may shrink substantially, reducing protective cover and feeding areas accordingly. Furthermore, nests may be more easily flooded when water levels rise suddenly (Figure 8.4). The islands do not really start to flood (10% submerged) until the depth reading reaches 5.4 m. It has also been demonstrated that a water level increase of no more than 20 cm in late June can swamp 15 to 20 times as many nests when the water level recorded at the Sorel station hits 5.4 m as when it stands at 4.0 m.

Nest flooding may have a certain impact on the productivity of the dabbling ducks that breed in the stretch of the river under study, though the impact may usually be very slight. It has been estimated that each nest lost to flooding diminishes dabbling duck productivity by a mere 0.0015 immature ducks per adult female (Lehoux et al. 2005). Thus, an annual loss of some 100 nests, roughly the average nest loss under Plan 1958DD between 1968 and 2002, cuts overall annual dabbling duck productivity in the system by less than 2%, and this would happen only in years when many water-level increases (three or four) of high amplitude (> 20 cm) occur while water levels at Sorel are high (> 5.0 m) and at the most critical points during breeding (mid-May to early July) with an appreciable impact (about 10%) on productivity.

The fact that waterfowl hunting in the Montréal area generates economic spin-offs of some $10 million annually provides another justification for better management of water levels in this part of the St. Lawrence.

Species at risk

In 1999, the Great Lakes–St. Lawrence Lowlands ecoprovince was home to 49 species at risk, the second highest number of species at risk in Canada (Natural Resources Canada 2004). Alterations in the hydrology are a contributing factor in the scarcity of many of these species. In the International Lake Ontario–St. Lawrence River Study, only the five species currently protected under the *Species At Risk Act* and the *Act respecting threatened or vulnerable species* were taken into consideration. Two criteria were used to specify which of these five species are really influenced by hydrological fluctuations in the fluvial section of the St. Lawrence: 1) whether the species currently occur in the St. Lawrence corridor, and 2) how much they use habitats associated with the river (Table 8.1). Only two species met these criteria: the least bittern and the yellow rail.

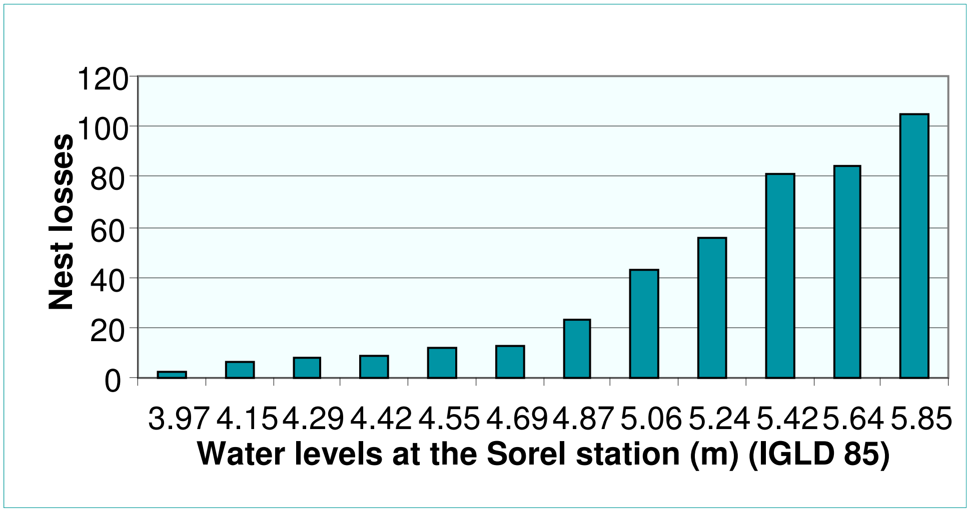


Figure 8.4 Estimate of the number of nests lost to a 20-cm water level increase at various water elevations

TABLE 8.1
Endangered bird species considered in this report

Species	Federal status	Provincial status	Use of floodplain	Presence confirmed
Least bittern	Threatened	LDTV	Obligate	Yes
Yellow rail	Special concern	LDTV	Obligate	Yes
Peregrine falcon	Threatened	Vulnerable	Facultative	Yes
Cerulean warbler	Special concern	LDTV	Terrestrial species	No
Loggerhead shrike	Endangered	Threatened	Terrestrial species	No

LDTV: Likely to be designated threatened or vulnerable.

Given the scarcity of these two species (and hence the paucity of survey data for the St. Lawrence), we worked with the concept of potential habitat. For each species, a habitat suitability index (HSI) was developed using a review of the literature, amplified by a poll of expert opinion on the species. Using the habitat suitability indices, the quantity of potential habitat was modelled as a function of various hydrological conditions during the breeding season.

The habitat suitability indices thus developed were used to rate the potential of various wetland habitats for satisfying the breeding requirements of the two species considered. The appeal of the various potential sites was then qualified in terms of their vulnerability to variations in hydrological conditions. Elimination of areas likely to be affected by water-level fluctuations during the breeding season yielded potential safe habitat (Giguère et al. 2005). This indicator may only be used to make a relative assessment of the performance of each of the water-level regulation plans. In fact, in making a valid assessment of the effect of water-level fluctuations on this part of the life cycle of the yellow rail and least bittern, several other variables with a significant role in breeding success have been ignored in this work (e.g. productivity and food resources). In the case of the least bittern, a breeding index was modelled in the same way as for other wetland indicator species.

The performance indicator (PI) developed for the yellow rail has a tolerable confidence level. The data in the literature are sparse, but much of the information comes from the study area and has been corroborated by a specialist. Only two records obtained during the breeding season were available to validate the model, and these did not match the habitat predicted by the model. The PI designed for this species can therefore be used in analyzing the various regulation plans, but certain caveats are in order. Indeed, the uncertainties mean that there are risks in determining a specific threshold at which a regulation plan would have significant effects on the species. Close study of the results may nonetheless help pinpoint plans that would trigger serious difficulties for the yellow rail. The indicator designed for the least bittern has an acceptable confidence level, facilitating the relative assessment of the effects of various regulation plans on the breeding potential of this species. This PI was designed on the basis of an appreciable body of data, of which a good proportion comes from the study area. Expert opinion was again used in developing certain parts of the PI. The potential breeding habitat model was further validated by field work and a number of independent observations, which produced a close match with the predicted habitats.

Economic Outlook and Trends

A regulation plan for birds

The integrity of freshwater ecosystems depends on water quantity and quality and on variations in levels and flows at regular intervals (Baron et al. 2002). The permanence of these ecosystems normally requires natural fluctuations to be maintained. Since water regulation may entail loss of wetlands, it may have an impact on the composition and diversity of the avian assemblages that use these habitats, and any alteration, however slight, in the speed at which water levels rise or fall may have a marked effect on breeding success, by either flooding nests or exposing them to exploitation by terrestrial predators, sometimes to the point of jeopardizing a population's capacity to survive.

Though the studies conducted by the Environmental Technical Working Group (ETWG) have identified a number of biotic performance indicators for evaluating water regulation plans, our current knowledge of the complex ecological processes with a bearing on these indicators is limited, so that it would be more prudent to opt for a regulation plan that alters the natural hydrology of the Lake Ontario–St. Lawrence River basin as little as possible. This is the approach that is recommended in many other water regulation studies (Baron et al. 2002; Kozlowski 2002; Ward and Tockner 2001; Nilsson and Dynesius 1994). A detailed assessment of the impact on bird life under various proposed regulation plans (DesGranges et al. 2005) concludes that in cases where the natural fluctuations in the levels of Lake Ontario and the St. Lawrence River clash with users' needs, the performance indicators identified can be used to assess the regulation criteria developed to minimize the impact of fluctuations (see box below).

Hydroelectric dams and other control structures built in the Lake Ontario–St. Lawrence system do exactly that: they alter the natural water levels and flows. In cases where the criteria for regulating levels and flows in Lake Ontario and the St. Lawrence River cannot be modified so as to prevent predictable adverse effects on the environment, measures will need to be taken to protect the integrity and diversity of wetlands against the cumulative impact of human activity.

If necessary, restoration measures, founded on sound ecological principles, can be implemented to conserve certain environmental values (e.g. habitat for species at risk). With regard to habitat conservation for wetland birds in the Lake Ontario–St. Lawrence River basin, there exist a number of proposals based on the latest scientific data in the *North American Waterbird Conservation Plan* (Kushlan et al. 2002) and in the *Framework for Guiding Habitat Rehabilitation in Great Lakes Areas of Concern* (Environment Canada 2004).

Accordingly, recommended regulation criteria for the Lake Ontario–St. Lawrence River basin should include the following categories of mitigation measures:

- A mitigation strategy (reduction of adverse effects) in cases where the regulation plan envisaged for a given use (hydroelectric power generation, navigation, industrial and municipal water intakes) entails excessive adverse impacts (relative to Plan 1958DD) with respect to economic, social or ecological benefits. (In this case, the mitigation measure practically amounts to developing a better regulation plan).
- Ad hoc mitigation measures in cases where the regulation plan envisaged is deemed acceptable overall in relation to the objectives, but unacceptable for one of the main indicators (e.g. species at risk, minimum depth for navigation at Montréal).
- Performance improvement measures for the plan envisaged in connection with one of the main indicators (e.g. improved functioning of wetlands by regulating their water levels independently of those in the lake or provision of facilities for making navigation safer when water levels are high).

Summary of the main proposed hydrological criteria for improving the situation for birds

1. During spring migration, from April 10 to May 7, maintain the water level at Sorel above the 5.4 m mark to ensure minimum waterfowl occupancy of the floodplain (> 20% of the total number of birds expected).

2. During the growing season (April to October), maintain mean water levels at Sorel between the 4.9 m and 5.5 m marks to ensure good waterfowl breeding productivity in the fluvial section of the St. Lawrence.

3. During the breeding season for wetland birds (mid-May to mid-July), maintain a minimum water depth of 50 cm in marshland and avoid weekly level fluctuations exceeding 20 cm. This criterion also applies in the case of the least bittern, a species at risk.

4. At the height of the waterfowl rearing season (July and August), maintain mean water levels at Sorel above the 4.5 m mark to ensure that quality rearing marsh is available in sufficient quantity and to prevent pooling of stagnant water, which is conducive to bird botulism.

5. At the height of the breeding season (April 29 to July 21), when at least 10–15% of females are on their nests, if water levels at Sorel top the 4.9 m mark, avoid any rapid increase exceeding 40 cm from April 29 to May 5, exceeding 30 cm from May 6 to the end of June and exceeding 30 cm during the first three weeks of July, so that nests will not be flooded, which would be a further blow to productivity.

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Chapter 9

IMPACT OF WATER LEVELS ON AN AQUATIC MAMMAL: THE MUSKRAT

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Introduction

Wetlands are essential components of terrestrial ecosystems, helping to keep them in balance. They sustain a large number of plant and animal species, and play an important role in retaining and purifying the water that passes through them. In the last century, wetland area along the St. Lawrence River declined steadily owing to pressure exerted by anthropogenic activities such as agriculture, urban development, forestry and water-level regulation. Nearly 70% of the St. Lawrence wetlands are believed to have disappeared (Blanchette 1991).

The muskrat (*Ondatra zibethicus*) is the only herbivorous mammal that directly influences wetland dynamics along the St. Lawrence; however, it is difficult to evaluate the species's impact. Water-level fluctuations have a direct effect on muskrat survival, particularly in the winter, which is a critical period for this species (Errington et al. 1963). There are many factors that cause the muskrat's very high winter mortality, the most significant one being water-level fluctuations (Clark 1994). Increases in water levels seem to be the main problem. In November, muskrats finish building their lodges, which serve as shelter during the winter. The increases in water level that occur after this period can compromise the muskrats' use of their lodges and even their access to certain food sources. These disturbances increase the animals' vulnerability to predators and to death from starvation. It is therefore very important to learn more about how wetland composition and water-level fluctuations affect this species.

Thanks to advances in two-dimensional (2D) habitat modelling, an integrated model has been built to predict the distribution of muskrat lodges along the St. Lawrence. A winter habitat model has also been developed; it is used to estimate the number of lodges that are affected by increased winter water levels over long periods of time or by increases associated with a flow regulation plan.

This chapter deals with certain aspects of muskrat biology that are essential to understanding the species's interaction with wetlands and winter water-level fluctuations. It describes the winter fluctuation impact model and the primary results obtained. The chapter ends with a discussion of the ecological implications for muskrats of flow regulation in the St. Lawrence.

Muskrat Biology

Range and life cycle

In North America, the muskrat inhabits all of southeastern Canada, including Newfoundland, Prince Edward Island, New Brunswick and Nova Scotia. Its geographic distribution also extends from western Quebec to Manitoba and takes in the northeastern United States. Muskrats also range from Georgia to Arkansas, but they are absent from the Atlantic coast and the area south of Delaware Bay (Dilworth 1966). In the St. Lawrence River proper, this species occurs mostly in the marshes and wetlands of the St. Lawrence islands, particularly around the Îles de la Paix sector of Lake Saint-Louis, the Îles de Sorel and Lake Saint-Pierre.

The mating period usually starts in April, not long after ice break-up (Traversy et al. 1994). The first litter is born around mid-May, and females often have another litter during the summer (Blanchette 1991; Errington 1943). When ice break-up occurs very early in the spring, a female can have up to three litters, rarely four, during the summer season (Mousseau and Beaumont 1981). Litter size has been found to vary with the region inhabited and the quality of muskrat habitats, but it may also vary as a function of population density in the area (Errington et al. 1963). In Quebec, females have an average of 6.3 to 7.1 kits per litter (Proulx and Gilbert 1984). Elsewhere in the world, a litter can vary between 5.0 and 5.4 kits and can comprise as many as 8.3 (Dilworth 1966). The young are usually able to reproduce the following mating season. Muskrats can live up to four years, but rarely live past three (FAPAQ 2004).

These animals are just as vulnerable to diseases and parasites as they are to various predators (Dilworth 1966; Errington 1963). The American mink (*Mustela vison*) is the muskrat's principal predator. In Quebec, minks, along with northern pike (*Esox* spp.) and common snapping turtles (*Chelydra serpentina*), represent the main cause of juvenile mortality (Mousseau and Beaumont 1981). Trapping activities also appear to be a significant cause of mortality for the species (Willner et al. 1980).

About 13% of muskrat deaths are caused by predators, while more than 70% of causes remain a mystery (Blanchette 1991). Summer mortality generally reaches 30–50% for subadults and about 10% for adults (Traversy et al. 1994). In winter, however, the mortality rate can vary between 47% and 75% for both segments of the population (Proulx and Gilbert 1984).

Habitat

Feeding

This mammal's diet consists of a variety of emergent plants depending on seasonal availability and nutritional value. Cattails (*Typha* spp.) have been repeatedly identified as a preferred food for the species (Allen and Hoffman 1984; Bellrose and Brown 1941). Several studies have shown that muskrats living in areas rich in cattail growth are bigger and have a heavier body mass and higher percentage of fat than those that feed on other emergent plant species (Friend et al. 1964; Dozier 1945). In Quebec, in addition to cattails, muskrats feed mainly on aquatic emergents and readily accessible plants during the summer, such as bulrushes (*Scirpus* spp.), reed canary-grass (*Phalaris arundinacea*), sedges (*Carex* spp.), sweetflag (*Acorus calamus*), arrowheads (*Sagittaria* spp.), pickerelweed (*Pontederia cordata*) and broadfruit bur-reed (*Sparganium eurycarpum*) (Traversy et al. 1994; Mousseau and Beaumont 1981).

Lodge construction

Depending on their seasonal needs, muskrats build four types of dwellings: a) lodges and feeding stations, b) burrows, c) snow shelters and d) winter lodges. The building of winter shelters peaks in November (Darchen 1964), since it is more difficult to build new lodges or modify them after freeze-up. This explains why subsequent water-level fluctuations affect the use of lodges and hence the muskrats' winter survival.

In general, muskrats build their winter lodges in water depths of 19 cm to 90 cm (Léveillé and Bélanger 1983). However, the species appears to have a marked preference for a depth of 30 cm to 70 cm (Proulx and Gilbert 1984; Danell 1978; Dilworth 1966; Bellrose and Brown 1941). Muskrats build their lodges with a wide variety of materials; however, as is the case for feeding, they show a preference for cattails (Connors et al. 1999). Areas with good cattail growth can support a higher density of muskrats (Clark 1994). These animals use plants within a radius of 6–12 m around their lodges, creating an area that is cleared of emergent vegetation. The cleared areas can serve as habitat for other animals, particularly as spawning sites for certain fish species (Danell 1978).

Muskrat lodge dimensions vary as a function of location and available construction materials (Figure 9.1) (McNicoll and Traversy 1985; Darchen 1964). According to preliminary results obtained in 2004–2005 in Lake Saint-Pierre (Ouellet 2006), water-level fluctuations appear to influence lodge size. In fact, lodges built in areas where water levels are not controlled have been found to be higher (about 30 cm) than those built in managed environments. This adaptation in muskrats might be linked to semilunar tide signals, which can cause a 25–35 cm variation in water levels in the Sorel region and in Lake Saint-Pierre (Morin and Bouchard 2000).

Main ecological functions of the muskrat

Muskrats are intimately linked to wetland dynamics. They are considered to be a significant ecological agent that can noticeably modify habitat (Clark 1994; Allen and Hoffman 1984). Muskrats use large quantities of a variety of plant species in their building and feeding activities (Takos 1947). These activities have a significant impact on prolific species such as *Typha*. (cattails), the muskrat's preferred type of vegetation (Mirka et al. 1996; Clark 1994; Bellrose and Brown 1941). This rodent uses cattails as a food source as well as for building lodges. Consequently, muskrats can curb cattail growth in areas where they are present in large numbers (Farrell et al. 2004; Lacki et al. 1990). Muskrat activities can be beneficial to other species that live in wetland areas. For example, certain bird species use the remnants of muskrat lodges to build their nests (Bishop et al. 1979; Danell 1978). Moreover, it is likely that the pools of water and the channels maintained by muskrats provide access to spawning sites or even become spawning sites for certain fish species.

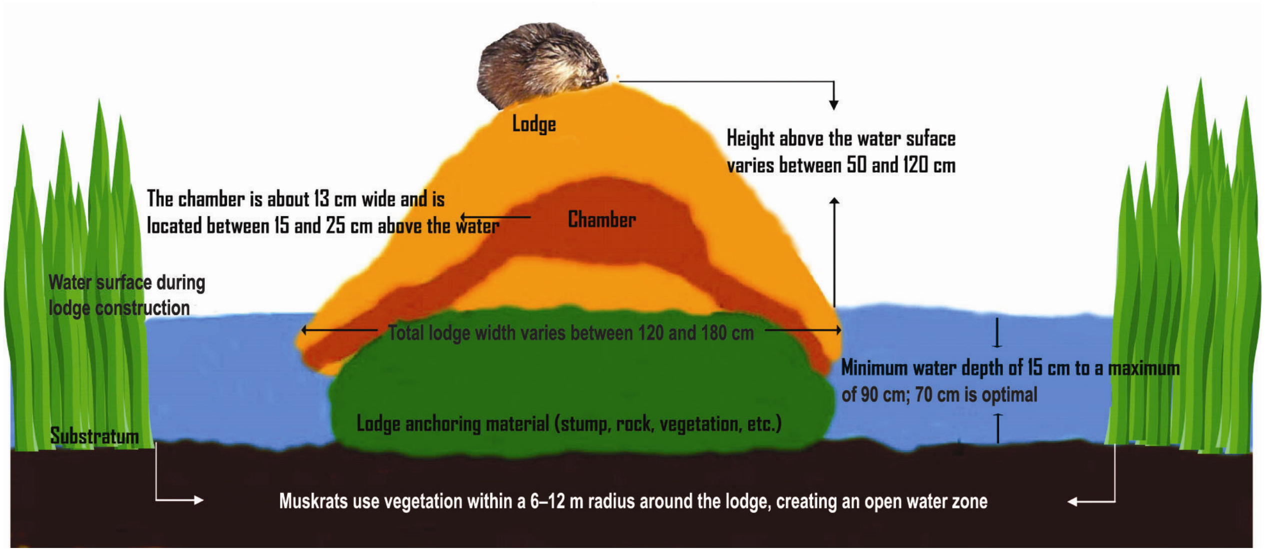

Figure 9.1 Characteristic parameters associated with the construction of a muskrat's winter lodge

Current population status

It is difficult to establish an accurate portrait of muskrat populations in the St. Lawrence River. According to wildlife managers and trappers working in the Lake Saint-Pierre area, it seems that the muskrat population has decreased in the last few decades. In fact, trapping data show a decrease in the number of captured individuals, despite the fact that permit sales have remained fairly stable (FAPAQ 2004). However, given that trapping has become a sport rather than a livelihood, these data do not provide an accurate picture of the status of muskrat populations. Highly variable winter weather conditions, such as those that characterized the winters of 2003, 2004 and 2005, can have adverse effects on the species and significantly increase its mortality rate. This is a situation that many trappers have observed around Lake Saint-Pierre over the last few years.

Threats and issues

The muskrat, wetlands and water-level fluctuations

Seasonal fluctuations in water levels can have an indirect impact on muskrats by influencing vegetation composition in their habitat. High water levels and periods of low water also have major impacts on wetlands, since the hydroperiod has a direct influence on the type of plant species that are present (Turgeon et al. 2004). The most important plant species for muskrats are those of the genus *Typha*, which occur in both deep marsh and shallow marsh. These plants grow in areas where the water table is close to the surface and in water up to 50 cm deep depending on the species (*Typha latifolia, T. angustifolia* and *T. x glauca*). In view of this, high water levels that are sustained over long periods could have a primary impact by preventing seed germination and thereby limiting or modifying muskrat habitat. Conversely, if excessively low water levels persist for a prolonged period, more terrestrial types of plant species that are less favourable for muskrat feeding and lodge construction activities could spread across the landscape.

Water depth is an especially important factor in lodge construction, since they are built according to the water levels that exist in November (Allen and Hoffman 1984; Bélanger 1983; Proulx 1981). A winter decline in water level can lead to the freeze-up of pools in which muskrat lodges are built, thereby blocking the access channels and preventing the muskrats from reaching the plant rhizomes under the ice (Léveillé and Bélanger 1983; Mousseau and Beaumont 1981). Water-level increases occur frequently in the St. Lawrence River and they are often of large magnitude. Winter increases, depending on their intensity, can flood lodges and destroy or block access to food sources (Bélanger 1983). Following such disturbances, muskrats may be forced to seek new shelters and alternative food sources, exposing them to the risk of predation and death by starvation.

Furthermore, it appears that decreases in water levels are less problematic than increases. It has been observed that, following freeze-up, muskrats dig small channels directly in the marsh substrate to reach their lodges or feeding sites. Muskrats can also use air pockets trapped in the ice in order to move around (Prowse and Gridley 1993). This is not an ideal situation, however, since it makes the animals more vulnerable to predation. In general, winter fluctuations can be lethal for muskrats, and they represent a limiting factor for muskrat populations (Blanchette 1991; Bélanger 1983; Bellrose and Brown 1941). A number of studies have shown that wetlands with a fairly stable winter water level can support a greater density of muskrats than marshes in which water levels fluctuate (Farrell et al. 2004; Thurber et al. 1991; Allen and Hoffman 1984).

Modelling of Winter Lodge Performance

In analyses of the impact of water-level fluctuations, winter appears to be the only period during which fluctuations have a direct impact on the muskrat. This stressor can be assessed using a model that estimates lodge losses during the winter. A 2D habitat model has been designed for the area extending from Lake Saint-Louis to Trois-Rivières (excluding the La Prairie Basin). This model, which is similar to the habitat suitability index (HSI), has been developed specifically for the muskrat and can be used to estimate lodge density (Ouellet et al. 2005). The HSI is a mathematical model used to evaluate habitat value for a given species on the basis of biological and physical variables. The range of values is from 0, for a habitat with no potential, to 1, for a habitat with excellent potential (see Chapter 6). Once calibrated and validated with field data, this model can be applied to various water-level series to determine the number of lodges affected during the winter.

Muskrat winter lodge model

The muskrat winter lodge model is designed to determine the potential use of an environment for lodge construction (details in Ouellet et al. 2005). The index was developed using two environmental factors of significance for the species: the presence of *Typha angustifolia* and water depth in November. The water depth variable combines two-dimensional hydrodynamic results and the digital terrain model, whereas the presence of *T. angustifolia* is determined through logistic regression analyses based on biotic samples and on abiotic variables for which prediction performance is 81% or higher (Morin et al. 2005). The results can be used to visualize spatial and temporal changes in the distribution and quality of habitats available for winter lodge construction. Lodge density is then estimated by calibrating the HSI results with data from a FAPAQ survey of more than 500 lodges conducted in fall 1988 at Lake Saint-Pierre. This makes it possible to estimate the number of lodges potentially affected each year by winter water-level fluctuations.

The geometry of a typical lodge (average lodge) was modelled using data from the scientific literature: lodge dimensions (e.g. chamber size, water depth for lodge construction and the maximum possible water level increase) (Figure 9.2). These data are used to determine how feasible it would be for muskrats to raise the lodge chamber floor following an increase in water level. When the winter water level increases beyond muskrat capacity to raise the floor, the lodge is removed from the modelling process. The number of lodges is recalculated in November of each year, because muskrat lodges are destroyed during ice break-up in the spring.

Using the mean water level in November, the model can estimate the potential number of lodges as a function of cattail density during the previous growing season and local water depth. The maximum increase in water levels observed during December, January and February is then used to determine the number of lodges that become flooded.

Results obtained with the predictive model

The results shown in Figure 9.3 correspond to the distribution of lodge densities for a mean flow of 9500 m^3/s and for an "average" spatial distribution of cattails. Flow of 9500 m^3/s represents near-average long-term water levels over three consecutive years. "Average" cattail distribution means that resulting from more than three consecutive years of mean hydraulicity during the growing period (see Chapter 5). The highest habitat suitability index values are found around Lake Saint-Pierre, in the bays and islands of the fluvial section and in Lake Saint-Louis. The distribution of densities is consistent with the distribution of potential habitat. Very few potential habitats are found elsewhere in the fluvial section of the St. Lawrence given the low abundance of marshland.

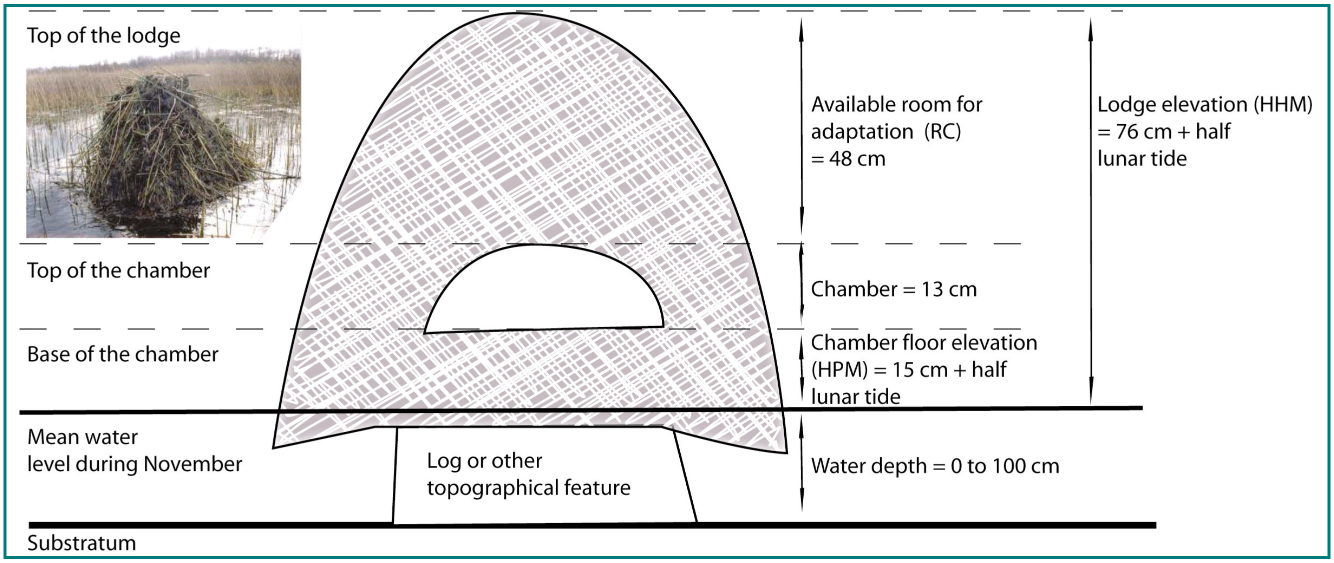

Figure 9.2 Definition of the main parameters of a typical lodge, used in the winter water-level impact model

Validation of the model was done by using muskrat lodge survey data from 1988 for various areas: Maskinongé Bay, Île du Moine, Anse du Fort, Percé Islets and Pointe aux Raisins. Table 9.1 provides a comparison of the results obtained with the model and field data. It can be seen that the model accurately predicts the number of lodges in a given area (error of 4–20%, except in the Pointe aux Raisins area, where lodge density is fairly low at 58.53%).

TABLE 9.1

Lodge density calculated by the model and density observed during the 1988 survey at Lake Saint-Pierre

	Number of lodges	
Sectors	**Survey**	**Prediction**
Île du Moine	57	70
Pointe aux Raisins	9	22
Percé islets	155	124
Anse du Fort	50	47
Maskinongé Bay	230	220

Application of the model to time series

The model can be applied to various measured or simulated water level time series such as those representing the different regulation plans for the St. Lawrence River. In the present case, the model was applied to Plan 1958DD, which has been in use since 1963, and to the conditions that existed prior to regulation (pre-project). By applying the muskrat lodge model to these hydrological regimes, it is possible to determine the effects of various hydrological conditions on winter survival.

When the simplified model was applied to the two regimes (with and without regulation), slight differences were found in the number of potentially active lodges during the winter season (Figure 9.4). A stable plateau of some 1000 lodges can be seen; they are located in natural residual and managed marshes that act as stabilizing elements for the population. Although similar trends are observed for the two regimes, temporal persistence is greater with Plan 1958DD. The modelling results also show that the St. Lawrence is not an excellent habitat for the muskrat.

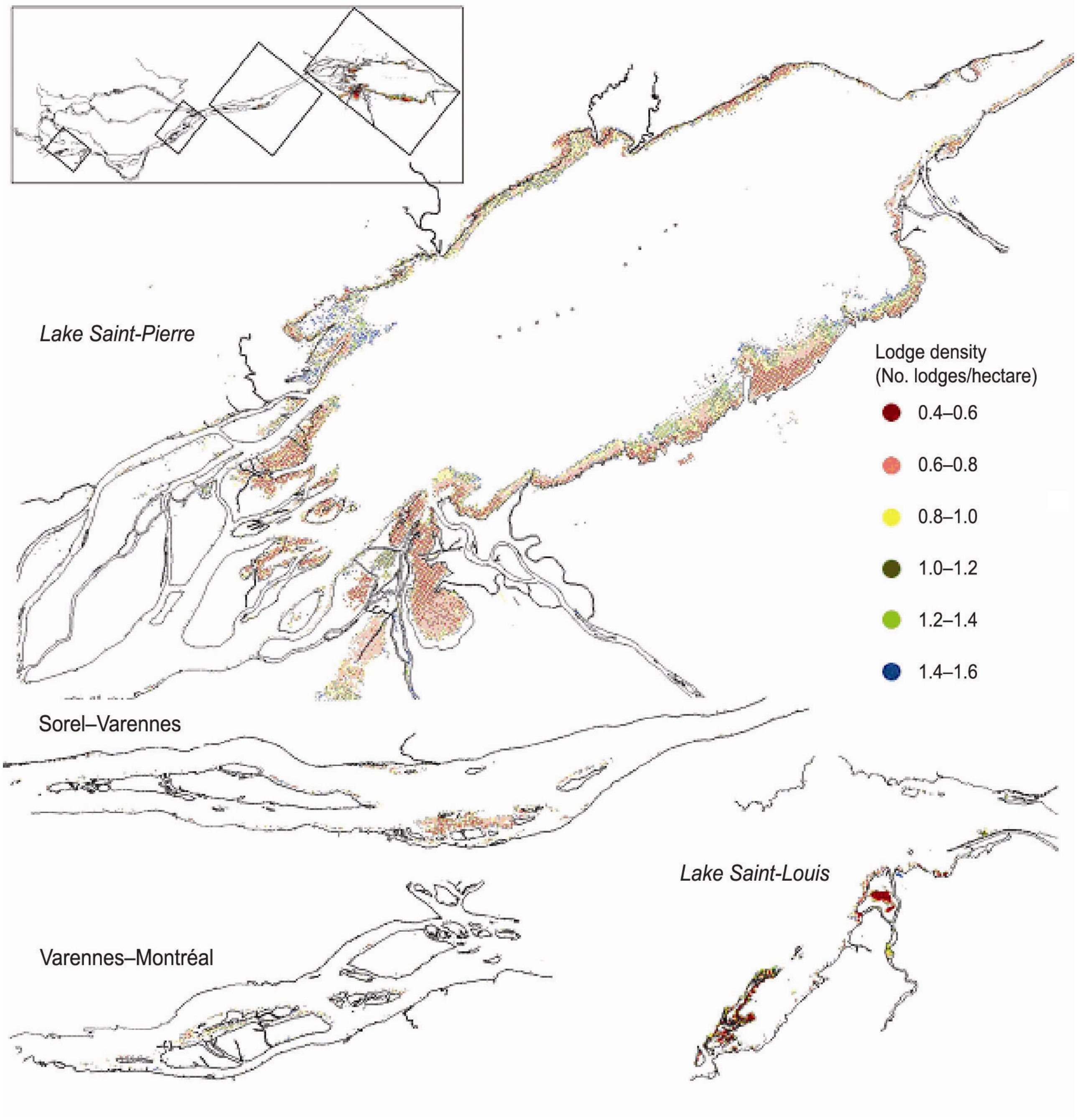

Figure 9.3 Distribution of lodge densities in the fluvial section between Lake Saint-Louis and Trois-Rivières for average cattail density and flow of 9500 m^3/s

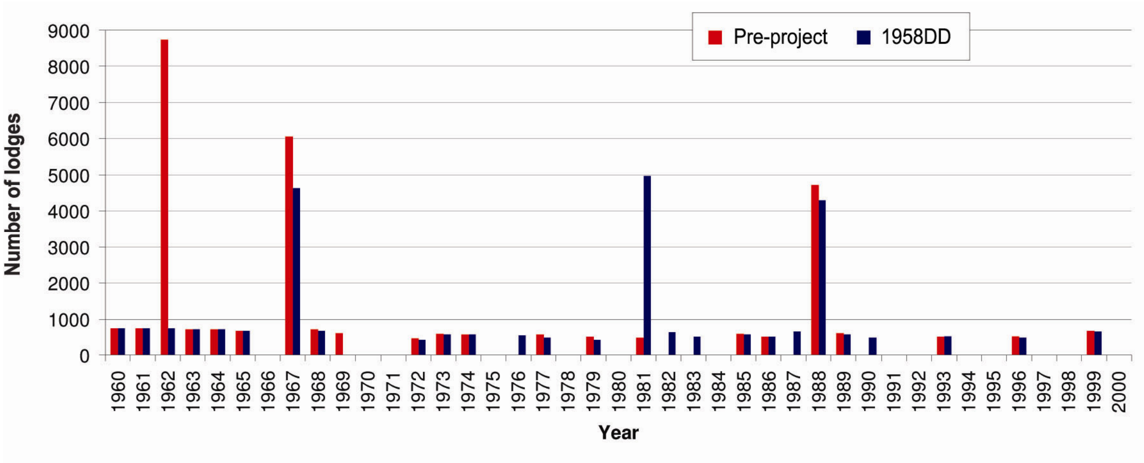

Figure 9.4 Comparison of the number of muskrat lodges estimated for Plan 1958DD and for the pre-regulation regime, in the Lake Saint-Pierre area, 1960–2000

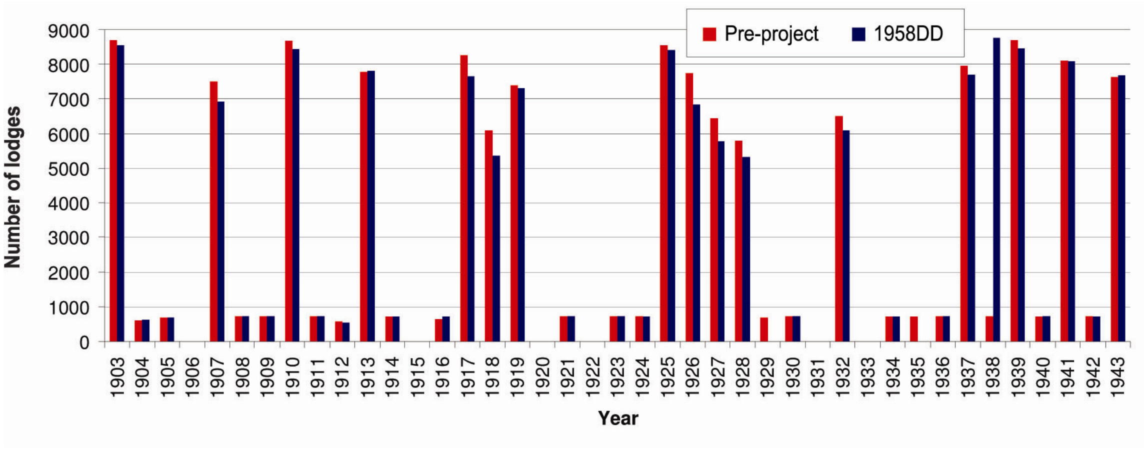

Figure 9.5 Comparison of the number of muskrat lodges calculated by the model for Plan 1958DD and for the pre-regulation regime, in the Lake Saint-Pierre area, 1903–1943

By contrast, when the model is applied to the time series representing the hydraulic conditions existing at the start of the 20th century, a much more favourable trend is observed for winter survival (Figure 9.5). It can be seen that a large number of lodges are spared the effects of flooding during several winters. The total number of active lodges is five times greater than during the 1960–2000 period, and temporal persistence is much greater. This difference between the beginning and the end of the 20th century is not attributable to regulation of Lake Ontario since performance is similar for both Plan 1958DD and the pre-project situation. The difference is most likely linked to the construction of dams and to winter management of flows on the Ottawa River with a view to electricity production.

Ecosystem Outlook and Trends

Ecological implications

Balanced management of muskrat populations is important, and it has long been known that this aspect needs to be addressed in wetland management plans. Muskrats are intimately linked to marsh dynamics, and it is clear that their population density can have many impacts on the ecological processes of marshland habitat.

Comments and fragmentary data received from trappers along the St. Lawrence River suggest that there has been a decline in muskrat numbers since the mid-20th century. As the model shows, this decline appears to coincide with changes in the management of winter water levels on the Ottawa River. It is nonetheless difficult to assess the impact that this population decrease may have had in the riparian zones of the St. Lawrence. Sufficiently precise data are not available on vegetation fragmentation in the St. Lawrence wetlands before the 1960s. Such data would make it possible to show the direct influence that muskrats have, through the channels they maintain, on the reproduction of fish species and wetland birds.

At present, one key question remains unanswered: Is an increase in the muskrat population essential for maintaining the biodiversity of wetlands? It is known that the “natural hydrology” provides much more favourable conditions for muskrats than the current management regime. Furthermore, a higher density of muskrats would translate into increased predation opportunities and therefore an increase in the numbers of many predator species.

The main effect of very low muskrat density is the proliferation of certain plant species, such as cattails, to the detriment of others, a phenomenon that could lead to the establishment of monospecific habitats (Connors et al. 1999). Along the St. Lawrence, the muskrat population has not declined to the same extent as around Lake Ontario and in the St. Lawrence upstream of the Moses-Saunders Dam (Cornwall). In these regions, the decrease in muskrat populations is believed to be largely responsible for cattail dominance in marshes (Farrell et al. 2004).

From the standpoint of muskrat management, managed marshes and residual perched marshes (natural marshes located in topographic depressions in the floodplain) have a stabilizing effect on the muskrat population. Some of these habitats have high muskrat densities. Creating managed marshes or restoring natural marshes that have been drained for agricultural purposes would be an excellent way to support this population. Research on the management of Ottawa River flows should also be envisaged.

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Chapter 10

IMPACTS OF HYDROLOGICAL CHANGES ON SPECIES AT RISK

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Current Status of Species at Risk in the Fluvial Section of the St. Lawrence

The Great Lakes–St. Lawrence Lowlands ecoprovince is home to the second-largest number of species at risk in the country (NRCan 2004). The omnipresence of anthropogenic activities undoubtedly has something to do with this. The causes most frequently cited to explain the decline in these species include habitat loss or alteration, chemical contamination, intensive agriculture, degradation of water quality and man-made hydrological changes. The International Lake Ontario–St. Lawrence River Study provides an opportunity to improve our knowledge of the impacts of changes in hydrology on species at risk and, specifically, about the impacts of fluctuations in water levels and flows.

Legal instruments that protect species at risk

In Quebec, species at risk are protected under two sets of legislation: the federal *Species at Risk Act* (SARA) and the provincial *Act respecting threatened or vulnerable species* (ATVS).

The *Species at Risk Act* is managed by two departments: Environment Canada and Fisheries and Oceans Canada (DFO). DFO has responsibility for all marine species as well as for freshwater fishes, while Environment Canada has responsibility for all the other species at risk. The Parks Canada Agency, which reports to the Minister of the Environment, is responsible for the species at risk found on Parks Canada land. The general prohibitions in the *Species at Risk Act* apply only to the species designated “extirpated,” “endangered” or “threatened,” listed in Schedule 1 of the Act. Although not protected in the same way as the aforementioned species, species designated “of special concern,” listed in Schedule 1 of the *Species at Risk Act*, are also afforded protection under certain legal provisions. In fact, the responsible departments are required to produce a management plan for these species. At the provincial level, two ministries share responsibility for species at risk and for managing the *Act respecting threatened or vulnerable species*. The Ministère des Ressources naturelles et de la Faune manages animal species, while the Ministère du Développement durable, de l’Environnement et des Parcs is responsible for plant species. Only the species designated “threatened” or “vulnerable” are protected under this Act (Table 10.1).

TABLE 10.1
Categories of species at risk protected and not protected by provincial and federal legislation

Acts and departments responsible	Protected categories	Unprotected categories
Species at Risk Act enforced by Fisheries and Oceans Canada and Environment Canada	Extirpated species* Endangered species* Threatened species* Species of special concern*	Candidate species Data deficient Species not at risk
Act respecting threatened or vulnerable species enforced by the Ministère des Ressources naturelles et de la Faune and the Ministère du Développement durable, de l’Environnement et des Parcs	Threatened species Vulnerable species	Species likely to be designated threatened or vulnerable

* The legal provisions apply only to the species listed in Schedule 1 of the *Species at Risk Act*.

Other legislation also provides additional protection for these species: at the federal level, the *Fisheries Act* and the *Migratory Birds Convention Act, 1994*, and, at the provincial level, the *Act respecting the conservation and development of wildlife*.

Uses of the St. Lawrence by species at risk

Only the species protected by the *Species at Risk Act* or by the *Act respecting threatened or vulnerable species* were included in the International Lake Ontario–St. Lawrence River Study. These 26 species have a distribution that covers the fluvial section of the St. Lawrence (Table 10.3). However, only 16 of these species have been recorded there since 1990. Fish (n = 5), vascular plants (n = 4), birds (n = 3), reptiles (n = 2), amphibians (n = 1) and Lepidoptera (n = 1) have at least one representative that uses the study area, while no mammals at risk appear to do so. In addition, the 26 species initially considered do not use the floodplain and aquatic habitats with equal intensity. Some use these habitats on an obligate basis throughout their life cycles, while others use them only on a facultative basis for part of their life cycles (Table 10.2).

Hydrological fluctuations are responsible for creating many types of habitats (wetlands, eroded banks, etc.) that are colonized in different ways by species at risk. Some species, such as the least bittern, will use only emergent marshes throughout their life cycles, while others need several types of habitats. For example, the map turtle requires a beach on which to lay its eggs, but needs a fairly deep, well-oxygenated aquatic environment for its hibernation period (Figure 10.1).

TABLE 10.2

Indicator of use, by the species at risk considered, of habitats affected by water-level fluctuations

Code	Category	Details	Number of species
AQUA	Aquatic	The species uses only aquatic environments.	5
OBLI	Obligate use of the floodplain	At least one period of the life cycle must take place in the floodplain. Plus signs (+) indicate that several periods of the life cycle take place in the floodplain.	8
FACU	Facultative use of the floodplain	At least one period of the life cycle must take place in the floodplain, but the species is not restricted to it.	4
TERR	Terrestrial	The species mainly uses terrestrial habitats.	9

Denuded bank	Aquatic environment without vegetation	Wetlands				Riparian forest
		Aquatic grass bed	Marsh	Wet meadow	Shrub and forested swamp	
5 species	6 species	9 species	3 species	6 species	7 species	9 species

Source: Adapted from the St. Lawrence Centre and Laval University 1990.

Figure 10.1 Use, by the species at risk considered, of the various habitats created by water-level fluctuations

Species at risk whose survival depends on hydrological conditions

Out of a total of 26 species at risk that were likely to encounter hydrological fluctuations, 11 were deemed a priority (i.e. they concretely use habitats affected by the regulation of St. Lawrence water levels). Hence, hydrological conditions (e.g. flood amplitude, duration and recurrence) are good indicators of the composition, location and surface area of the various habitats used by the least bittern, yellow rail, map turtle, spiny softshell, American shad, copper redhorse, eastern sand darter, channel darter, bridle shiner, American water-willow and green dragon (Table 10.3).

TABLE 10.3

Species at risk considered on the basis of their legal status, actual presence in the fluvial section of the St. Lawrence and use of habitats affected by hydrological fluctuations

	Status*				
Species	**SARA**	**ATVS**	**Use codes**	**Present****	**Aquatic or floodplain habitats used**
Least bittern	Threat.		OBLI+	Yes	Emergent marsh
Yellow rail	Conc.		OBLI+	Yes	Wet meadow
Map turtle	Conc.	Vul.	OBLI+	Yes	Aquatic habitat and denuded bank
Spiny softshell	Threat.	Threat.	OBLI+	Yes	Aquatic habitat and denuded bank
American shad		Vul.	AQUA	Yes	Aquatic habitat without vegetation
Copper redhorse	Threat.	Threat.	AQUA	Yes	Aquatic habitat without vegetation
Eastern sand darter	Threat.		AQUA	Yes	Aquatic habitat without vegetation
Channel darter	Threat.	Vul.	AQUA	Yes	Aquatic habitat without vegetation
Bridle shiner	Conc.		AQUA	Yes	Submerged grass bed
Green dragon	Conc.	Threat.	OBLI	Yes	Forested swamp, wet meadow
American water-willow	Threat.	Threat.	OBLI	Yes	Denuded bank, marsh, wet meadow
Peregrine falcon	Threat.	Vul.	FACU	Yes	Open wetland and shoreline
Grey fox	Threat.		FACU	No	Forested swamp
Wood turtle	Conc.	Vul.	OBLI+	No	Aquatic habitat, wetland and denuded bank
Western chorus frog		Vul.	FACU	Yes	Wet meadow, shrub or forested swamp
May apple		Threat.	FACU	Yes	Forested swamp
False hop sedge	End.	Threat.	OBLI	No	Wet meadow, shrub swamp
Monarch butterfly	Conc.		TERR	Yes	n/a
Wild leek		Vul.	TERR	Yes	n/a
Timber wolf	Conc.		TERR	No	n/a
Cerulean warbler	Conc.		TERR	No	n/a
Loggerhead shrike	End.	Threat.	TERR	No	n/a
Eastern milk snake	Conc.		TERR	No	n/a
American ginseng	End.	Threat.	TERR	No	n/a
Broad beech fern	Conc.	Threat.	TERR	No	n/a
Douglas knotweed		Vul.	TERR	No	n/a

* End.: Endangered. Threat.: Threatened. Conc.: Special concern. Vul.: Vulnerable.
** Recorded since 1990.
n/a: Not applicable.

Particular attention was also paid to two species with populations located near the St. Lawrence, even though they are not considered priorities given their ecological characteristics. The topographic elevations of a population of western chorus frogs as well as of a colony of May apples were calculated using a digital terrain model (see Chapter 3) in order to determine whether these populations were in fact affected by fluctuations in St. Lawrence water levels. The population of western chorus frogs is located on the Îles de Boucherville, approximately 10.30 m above mean sea level according to the digital terrain model. For an extreme flow of 20 500 m^3/s (Varennes gauging station), the water level would be 9.06 m above mean sea level. This flow corresponds approximately to a 7000-year flood recurrence. The risk that an event of this magnitude would occur and affect this species is therefore minimal. In addition, the criteria established for other uses (such as flooding of shoreline properties; see Chapter 11) further reduce the probability of such an event. The sole known population of May apples along the fluvial section of the St. Lawrence is located in a swamp on Léonard Island. This island is located in Lake Saint-François. Water-level fluctuations in this water body are negligible, since the lake's water levels are highly regulated. The maximum intra-annual variation in water levels is approximately 15 cm (Morin and Leclerc 1998). Hence, there is little likelihood that water-level fluctuations will affect this population.

Threats and Issues

Hydrological fluctuations

The St. Lawrence River is one of the largest rivers in the world. Like other watercourses in temperate environments, the St. Lawrence is subject to major seasonal and interannual variations in water levels and flows. The amplitude, frequency and synchronism of these variations are both vital and potentially fatal for the species that live there. On the one hand, hydrological variations are mainly responsible for creating the various types of habitats in the St. Lawrence floodplain. On the other, these variations can have many adverse effects. Table 10.4 presents the main direct adverse effects of water-level fluctuations recorded for the reproductive period of the priority species at risk. Just because a species is not listed in this table does not necessarily mean that there is no impact. These impacts may quite simply not have been documented.

TABLE 10.4

Documented main direct adverse effects of hydrological fluctuations on the priority species at risk

	Impacts				
Species	**Increases in level can kill/injure individuals (e.g. eggs)**	**Decreases in level can kill/affect developing stages**	**High/low levels can reduce the quantity/quality of breeding areas**	**Sudden changes in water flow, depth or temperature can affect reproductive and developmental stages**	**Extreme high or low levels for lengthy periods of time affect the survival of individuals**
Least bittern	1	6	10		
Yellow rail	2		11		
Map turtle	3				
Spiny softshell	4		12		
American shad				16	
Copper redhorse		7	13	17	
Eastern sand darter			14	18	
Channel darter		8		19	
Bridle shiner		9	15	20	
Green dragon	5				21

1. Post 1998; McVaugh 1975; Weller 1961; Nero 1951. 2. Alvo and Robert 1999; Robert and Laporte 1996; Bookhout and Stenzel 1987. 3. Bider and Matte 1994; Ewert 1979. 4. Seburn and Seburn 2000; Graham and Graham 1997; Doody 1995; Ewert 1979; Breckenridge 1960. 5. Menges and Waller 1983. 6. Post 1998; Post and Seals 1993; Weller 1961. 7. Prowse and Conly 1996; Balon 1975. 8. Holden 1979; Winn 1958. 9. Deduced from Holm et al. 1999. 10. Post 1998; Weller 1961; Nolan 1952; Murchison 1893. 11. TNC 1993. 12. Seburn and Seburn 2000; Janzen 1993; Stukel 1993; Plummer 1976. 13. Mongeau et al. 1986. 14. Facey 1998; O'Brien and Smith 1979. 15. Balon 1975; Harrington 1947. 16. MRNF 2005; Stier and Crance 1985; Bradford et al. 1966; Leach 1925; Leim 1924. 17. Vachon 2003; Prowse and Conly 1996; Scott and Crossman 1973. 18. Prowse and Conly 1996. 19. Prowse and Conly 1996; Winn 1958; 1953. 20. Prowse and Conly 1996. 21. NHNHI 2004.

Assessment of the effects of hydrological fluctuations on species at risk

Assessing the effects of water-level fluctuations in the St. Lawrence fluvial section on species at risk is not a simple task. Indeed, despite the high value attached to species at risk, there is no assessment criterion or recognized critical threshold for the conservation of these species, unlike the situation for water quality (criteria for aquatic life, for human consumption and for contact activities) (Robichaud and Drolet 1998). Despite the fact that hydrological data related to the Great Lakes and the St. Lawrence River have been collected since the turn of the 20th century, there are no monitoring data for the natural components (IJC 1993). Species at risk are not an exception to this rule, and there is no documentation dealing with this subject for the St. Lawrence. Nonetheless, a number of anecdotal observations on the species at risk discussed here and on the hydrology have been drawn from the available literature and are helpful for this purpose (Table 10.4).

The paucity of information was a decisive factor in choosing the study approach. First of all, it was decided to focus on the breeding period of the priority species, since this period is generally better documented, in addition to being considered essential to the survival of these species. For most of the priority species, this period runs from May to July, precisely when water-level fluctuations are frequent (spring freshet and recession). With the existing information and tools (see Chapter 3), the most reliable method for assessing the effects of hydrological fluctuations on the species at risk was to develop habitat suitability index models.

Habitat suitability indices were developed based on a review of the literature and with the advice of experts. Their purpose is to determine the suitability of the breeding habitats found in the St. Lawrence for each of the priority species. The most suitable areas according to the habitat suitability indices are considered potential habitats. In order to assess with greater accuracy the effect of water-level fluctuations on these species during this period of their life cycle, the concept of potential habitat was refined so as to determine the proportion of the potential habitat that can be safely used for breeding purposes by the species under study.

The meaning of the term “safe” is defined here solely with respect to water-level fluctuations. For example, the potential habitat of the map turtle during the egg incubation period consists of bare (vegetation-free) banks with gravely or sandy substrates. Areas that match these characteristics, but are flooded during the egg incubation period (which would drown the embryos) are excluded when determining safe potential habitat.

Once this tool has been developed for each species, it will be possible to provide a comparative analysis of the various water-level management scenarios (Figure 10.2).

Ecosystem Outlook and Trends

A regulation plan based on the needs of each species

The tools developed to assess the effects of water-level fluctuations on species at risk were intended to be used solely for the purposes of comparing the regulation plans proposed by the International Joint Commission. In fact, in order to accurately assess the effect of water-level fluctuations on this part of the life cycle of these species, a number of other variables that play an important role in their breeding success were not considered (productivity, predation, food resources, etc.).

*The least bittern (*Ixobrychus exilis*)*

According to the literature, the least bittern generally nests in emergent marshes dominated by *Typha* spp. (cattails), usually between 20 cm and 80 cm above the water level. This species normally chooses a site where the water depth is sufficient to minimize terrestrial predation. Hydrological fluctuations can have a direct (flooding of nests) or indirect (changes in the location and composition of emergent marsh) impact on this species. Table 10.5 summarizes the main information used to assess the impacts of water-level fluctuations on the least bittern.

The least bittern is the only species at risk for which sufficient data exist to develop a tool offering greater accuracy than available safe potential habitat surface area. This tool is the index of reproductive potential which is obtained by multiplying 1) potential breeding habitat surface area, 2) estimated density of breeding pairs in the study area and 3) estimated nesting success as a function of water-level fluctuations.

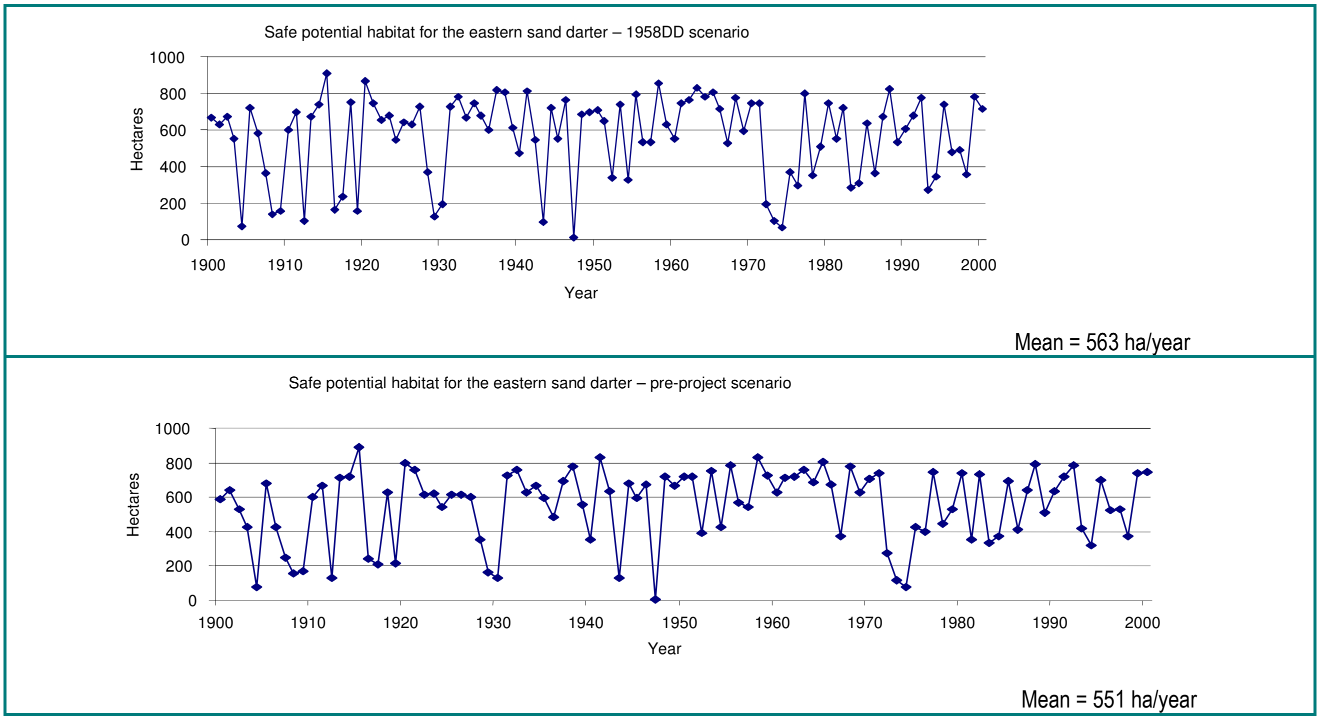


Figure 10.2 Safe potential habitat surface area available annually in the fluvial section of the St. Lawrence for the eastern sand darter according to regulation Plan 1958DD and the pre-project hydrological regime

*The yellow rail (*Coturnicops noveboracensis*)*

According to the available literature, the yellow rail nests exclusively in wet meadows, especially those dominated by the genus *Carex*. It builds its nest near the water, directly on or a few centimetres above the ground. The substrate under the nest is saturated with water or covered by a few centimetres of water. Hydrological fluctuations can have a direct (flooding of nests) or indirect (changes in the location and composition of wet meadow) impact on this species. Table 10.6 summarizes the main information used to assess the impacts of water-level fluctuations on the yellow rail.

*The map turtle (*Graptemys geographica*) and the spiny softshell (*Apalone spinifera*)*

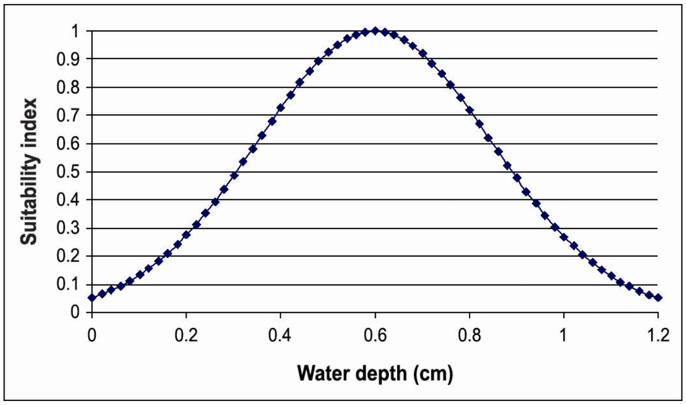
The most recent record of the spiny softshell in the St. Lawrence dates back to 1987, despite numerous studies on this species. It is therefore probable that this species is no longer present. As a precaution, this species was nevertheless combined with the map turtle, which is present in the fluvial section of the St. Lawrence and with which it shares the same breeding period and the same breeding habitat needs. In fact, according to the available literature, both of these turtle species prefer to lay their eggs near water; the nest is usually 50 to 100 cm above the ground. They look for areas free of vegetation with a sand or gravel substrate. Fluctuations in water flows and levels can have a direct (flooding of nests) or indirect (changes in the location and composition of banks) impact on these species. Table 10.7 summarizes the main information used to assess the impacts of water-level fluctuations on these two turtle species.

*The eastern sand darter (*Ammocrypta pellucida*)*

As its name indicates, the eastern sand darter is a fish typically associated with sandy bottoms. Indeed, it spends its entire life cycle, including the spawning period, on sandy bottoms. In addition to this substrate preference, the spawning sites of the eastern sand darter are characterized by fairly shallow water depths and a fairly low current velocity. Hydrological fluctuations can have a direct (dewatering of eggs) or indirect (changes in the location of sand banks) impact on this species. Table 10.8 summarizes the main information used to assess the impacts of water-level fluctuations on the eastern sand darter.

TABLE 10.5

Main information used to assess the impacts of water-level fluctuations on the least bittern

Components	Details
Period and area considered	From mid-May to late July, from Lake Saint-Louis to Lake Saint-Pierre, except the La Prairie Basin
Parameters and values used	**Potential breeding habitat (PBH)** $PBH = (TA^{0.2}) \times (TL^{0.2}) \times (DM^{0.1}) \times (DEPTH^{0.5})$ where TA: probability of the presence of *Typha angustifolia* TL: probability of the presence of *Typha latifolia* DM: probability of the presence of deep marsh vegetation (*Scirpus fluviatilis*, *Scirpus americanus*, *Sagittaria rigida*, *Sagittaria latifolia*, etc.) DEPTH: water depth suitability indicator  The PBH is considered suitable and is used to calculate the index of reproductive potential when the probability obtained by the above equation is greater than 50%. **Density of breeding pairs** A fixed density of 0.06 breeding pairs per hectare is used, based on an estimate from ground and helicopter surveys in the Ottawa River area (Chabot and St-Hilaire 1996). **Nesting success (Desgranges et al. 2005)** Nesting success rate = $n_1 + [(1 - n_1) \times RR \times n_2]$ n_1 or n = nesting success attempt 1 or 2 where n_i = BN × (1 - PF) **or** BN × [1 - (PS × PSF)] and where PF: probability of nest flooding as a function of the magnitude of the increase in water level PS: probability of nest stranding as a function of the magnitude of the decrease in water level PSF: 50% probability of predation or abandonment of eggs if nest is stranded BN: 60% baseline nesting success RR: 60% probability that the female will renest if the first attempt is unsuccessful
Validation	The Suivi de l'occupation des stations de nidification des populations d'oiseaux en péril du Québec (SOS-POP, a program to monitor the nest sites of populations of bird species at risk in Quebec) database was used to validate the potential breeding habitat. 41 observations (16 sites monitored annually) were used and the rate of correct predictions is equal to 75.6%. The reproductive success model was not validated.
Confidence rating	**Good** 1. A significant quantity of data largely derived from the study area were used. 2. The opinion of experts was used. 3. The model provides good validation results.

Source: Adapted from Giguère et al. 2005.

TABLE 10.6

Main information used to assess the impacts of water-level fluctuations on the yellow rail

Components	Details
Period and area considered	From the second week of May to the third week of June, from Lake Saint-Louis to Lake Saint-Pierre, except the La Prairie Basin
Parameters and values used	**Potential breeding habitat** is considered present if: • water depth > -0.5 m and < 0 m (dewatering with saturated soil); • presence of wet meadow. All potential habitat areas affected by an increase of more than 10 cm were excluded when determining safe potential habitat.
Validation	The SOS-POP database was used to validate the potential breeding habitat. The two reported occurrences do not match the predicted habitat. One of the two observations is located less than 200 m from a predicted habitat, while the other is about 350 m away.
Confidence rating	**Fair**: 1. There are few data in the literature. 2. The validation does not match the predicted habitat. 3. Breeding of the yellow rail has never been confirmed in the study area. 4. The wet meadow models do not yield very accurate results.

Source: Adapted from Giguère et al. 2005.

TABLE 10.7

Main information used to assess the impacts of water-level fluctuations on the map turtle and the spiny softshell

Components	Details
Period and area considered	From early June to late October, Lake Saint-Louis (only area where the map turtle is found)
Parameters and values used	**Potential breeding habitat** is considered present if: • water depth is negative (dewatering); • slope < 30; • sand or gravel substrate; • vegetation density < 5%. All potential habitat areas that become flooded during the incubation period were excluded when determining the safe potential habitat.
Validation	The database of the Société d'Histoire naturelle de la Vallée du Saint-Laurent (*Atlas des amphibiens et reptiles du Québec*) was used to validate the potential breeding habitat. The only reported observation for the study area does not match the areas selected by the model. This poor correlation can be explained by the fact that the section of the shore where the species was observed was not completely characterized in the database used for the modelling. The areas identified by the model were also visited and had the characteristics sought by these species.
Confidence rating	**Good**: 1. A significant quantity of data was used. 2. The opinion of experts was used. 3. Validation of the model is good (visits to potential areas).

Source: Adapted from Giguère et al. 2005.

TABLE 10.8

Main information used to assess the impacts of water-level fluctuations on the eastern sand darter

Components	Details
Period and area considered	From the second week of June to the third week of July, from Lake Saint-Louis to Lake Saint-Pierre, except the La Prairie Basin
Parameters and values used	**Potential breeding habitat** is considered present if: • water depth ranges from 15 cm to 120 cm; • sandy substrate (> 70%); • current velocity between 0 cm/s and 20 cm/s. All potential habitat areas where the water depth drops below 10 cm during the period considered were excluded when determining the safe potential habitat.
Validation	In the study area, there were no observations of eastern sand darter during the reproductive period. Historically, this species has been caught in the Châteauguay, Yamaska and Saint-François rivers. The outlets of these rivers match the parameters selected in the model. In the St. Lawrence River, the eastern sand darter was also caught in the Chenal aux Ours. Depending on the hydrological conditions, certain portions of the Chenal aux Ours are identified by the model. Several observations during the summer period are reported in the Réseau de suivi ichtyologique du Saint-Laurent (RSI). Since the species does not appear to migrate to spawn and since the summer habitats and breeding habitats are similar, a summer flow similar to that recorded during the RSI surveys was simulated to validate the model. The four sites at which it was observed match the characteristics selected, except the percentage of sand (40% instead of 70%).
Confidence rating	**Good**: 1. The data from the literature are relatively abundant and accurate in describing the species's habitat. 2. Validation of the model is not very conclusive. The difficulty in detecting microhabitats is one possible explanation for this result. Given the high confidence rating of the parameters selected to construct the model, the results obtained are considered representative of the species's needs.

Source: Adapted from Giguère et al. 2005.

*The channel darter (*Percina copelandi*)*

According to the available literature, the channel darter is a fish that migrates to areas of fast-flowing water to spawn. In addition to a fast current, the spawning sites are characterized by a coarse substrate. This characteristic appears to be predominant, since lacustrine areas with a suitable substrate are also used. Hydrological fluctuations can have a direct (dewatering of eggs) or indirect (changes in the location and composition of the substrate of spawning grounds) impact on this species. Table 10.9 summarizes the main information used to assess the impacts of water-level fluctuations on the channel darter.

*The bridle shiner (*Notropis bifrenatus*)*

The bridle shiner is a fish found exclusively in areas of abundant aquatic vegetation. The eggs released by these fish during spawning adhere to submerged vegetation. Hydrological fluctuations can have a direct (dewatering of eggs) or indirect (changes in the location and composition of submerged vegetation) impact on this species. Table 10.10 summarizes the main information used to assess the impacts of water-level fluctuations on the bridle shiner.

The other priority species at risk

The impacts of fluctuations in St. Lawrence water levels have not been assessed for four species at risk, although they meet the same criteria as the species discussed above. The American shad (*Alosa sapidissima*) could not be considered since two of the habitat parameters recognized in the literature as being important for this fish cannot be modelled at present: dissolved oxygen concentration and summer water temperature. If these variables were known, it would be relatively easy to conduct research on this species, since it is well documented and the HSI models for its critical stages have already been constructed. For the green dragon (*Arisaema dracontium*) and the American water-willow (*Justicia americana*), the assessment of the impacts of water-level fluctuations is unreliable due to the lack of data. In both these cases, we do not know the thresholds above which the amplitude, recurrence and duration of flood or low-water periods adversely affect these species. For the copper redhorse (*Moxostoma hubsii*), an HSI was initiated to assess the effect of water-level fluctuations on potential breeding habitat in the St. Lawrence. However, 20 copper redhorse present in the St. Lawrence and in the Richelieu River were followed using telemetric tracking in 2004. This project revealed that all of the individuals present in the St. Lawrence migrated to the Richelieu River at the start of the spawning period. Combined with the fact that no breeding sites have ever been identified in the St. Lawrence, the results of this telemetry project led to the abandonment of this HSI, since it did not appear to accurately represent the real situation.

TABLE 10.9

Main information used to assess the impacts of water-level fluctuations on the channel darter

Components	Details
Period and area considered	From mid-June to the first week of August, from Lake Saint-Louis to Lake Saint-Pierre, except the La Prairie Basin
Parameters and values used	**Potential breeding habitat** is considered present if: • water depth ranges from 45 cm to 150 cm; • gravel substrate; • current velocity > 5 cm/s. All potential habitat areas where the water depth drops below 15 cm during the period considered were excluded when determining the safe potential habitat.
Validation	The firm Environnement Illimité captured channel darters at two sites in Lake Saint-Louis during the reproductive period. One of the two observations matches the predicted safe potential habitat.
Confidence rating	**Fair**: 1. There are few data in the literature. 2. It is difficult to evaluate the validity of the model. 3. This species generally migrates to tributaries to spawn. 4. In fluvial lakes, current velocity is not the only parameter that influences substrate composition. Wave action can also be very important in the formation of areas of suitable substrate. It would have been preferable to use the energy above the substrate as a parameter, rather than current velocity. 5. The channel darter belongs to the “obligate riverine fish” guild. This factor was not considered in the HSI, and a large proportion of the habitats identified by the model are located far from riverbanks.

Source: Adapted from Giguère et al. 2005.

TABLE 10.10

Main information used to assess the impacts of water-level fluctuations on the bridle shiner

Components	Details
Period and area considered	Early June to the third week of July, from Lake Saint-Louis to Lake Saint-Pierre, except the La Prairie Basin
Parameters and values used	**Potential breeding habitat** is considered present if: • water depth ranges from 45 cm to 120 cm; • fine substrate (clay, silt or sand); • current velocity between 0 cm/s and 15 cm/s; • medium or high density of submerged vegetation. All potential habitat areas where the water depth drops below 30 cm during the period considered were excluded when determining the safe potential habitat.
Validation	In the study area, there are no known observations of the bridle shiner during the spawning period. However, the RSI includes a number of observations during the summer period. Since the species does not appear to migrate very far to spawn and since the summer and breeding habitats are similar, a summer flow similar to that recorded during the RSI surveys was simulated to validate the model. The percentage of correct predictions is 79.7%.
Confidence rating	**Good**: 1. The literature is unanimous concerning the type of habitat used by this species during reproduction. 2. The model provides good validation results.

Source: Adapted from Giguère et al. 2005.

Poor relative performance of the current regulation plan

One of the premises of the International Lake Ontario–St. Lawrence River Study is that the regulation plan that is ultimately selected should not be worse for the environment than the current plan (1958DD). The current regulation plan was therefore used as the basis for a comparative analysis of the five regulation plans proposed by the IJC. That being said, it was difficult to accurately determine whether these alternative plans would have definite effects on the species at risk. In fact, considerable uncertainty is associated with both the source of the data and the methodology used (precautionary principle) to develop the decision-support tools. Moreover, this uncertainty was too great to allow the tools developed for the yellow rail and the channel darter to be used. Consequently, only the tools developed for the following five species had a sufficient confidence rating to allow them to be used for analyzing the proposed plans: least bittern, map turtle, spiny softshell, eastern sand darter and bridle shiner. In order to carry out this evaluation, it was necessary to rely on several different methods for comparing the results. What we found was that only the performance indicator developed for the eastern sand darter identified definite adverse impacts in one of the alternative plans, and then only when the time series representing extended periods of drought was used (climate change). Although it is difficult to offer an opinion on the "degree of significance" of the impacts observed, it also appears that two other alternative plans could affect the turtle species at risk when this same time series is used. The current regulation plan ranked lowest in the comparative analysis, but most of the impacts associated with this plan are considered non-significant (Giguère et al. 2005).

Need for Additional Research

Despite the good representativeness of the species at risk examined in the International Lake Ontario–St. Lawrence River Study and the knowledge acquired about them, further research would be useful to consolidate the findings obtained and to fully assess all the species at risk. To begin with, the accuracy of the tools created could be improved for several species. More broadly speaking, obtaining more extensive data sets for the St. Lawrence would be helpful in developing better models. Also, it was not possible to incorporate in the habitat suitability indices all of the important habitat characteristics at a very fine scale. Furthermore, some species that are particularly sensitive to water-level fluctuations could not be fully incorporated into this analysis. The case of the American shad, the copper redhorse, the green dragon and the American water-willow are particularly good examples of this and demonstrate that further research is needed. This is also the case for certain species that are at risk, but that were not studied here because they do not have specific legislative protection or a special status (e.g. the grass pickerel).

Other, more specific recommendations were made concerning avenues for further research on this group of species:

- It is possible that certain species at risk are present in the St. Lawrence, but were not detected (e.g. the false hop sedge). Since the status of several groups of species (such as insects and mussels) is not well known in Quebec, we must keep a lookout for any new information about them and take this data into consideration.
- It may be important to consider periods other than the breeding period, especially in the case of the copper redhorse, which uses the St. Lawrence except during the spawning period. The winter period is also recognized as a critical time for a number of species, including the map turtle and the spiny softshell.
- Other types of impacts created by water-level fluctuations, such as erosion, were not examined by this study and should be considered in the final selection of a regulation plan.
- The findings of this study apply only to water inflows from Lake Ontario. Other major tributaries of the St. Lawrence, including the Ottawa River, should be taken into consideration in the management of water levels.

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Chapter 11

WATER REQUIRED FOR OTHER USES OF THE ST. LAWRENCE

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Introduction

Water availability is certainly an issue for ecosystem components, but it is also a constraint on uses of the St. Lawrence. From the perspective of integrated management of the St. Lawrence, it would therefore seem useful to document the requirements associated with the main uses of the St. Lawrence River and determine their vulnerability to water-level fluctuations.

This chapter first provides an overview of the uses of the St. Lawrence, then discusses one by one the main human requirements and the uses associated with them, as well as the threats and issues that they represent for water availability. We then go on to examine some poorly understood indirect links between uses and ecosystem components, and conclude with an overview of research on uses in a context of global environmental change.

Uses and the Socio-economic Dimension

Demographic trends are always a good indicator of water consumption trends in Canada. The shores of the Great Lakes and the St. Lawrence River continue to attract Quebecers and other Canadians. It is estimated that within 20 years, nearly 50% of Canadians will reside within the Great Lakes Basin. In Quebec, most of the ecumene is already concentrated along the axis of the St. Lawrence (St. Lawrence Centre 1996).

In the context of the water availability issue, the International Joint Commission and the Lake Ontario–St. Lawrence River Study Board (IJC 1999) identified a certain number of requirements and issues that are particularly vulnerable to fluctuations in water levels and flows. These requirements are, above all, public drinking water supply, followed by hydropower generation, commercial navigation and, lastly, the issues of protecting shoreline properties, recreational activities, and hunting and fishing. However, these water requirements and these issues are not all of the same nature. Some involve water withdrawals, while others assume a certain difference in head or a minimum water level in order to accommodate ships or small craft. In this context, water accessibility is limited by the nature of the existing infrastructures and services. Hence, this is not a problem of availability, but rather a technical problem. In the same way, vulnerability to variations in water levels is directly linked to technical decisions made in the past.

Water required for public drinking water supply

The location of drinking water intake pipes is one of the most important issues affecting the public interest. In the section of the St. Lawrence located between Saint-Zotique (Lake Saint-François) and Varennes (eastern tip of the Island of Montréal), 16 municipal filtration plants produce drinking water for 2.1 million people (École Polytechnique de Montréal 2003a). The infrastructure and water treatment processes used vary considerably from one filtration plant to another, mainly owing to their date of construction and specific features. The use of water for domestic purposes by municipal water supply systems is basically limited by two technical factors: the rated capacity of the water treatment plants and the location of the water intakes relative to water level. In both cases, water availability is linked to the capacity of the infrastructures used and the lack of more cost-effective alternative sources of equal quality and abundance than the St. Lawrence. Groundwater sources present issues related to the lowering of the water table and the quality of the groundwater.

In the past, high water levels did not pose problems, but low levels did (Domestic, Industrial and Municipal Water Uses Technical Working Group 2004). In this case, the direct effect is the easiest to assess, since the relationship between water level (water level/depth at the main water intake) and water quantity is relatively linear. An infrastructure survey, conducted under the auspices of the International Joint Commission, indicated that eight plants (serving 200 000 residents, or 10% of the area's population) were vulnerable to the decreases in levels that occurred in 2003 (École Polytechnique de Montréal 2003a).[1] However, this figure excludes the City of Montréal, which re-activated a former emergency intake to circumvent problems encountered at the water intakes of the Atwater and Charles-J. DesBaillets plants during the summer of 2003. If the City of Montréal is included, the result would show that close to 2.2 million residents were affected by low water levels.

In Lake Saint-Louis, where simulations were carried out (Bibeault et al. 2004) using various scenarios, including extreme situations (Morin and Bouchard 2001), it was observed that the only plant that is never at risk is the île Perrot plant. The two Pointe-Claire water intakes are vulnerable once flows to the LaSalle plant fall below 6997 m^3/s. It should be noted, however, that a water intake will never be completely dewatered. This is very important for ensuring an uninterrupted water supply for the communities around Lake Saint-Louis and residents of the Island of Montréal. That being said, the problem affects pumping, which can be disrupted, particularly in late summer, as has occurred in the past.

More specifically, a damage-level curve was established by Carrière and Barbeau of the École Polytechnique de Montréal (2003a, 2003b) as a function of the sensitivity of the infrastructures to different water levels. Three thresholds were identified, to which a fourth was added: the level at which the Montréal emergency water intake is activated in order to reduce the impact of infrastructure vulnerability problems. Table 11.1 provides a summary of the problem as well as the critical water level based on the Pointe-Claire gauging station. Infrastructure adjustment costs can range from $1 million to $25 million, depending on infrastructure requirements.

The duration of the impact (several hours to several weeks), the impact period relative to demand (summer peak) and the recurrence interval of the problem (annual or once every ten years) will influence the degree of risk and capital investment decisions.

The indirect impact caused by water quality degradation is more complicated, since it depends on multiple interactions of environmental factors (flow from tributaries, sunshine, temperature, quantity of nutrients in the water) and living microorganisms. The spatial delimitation of water masses can also vary, which can cause a problem in terms of selecting the appropriate water treatment adapted to the physical and chemical characteristics of a particular water mass.

For instance, water coming from Lake Ontario requires minimal treatment, whereas water coming from the tributaries requires more complex treatment, especially during heavy flow periods, when particulate matter and coloured substance levels are highest (École Polytechnique de Montréal 2003b). From January 1998 to December 2000, water quality criteria at the mouth of the Ottawa River were exceeded 100% of the time for turbidity, 25% of the time for total phosphorus and 7% of the time for fecal coliforms. By comparison, St. Lawrence water originating from Lake Ontario rarely exceeds water quality criteria, since this water has low turbidity and low total phosphorus and fecal coliform levels (Hudon 2000; Hudon and Sylvestre 1998).

TABLE 11.1
Water levels required (thresholds) for drinking water supply

Degree of alert	Threshold (m)	Justification
Alert threshold	21.05	Opening of the emergency water intake (case of Montréal)
Economic threshold (large-scale investment in treatment)	20.53	Frequent episodes of off-odours and off-tastes Investments required to upgrade/modify main water intakes
Intermediate critical threshold	20.45	Investments required to upgrade/modify the smallest water intakes
Extreme critical threshold	19.78	Investments required to upgrade/modify the plant at lowest risk among the six

The proliferation of microalgae and aquatic plants is a potential indirect effect. Under certain conditions, microscopic algae can proliferate to the point of clogging the filters of municipal filtration plants. This phenomenon was reported in the past in Montréal (Brunel 1956). Some 161 of the 357 species of microscopic algae identified to date in the St. Lawrence are found in Lake Saint-Louis (Paquet et al. 1995). However, planktonic algal concentrations are low in the St. Lawrence near Montréal and appear to increase as a function of flow (Hudon 2000), since they are carried to the area by the tributaries, where conditions are more favourable for them (Basu and Pick 1996). The proliferation of certain species of cyanobacteria, although not yet detected in significant concentrations in the St. Lawrence River, could eventually cause public health problems given the ability of some of them to generate toxins that are released into the water during treatment.

The appearance of off-odours and off-tastes in drinking water could be linked to the decomposition of plants and algae (Ridal et al. 1999). In the Montréal area, 8 of the 16 filtration plants (495 410 residents, or 28% of the population) are periodically affected by this problem to varying degrees (École Polytechnique de Montréal 2003a). An increase in levels of certain algae during low water level situations could aggravate these taste and odour problems, and necessitate additional treatment of drinking water (addition of activated charcoal or ozonation), thereby raising municipal water treatment costs (École Polytechnique de Montréal 2003b).

Finally, low water level conditions can facilitate the spread of certain undesirable species that adversely affect water supply infrastructures. The zebra mussel is frequently cited as an example. The slow currents associated with low discharges could provide favourable conditions for zebra mussel settlement on the river bottom, at the end of their planktonic phase, which occurs during the summer (June–August) (de Lafontaine 2002).

Water required for hydropower generation

Hydropower generation is one of the two main uses (along with commercial navigation) that justified the development of the Seaway and the introduction of Regulation Plan 1958D. The Moses-Saunders hydroelectric dam, operated jointly by the New York Power Authority (NYPA) and Ontario Power Generation (OPG), is the main regulation structure. Upstream of the St. Lawrence, there are also the Long-Sault Dam and the Iroquois Dam.[2] These two complementary structures (dikes) help to manage surplus water quantities likely to affect power generation.

In Quebec, the Beauharnois–Les Cèdres complex[3] receives water inflows from Lake Ontario. The Beauharnois generating station is the fifth-largest hydroelectric generating station in Quebec.[4] Most of the volume of water from Lake Ontario (approximately 85%) is turbined at this generating station, with the rest being diverted to the Les Cèdres sector and four retention basins before being released into Lake Saint-Louis. For the most part, the hydropower is generated at the Beauharnois generating station. The optimum generation level is 1574 MW (max. 1670 m^3/s), compared to 1867 MW for the Moses-Saunders complex. The power generation efficiency rate (optimum/maximum generation) is 94% for the Beauharnois dam, compared to 85% for the Moses section and 95% for the Saunders section (90% when combined). Annual output of the Beauharnois generating station is approximately 12 million MWh (13 million MWh for Moses-Saunders) (International Lake Ontario–St. Lawrence River Study Board 2004).

Hydropower generation depends primarily on the hydraulic head, combined with the existing infrastructure. Differences in water levels between upstream and downstream must be maintained in order to maximize the head, and that hydropower generation at Beauharnois, for example, can easily accommodate low levels in Lake Saint-Louis, since the level upstream (Lake Saint-François) must remain high and stable in order to accommodate commercial navigation. But this is true only up to a certain limit.

This limit, determined by generating capacity, is 8340 m^3/s at Beauharnois and 1500 m^3/s through the Les Cèdres diversion. Upstream, the limit is 10 070 m^3/s at Moses-Saunders. Another constraint is imposed by ice formation in winter, which modulates the quantity of water available for power generation, and by the risk of ice jams and freeze-up of infrastructures. Plan 1958D sets this limit at 6230 m^3/s (generally, during the period from mid-December to early February). For the basin on the Les Cèdres side (former bed of the St. Lawrence River), the minimum expected water level is 46.36 m at Coteau-Landing (max. 46.63 m), 39.2 m upstream of the Juillet Island structure (max. 40.50 m) and 23.9 m during the summer, upstream of Pointe-des-Cascades (max. 24.84 m) (Robert 1997, quoted in Jourdain 1998).

However, under extreme conditions, these limits can be called into question.[5] During emergencies, the authorities in charge of the structures advise the Control Board and the International Joint Commission. The Control Board may then attempt to compensate for the effects of this emergency situation.

Several factors make it impossible to obtain a precise and relevant profile of the economic impacts by generating station, on account of the interconnectedness of the grid[6] and the services, and the flexibility in allocating power over the territory. It is therefore illusory to establish a simple relationship between water stage at a particular generating station and the economic value attributable to energy generation.

Finally, the demand profile is changing.[7] Hydro-Québec has forecast an increase in overall demand of approximately 12% by 2014 (164.8 to 184.8 TWh), while the projected increase in winter peak demand is 9%, based on 2004–2005 data (34 184 MW to 37 365 MW).[8] Energy demand is continuing to increase despite energy conservation efforts (both past and present), not to mention the fact that alternative energy sources are more expensive and often more polluting. Furthermore, the option of resorting to energy imports during new summer peak periods is limited by the rising energy requirements of major urban centres (New York, Boston) in July and August, when water levels are likely to be lowest.

Water required for commercial navigation

Commercial navigation is an essential use of the St. Lawrence. Indeed, this activity has been associated with trade and human occupation of the area for more than three centuries. Furthermore, it is commercial navigation that has, historically, shaped international waterways law (Paquerot 2005)[9] and was the driving force behind the Canada-U.S. *Boundary Waters Treaty*, the creation of the St. Lawrence Seaway and Regulation Plan 1958D.

Development of the Seaway in the Quebec section resulted, from upstream to downstream, in a rise in level and stabilization of Lake Saint-François, construction of a navigation canal (Beauharnois) and the separation of St. Lawrence River flow between a large basin (La Prairie) and a small basin separated by a dike and accompanied by a system of two locks (Jourdain 1998). Despite these various structures and enhancements, shipping traffic along the Seaway has been stagnating since the 1980s. Although there were certainly a few good years in the 1990s, the 1977 historic peak has never been reached again. Furthermore, it is estimated that between 1995 and 1999, the Seaway was used to only 45% of its capacity (Commercial Navigation Technical Working Group 2004). In 2003, transit tonnage was estimated at close to 28.9 million tonnes for 2579 ships.[10] Given the changes in size, length and draft of new ships, it is very unlikely that this situation will change, at least for international trade. In addition, there is no activity during the winter (from mid-December to mid-March) because of the expected ice cover (International Lake Ontario–St. Lawrence River Study Board 2004).

In view of the constraints on navigation in the Seaway, the Port of Montréal, which is able to accommodate larger, deeper-draft ships, has significant requirements. Moreover, the Port of Montréal specializes in container ships, whose numbers are steadily increasing.[11] By comparison, the Seaway can accommodate a maximum draft of only 8.2 m (The St. Lawrence Seaway Management Corporation 2003), while the Port of Montréal can accommodate drafts of 11.3 m (Villeneuve and Quilliams 2000), which has contributed over the years to the development of specific categories of cargo and promoted more intensive and systematic dredging of the ship channel between Québec and Montréal. In 2003, more than 20.78 million tonnes of goods were transshipped at the Port of Montréal, including 9.76 million tonnes of containers[12] (Port of Montréal 2004a).

In principle, periods of low water levels result in a decrease in the volume of goods transshipped, a reduction in ship speed or even, if the low level period persists, fewer trips. In open water, the main constraint to navigation continues to be available draft, to which a safety margin is added in order to avoid groundings. To date, such occurrences have been rare. Data from recent years show there are very few occasions when the Port of Montréal cannot accommodate carriers. Moreover, the minimum level of 4.0 m in the port (5000 m^3/s at the outlet of Lake Saint-Louis) is below chart datum (5.55 m). In terms of the maximum level, the port can continue to receive ships and transfer cargo up to a maximum depth of 11 m (17 000 m^3/s at the outlet of Lake Saint-Louis) (International Lake Ontario–St. Lawrence River Study Board 2004). It will be recalled that in 1964, a record year for low levels, the mean depth was 5.53 m, and that in 1973, the highest mean depth was 7.23 m (Millerd et al. 2004). In addition, for carriers, when vessel speed decreases, squatting is reduced, making ships less vulnerable to low levels and hence able to move with even less water. At lower speeds, both fuel consumption and fuel costs are reduced (Maritime Innovation, HLB Decision Economics Inc., Lauga & Associates Consulting Ltd., J.D. Pace & Associates Inc., Trevor Heaver 2004). Finally, carriers can distribute the overall costs among more than one customer. Provided that depth in the channel does not fall below the minimum level, low water levels will not necessarily have a dramatic effect, all things considered.

The value of goods in a container can total more than $200,000. However, the potential monetary loss associated with an episode of low water levels is significantly mitigated by the regulation plan in effect[13] and by the fact that the loss is attributable to only a few extra hours of overtime before the ship arrives in port to unload its cargo.[14] Furthermore, even though commercial navigation has been carried out year-round on the St. Lawrence River since the 1960s, the critical period tends to be increasingly concentrated in late fall and close to the Christmas holidays, which generates intense commercial activity in Canada and in the U.S. Midwest. During these periods, current velocity and wave amplitude can slow down the movement of ships and therefore reduce trip profitability. In addition to water levels, current and wave stability are also key factors that affect shipping (Commercial Navigation Technical Working Group 2005). Finally, although variations in levels remain unpredictable, commercial navigation could, in principle and for short periods of time, tolerate a fairly significant difference between low and high levels (5000 m^3/s to 17 000 m^3/s at the outlet of Lake Saint-Louis).

Water required for recreational boating, cruises and boat excursions

Boat launch ramps continue to be the main type of facility used by recreational boaters for access to the water. However, municipalities do not keep records on the use of these facilities and are not particularly concerned about water levels. Infrastructure adaptation costs, which vary considerably from municipality to municipality, can range from $30,000 to $150,000 to replace ramps, and from $3,000 to $5,000 for maintenance, depending on the number and quality of the ramps on their territory. No provision was made for these costs under regular maintenance expenses in municipal budgets in 2000 (Boudier and Bibeault 2001).

In the case of marinas and yacht clubs that provide a wide variety of services, it is more difficult to assign a specific cost to variations in water levels. Nevertheless, we noted that more than 90% of docks on the St. Lawrence are floating docks (compared to less than 65% on Lake Ontario). This type of dock allows some degree of adaptation to water-level fluctuations, provided there is a minimum level for boats. In fact, at chart datum, it is estimated that more than 15% of slips are unusable. This proportion increases sharply thereafter as the level drops. The proportions vary depending on the body of water in question, with Lake Saint-Louis being more sensitive to low levels than the other water bodies because of the specific composition of its fleet, followed by Lake Saint-Pierre and the fluvial section (Montréal–Contrecœur).

By examining boating activities by water body, we were able to conduct simulations that more accurately identify the sectors where mobility would be reduced in the event of very low levels (scenario 1P for spring, 4572 m^3/s at LaSalle). The scenario chosen here, devised by Morin and Bouchard (2001), is an extreme case of low levels and was used as part of a study focussing on the impacts of climate change (Bibeault et al. 2004; Bibeault and Rioux 2004). On this basis, we observed a distribution in critical areas (shown in red), difficult-to-navigate areas (yellow) and low risk areas (green) for recreational boating (Figure 11.1). For instance, in the Îles de la Paix sector (south shore), Baie de Valois and around Perrot Island, the low level and low flow scenarios (mainly 1P and 2P) indicate a loss of minimum safe depth over significant areas that would force boaters to restrict their movements to well-marked areas. Mobility in the event of low water levels is therefore reduced along the shores and islands. Moreover, it is estimated that more than 62% of boats cannot use the docks or other access facilities on Lake Saint-Louis when water depth at the dock is less than 1.07 m (Bibeault and Rioux 2004).

Recreational boaters are the “end users” of boating services. In this case, they represent demand, relative to services, which represent supply. Based on the most recent survey on the effects of water-level variations on recreational boating, it appears that recreational boaters have a strong tendency to use the same body of water and the same access facilities. Thus, it may be assumed that they are not very likely to go elsewhere in the event of water level problems. However, the type of boat used on the St. Lawrence River generally requires shallower drafts (approximately 1 m on average) than those in the Lake Ontario fleet. Recreational boaters are generally experienced (74.6% have been boating for more than 10 years) and have a relatively high average income (i.e. $77,000 [2002]). With an average age of 56, they remain fairly active, with an average of 47 days of recreational boating per season (little difference by type of boat), the majority between June and October. The busiest months are July and August, and the critical months for the water stage required to haul boats for winter are September and the first two weeks of October. The daily impact of low levels can, in some cases, mean a decrease or loss equal to average daily spending ($125 to $150 per day per recreational boater), as well as impacting annual spending ($3,330 per boater) (Gardner Pinfold Consulting 2003). The socio-economic importance of recreational boating, overall, was illustrated by, amongst other studies, the first major survey conducted on uses of the St. Lawrence (see Dewailly et al. 1999),[15] which indicated that 13.3% (Montréal area) to 23% (Montérégie) of shoreline residents had engaged in this activity at least once. In 2001, a new survey conducted using a different stratification revealed that recreational boaters made up 15.4% of the population in the Montréal area (Duchesne et al. 2004).

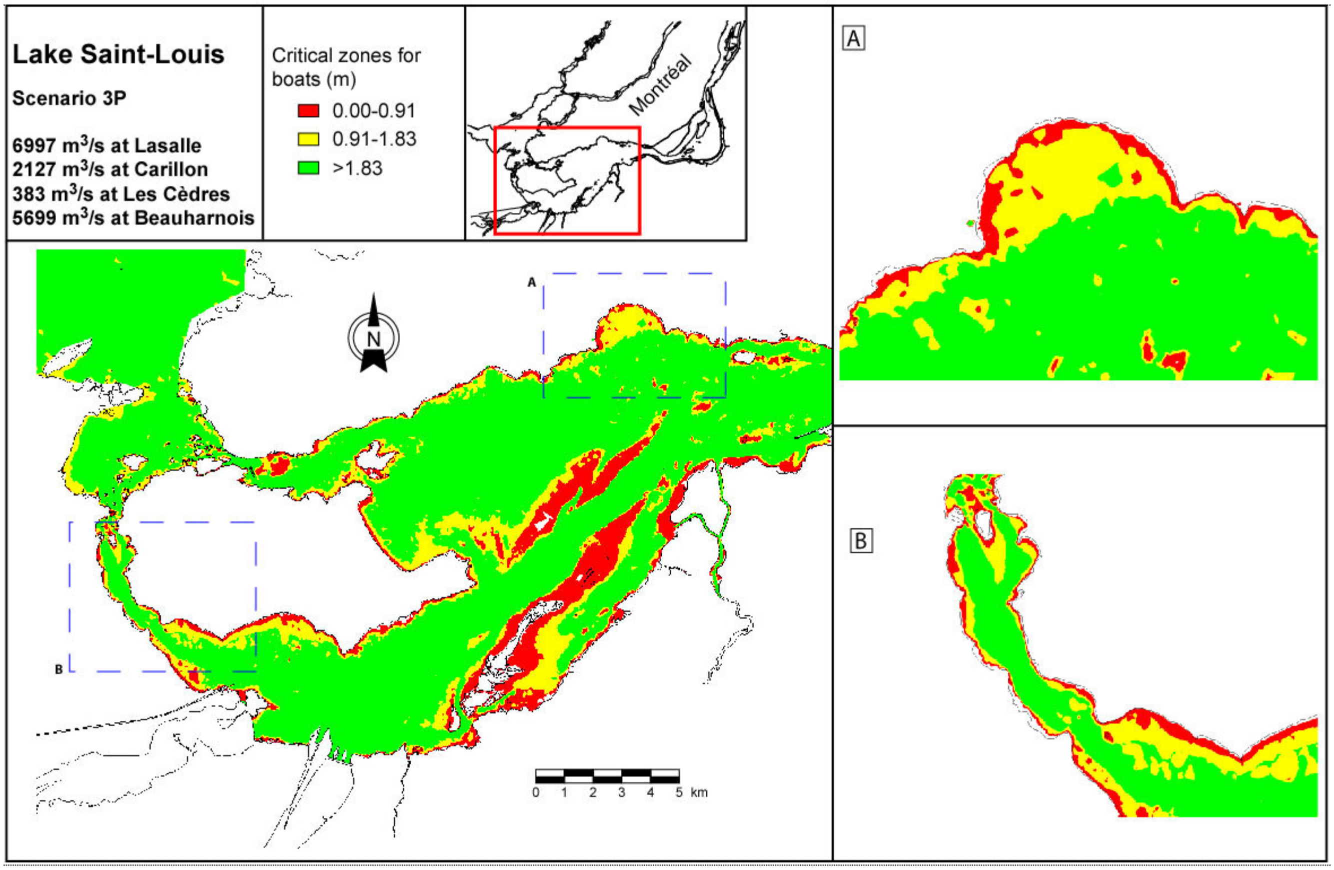

Figure 11.1 Mapping of Lake Saint-Louis in an extreme low level situation

In terms of the critical thresholds specific to recreational boating, based on the fleet estimated in 2001 and 2002, there is a negative impact on Lake Saint-Louis when the level drops below 20.9 m, which becomes even more significant when the level drops below 20.4 m (chart datum at the reference gauging station of Pointe-Claire). For the Montréal–Contrecœur section, losses are very gradual and low from 6.0 m (Varennes gauging station), then increase to the inflection point, which corresponds to approximately 5.25 m (slightly above chart datum). In Lake Saint-Pierre, losses are noted as soon as the level falls below 4.25 m (Sorel gauging station), then increase, especially when the level drops below 3.9 m (just above chart datum at this location) (see Connely et al., 2005). That being said, when water-level conditions are sufficient on Lake Saint-Louis, they are also sufficient elsewhere on the St. Lawrence to the outlet of Lake Saint-Pierre, with the exception of a few infrastructures that are poorly adapted.

Short and long excursions on board commercial vessels are less vulnerable to low levels than small craft. They generally have good docking arrangements and often stay within the commercial navigation channels. This is particularly the case for services operating from the Old Port of Montréal site, Trois-Rivières and Québec. In fact, if water levels were to be maintained at chart datum, there would likely be no impacts. Moreover, most operators are more concerned about the economic and general regulatory context and factors that reduce tourism volume, such as the weather (Gardner Pinfold Consulting 2003; Audet 2002). Nevertheless, it is recognized that there are some more critical sectors such as the Berthier–Sorel islands, the area around the Îles de Boucherville in late summer and the Lachine Rapids in May.

Over the years, cruise boat operators have taken certain measures to adapt to low water levels (Gardner Pinfold Consulting 2003). The extent of these adaptations depends on sales and seasonal revenues ($45,000 to more than $2 million, depending on the size of the vessels) (Chaire de tourisme de l’UQAM 2003). On the whole, damage to date has been fairly minor, all things considered.

Protecting shoreline properties from flooding

For several centuries, the shores of the St. Lawrence have been a preferred site of human occupation. However, most of the early homes were built outside the floodplain; residential construction in the floodplain is a relatively recent phenomenon. In the last few decades, certain secondary residences (such as cottages) have become primary residences, attesting to the growing interest in living year-round near the St. Lawrence River. In 2003, there were 5767 residences within the 100-year floodplain of the St. Lawrence River between Cornwall and Trois-Rivières, for a total value of approximately $460 million. In addition to this stock of housing there are some 615 other commercial, industrial or agricultural buildings (Doyon et al. 2004b).

The land adjacent to the St. Lawrence River has been divided into just over 42 000 lots, and it is estimated that some 20 000 people live along the banks of the St. Lawrence River or within its 100-year floodplain between Cornwall and Trois-Rivières. Depending on the various land use and development plans, the dominant land use is either agricultural or natural environments (or wetlands). Only 3% of the territory is urbanized (Côté et al. 2003). The most heavily urbanized sectors have residential land occupancy rates of 90%. This is the case for the cities of Montréal, Longueuil, Trois-Rivières, Repentigny and Sorel. The moderately urbanized sectors have a residential land occupancy rate of approximately 50%. Finally, despite its urban zoning, the land surrounding Lake Saint-François and Lake Saint-Pierre and the land that forms the Îles de Sorel have residential land occupancy rates of less than 20%, for the most part. Furthermore, some of these sectors are occupied almost exclusively by seasonal residences. In 2003, the average value of residences in the heavily urbanized sectors was $213,000, while values in the moderately and less urbanized areas averaged $80,000 and $43,000, respectively. In most residential areas, waterfront property is the most desirable and, therefore, the most expensive.

Flooding occurs only sporadically in the St. Lawrence River. Over the last 30 years, there have been only three instances of flooding serious enough to cause a problem: shoreline residents of Lake Saint-Louis and the Îles de Sorel sector incurred heavy damage during the 1974 and 1976 floods, and the 1998 flood forced the evacuation of 1000 residents in the Îles de Sorel sector. Flood damage is driven by climatic factors and therefore inherently random; it is difficult to anticipate when more damage will be caused by flooding.

That being said, it is possible to compare certain water control options, and the work carried out by Doyon et al. (2005) for the International Lake Ontario–St. Lawrence River Study identified the following indicators: total area of flooded lands and total length of flooded roads, number of flooded residential buildings, number of properties that could be expropriated (according to provincial legislation) and cost of residential damage for the structure and contents of homes.[16] However, these indicators reflect only part of the direct damage. The key performance indicator is the cost of residential damage (structure and contents), since 89% of the buildings built in the 100-year floodplain are residential (Doyon et al. 2004a). However, the damage is not limited to the residential sector. Significant damage can also be caused to commercial and public infrastructures such as telephone and electricity services, roads, railways and other public utilities. Other types of damage (Grigg and Helweg 1975; Blin et al. 2005), that are more difficult to estimate, can be caused by a rise in water levels: indirect damage[17], intangible damage[18] and secondary damage.[19]

In general, when steps are taken to prevent or minimize property damage caused by flooding, this reduces the cost of repairs as well as the emotional, social and psychological stress experienced by affected residents. A survey conducted by Doyon et al. (2004a) revealed that shoreline residents affected by a flood do not necessarily take steps to protect their property against subsequent floods, regardless of the severity of the damage. For example, substantial damage was reported after the floods of March 31, 1998; May 10, 1983; and February 23, 1981—despite the fact that these floods were less serious than the 1974 and 1976 floods. If all the property owners who had suffered significant damage during the 1974 and 1976 floods had taken steps to protect themselves, the subsequent minor floods would have caused virtually no damage. The reluctance to invest in prevention is attributable to the fact that these floods occur at very irregular intervals.

Since the 1980s, a number of provincial programs, policies, acts and regulations have been developed in an effort to prevent construction in the floodplain and compensate for the lack of individual protection measures. These regulatory efforts cover land use, shore and floodplain protection and environmental protection. For example, the Canada–Quebec Agreement Respecting Flood-Risk Mapping was signed in 1976. Then, in 1987, Quebec introduced its Protection Policy on Lakeshores, Riverbanks, Littoral Zones and Floodplains. Since then, the main components of the policy have been incorporated into most of the land use and development plans of Quebec's regional county municipalities or MRCs (*municipalités régionales de comté*).

However, these programs and policies have had only a limited impact on construction in floodplains. Residential development in the floodplain has continued and in some cases even intensified (Forget et al. 1999; Bouillon et al. 1999; Roy et al. 1997). In the last 30 years, floodplain occupancy and its economic value have increased in Quebec. In addition, since 1998, the province has established exception mechanisms to allow construction in the floodplain under certain conditions.

Despite these exception mechanisms, there are increasing controls on construction in floodplains, resulting in a significant decrease in construction within the floodplain in the Lake Saint-Louis area as well as in the Montréal–Sorel section. Based on the water level measured at the Pointe-Claire gauging station, the following profile of flood levels is currently recognized: flood alert level at 22.10 m and flood level at 22.33 m (International St. Lawrence River Board of Control 2005). In heavily urbanized areas such as Montréal and Longueuil, most waterfront land along the St. Lawrence has already been developed, and there is limited potential for additional development in these areas. However, the control mechanisms have had much less impact in the Îles de Sorel area, where residential density in the floodplain is steadily rising.

Wildlife concerns

The indirect effects of water-level variations have not been assessed to date. During consultations held at Lake Saint-Louis, some fishermen reported that they have noticed a recent change in catches (smaller specimens), likely reflecting changes in the Lake Saint-Louis fish population. This problem particularly affects sport fishermen and the three or four fishermen who hold commercial licences in Lake Saint-Louis. The traditional knowledge of fishermen could be used to supplement fish monitoring data, especially for identifying species movement patterns. Knowledge of the condition of undisturbed natural habitats and the status of threatened species in Lake Saint-Louis should also be updated (Bibeault et al. 2004).

In Lake Saint-Pierre, some commercial fishermen have expressed concerns about catches, without offering any systematic observations as evidence (CSRBLSP 2004). The main species targeted by recreational and commercial fishermen continue to be yellow perch, walleye, brown bullhead and northern pike (Lake Saint-Pierre). The Coopérative de solidarité de la Réserve de la biosphère du lac Saint-Pierre (2004) is calling for the development of water-level criteria for 17 fish species.

Threats and Issues

In the case of water uses, the threats or issues relate to how stakeholders perceive their current and future vulnerability to climate change, in particular, and how they plan to adapt to water availability problems. The points raised here refer to consultations held as part of a project focussed on climate change. Although preliminary, this information nonetheless highlights a certain number of concerns about more effective integration of water use management and environmental considerations.

In the fall of 2003, meetings were held in the shoreline areas of Lake Saint-Louis to discuss the impacts of water-level fluctuations and adaptation measures. Although the points raised are essentially qualitative, they nevertheless provide some useful factors for assessing future issues. The main points raised are summarized below:

- Increased calls for dredging to compensate for low water level problems.
- Future encroachment on drained wetland areas and the accompanying artificialization of the shoreline in order to provide protection from high water, perhaps less frequent in the future, but still problematic in certain locations.
- The increase in winter and summer temperatures could change the annual distribution of domestic electricity consumption (increase in air conditioning). This could result in changes in hydroelectric dam operating methods and flow management, on both the St. Lawrence River and the Ottawa River.
- Significant degradation of water quality could occur in summer, when the flow of the St. Lawrence River is at its lowest, during heavy rains causing a sudden rise in the tributaries, especially those in areas of intensive industry or agriculture.
- The chronic reduction in St. Lawrence River flows also raises the sensitive issue of the dilution of contaminants from municipal and industrial wastewater, especially as it relates to water uses (drinking water, recreation) and ecosystems located downstream from the discharge points.
- The prospect of milder winters increases the probability of the establishment of plant and animal species that currently live farther south.
- A warmer climate would encourage the development of beaches, but the occasional water quality problems, especially after heavy rain, should be taken into consideration in order to control health risks.
- Low water levels will pose greater risks to navigation and require increased monitoring by public authorities as well as greater compliance with safety rules by recreational boaters.
- A larger number of extreme events disrupting water availability may require higher levels of public and

private investment to prevent and mitigate damage and to repair and rehabilitate infrastructures.

- Flooding caused by extreme events could have serious impacts on farmers and other shoreline property owners. While various forms of government assistance are available for farmers, we also rely on the ability of individuals to prevent damage.

The issue of availability of water for the main uses of the St. Lawrence requires anticipating both the opportunities for more integrated management and the risks. Climate change, which is creating pressure to accelerate the decision making process, is making it imperative that we take preventive action and will require adaptation on the part of users in their practices.

Perspective on Uses: The Role of Adaptation

In the coming years, it is projected that population growth will be low, although the composition of the population (age structure, origin, etc.) will change more quickly. However, demographic pressure on the resource will be more indirect, since water uses will also depend on technological developments, institutional innovations and changes in culture concerning water usage. In this regard, certain points for discussion are proposed, with the goal of considering and anticipating these changes.

In the future, water use for domestic and industrial water supply purposes could be more efficient as a result of more intensive awareness raising on sustainable water use and the development of new, low-water-consumption products. However, even if per capita consumption decreases, low water levels still pose a risk for infrastructures with a planned service life of several decades, as is the case for water intakes. Critical low level episodes can still be anticipated, particularly in late summer.

Even if energy demand were to stabilize within a few years, hydropower needs are projected to increase because preference will be given to renewable energy sources that are less polluting than fossil fuels. The role and strategic value of the Beauharnois generating station will decline as the power generation network increasingly reflects the North American distribution system (interconnection of grids). In this context, the particular vulnerability of this station to water-level variations would be reduced.

With respect to commercial navigation, ship size (depth, beam) and draft will be factors increasing vulnerability to low levels. The trend in the international fleet is toward ever larger ships, which is likely to pose problems at Deschaillons (critical curve in the navigation channel), Lake Saint-Pierre (depth) and the Port of Montréal (wharf access). This could also result in an increased environmental risk from spills attributable to navigational difficulties. However, it may be possible to reduce this risk through technical improvements in predicting water levels and ship traffic control measures. Nonetheless, a major problem could occur if levels were to drop 50 cm below the means of low water years. This could lead to calls for deepening of the Seaway or for construction of new water-level control infrastructures.

For the recreational boating sector, low level conditions in late summer will remain a concern. However, it is possible that the evolution of the fleet could take this factor into consideration, with recreational boaters favouring shallower-draft boats and manufacturers improving boat hydrodynamics while reducing draft.

In terms of flooding, it is anticipated that the downward trend in water levels will result in less damage to shoreline properties and infrastructure. Rather, the issue will be to limit urban expansion and artificialization of the more frequently exposed shorelines. It is possible that a new conservation area will be gained as a result.

Finally, it is reasonable to assume that the landscape of the St. Lawrence will change and that new uses could be gained or permitted, provided that water quality does not pose any additional problems. In this case, it will be less a matter of managing the risks than of taking advantage of the opportunities created by new natural conditions, contingent on increased control of nonpoint-source pollution.

The trends in changes remain to be confirmed, especially in light of the various scenarios concerning pressures on water availability. In addition, scenario-based assessment should evolve in order to consider natural, technological and economic factors more systematically.

In all cases, it is essential to look to the future because the St. Lawrence will inevitably evolve, as will the Great Lakes, and so will the behaviours and perceptions of users.

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NOTES

1. Some water supply plants, such as Varennes, serve a population that does not live along the shores of the St. Lawrence River, while other plants located on the shores of the St. Lawrence River, such as the Sorel–Tracy plant, obtain their water from a tributary of the St. Lawrence (Gratton and Bibeault 1998). On the north shore, in Lake Saint-Pierre, only one plant, the Berthierville plant, drew water from the St. Lawrence River (Auclair et al. 1991).

2. The Long Sault dam is operated and maintained by the New York Power Authority, while Ontario Power Generation manages the Iroquois dam.

3. This complex includes the Beauharnois run-of-the-river hydroelectric generating station and a headrace canal—Beauharnois Canal—which commercial ships use as far as the locks of the same name, three control structures (Coteau-1, Coteau-2 and Coteau-3 dams), dikes (Coteau-4), the Juillet Island control structure, three compensating works (Saint-Timothée, Pointe-du-Buisson, Pointe-des-Cascades) to maintain minimum water levels in the basins so as to allow recreational uses and ensure a minimum flow of 240 m^3/s for fish—which can reach a maximum of 440 m^3/s during the spawning period (Jourdain 1998).

4. The installed capacity is 1658 MW, compared to 12 919 MW for the other four generating stations in the La Grande complex (La Grande-1, Robert-Bourassa, La Grande-3 and La Grande-4) (Hydro-Québec, *Discover our Hydroelectric Facilities*, online at: http://www.hydroquebec.com/generation/hydroelectric/index.html, 2004).

5. This was the case in the fall of 2003 with the collapse of the northeastern U.S.–Ontario power distribution system, which forced a massive release of water, the effect of which was quickly felt in Lake Saint-Louis—as well as during the ice storm in Quebec.

6. The New York Power Authority, Ontario Power Generation and Hydro-Québec markets are relatively independent. For the time being, power generation tends to be complementary, facilitated by interconnection of the distribution systems (International Lake Ontario–St. Lawrence River Study Board 2004). In Quebec, prices are set institutionally according to various rates. There are also a number of possible benchmarks for setting rate value based on demand; in this case the domestic market and the industrial market have different rate scales. This makes it difficult to determine the unit marginal cost. For example, for the domestic rate, there are four different methods (D, DM, DT and DH rates). For the industrial sector, there are three user categories, with several possible options for each category. For instance, the L, LC, LP, H and LD rates apply to the biggest consumers (5000 kW or more) [Hydro-Québec 2004a]. The most reliable figure for estimating generation cost is $0.0279/KWh, set by the Régie de l'énergie for base generation of 165 TWh (Régie de l'Énergie 2004, p. 12), a threshold that was not reached in 2004.

7. Based on demand forecasts, current demand reduction measures continue to have a marginal impact (barely 1%) (Hydro-Québec 2004c, p. 35).

8. These are Hydro-Québec distribution projections (Hydro-Québec 2004d).

9. Shipping is still the preferred means of transport for 90% of worldwide foreign trade, not counting the fact that nearly 80% of the world's population lives less than 2000 km from the coast. Finally, maritime power frequently reflects economic power. In 1980, the two largest ports were Rotterdam and New York, while in 2002, this title went to Hong Kong and Singapore (Auffray 2004).

10. It should also be pointed out that some 10 433 pleasure craft passed through the locks, as well as 4108 passengers (St. Lawrence Seaway and St. Lawrence Seaway Development Corporation 2004).

11. While container ships in 1968 carried an average load of nearly 500 TEU (20-foot equivalent units), with a length of 160 m and a draft of 7.9 m, in 2003, the average load had increased to more than 8000 TEU, with an average length and draft of 323 m and 14.5 m, respectively (Comptois and Slack 2005). The Port of Montréal can accommodate these ships, unlike the Port of Havre in France (Scherrer 2003).

12. In 2004, cargo handled totalled 23.64 million tonnes, 46% of which consisted of containers (Port of Montréal 2004b. *Statistics*, www.port-Montréal.com).

13. A comparison of regulation plans (initial plan 1958D relative to changes made) shows a cumulative variation (loss) of $8.37 per 1000 tonnes per kilometre for the Beauharnois–Montréal sector (in the Seaway) and $1.93 per 1000 tonnes per kilometre for the Montréal–Bécancour sector (navigable waterway) [Millerd et al. 2004].

14. The first effect is a reduction in speed in order to remain within the Coast Guard's under-keel clearance standards. For example, a ship moving at 7 knots (close to the safe minimum) can travel with an under-keel safety margin of 0.58 m, while the same ship moving at 14 knots must maintain a manoeuvrability margin of 0.91 m (Canadian Coast Guard, undated).

15. The first major survey was conducted in the early 1980s as part of the Archipel project by the then-Ministère des Loisirs, de la Pêche et de la Chasse (Cournoyer 1982).

16. The possible costs of flood-damage were estimated by compiling comparable data taken from a survey of waterfront property owners in the study area (Doyon et al. 2004a). The survey asked questions about the costs and types of damage caused by the most recent major flood that affected the Iles de Sorel region in spring 1998. "Submersion depth-damage" curves applicable to homes in the area were constructed for the purposes of the study.

17. Not-insignificant damage may result from the breakdown of physical links and the temporary interruption of economic activities: lost sales, reduced productivity, additional costs of alternative routes if roads and rail lines are down. These are all indirect damages. The costs of relocating evacuees and of deploying contingency measures are other examples of indirect damage.

18. Another category of flood-induced damage is "intangible damage." Communities weather a fair amount of intangible damage in the wake of a flood, including factors such as loss of life or loss of enjoyment of life, the costs of planning emergency measures, the inconveniences, evacuation and isolation, stress and anxiety, disruption and other health problems. Intangible damage is not easy to quantify and is sometimes omitted from economic indicators.

19. Though some secondary impacts can be quite subtle, they are no less significant. On valuation rolls, for example, high-risk properties are generally under-valued. For this reason, they constitute a loss of revenue in school and municipal taxes for local authorities (Blin et al. 2005).

Chapter 12

PERFORMANCE INDICATORS

Technical Working Sub-Group on the St. Lawrence River Environment for the Study of the Impacts of Flow Regulation[1] for the International Joint Commission

[1] The sub-group is composed of experts from Environment Canada, Quebec Region and the Ministère des Ressources naturelles et de la Faune du Québec. The various sections of this chapter represent the opinions of their authors and do not necessarily reflect the group's work as a whole or federal policy.

Introduction

Understanding the functional processes of an ecosystem is a lengthy and very complex process. Scientifically speaking, this is equivalent to determining the composition and configuration of a complex environment within which many biological and physical factors interact in space and time. In order to study the effect of a single stressor on the environment, it is necessary to simplify the ecosystem by breaking it down into its most obvious components. This is an incomplete exercise, but one which nevertheless facilitates decision making. The summary presented in this chapter clearly demonstrates that, by conceptualizing the ecosystem and supported by reliable scientific data, we can study complex environmental issues. This is the spirit in which the Technical Working Sub-Group on the St. Lawrence River Environment for the study of the impacts of flow regulation approached its work and provided the International Joint Commission with the best scientific tools available in order to understand the effect of the regulation of Lake Ontario flows on the Great Lakes–St. Lawrence system.

Environmental indicators are effective tools for environmental monitoring that enable us to break an ecosystem down into its primary components, describe their evolution and provide an overview of the changes that may have occurred or could occur as a result of environmental policies, management decisions or changes in external forcing mechanisms (climatic variations, anthropogenic modifications, etc.). These indicators demonstrate clearly and concisely the potential environmental consequences of management choices, thereby facilitating informed decision making.

In principle, environmental indicators should have the following characteristics:

- represent priority issues;
- provide an accurate and clear picture of environmental conditions;
- be scientifically recognized;
- be accompanied by a reliable, practical and cost-effective measurement method.

As such, indicators represent a simple way of understanding and measuring the changes in a complex environment and of assessing the impacts of human activities. Performance indicators are also quantitative indices that measure the progress made relative to a specific objective. When analyzing results, it is important to remember that a good indicator goes beyond the immediate properties observed. Performance indicators can be considered more reliable when they are compared to other performance indicators or when they provide, in some sense, a more accurate overall reflection of environmental changes.

In this particular instance, the most appropriate indicators used in the study are those that examine the responses of the St. Lawrence fluvial ecosystem to the regulation of Lake Ontario water levels and changes in its flow regime. We based the selection of key performance indicators on the principle of ecological integrity, which is defined as achieving a balance between biological components in an assemblage that, in theory, maximizes overall productivity, diversity and biomass. Hence, according to this principle, the conservation of diversity would require that, over time, water-level variations allow all types of wetland habitats to exist, with the necessary connections to the main body of water, so that all organisms that require a specific type of habitat critical to their survival are able to have access to it in order to meet their basic needs at least once during their lives.

In order to meet these requirements, a large number of indicators (more than 200) with different and independent responses were developed. About 20 key indicators were then selected in order to compare the plans proposed by the International Joint Commission. The methods used to select the key indicators were chosen with the goal of obtaining a group of indicators more sensitive to flow regulation or that react in a manner that provides useful information for experts and managers. This core set of indicators also contributed valuable information to support decisions concerning a new plan and will be useful in the coming years for identifying the long-term impacts of anthropogenic pressures.

The sections that follow describe the different, but complementary, methods recommended by the Sub-Group for developing, analyzing and selecting performance indicators.

The first section describes the process of developing performance indicators using empirical models (i.e. models based on measured data), as well as the application of these indicators.

The second section provides a detailed description of the development of performance indicator modelling and examines in particular the integrated two-dimensional modelling approach, accompanied by some operational examples.

The third section discusses the approach used to select the key indicators from an ecosystem perspective and by considering the sensitivity, performance, similarity and significance of these indicators.

The fourth section provides a brief description of proposed hydro-ecological criteria for the fluvial section of the St. Lawrence.

The chapter concludes with a discussion of the strengths and limitations of the development of indicators.

While reading this chapter, the reader will note that this exercise contributed significantly to our scientific and management experience. This chapter includes complementary approaches that are necessary for the development and thorough evaluation of the indicators and of the risks and benefits of an alternative regulation plan. Monitoring and information requirements for adopting adaptation measures are also discussed.

I Empirical Models

Water-level variations are a major factor determining the distribution, composition, diversity and productivity of aquatic and riparian communities, including the habitats and the flora and fauna that depend on them. The development of performance indicators is based mainly on knowledge and measurement of the links between certain ecosystem components and their associated hydrological characteristics.

The process of developing performance indicators using empirical models comprises six main steps, which will be described in the following paragraphs.

Setting environmental objectives

The members of the Environmental Technical Working Group for the International Joint Commission study identified two essential environmental objectives, which constitute the framework of reference for the studies to be conducted by the group's members.

- Maintain a sufficient surface area of all habitat types (floodplains, forested and shrub swamps, wet meadows, marshes, submerged grass beds, mud flats, open water and rapids) and of all the shoreline morphological facies (beaches, barrier, gravel, cobble, dunes and islands) to support the communities and populations of organisms that depend on them.
- Maintain hydrological and spatial connectedness in order to ensure that aquatic wildlife have access, in space and time, to a sufficient surface area of all the habitats that they need to complete their life cycles.

The link between hydrology and the biological components of the ecosystem may be manifested either directly (effect of hydrology on plant and animal species, populations, communities) or indirectly (effect of hydrology on the availability of and access to potential habitats and morphological facies for flora and fauna) (Figure 12.1).

Wetlands are a priority for the Environmental Technical Working Group, since these environments are heavily dependent on the hydrological regime and provide a variety of critical wildlife habitats. The two objectives take into account the hierarchical organization of ecosystem components (species, populations, guilds, communities) that are impacted by hydrological variations at different spatial and temporal scales.

Placing the emphasis on habitat preservation enables us to avoid targeted interventions aimed at promoting a particular wildlife species, undoubtedly chosen on the basis of an arbitrary judgement of its "value," to the detriment of other species. However, including "emblem" wildlife species (pikes, ducks) nonetheless has considerable educational merit for illustrating certain impacts (Figure 12.2).

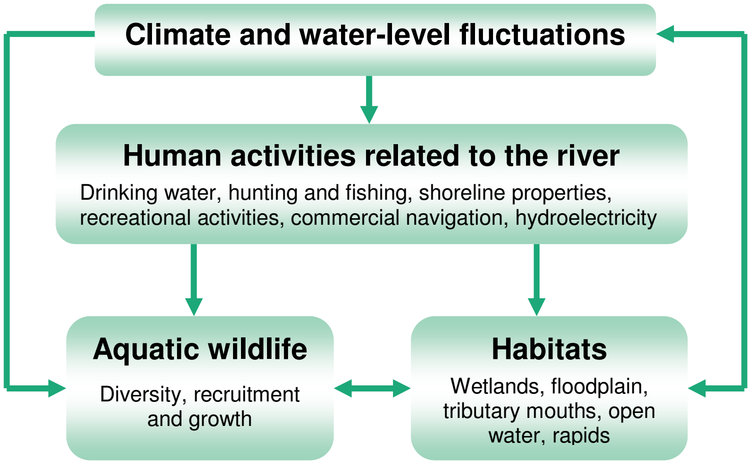


Figure 12.1 Direct and indirect relationships among climatic and hydrological conditions, uses and performance indicators for habitats and wildlife

In addition to the merits of preserving a mosaic of habitats, the environmental objectives emphasize the importance of habitat variations in space and time as a function of the climatic and natural hydrological regime. The definition of "sufficient" surface area refers to the surface area that would exist in a no-regulation situation and therefore constitutes the baseline hydrological regime against which the proposed regulation scenarios must be compared. Under natural conditions, episodes of spring high water and late summer low water maintain a wide strip of riparian vegetation, where only plant species tolerant to fairly long periods of flooding can persist depending on their elevation on the shoreline. By reducing the amplitude of seasonal variations, regulation reduces the width of the periodically flooded shoreline strip on which wetland plants depend. This allows terrestrial vegetation to invade the now less frequently flooded areas, and hardy emergent plants (cattails) and submerged plants (water milfoils) to proliferate in the shallow environments that are now less frequently dewatered. Over the millennia, the life cycles of the organisms of a water body have adapted to the cycles of abundance of riparian habitats. For instance, each species benefits from short periods during which habitat conditions are optimal to produce a cohort that will support the population during the period when those conditions will be lacking.

Furthermore, restoring a hydrological regime similar to natural conditions would enable ecosystems to recover on their own, without human intervention, and would make them more resistant to the proliferation of invasive species (Bunn and Arthington 2002).

Identifying the hydrological characteristics affected by regulation

The changes in the hydrological regime brought about by regulation must be clearly identified in order to demonstrate the biological impacts and select alternative plans that most closely approximate natural conditions. This step requires collaboration between hydrologists, engineers and biologists, in order to properly determine the limiting factors and the order of magnitude as well as the spatial and temporal scale of the hydrological differences whose impact we are endeavouring to assess. It does not appear to be possible to detect the biological effects of hydrological variations occurring at spatial and temporal scales finer than the resolution of the basic data.

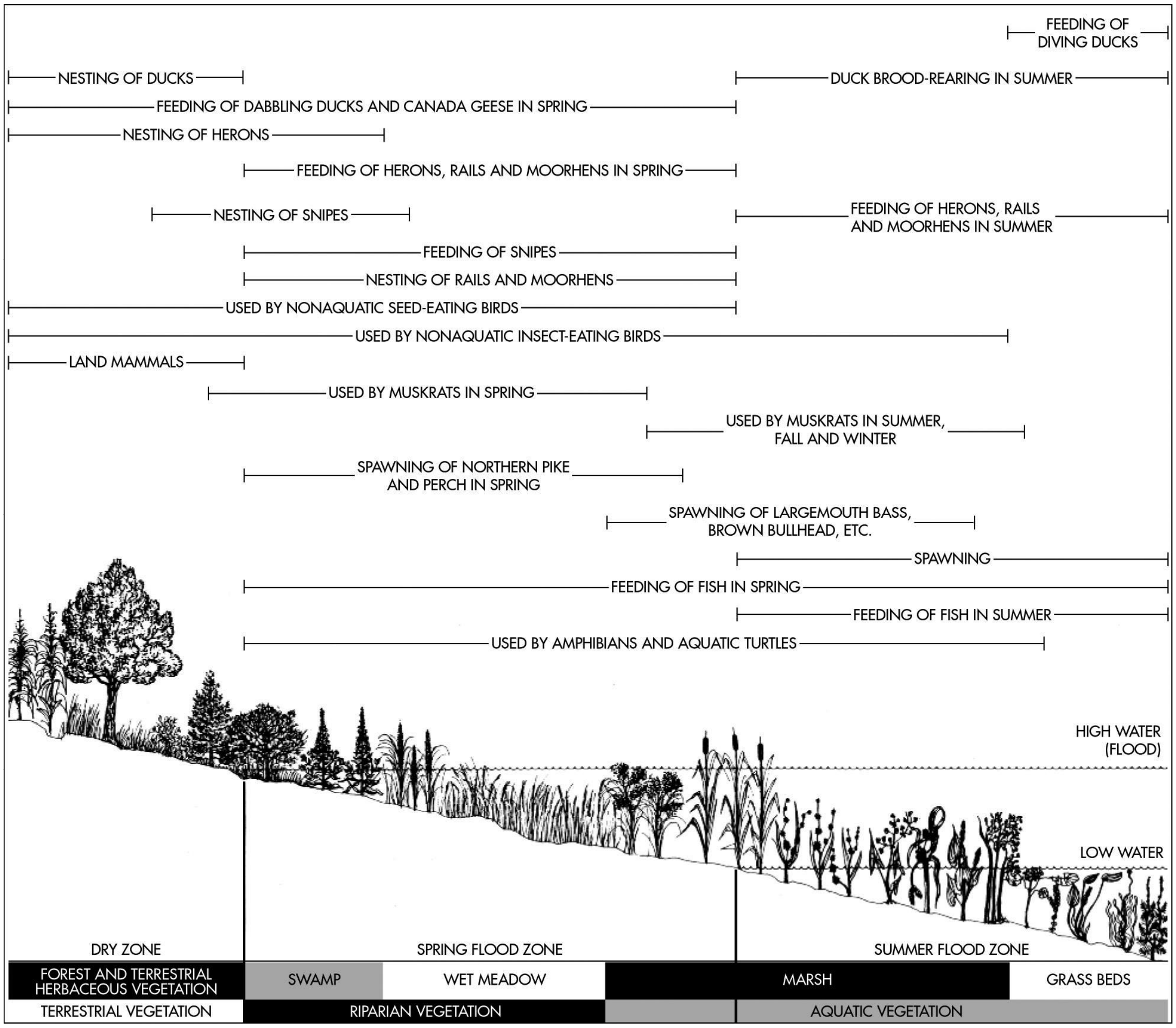


Figure 12.2 Relationships among seasonal water levels, wetland habitats and certain life cycle stages of the wildlife species that depend on them

The following are a few examples of the main operational and technical constraints that biologists had to deal with when developing performance indicators:

- Because of logistical constraints, the study on the effects of regulation was limited to a temporal scale of quarter-months (48 equal intervals per year, at a rate of four intervals per month). This temporal scale masks the variations that occur at a finer scale (weekly, daily, hourly), yet which are important for living organisms. In fact, the presence or absence of water in a spawning ground or nesting area, even for just one hour, can mean the difference between life and death for fish and bird eggs.
- The performance of alternative plans was compared to the regulation plan currently used (1958D with deviations) in an effort to improve conditions under the current management approach. However, no studies have been done to demonstrate the environmental viability of the current plan, and an alternative plan offering an ostensibly "better"

environmental performance than Plan 1958DD might still not be environmentally sustainable. From an environmental perspective, the conditions that existed prior to regulation are the best baseline conditions against which the alternative plans should be compared.

- The influence of the Ottawa River and other tributaries and tidal action tend to mitigate the effects of regulation and increase the variations in the hydrological regime in a downstream direction.
- The digital elevation models are accurate to within 25 to 50 cm, depending on the environment, which makes it impossible to detect the effects of water-level variations smaller than this. However, most of the differences between the plans fall within this range of variations.
- Historically, the effects of regulation are added to the numerous structural changes made to the river bed (excavation of the navigable channel, deposition of dredged material, reservoirs) and to the shoreline (encroachment, erosion, various manmade structures), and ice management (preventing ice jams, controlling ice cover), which have significant additional effects on the hydrological variations (Hudon 2004). In order to eliminate the effect of anthropogenic changes and isolate the effect of regulation of the outflow from Lake Ontario, the time series of water levels in the fluvial section were simulated using the current configuration (channel, locks, dams, shoreline, etc.) and ice management. The simulated historical values therefore differ significantly from the time series of measured levels (those experienced by the ecosystems over time), particularly in the Montréal area.
- The regulation of water levels and flows is one factor among many other environmental factors (current velocity, water temperature) that also influence the life cycle of organisms, but that cannot be taken into consideration for the purposes of dam management. For instance, the recruitment of a species may be compromised if the spring temperature is too low, even under optimal water-level conditions. Moreover, marginal differences in summer levels can result in significant differences in current velocity, temperature and dissolved oxygen, depending on the type of environment, with significant consequences for organisms.

Nonetheless, we can identify four major categories of hydrological changes induced by the regulation of Lake Ontario and the St. Lawrence (in decreasing order of importance):

- **Reduction in high-level periods on Lake Ontario**. – At the decadal scale, the St. Lawrence Control Board has departed from the rules of the current regulation plan to reduce the high levels of Lake Ontario in order to protect shoreline properties from erosion. This has had the effect of reducing the diversity of Lake Ontario wetlands and promoting the dominance of cattails (*Typha*) in marshes. For the Lower St. Lawrence, this modification has resulted in higher discharges during periods of increased inputs of water to the watershed and in decreases during periods of reduced inputs.
- **Reduction in the amplitude of the spring freshet in the Lower St. Lawrence**. – Flood control is required mainly to protect shoreline properties against flooding and erosion, which particularly affect properties located within the floodplain. Deviations from the current regulation plan occur when the freshet of the Ottawa River or other tributaries threatens public safety or property. Reducing freshets decreases the surface area and duration of flooding of the floodplain, a transitory habitat that is important for reproduction and feeding in many animal species in spring and for the conservation of natural wetlands.
- **Increase in late summer low-water levels in the Lower St. Lawrence**. – The low water levels that normally occur in late summer (August–September) are a hindrance to commercial navigation and recreational boating. Consequently, there have been numerous deviations from Plan 1958D at the request of vessel operators to allow ships to pass with a greater payload, reduce the risks of grounding and facilitate access to recreational boating infrastructures. The rise in low water levels prevents the periodic dewatering of marshes and submerged grass beds in shallow water, allowing emergent plants to renew their seed bank and reducing the biomass of submerged plants.
- **Reduction in the amplitude of seasonal variations on Lake Ontario and in the Lower St. Lawrence**. – The combination of a decrease in freshets and an increase in low water levels results in a decrease in the annual seasonal tidal range, which ultimately reduces the total surface area and diversity of wetland fringes. Trees and terrestrial shrubs gradually invade swamps, while marshes are invaded by hardier species such as cattails, purple loosestrife and common water weeds (Wilcox 2004; Hudon 1997).
- Selecting the ecosystem components affected by the hydrological regime

The components (habitats, communities, guilds, populations, key species) to be studied were selected based on a nine-item evaluation checklist provided below (in decreasing order of importance):

1. Relevance and sensitivity to variations in the hydrological regime, based on a documented biological mechanism, including verifiable alternative hypotheses.
2. Applicability for formulating regulation criteria and testing alternative regulation scenarios.
3. Quantitative relationship with a hydrological characteristic directly affected by regulation.
4. Quantity and quality of existing information, expertise and data (published documentation, reports, databases, additional acquisition), peer-reviewed if possible.
5. Potential for integration and correlation with other indicators of the same type developed for Lake Ontario and the fluvial section of the St. Lawrence.
6. Clarity of the units of measurement, area of application and interpretation of results.
7. Region of application.
8. Time, investment and effort required to attain the results.
9. Particular interest in terms of legislation (protection of rare and endangered species [USFWS 1973; COSEWIC 2004], *Fisheries Act*, *Policy for the Management of Fish Habitat* [DFO 1998], legislation governing parks and ecological reserves), decision makers, interest groups (sanctuaries, wildlife enhancements, Priority Intervention Zones, hunting and fishing areas) and the Public Interest Advisory Group of the International Lake Ontario–St. Lawrence River Study.

Establishing relationships between hydrology and biology

Various mathematical methods can be used to measure relationships between hydrology and biology: the hierarchical binary approach, simple or multiple linear regressions, non-linear, exponential or parabolic relationships, etc. The primary goal is to obtain a functional, empirical (based on measured data) and predictive relationship between each biological component and the hydrological characteristics that determine variations therein. It goes without saying that hydrological factors must generate a stronger signal than other potentially confounding environmental factors such as temperature, current velocity or the presence of toxics, to name but a few. Unfortunately, this is not always easy, since hydrological conditions are frequently correlated with environmental variables (depth, turbidity, transparency, current). Under these conditions, knowledge of the environment and the experience of scientists (judgement of experts) constitute an important element in interpreting results.

In order to develop a few empirical relationships that will be useful for estimating the surface area of habitats available to wildlife, it is necessary to group these habitats into a small number of fairly comparable and uniform categories: forested and shrub swamps, wet meadows, marshes, submerged grass beds, mud flats, fast-flowing water (rapids). The same type of reasoning applies to fish and bird fauna, which can be grouped into "guilds" based on their simultaneous use of the same habitats for reproduction, rearing of young or feeding. This type of aggregation increases the scope of the performance indicators derived from them, since the relationships are more general and apply to a set of species.

However, the link between habitats and wildlife must be made based on the needs of each type of wildlife, since every animal species perceives and uses its habitat according to its needs and size and at different scales. For example, wetland birds are sensitive to the vertical heterogeneity of the canopy (herbaceous vegetation, shrubs, trees) as well as to the mosaic of ground vegetation (swamps, meadows, pools) in a wider radius than vertebrates with a smaller range (anurans, juvenile fish).

Establishing relationships between hydrological aspects and a wildlife species based on the availability of its habitat presupposes that the habitat surface area limits the abundance of the species in question—which has not necessarily been demonstrated. Using an intermediate step linked to the habitat adds a supplementary layer of additional uncertainty to the results of this type of performance indicator. For example, the relationship between the freshet level and the surface area of pike spawning ground is a less robust indicator than the relationship between the freshet level and the pike recruitment index (Casselman and Lewis 1996).

The robustness of relationships is particularly important since the relationships will be tested using different stochastic scenarios of water inputs to the watershed, in order to take climatic conditions of varying temperature and precipitation into account, as well as different climate-change scenarios. This could cause the performance indicators to produce environmental predictions for hydrological conditions outside the range of values for which they were developed—a real possibility if the climate-change scenarios become reality. Once again, the experience of scientists is an important element in interpreting results.

Validating the indicators

Validating the predictions using independent data is an essential step in the development of performance indicators linking hydrology and biology. This evaluation helps determine the reliability of the relationship as well as the degree of uncertainty associated with the predictions, both of which are needed to determine the impacts, which may be classified as significant (i.e. different from zero, considering the errors inherent in the process), adverse (i.e. unfavourable because of their duration, frequency, geographic scope or irreversibility) and likely (i.e. likely to occur, depending on the uncertainty associated with each indicator) (CEAA 1992).

Hence, the performance indicators derived from indirect relationships between the hydrological regime and wildlife (based on the availability of certain habitats considered critical) are subject to additional uncertainty owing to the fact that errors accumulate at each stage in the process.

The indicators can be validated by means of a subset not used during development of the models or additional data from previous studies. There are numerous examples of hydrology/biology relationships in the literature, which constitutes a valuable source of information for comparison and validation, at least summarily so.

In addition to the variability induced by measurement errors, it should be noted that the "noise" from hydrology/biology relationships constitutes an intrinsic manifestation of adaptability and natural variability, which improves the probability of survival in marginally favourable conditions. For example, for pike, a reed canary-grass wet meadow is a more suitable spawning habitat than a common water reed meadow or a cattail marsh, although adults can still spawn (with a lower success rate) even in submerged grass beds if their preferred habitats are not available. It is not to nature's advantage to "put all its eggs in one basket"!

Selecting an alternative regulation plan using performance indicators

There are certain basic rules that must be followed when using indicators to select an alternative regulation plan, in order to ensure consistency with the environmental objectives while remaining within the indicators' scope of interpretation. We must bear in mind, first of all, that the regime of hydrological variations that the most desirable alternative plan should most closely approximate is represented by the natural conditions that existed prior to regulation. In this regard, simply comparing hydrological characteristics between alternative plans and unregulated conditions should serve as a guide, in the same way as performance indicators based on some hydrology/biology relationship. Several other principles may be useful in guiding the decision making process:

- avoid mathematical aggregation and calculations that combine several different indicators (e.g. total, mean, ratio);
- evaluate performance indicators based on their degree of robustness and reliability and not on an economic value, weight or some other arbitrary "value";
- adopt a holistic approach that considers all the indicators and all the regions subject to water-level and flow management;
- give preference to a series of indicators developed for hydrological characteristics covering all periods of the year, in order to ensure that all the events of the hydrograph generated by each plan—i.e. amplitude, frequency, variability, freshet and recession rate—are evaluated under both normal conditions and extreme events (Poff et al. 1997; Petts 1984);
- represent a wide range of spatial scales and habitat types for the entire Lake Ontario and St. Lawrence River system;
- endeavour to reduce the adverse effects associated with regulation without trying to "improve" the environment;
- avoid compromises or bargaining of gains for one species to the detriment of another;
- identify the "desirable" conditions: more is not necessarily a guarantee of better environmental health, hence the basic concept that the objective is to approximate the unregulated natural regime of hydrological variations as closely as possible;
- adopt the precautionary principle when selecting an alternative plan;
- track a subset of the indicators selected to determine whether the new regulation plan attains the environmental objectives and adjust the plan accordingly.

Example of the evaluation of plans using a performance indicator

A performance indicator was developed to evaluate the variations in surface area (in square kilometres) of wet meadows present every year in Lake Saint-Pierre based on the mean level conditions at Sorel (in metres, according to the International Great Lakes Datum of 1985) during the vegetation growing season (April 1 to September 30).

The surface area of wet meadows that would have been observed in Lake Saint-Pierre for a 101-year period was calculated by applying this equation to each level value during a quarter-month observed (simulated) at Sorel, if water levels had been managed using the current plan (1958DD) or each of the alternative plans. The plan favouring the economy (plan A+) aims to minimize the variations in Lake Ontario, while the plan favouring the environment (plan B+) endeavours to restore the Lake Ontario–St. Lawrence River system to a more natural and more variable regime, creating conditions similar to those that existed prior to the hydroelectric project in the St. Lawrence River, while also seeking to minimize the economic damage. The balanced plan (plan D+) endeavours to maximize the net economic and environmental benefits of regulation relative to the current plan (1958DD), without disproportionate losses in the other sectors of the region's economy (hydroelectricity, navigation, trade, etc.). The surface area of wet meadows that would have resulted if there were no regulation ("no regulation" plan [plan E] allowing the maximum seasonal variations in the lake and the St. Lawrence, but that could cause flooding in the short term) is then compared to the surface area obtained with each of the plans, for the same period (Figure 12.3).

The "no regulation" plan (plan E), developed during the IJC study, most closely approximates natural flow conditions while maintaining uniform ice cover on the St. Lawrence River to limit ice jams. However, it is assumed that the infrastructures (bridges, dams, etc.) are still in place. This plan is used primarily as a basis for comparison when assessing impacts.

The comparison of wet meadow surface area obtained with each of the three alternative plans shows that the plan favourable to the environment (plan B+) most closely approximates unregulated conditions (Figure 12.3, upper right), since nearly all the dots are located near the 1:1 straight line and have the highest coefficient of determination. The balanced plan (plan D+) and the current plan (1958DD) (Figure 12.3, bottom graphs) have a wide dispersion of dots, higher confidence intervals, a different slope and the lowest coefficient of determination values.

An examination of the differences between each of the plans and unregulated conditions (Table 12.1) confirms that the plan favourable to the environment (B+) is the one most similar to unregulated conditions. In addition, the balanced plan (D+) results in significant differences from unregulated conditions in terms of mean level and surface area that even exceed those under the current plan (1958DD), and are therefore the most damaging to the environment.

II Integrated Modelling of Performance Indicators

Regulation and performance indicators

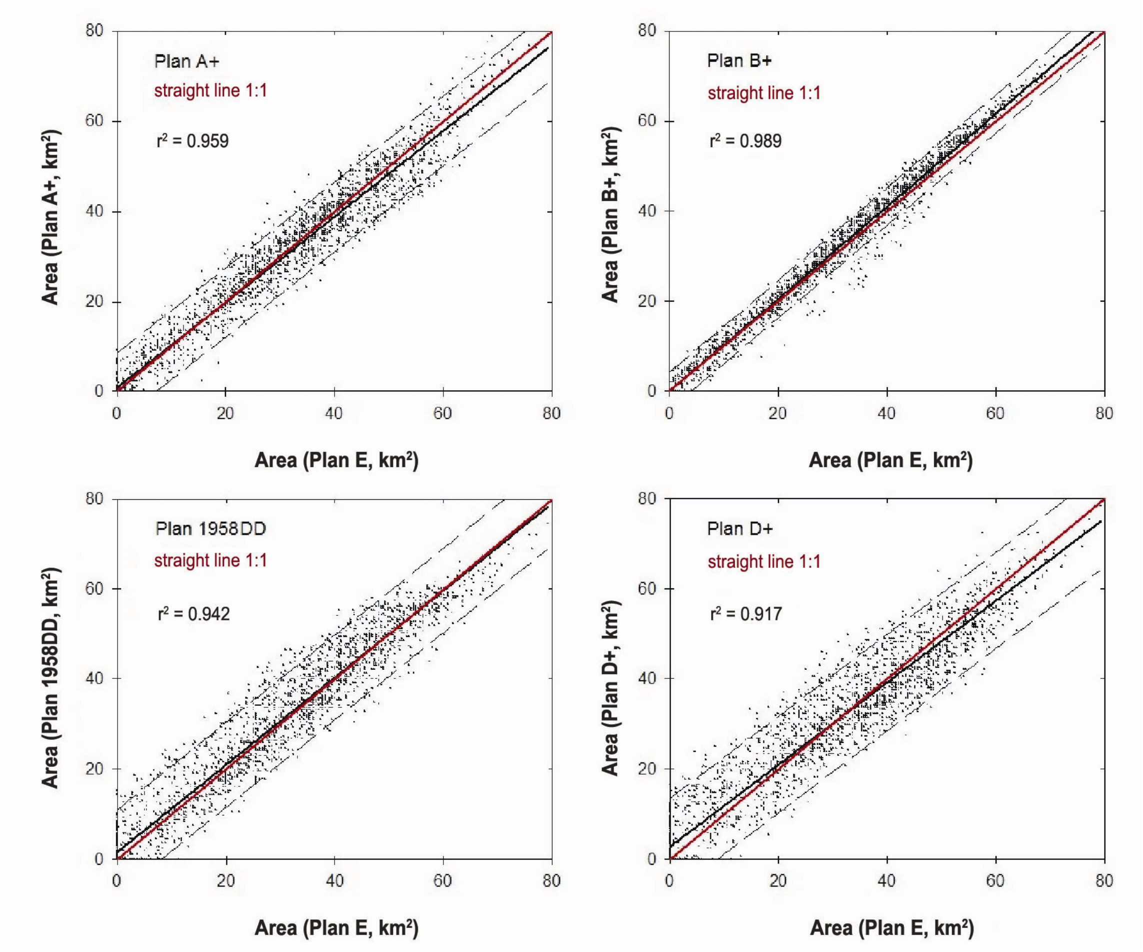
The overall effect of the regulation of Lake Ontario can be seen in the annual hydrograph as a decrease in spring discharges, of 250 m^3/s on average (period from 1960 to 1997), and an increase in summer discharges (Morin and Bouchard 2000). In other words, regulation stabilizes discharge and minimizes the extremes (highs and lows) (Figure 12.4). As well, the freshet peak is delayed by several weeks compared to the "natural" discharge (Morin and Leclerc 1998). In addition to the distribution of discharges during the year, regulation results in significant fluctuations in weekly as well as intraweekly discharges.

TABLE 12.1

Comparison of the standard deviation and minimum and maximum differences in wet meadow level and surface area for each regulation plan with unregulated conditions

	Level (m, IGLD 85)		Wet meadow surface area (km^2)	
Plans	**Min.-Max.**	**Standard deviation**	**Min.-Max.**	**Standard deviation**
Current plan (1958DD)	-0.7–0.5	0.13	-17–14	3.44
Plan favourable to the economy (A+)	-0.7–0.5	0.13	-14–13	2.88
Plan favourable to the environment (B+)	**-0.6–0.4**	**0.07**	**-7–12**	**1.59**
Balanced plan (D+)	-0.7–0.4	0.14	-17–19	4.06

Note*:* The plan favourable to the environment (B+) exhibits the smallest differences and is the plan that most closely approximates unregulated conditions.



Note: The regression line (black line) and the confidence interval (dotted lines) indicate the general trend in surface area obtained for all the quarter-months (dot). The 1:1 straight line (red line) represents perfect agreement between the two plans. The coefficient of determination (r^2) indicates the degree of agreement between the two plans and would be equal to 1.00 if the two plans generated identical wet meadow surface areas.

Figure 12.3 Relationship between wet meadow surface area obtained in the absence of regulation (plan E "no regulation," X axis) and the surface area obtained by applying the current plan (1958DD) and each of the alternative plans (A+ "economy," B+ "environment" and D+ "balanced")

From an operational standpoint, the St. Lawrence is regulated on a weekly basis. For the purposes of the study, it was decided to analyze the impacts by quarter-month because this period facilitates interannual comparison of the hydrological regime and the application of temporal models. It was also decided that the plans would be evaluated using 101-year hydrological series beginning in 1900 and ending in 2000. However, in the downstream section of the St. Lawrence, the changes in the hydrology of the Ottawa River watershed required that the time series be shortened to the 1960–2000 period.

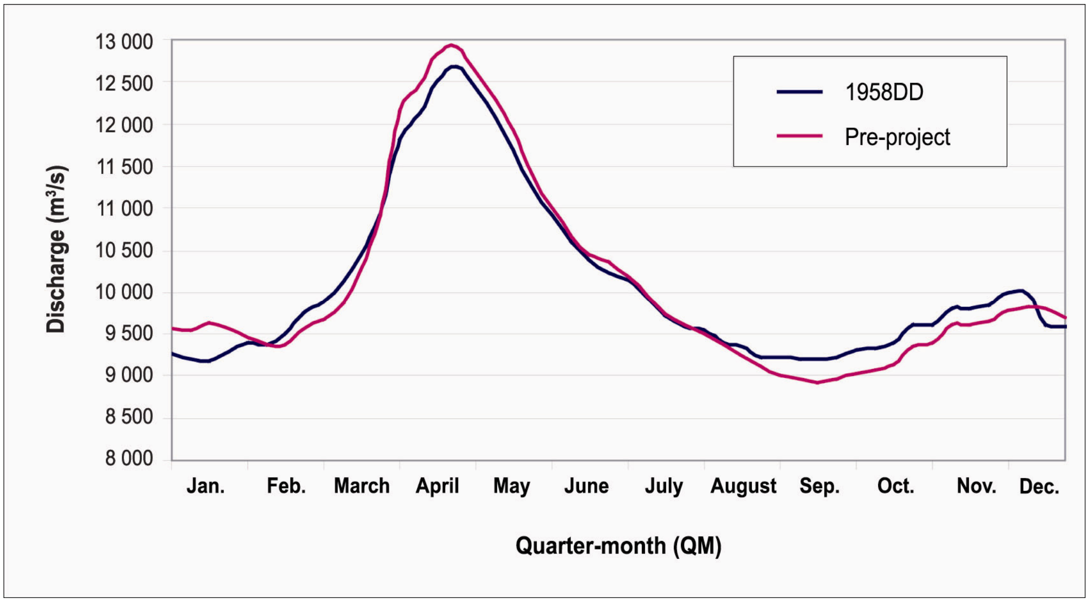


Figure 12.4 Mean discharge per quarter-month at Sorel between 1960 and 2000, with and without regulation of Lake Ontario

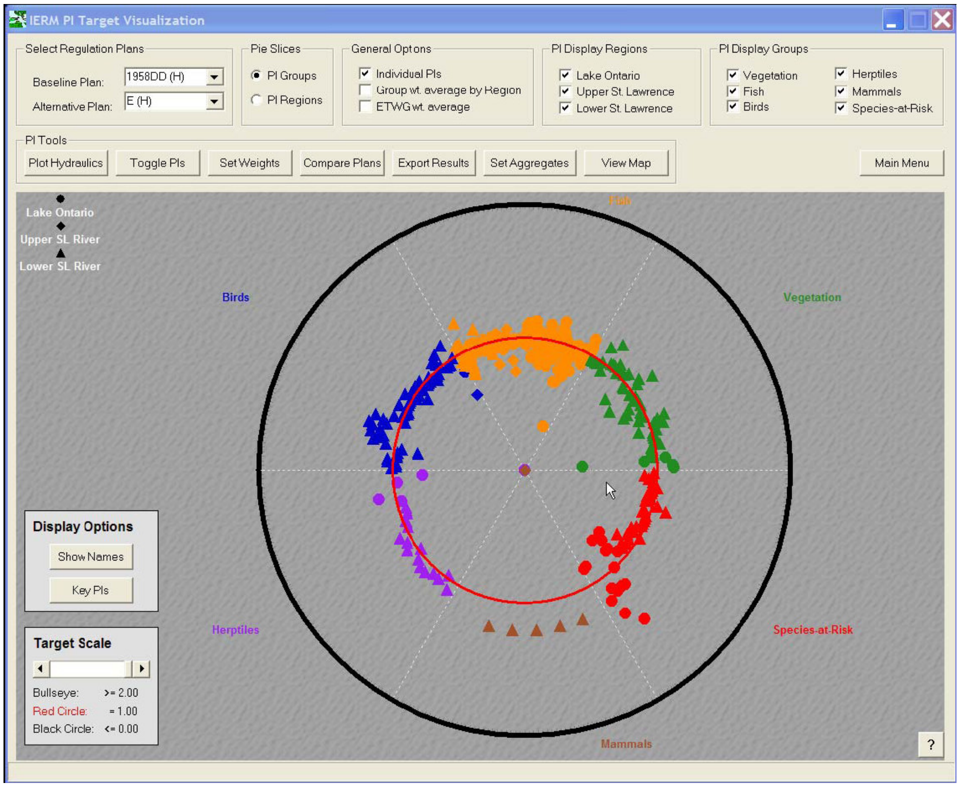
In order to select the best regulation plan, the indicators were calculated for each year of the series and the data collated to identify the plan with the best performance relative to the most important indicators.

The St. Lawrence River is a huge system composed of more than 2000 km² of plant and wildlife habitats whose hydrological characteristics are highly variable in space and time. Since the hydrological regime of the St. Lawrence has long flow cycles ranging from 10 to 30 years, the location of swamps and marshes changes as a function of mean water levels over these long periods (Morin et al. 2005). The availability of wetlands for wildlife therefore varies as a function of previous years' discharges, which determine their spatial distribution, while the current water level influences access to these environments. This complexity means that the relationships between hydrology and the habitats of various species are also complex and vary in space and time. Consequently, it was necessary to develop a powerful and flexible modelling approach in order to correctly evaluate these interactions over an area as large as the St. Lawrence.

Two-dimensional (2D) modelling is very well suited to the analysis of the impacts of various environmental changes, since it enables us to use relationships based on local observations to generate predictions applicable to large areas. In order to meet this challenge, the Environmental Technical Working Group produced a spatialized modelling system called the two-dimensional Integrated Ecosystem Response Model (2D IERM), in which the vast majority of the ecosystem indicators were developed.

The Integrated Ecosystem Response Model (IERM)

An Integrated Ecosystem Response Model (IERM) was designed to evaluate a set of performance indicators as a function of various regulation plans proposed by experts and by the International Joint Commission Study Board in order to facilitate the comparison of environmental factors with commercial, recreational and government interests. The IERM was developed by researchers from Ontario and Quebec working on the study in close collaboration with specialists from LIMNO-TECH, a U.S. company that specializes in ecological modelling. The final product is an easy-to-use computerized interface that allows managers, advised by specialists, to obtain information on the predicted environmental responses associated with the proposed plans (Figure 12.5).



Select Regulation Plans
Baseline Plan: 1958DD (H)
Alternative Plan: E (H)

Pie Slices
● PI Groups
○ PI Regions

General Options
☑ Individual PIs
☐ Group wt. average by Region
☐ ETWG wt. average

PI Display Regions
☑ Lake Ontario
☑ Upper St. Lawrence
☑ Lower St. Lawrence

PI Display Groups
☑ Vegetation
☑ Fish
☑ Birds
☑ Herptiles
☑ Mammals
☑ Species-at-Risk

Target Scale
Bullseye: >= 2.00
Red Circle: = 1.00
Black Circle: <= 0.00

Figure 12.5 Comparison of the plans using the Integrated Ecosystem Response Model (IERM)

The hydrological regime and the flora and fauna of the St. Lawrence are subject to numerous stresses. Some examples that come quickly to mind are the dredging of the St. Lawrence, alteration of riverbanks, invasion of habitats by exotic or invasive species, and inputs of nutrients and toxics from the tributaries and from agricultural runoff. One of the premises used in developing the model relates to the specificity, sensitivity and significance of the performance indices (PIs) relative to water-level variations, apart from the other factors.

IERM is a tool that integrates functions, sub-models and empirical relationships with the hydrological parameters developed for a series of PIs. It uses a standardized comparison scale that makes it possible to evaluate and rank the alternative regulation plans relative to Plan 1958DD using all the performance indicators produced by the studies.

The IERM program is sufficiently flexible that the baseline scenario can be varied, different PI subsets can be selected based on the geographic areas or types of organisms, and a different weight can be assigned to the PIs selected. The performance of each indicator is evaluated by using a ratio relative to the values of Plan 1958DD.

The integrated two-dimensional modelling approach for producing indicators

The selected modelling approach integrates a wide variety of information and knowledge and simulates their interaction, incorporating the results in nodes distributed throughout the St. Lawrence. The nodes are assembled in a grid (2D IERM grid) that covers the St. Lawrence and its floodplain, and are managed by a powerful georeferenced database that makes it possible to simulate interactions between the different layers of information. The Beauharnois to Trois-Rivières grid comprises a total of 124 000 nodes, with a resolution ranging from 20 m to 160 m depending on the topography.

Very precise topographic data, sediment characteristics and various other data describing the terrain are transferred to this grid. Then, using numerical modelling, the hydrodynamic data (currents, levels, depths and other variables), which represent a large number of possible flow conditions, are entered in the database. Other types of numerical models are then used to describe a series of physical variables such as bottom light intensity, sedimentation of fine particles, water temperature, the distribution of water masses or the effect of wind-generated waves, for all flow conditions and wind direction and intensity conditions.

Variables of varying degrees of complexity, such as bottom slope, hydroperiod parameters, parameters combining wave energy and currents, are also added. This grid therefore contains all the information needed to produce the basic data for the quarter-monthly time series. For example, for each node in the 2D IERM grid, we have a set of spatial data on water levels, over the entire fluvial domain for a given quarter-month, but also temporally (Figure 12.6) for the several tens of physical variables, for the 100 years of the series analyzed.

This descriptive richness applies to the sets of data measured in the field, to the numerical simulations of fluvial physical conditions, as well as to the results of the biological models or indicators developed.

Several biological models were developed during the International Joint Commission study. These models can be used to measure the response of living organisms, both plant and animal. The expert or manager can then view the hectares of potential habitat, the number of nests or the distribution of vegetation classes for a quarter-month, a year or even a multi-year mean. This makes it easy to incorporate the results for the entire domain in order to determine, for example, the estimated number of nests for a species or the number of hectares of habitat suitable for a species.

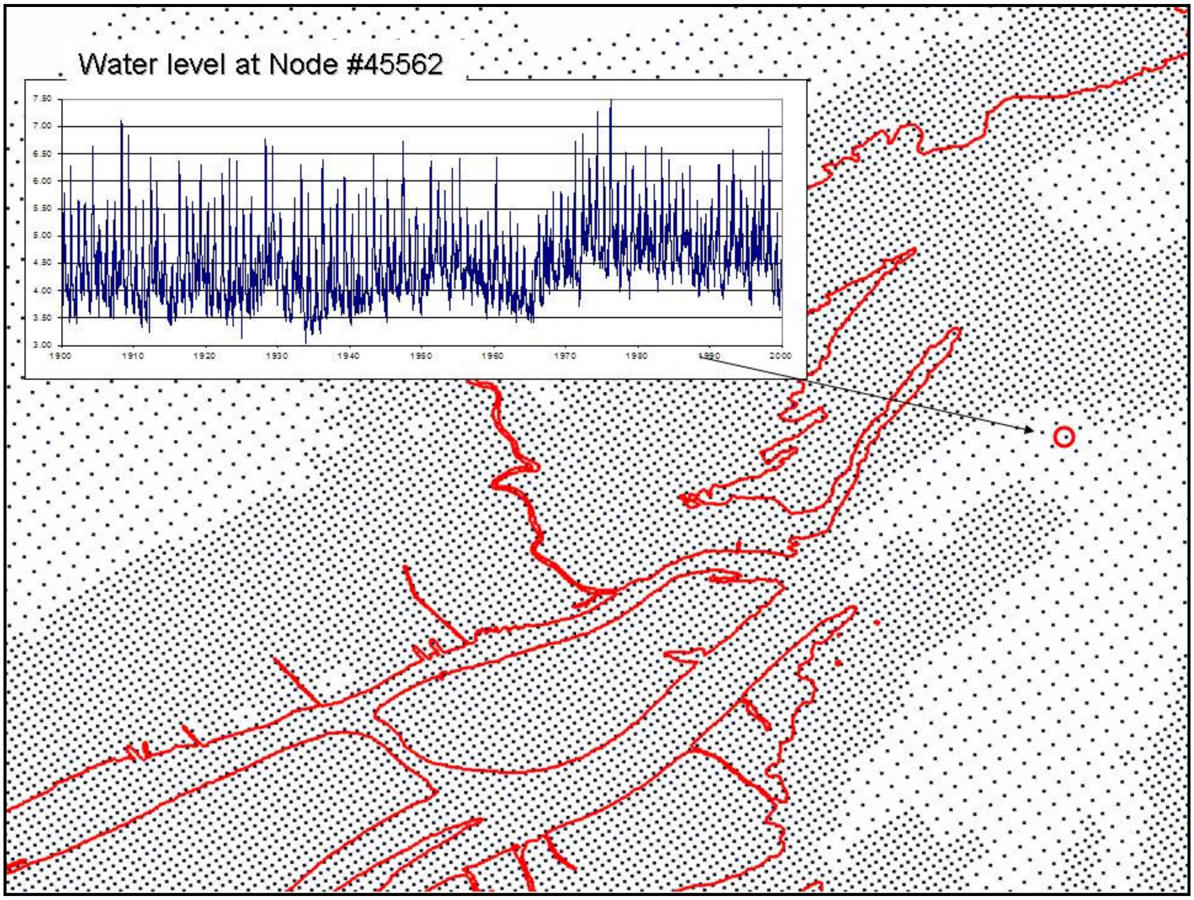


Figure 12.6 Detailed view of a section of the 2D IERM grid showing the wealth of information contained in a node

Flexibility of the approach: Spatial integration and residual marshes

Since the St. Lawrence fluvial system has a number of unique lentic and lotic environments that exhibit considerable heterogeneity, it is essential to determine how the various sectors of the St. Lawrence evolve rather than simply obtaining an overview. Hence, for the IJC's International Lake Ontario–St. Lawrence River Study, the river was divided into four sectors whose behaviour can differ even for the same hydrological scenario (Figure 12.7).

For several biological models, four results or indicators corresponding to different sectors were produced, in addition to a fifth indicator covering the entire St. Lawrence. The 2D IERM grid is very flexible and it is easy to analyze the status of an indicator for a given section of the St. Lawrence or for a very limited area, such as a recreational area or an individual property.

The complex hydrology and topography of the St. Lawrence River floodplain creates perched or residual marshes in a number of locations (Figure 12.8). These marshes can be defined as areas whose hydrology is similar to that of the St. Lawrence when the local water level is greater than or equal to the boundaries of the marsh, but whose water level becomes independent when the level of the St. Lawrence falls below this level. The hydrological behaviour of a perched marsh is thus controlled by the precipitation/evaporation balance. A similar phenomenon occurs in managed marshes created to compensate for wetland losses.

Managed marshes have two main functions: to increase the habitat available for migrating waterfowl and to increase high-quality habitat for spawning fish in spring. In managed marshes, water levels are managed differently from site to site depending on local constraints and characteristics—agriculture, forests, etc.—and with the goal of optimizing conditions for certain species.

The flexibility of the modelling approach with the 2D IERM grid makes it possible to take the specific characteristics of these environments into account. In residual marshes, the local water level is calculated based on the assumption that the marsh is filled during spring melt conditions. During the season, if the level is higher than the boundaries of the marsh, the local water level is the same as the water level in the St. Lawrence, whereas if the level of the St. Lawrence falls below the level of the marsh, a constant evaporation function is applied from the last quarter-month when the level was higher than the threshold level. A more complex evaporation function, which takes solar radiation, wind and temperature into consideration, could be applied later.

This method has been adopted for managed marshes as well. Human management is taken into consideration as a function of the operating levels of the different facilities. Therefore, for each node in the 2D IERM grid that corresponds to a residual perched marsh or a managed marsh, a special calculation is performed to address specific local characteristics in a transparent manner. Thus, these environments are taken into account correctly in the biological models, and as we will see later, they have an important stabilizing effect on several groups of wildlife.

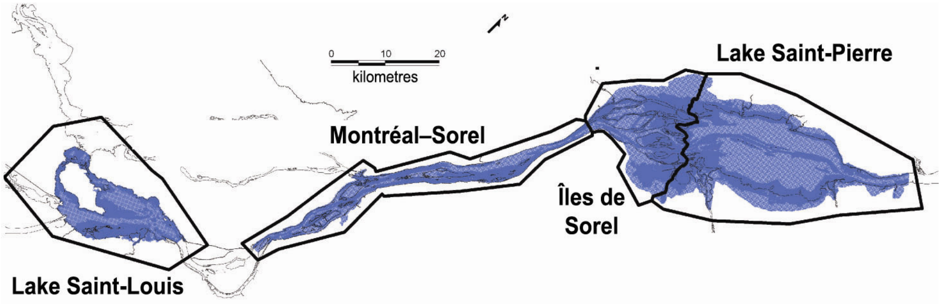


Figure 12.7 Distribution of nodes in the 2D IERM grid (blue) and identification of specific sectors where the indicators are combined to generate four regional indicators and one indicator applicable to the entire study area

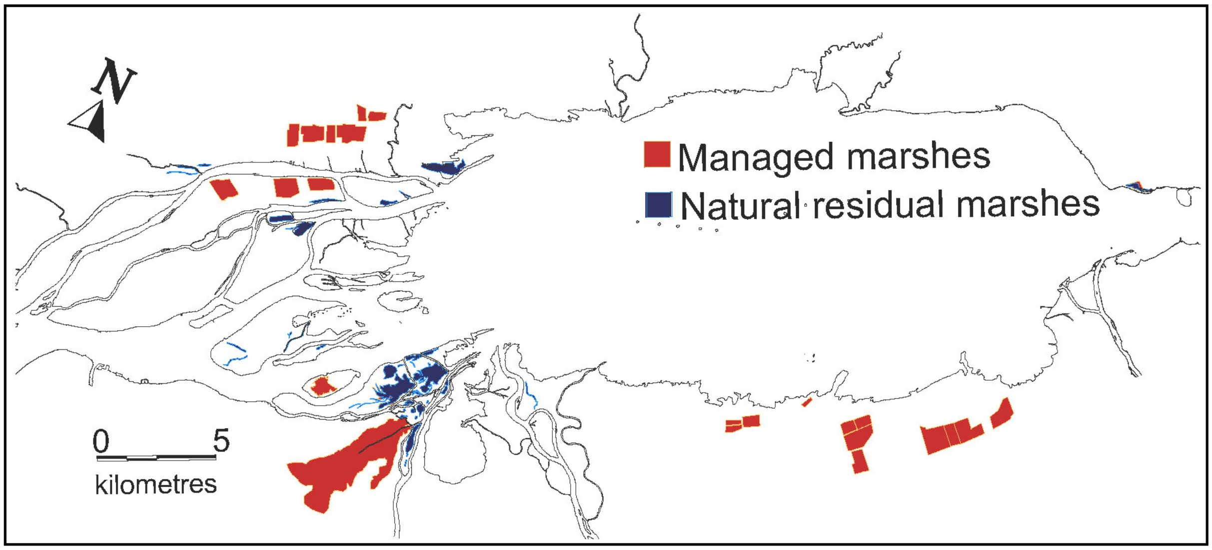


Figure 12.8 Spatial distribution of residual marshes and managed marshes whose water levels are partially out of phase with those of the St. Lawrence (Lake Saint-Pierre floodplain)

Biological models: Indicators of the impact of water-level fluctuations

The living organisms of the St. Lawrence River are adapted to their environment, which is shaped primarily by the interactions of topography and hydrology. The presence of organisms in the St. Lawrence or its floodplain is largely influenced by local physical conditions such as current, depth and light intensity. Because of the species's preference for certain physical conditions, it is possible to identify a preferred territory. The biological models developed vary in complexity depending on the organism and the life stage studied. However, they all use the concept of "microhabitat" to make the connection between biological observations and physical variables. For all the biological models used in the International Joint Commission study, the hydrological variables are the only independent parameters that have an impact on habitats and can thus be used to assess the effects of regulation.

The Environmental Technical Working Group developed 50 two-dimensional biological models in order to produce 205 performance indicators, most of which are applicable to each section of the St. Lawrence (Lake Saint-Louis, Montréal–Sorel, Îles de Sorel and Lake Saint-Pierre). Most of the indicators relate to the habitat surface area available as living environment or as breeding environment for plant and animal species or groups. The models have a prediction accuracy ranging from 60% to 95% for plants, and from 30% to 70% for wildlife.

Types of biological models

Several types of biological models were produced during the study. The habitat suitability index (HSI) (Bovee 1982) and habitat probability index (HPI) (Guay et al. 2000) approaches were used to determine habitat preferences in combination with simulated two-dimensional physical data from the 2D IERM grid (Morin et al. 2005). In fact, several combinations and modifications of these approaches were used with considerable flexibility, relying primarily on existing biological data and as dictated by the complexity of the phenomena under study. The types of habitat models used in the study can be broken down into four groups: a) the intersection model, a conventional approach, b) the habitat suitability (HSI) model, c) the method using habitat probability (HPI) models and, finally, d) a combination of a probability model and a rule-based system that can be used to reproduce complex phenomena.

The intersection models are very simple and are used when little information is available on a species's habitat preferences as a function of environmental variables and when there are few or no georeferenced biological observations (n < 10). This type of model was used for the species at risk for which there are few observations (Giguère et al. 2005). In this case, the opinion of experts is used to determine the potential limits of this species's "preferences" for the key variables (current, depth, plants, etc.). Validation of this type of model is obviously limited by the low number of observations.

The potential habitat models based on HSI are constructed using preference curves for important environmental variables. These curves are constructed using observations reported in the literature or measured in the field without geographic positioning. The disadvantage of this technique stems from the fact that the combined effect of several variables cannot be considered. During the study, HSIs were used for organisms for which the number of observations was relatively low (10 > n < 30). This type of model was used for herpetofauna models, muskrat lodges and dabbling ducks. These models were validated by using some of the observations set aside prior to construction of the preference curves.

The probable habitat models were used for biotic groups for which the quality and quantity of observations are high (50 > n < 11 000). Based on explanatory variables corresponding to the conditions of observation of biotic data, significant relationships were established using various statistical tools: logistic or multivariate regressions, canonical analyses, etc. Logistic regression is the most frequently used method because it has the advantage of being very powerful and can produce significant and robust predictive relationships. This approach was therefore used to construct most of the biological models, including those for aquatic plants, wetlands, fish (life and reproduction) and wetland birds. Generally, the process involved setting aside a portion (~ 10%) of the biological data in order to validate the models.

Complex biological models were developed to study plant succession in wetlands in order to consider the effects of water-level variations on nests and fish larvae as well as to make allowance for renesting of wetland birds. These models generally use logistic regression to establish links between habitats and the explanatory variables and biotic data. Various rules are then added to modulate the effects of water-level variations by taking critical values into account. These models are validated by comparing the results with a portion of the biological data that was not used for calibration. The models constructed for wetlands, dabbling ducks, wetland birds, fish breeding and the number of muskrat lodges used variants of this method.

For all the biological observations used to develop the habitat models, explanatory variables were produced for the conditions that matched the observations. For example, to construct the habitat models for fish, physical variables such as currents, depth and light were simulated based on the water flow and level conditions that prevailed at the time the fishing gear was installed. In addition, "biological" variables, such as the distribution of submerged macrophyte species and major classes of wetlands, were also produced for the conditions during which the sampling was carried out. It is interesting to note that the results of the submerged macrophyte models are significant as explanatory variables for several species.

Structure and integration of indicator biological models for the St. Lawrence

The 2D IERM grid enabled us to develop a method for measuring the potential impacts on the ecosystem. This is an integrated modelling system since all the physical variables controlling habitat are on the same data medium as the biological models and since hydrology has a direct impact on the biological models. Figure 12.9 shows the cascading links as they exist in the IERM. The physical variables and biological models are organized into three separate levels: the physical variables and models, the biological vegetation models and the wildlife models.

The physical variables are determined by the time series of flows that modulate currents, levels, depth, etc. By combining these variables with climatic series, we can obtain water temperature data that are used in the fish breeding models. The vegetation models consist of predictive models for submerged plants and wetland classes. The vegetation models are influenced only by the physical variables of the 2D IERM grid. The wildlife models are slightly more complex, since they are all directly influenced not only by changes in the physical variables, but also by changes in the vegetation. Submerged plants are significant variables in the fish habitat models, and all the wildlife models contain a variable describing one or more wetland classes.

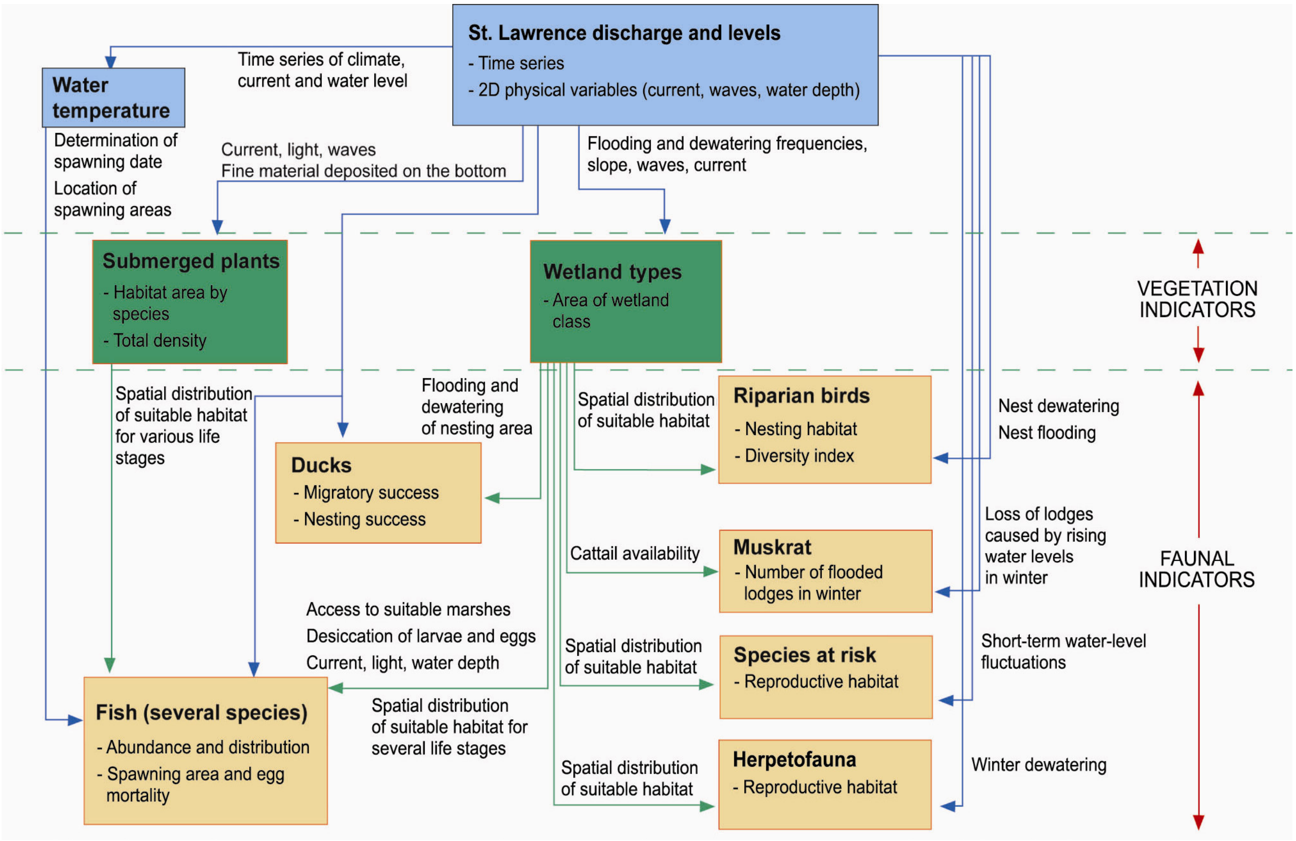


Figure 12.9 Logical structure and organization of links between the physical fluvial variables, vegetation models and wildlife models in the 2D IERM grid

If we exclude the links between hydrodynamics and vegetation, there is no feedback in the current version of the 2D IERM. For example, it does not consider the links between the increase in muskrat populations and the abundance of cattails in marshes. The links are therefore one-way, from physical characteristics to vegetation, and then to wildlife.

Perspective on the indicators developed

Measuring the impacts of human interventions on the living organisms of an ecosystem is a major challenge, given the complex links that influence living organisms. While the two-dimensional modelling approach made it possible to integrate several levels of knowledge based on the physical variables and habitat models, this does not yet constitute a true ecosystem model.

In the context of the International Joint Commission study, all the biological models are based exclusively on hydrological variables and serve to quantify the effect of regulation. Although all the indicators created for the study are sensitive to water-level fluctuations, they are not all sensitive to regulation.

It is important to understand that the system for regulating Lake Ontario does not have a large water-storage capacity. The regulation process does not have a multi-year effect and is barely able to accommodate the spring “surplus” and redistribute it over the rest of the year. Consequently, the impact is felt only during the current year. It is therefore impossible to offset the effects on the watershed of a drought that lasts more than one year.

It is also impossible to retain a large quantity of water during periods of abundance without significantly affecting the Lake Ontario ecosystem. Since wetlands respond to flows over several years, it is not possible to significantly influence their distribution.

Impacts of residual marshes

Perched or residual marshes and managed marshes are particularly important for the muskrat, for a number of bird species and for the reproduction of a number of fish species. In some years, these marshes are the only places where the annual cohort can survive following a significant drop in water levels during the spring. For muskrats, it is major increases in winter water levels that are the most harmful. During most years since 1960, these environments have been the only ones where muskrat lodges escaped flooding and the animals were able to survive in their overwintering lodge. Under natural conditions, prior to the regulation of the Great Lakes and especially prior to the regulation of the Ottawa River, massive flooding of lodges occurred much less frequently.

Vegetation and wildlife indicators

The reduction in the number of indicators continues to be a serious concern for selecting the regulation plan with the best performance. Although vegetation indicators are very sensitive to water levels, they are poor descriptors of the impact of regulation on the ecosystem, for several reasons. First of all, vegetation indicators are evaluated during the growing period, which is little modified by regulation (see Figure 12.3). Regulation therefore has relatively little impact on these environments. With the exception of a massive loss of a particular type of wetland, which is not possible in the current context of regulation, it is difficult to determine whether a greater or lesser quantity of a particular type of wetland is preferable or not. What is fundamental for the St. Lawrence River is not the variation in the surface areas of different types of wetlands, but rather the water level reached in the spring so that wildlife has access to the appropriate vegetation strata. Since wetland classes are an integral part of the wildlife models (implicit), adverse impacts on these environments will be reflected in the performance of the models and will be easily identifiable. The contribution of the wildlife models to the selection of the best plan is therefore a unique aspect of the study.

III The Ecosystem Perspective

Sensitivity, performance, similarity and significance of the indicators

As this exhaustive report shows, many factors were studied in order to document the sensitivity of the St. Lawrence ecosystem to variations in flows and to regulation. Initially, more than 230 indicators were developed. To facilitate management decisions, a number of rationalization exercises were carried out. To begin with, the researchers eliminated the indicators that, to the best of their knowledge, were redundant or not sensitive enough to flow variations. The experts then requested that the indicators' performance be analyzed using statistical tools. Specifically, the analyses had to evaluate the sensitivity and representativeness of these indicators as well as the prospects for combining certain indicators.

Sensitivity and statistical performance of the key indicators

Statistical measurements were specifically designed to evaluate the relevance and exhaustiveness of a more limited subset of environmental indicators. These measurements were based on an analysis of the behaviour of the indicators as a function of St. Lawrence water levels, simulated over 40 or 100 years, using different water inflow scenarios and regulation plans. For the purposes of the International Joint Commission, the criteria used to assess the relevance of the indicators include their responsiveness to changes in water-level management policies. A measurement of sensitivity that effectively reflects this ability is the relative maximum variation of each indicator for a set of policies. According to this criterion, the habitats of certain species located at the edge of the shoreline, especially in sectors of the St. Lawrence where the shoreline forms a narrow strip, are very sensitive indicators. Conversely, indicators that cover the entire length of the St. Lawrence are always less sensitive than those that apply only to a key sector.

In addition to being relevant, the key indicators selected had to provide as complete a picture as possible of the environmental consequences of water-level management. Its effects on each ecological compartment studied, on the threatened species, in each season and in all sectors of the St. Lawrence, had to be represented. But beyond this aspect of representativeness, it was also desirable to maintain within the system as a whole the widest possible variety of potential responses. This was evaluated by comparing each pair of indicators in response to hydrological scenarios and simulated management policies, in order to measure any differences between them. In a graphic representation of these differences, similar (redundant) responses formed compact clusters, with the indicators showing the most original patterns scattered around them. By comparing the space covered by the key indicators with that of the entire set of indicators, it was possible to represent the loss of original information from the subset on a relative scale.

However, this approach, which aims to maximize the expressiveness of the key indicators, did not provide a set of indicators unanimously favoured by the same management policy. On the contrary, they included strongly conflicting indicators, thereby highlighting the antagonisms that necessarily exist in an ecosystem as diversified as that of the St. Lawrence.

Similarity between indicators and significance of the main groups

Three principal component analyses (PCAs) were performed on the indicators. All the groups of living organisms and all the geographic regions were represented. The first analysis, applied to 59 indicators, clearly highlights groups of indicators associated with the hydrological seasons, including spring and summer, represented by a large number of indicators (70% variance on three axes). Within the same group, there were a number of conflicting indicators, indicating the positive or negative effect of regulation. The indicators representing emergent and submerged vegetation appeared in a separate group, demonstrating that they are sensitive to hydrological constraints other than the spring freshet or summer low water. This group also includes the muskrat indicator, the only one that applies to winter. The second principal component analysis, applied only to the spring, identifies a group of indicators representing wetland birds and a group that includes other birds and species at risk whose needs conflict with those of fish (65% variance on three axes). The spring freshet has at least two different effects on living organisms, and the indicators selected also illustrate the antagonistic effects of hydrology on birds and fish. The third principal component analysis, applied to the summer, identifies a principal group that includes the indicators for the summer habitats of fish and turtle breeding habitats (92% variance on two axes). This first group clearly highlights the conflicting effect of regulation in summer on lentic and lotic fish species. Another group includes two fish abundance indicators.

The statistical analysis of the environmental indicators' response to the simulated water-level scenarios revealed significant trends in the proposed ecological models. It also highlighted the fact that the species found in the St. Lawrence sometimes have conflicting needs and identified those that are more affected than others by water level management. This information was added to the complex set of considerations that guided the experts in their selection of the key indicators.

IV The Hydro-ecological Criteria of the Fluvial Section of the St. Lawrence

In addition to enabling us to develop performance indicators, the information acquired during the study on the various biotic groups that use the fluvial section of the St. Lawrence also served to develop hydro-ecological criteria. The initial consideration in developing the criteria was to assist in formulating new regulation plans that maximize the benefits for the species represented. This exercise was also helpful in summarizing the hydrological characteristics required by these wildlife groups and for various other purposes, including supporting the selection of key performance indicators. The hydro-ecological criteria determine an ideal range of levels, or level fluctuations, for a certain number of species during a given period of the year. These criteria were designed on weekly basis and can be divided into two types: 1) those that govern the maximum weekly rate of water level variations and 2) those that identify ideal water-levels in a given wetland class.

Using existing knowledge, ten wildlife criteria were developed for eight species or groups of species. These criteria generally apply to the part of the life cycle most vulnerable to hydrological fluctuations (Table 12.2). Nine of these criteria apply to the natural habitats of the St. Lawrence and are considered priorities relative to the second criterion (optional), whose goal is to maximize the effectiveness of managed marshes (Table 12.2). It is important to point out that none of these criteria conflict with each other.

In order to determine the water levels that would maximize the reproduction of a number of wildlife species, various criteria that identify ideal water levels were defined relative to the mean elevation of the vegetation stratum represented by shallow marshes. The spatial distribution of shallow marshes depends on the mean flows of the three previous growing seasons (see Chapter 4).

Spring recession is the hydrological period with the most hydro-ecological criteria, with eight of the ten criteria developed. This clearly shows the importance of this period for a number of species that reproduce here. Hence, during this period, as Table 12.2 illustrates, it is recommended that:

TABLE 12.2

Priorities and periods for application of the criteria developed

Priority	Species/group of species	Jan.				Feb.				March				April				May				June				July				Aug.				Sept.				Oct.				Nov.				Dec.			
1	Muskrat (overwintering)	■	■	■	■	■	■	■	■																																					■	■	■	■
1	Yellow perch + northern pike (reprod.)													■	■	■	■	■	■	■	■	■	■																										
1	Riverine fish – lentic envir. (growth)																													■	■	■	■	■	■	■	■	■											
1	Waterfowl (migration)														■	■	■	■																															
1	Waterfowl (reprod. and rearing)[1]													■	■	■	▩	▩	▩	▩	▩	▩	▩	▩	▩	▩	▩	▩	■	■	■	■	■	■	■	■	■	■	■	■	■								
1	Wetland birds (reprod.)																		■	■	■	■	■	■	■	■	■																						
1	Least bittern[2] (reprod.)																				■	■	■	■	■																								
1	Turtles at risk[3] (reprod.)																						■	■	■	■	■	■	■	■	■	■	■	■	■	■	■												
1	Bridle shiner[2] (reprod.)																					■	■	■	■	■	■	■	■																				
2	Yellow perch and northern pike (managed marshes)													■	■	■	■	■	■						■	■																							

[1] The dark section indicates the incubation period.

[2] Species at risk.

[3] Map turtle and spiny softshell.

- a minimum water depth of 35 cm be maintained in the marshes for the reproduction of northern pike and yellow perch, and that drops in water levels be limited to less than 30 cm per week (Mingelbier et al. 2005);
- water levels be maintained above 5.4 m at Sorel, so that at least 20% of migrating waterfowl use the natural floodplain of the St. Lawrence (Lehoux et al. 2005);
- mean water levels be maintained between 4.9 m and 5.5 m during the dabbling duck breeding and rearing season, and that increases in water levels be avoided (< 40 cm during the first week of May; < 20 cm between the second week of May and late June, < 30 cm in July) in order to minimize the risk of nest flooding (Lehoux et al. 2005);
- a minimum water depth of 50 cm be maintained in the marshes for wetland birds and that weekly fluctuations of more than 20 cm be avoided (Desgranges et al. 2005; Giguère et al. 2005);
- increases of more than 50 cm (relative to the mid-June level) be avoided in order to maximize the survival of turtle embryos, including the spiny softshell and the map turtle, which are species at risk (Giguère et al. 2005);
- decreases in weekly water levels of more than 20 cm be avoided, since they can affect the productivity of the bridle shiner (Giguère et al. 2005);
- and that a water level of over 5.6 m (Sorel) be maintained, even though this is an optional criterion, so that managed marshes have habitat surface areas suitable for the reproduction of yellow perch and northern pike. In addition, beginning in late June, a water level below 5.0 m helps attract new cohorts to the St. Lawrence (Mingelbier et al. 2005).

Two criteria relate to the summer period: the rearing period for dabbling ducks and the growth period for the riverine fish guild in lentic environments. This guild benefits when the water level is less than 4.6 m at Sorel. A single criterion covers the winter period. To promote winter survival of the muskrat, water level increases of more than 30 cm relative to the November water level must be avoided since they can flood the muskrat lodges, and water level decreases of more than 75 cm must also be avoided, since this can restrict access to food supplies (Ouellet et al. 2005). It should be noted that there are no criteria for the month of March. This is not totally accidental: this is the period with the highest variation in flows, since it corresponds to the snow-melt period.

Despite the fundamental importance of vegetation, no criterion was developed for vegetation. In fact, the distribution and abundance of plants are governed by hydrological variables over several consecutive years. However, since the International Joint Commission manages water on an annual basis, it is not possible to apply criteria for plants.

It must be borne in mind that the criteria listed target only a fraction of the species present in the St. Lawrence, and that only part of their life cycles were considered. Certain environmental principles should therefore take precedence over these criteria:

- the species living in the fluvial section of the St. Lawrence use a wide variety of habitats; the regulation of flows must improve, or at the very least maintain, the heterogeneity of the habitats and, consequently, the biological diversity that they support;
- interannual hydrological variations promote ecosystem health and diversity;
- and the regulation of the St. Lawrence should respect the natural hydrological cycle of this system.

The spring freshet and low-water periods are basic characteristics of the St. Lawrence. The modulation of flows, as they existed prior to the advent of regulation structures and activities, should be used as the basis for present-day regulation. In this regard, it is interesting to note that the criteria for freshet variation rates are similar to the natural pattern that existed in the St. Lawrence during the pre-regulation period, when the freshet was slightly heavier, providing access to a larger wetland surface area, while recession was relatively slow.

Strengths and limitations of the development of indicators

The International Joint Commission study demonstrated the power of modelling in ecosystem analysis and evaluation. The integrated modelling tool enabled us to construct a large number of indicators sensitive to water-level fluctuations, in addition to providing a host of information essential to research and to management of the St. Lawrence. The modelling tools, biological models and indicators were designed to be easily applicable to other environmental issues, such as the impact of modifications to the navigation channel or large-scale water exports from the Great Lakes.

However, the indicators produced during the International Lake Ontario–St. Lawrence River Study for the International Joint Commission cannot answer all the questions. The context of this study limited the scope of the work to level and flow variables only. Since only the hydrological characteristics modified by regulation were considered, the impacts of changes in the bed of the St. Lawrence River, caused by dredging and the disposal of dredged material, for example, were not examined. In fact, the system studied represents only the topography and the physical alterations existing in the system in 2005. Fluctuations in nutrients and their impacts on the vegetation are other factors that were not included. It is important to note that the only indicator that relates to the winter period is the muskrat indicator, and no biological model was produced for the consistently submerged part of the St. Lawrence. In fact, the biological databases contain virtually no data on the winter season, and for the time being, there are no hydrodynamic models that reproduce the conditions of flow under ice. It should also be pointed out that intraweekly water-level fluctuations were not analyzed by the indicators developed. The system is regulated weekly, and dam managers are required to adhere to the weekly mean and not the instantaneous flow. This situation could lead to significant differences if large fluctuations in intraweekly levels occur during the most sensitive period of the year.

Forecasting

In predictive mode, the biological models and indicators can be used to predict the state of an ecosystem and facilitate continuous monitoring. Environmental forecasts of the state of the ecosystem could thus be regularly issued to the public. Just as weather forecasts are continually updated by Environment Canada, forecasts of the state of the ecosystem could be prepared and released to researchers and the public. This is of particular interest for water temperature models or for biological models, such as the major classes of wetlands, whose summer characteristics are determined at the end of the previous year's growing season. Hence, by the end of November, it would be possible to forecast the extent and composition of wetlands in the St. Lawrence the following year. This approach would help maintain the indicators and the long-term accuracy of the models used to determine the new regulation plan. Any discrepancies between the models' forecasts and actual conditions would serve as an impetus for additional research, and the knowledge gained could then be used to improve the accuracy of our forecasts. Obviously, maintaining these models and this knowledge would allow them to be used in various research and environmental assessment contexts.

Conclusions and Recommendations

Resolving an environmental problem poses a major scientific challenge, especially when it involves ecological processes at the scale of an entire ecosystem. Collecting accurate data is very expensive, and validating environmental indicators is a laborious process, just to determine their scope and predictive value. In addition, despite the effort invested, the drivers of change in an ecosystem could also drift, thereby significantly reducing the scope of the results relative to the management solutions considered at the time of the study. In this context, it is obvious that our studies, summarized in this document, are simply the first step in our understanding of the ecology of the St. Lawrence. Although a considerable amount of demonstration work remains to be done, by using sophisticated empirical, statistical and numerical modelling techniques, we can clearly identify our approach in order to select the most appropriate indicators based on the specific needs of the International Joint Commission.

The hydrology of Lake Ontario is only one factor among many that influence the flow of the St. Lawrence River. In fact, several tributaries, including the significant effect of the Ottawa River, are important factors in flow variation. Since the main goal of regulation is to reduce fluctuations in Lake Ontario, it therefore contributes only a fraction of the total variation in water levels and flows on the St. Lawrence. The indicators must not only show the impact of hydrological variations, but also be sensitive enough to respond to regulation. This issue is complicated even further by how water levels were measured (mean/quarter-month), which could result in some finer ecohydrological covariances being overlooked.

However, using the indicators' response to environmental gradients and drifts is an arduous task. This is due to the difficulty of selecting appropriate ecological yardsticks that can be used for a management approach geared to maintaining proper ecosystem functioning rather than one driven by purely economic considerations. These yardsticks are usually historical and are generally used to determine the amplitude, frequency and intensity of the ecological conditions that existed prior to the introduction of an anthropogenic disturbance factor. In the case of water-level management, major changes have affected the physical flow properties of the St. Lawrence watershed over time. A few obvious examples include the extensive changes made to the St. Lawrence floodplain for agricultural purposes, the dredging of the navigation channel or the harnessing of some of its major tributaries. While simply restoring natural flows at the outlet of Lake Ontario would not restore the natural conditions that existed in the fluvial section prior to regulation, moving in that direction should reduce the ecological impacts of regulation under the current plan in the St. Lawrence (Hudon et al. 2005) as well as in Lake Ontario and the St. Lawrence upstream of the Moses-Saunders dam at Cornwall (Wilcox et al. 2005).

It is here that the strength of the modelling approach becomes apparent. This approach, based on geomatic tools, is used to develop functional predictive hydrodynamic models in which the interactions in space and time of a wide range of data can be simulated, based on statistical relationships between water levels and flows and events and occurrences. This approach thus makes it possible to assess on a large scale the impacts of specific environmental conditions, as well as to evaluate and quickly verify the underlying assumptions according to various scenarios. Because of the flexibility of this method, local conditions and specific habitat characteristics can be taken into consideration. This innovative approach is particularly useful in predicting the distribution and abundance of certain wildlife groups as a function of habitat use and suitability indices established on the basis of observations or predictions of vegetation distribution.

Empirical models also offer a solution. This approach involves developing a structure of indicators, which are classified by the type of measurements they represent. The key performance indicators are therefore selected:

- at the ecosystem scale (habitat suitability and surface area);
- as a function of the direct response to water-level variations (mortality);
- and as a function of the indirect response to variations in habitat suitability or surface area and/or to water-level variations.

Of the performance indicators developed, the first group shows an immediate response to water-level variations and includes measurements of surface area and depth of habitat; they most closely reflect phenomena at the ecosystem scale. These measurements could be considered "instantaneous" indicators and should always be studied when comparing plans. They form the basis of ecosystem productivity and diversity and should be used to determine whether different plans cause losses of wetland surface area or losses of aquatic plant composition.

The second group of performance indicators includes measurements of species that are immediately affected by water-level variations (i.e. organisms whose reproductive success is affected by flooding or dewatering of their nests, dens or residences). Consequently, immediate mortality and loss of productivity are directly attributable to water-level variations. These indicators should be considered key ecosystem performance indicators.

A third group of performance indicators reflects over varying terms the abundance or productivity of species as affected by changes in habitat conditions (e.g. higher duckling birth rate associated with an increase in wetland surface area and therefore nesting surface area). However, this relationship is subject to many variations and is statistically (error component factor) and biologically "flexible." These performance indicators should be considered to reflect a much more flexible wildlife response than is found in a functional relationship. Their inherent variability is greater and, consequently, the confidence intervals are larger.

The best strategy for conserving the ecological integrity of the St. Lawrence is to regulate the outflow from Lake Ontario so as to recreate in the fluvial section hydrological conditions similar to those that existed prior to regulation. Several methods have been described for developing, selecting and using indicators. Although based on quite different underlying concepts, these indicators all demonstrate that conservation of the structure and ecological functions of wetlands is optimized when the natural conditions of the St. Lawrence prior to its regulation are most closely approximated.

The results of this summary clearly show that variations in wetland surface areas in a fluvial ecosystem such as the St. Lawrence depend directly on recurrent flooding levels during the freshet period and on exposure (dewatering) levels during the low water period. For wildlife, regulation has an impact on the availability and suitability of habitat. Anthropogenic factors such as riverbank modification and climatic changes modify the water cycle and thus influence wetland management, the renewal of wetland water supply and, ultimately, wetland sustainability. Further detailed research work is necessary if we are to gain a better understanding of how wetlands and the ecosystems they support change in response to the hydrology of a watercourse.

The legacy of the International Lake Ontario–St. Lawrence River study

The research conducted over nearly 10 years on the impact of water levels and recently for the International Joint Commission study leaves a legacy of great value: an exceptional pool of expertise in Quebec and Ontario, with unique multisectoral specialties in large river ecology, an extensive body of knowledge on the environment as well as a modelling structure capable of incorporating empirical data so that they can be used and disseminated. The St. Lawrence now has a network of expertise that will be called upon to determine how regulated watercourses can continue to produce viable ecosystems in a context of pressures, encroachment and development that affect and are affected by hydrology. This report is a first step that provides a general outline and a few recommendations for the development and use of indicators, but considerable work remains to be done in this area. We hope that the work presented in this document can be used to develop environmental management processes and policies and offer guidance for approaches that can enhance the quality of life of Canadians while minimizing the impacts on the environment.

In addition to its usefulness for the International Joint Commission, this study has generated considerable dividends in terms of knowledge:

- more in-depth understanding of methods for selecting environmental performance indicators;
- identification of an optimal environmental framework and limiting factors associated with the ecological integrity of the fluvial section of the St. Lawrence;
- development of spatial and temporal ecosystem assessment tools, laying the foundation for adaptive management of the environment and the analysis of complex ecosystem issues;
- a relative comparison method for alternative management methods in a context of uncertainty about ecosystem response to anthropogenic disturbance factors;
- the creation, within Environment Canada, of areas of expertise specializing in the assessment of water-level impacts and in ecosystem modelling as well as in the formulation of scientific opinions on various development or management scenarios.

The environmental indicators developed as part of the studies on the St. Lawrence are useful tools for predicting ecosystem response to environmental pressures. Changes in fluvial ecosystems are being observed around the world, as a result of anthropogenic pressures, but the scope and implications of these changes are poorly understood.

One of the most serious issues for our modern society is the rapid pace of loss of wetland habitats and their benefits for living organisms, including humans. Although little is known about the interrelatedness of physical and ecological factors, it is obvious that wetlands are sensitive to hydroclimatic variations. Further research is therefore needed, particularly the development of a system for hydrodynamic and biological monitoring of the impact of regulation in a context characterized by multiple environmental factors. These studies should be guided by the need to understand riparian ecosystems in order to more effectively preserve them. This work is necessary because of the extensive changes and pressures to which natural ecosystems are exposed in an increasingly urbanized landscape, combined with the filling in of habitats and the effects of pollution.

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Chapter 13

OVERVIEW AND LOOKING TO THE FUTURE

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Managing the aquatic ecosystem of the St. Lawrence and society's water needs poses a number of challenges, the first of which is integration of information. A second challenge is to identify and implement priority courses of action in order to support decisions and evaluate outcomes more effectively. As Naiman et al. (2002) point out, not only must the science be of high quality and relevant, it must also be used.

The framework recently developed by Environment Canada (2004) focusses on environmental sustainability as a key factor for maintaining the competitiveness of the Canadian economy and is in keeping with this perspective. Knowledge, whether gained through long-term environmental monitoring, ongoing fundamental research or ecosystem modelling, must provide the necessary foundations for drafting regulations and for using complementary economic tools, for developing and implementing technical and technological solutions, as well as for raising awareness and mobilizing communities in support of local measures.

An Integrated-management Vision

Holistic vision

The integrated management approach of the 1990s, of which Environment Canada is a key proponent, provides a framework for considering problems and potential responses from the standpoint of their interactions and resulting synergy. The emphasis that is placed on actors (decision-makers and pressure groups) and on governance, in particular, serves to reinforce the links between knowledge and action. Some examples of this are intergovernmental co-operation, consultation and the development of co-operative programs (Cohen et al. 2004), as well as the protection of water resources and watershed integrity. Issues relating to the hydrological cycle and the factors that modulate it, interactions between the ecosystem and uses, the need to maintain a balance between water availability and needs or potential availability and actual availability (ensuring suitable water quality) are all matters that call for responsible and concerted action over the long term. The preceding chapters dealt with the pressures that are likely to impinge on ecosystem integrity, whether driven by ecological needs or anthropogenic uses.

By contrast, the research reported on here was carried out in a context centring on issues related to the regulation of water levels and flows. It involved the establishment of technical working groups on the environment, commercial navigation and recreational boating, erosion of coastal areas and flooding of riverside property, hydroelectric power, and domestic, industrial and municipal water uses. These studies, which all have the physical fluvial environment as their common denominator, constitute an important step toward integrated-ecosystem management. It is important to make use of this considerable body of knowledge, to identify certain key elements and to adapt them to the broader context of integrated management of a major ecosystem.

A wide range of players

The dynamics linking the various players and users has also received considerable attention in the process of establishing principles, objectives and mechanisms of co-operation as drivers of integrated management, continuing the momentum associated with the emerging concept of sustainable development and important international meetings such as the 1992 Earth Summit in Rio, Rio+10, Dublin, and the 3rd World Water Forum held in Kyoto in 2003 (Gangbazo et al. 2004). However, differing world views and diverse ways of interpreting sustainability have come to the fore (Gendron 2004; Guay 2004), complicating the process of decision making in pluralistic and democratic societies. The roles of the various players must therefore be supported by sound science that enables collective choices, in order to facilitate co-ordination of efforts and actions.

Scientific basis and integration of information

Ecosystem changes, whether induced by climatic variations, the export of fresh water outside the watershed or the implementation of new management plans, directly affect the ecosystem's physical characteristics. This leads to a dynamic process of adjustment of all ecosystem components, which are connected through links of varying degrees of complexity. This mutual dependence of the various ecosystem components underscores the need to adopt "integrated" approaches. These links are shown in Figure 13.1.

Indeed, one of the main goals of the study of water-level variations, the underlying causes and the associated impacts and adaptations, is to determine the relative role and importance of the various interests affected by the availability of the resource. Efforts are made to establish performance indicators and critical thresholds or ideal margins for level and flow fluctuations that may be acceptable or unacceptable for the different interests. The research and findings presented in this collective report constitute an initial contribution to this objective. These thresholds are fairly easy to determine in some cases, but they are the focus of ongoing research in others.

Pioneering work: The contribution to the Plan of Study for Regulation of Lake Ontario–St. Lawrence River Levels and Flows

In order to assess the responses of various ecosystem components to change, scientists were called upon to contribute their knowledge of physical variables such as water level, current velocity and water temperature (variables known for the entire domain) for different change scenarios. This is the process through which hundreds of indicators were developed to assess the "response" of the various ecosystem components by quantifying their "degree of satisfaction." The physical environment, which is the common denominator for all of the indicators and a linking factor for the different ecosystem components, can be simulated, opening the door to sophisticated ecosystem modelling and prospective assessment of the state of the ecosystem. The scientific merit of these prospective indicators of the state of the ecosystem is recognized, since they were developed by the best researchers in Canada and the United States and accepted by public officials. These indicators, along with Environment Canada's other scientific activities, form the basis of a tool capable of predicting the response of the various ecosystem components to different problems, while also incorporating socio-economic aspects. They reflect a scientific understanding of complex phenomena, which is expressed in simple, accessible and effective terms for decision-making purposes. It is now important that we build on our capacity to develop and select new indicators in response to more diversified needs associated with the drive to increase Canada's competitiveness and ensure the sustainability of its natural environment.

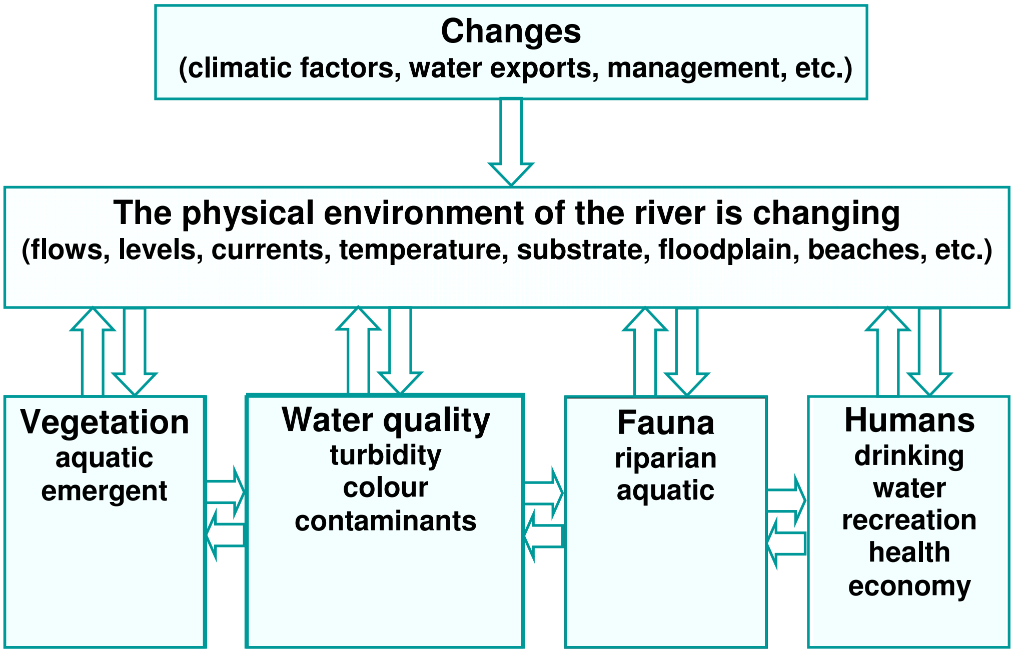


Figure 13.1 Schematic diagram of the links and changes among ecosystem components

In general, indicators enable us to quantify and track gains and losses affecting certain ecosystem components, to compare decision options on the basis of desired effects and, finally, to stimulate and guide discussion toward practical changes (Bibeault 2000).

Adaptive management and the prospective approach

Integrated ecosystem management must not be viewed as a static objective. The indicators selected and the criteria developed cannot be considered definitive. On the contrary, integration relies on knowledge and actions that vary spatially and temporally and can be adjusted to address the needs of future generations. Moreover, the role of the St. Lawrence ecosystem extends beyond the borders of Quebec and Canada. It is part of a larger system and reflects the concerns that other nations have about the need to maintain core ecological functions and the services they support (Millennium Ecosystem Assessment 2005). Adaptive management is an approach that seeks to take this complexity into account by establishing closer links among the following aspects:

1. research and the identification of issues and problems,
2. the development of solutions
3. the implementation of solutions
4. impact prediction and monitoring
5. the evaluation of management measures
6. adjustment of management measures (Parr et al. 2003).

Even more importantly, adaptive management involves a process of continuous interaction between these various steps.

Adaptive management nonetheless involves a set of conditions—namely, strategic goals and key questions that are based on an assessment of the ecosystem and its components, an examination of the causes and effects of environmental changes, and tracking of the actions taken and their outcomes.

Although these general questions may be applicable to all aquatic ecosystems, they are particularly relevant to the St. Lawrence River. Selecting prospective indicators and models that incorporate them, obtaining data to support, calibrate and validate them, and using statistical tests to specify their margins of uncertainty are all part of a chain in which each link of “integrated” knowledge counts.

Some key questions

Baseline assessment:

- What are the ecosystem changes caused by variations in water availability?
- What are the gains and losses?
- For how long and where have these gains and losses been observed?

Identifying and explaining the changes:

- What are the main factors of disturbance or change involved?
- How do they act?
- What factors act as catalysts or accelerators of these changes?

Measuring the ecological implications:

- Is the system resistant, especially to extreme water-level situations?
- Are there specific effects, early warning signals of extreme events?

Anticipating and developing decision options:

- Can we predict what will happen if no action is taken?
- Can we predict what will happen if a specific measure is taken?
- How can we strike a balance between the “rights” of nature and the “rights” of users?

Evaluating the actions taken and the underlying assumptions:

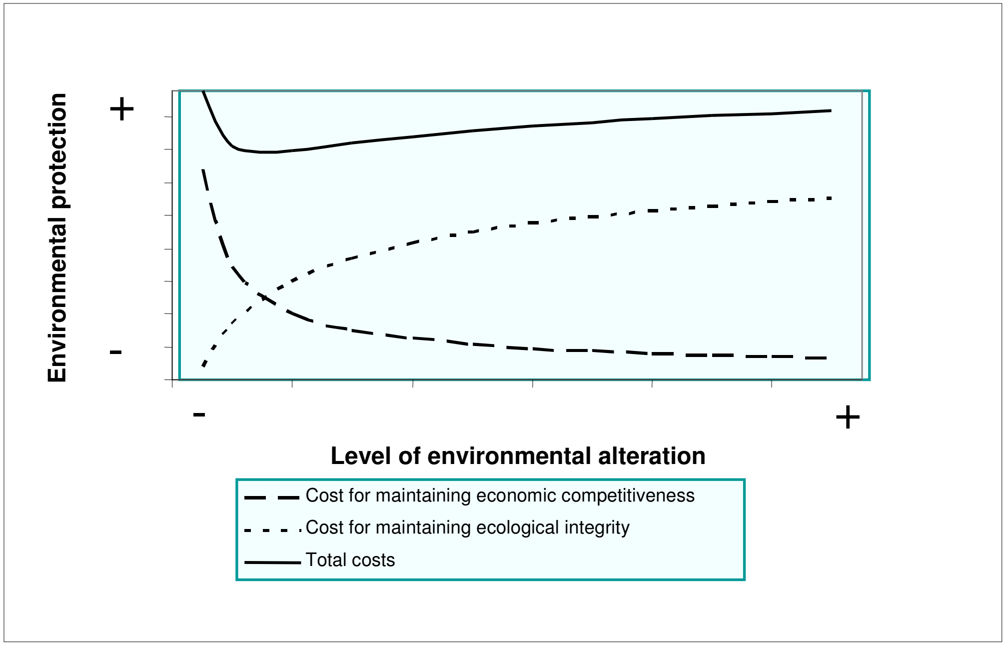
- Did the predicted events occur?
- Why?
- How can these predictions and forecasts be improved?
- What physical variables were excluded (e.g. nutrients, changes in topography, modification of riverbanks and floodplain)?
- What processes were discarded (e.g. feedback from physical/living components, impacts on trophic levels)?

Whether the goal is to evaluate the health of the fluvial environment or the health of humans who depend on the resource and related socio-economic aspects, the logic remains the same: identifying the optimal conditions that help to achieve or maintain the advantages of the system in its natural state, in balance with the advantages provided by management measures for the St. Lawrence. Figure 13.2 illustrates this concept.

From an adaptive management perspective and based on the knowledge gained, it is necessary to anticipate (impacts) and prevent them if possible (adaptations). To this end, priority should be given to environmental forecasting, which aims to anticipate the environmental changes engendered by variations in water availability. The work done by Environment Canada as part of its contributions to the International Joint Commission and the Lake Ontario–St. Lawrence River Study Board, particularly during the 2000–2005 period, included efforts to develop a number of key indicators for the future.

From the same perspective, knowledge can also provide a basis for discussion and evaluation of environmental conservation or restoration options. Moreover, precedents for the partial restoration of watercourses to their natural state already exist, as demonstrated by various initiatives in the United States, including the one focussed on the Ohio River (U.S. Army Corps of Engineers, Great Lakes and Ohio Division 2000).

Finally, and from a more general perspective, environmental forecasting can also promote the development of knowledge, if we consider the various structural changes that are likely to have an impact on the St. Lawrence. One example of this is the recent report, *European Environment Outlook* (European Environment Agency 2005), which endeavours to anticipate future changes on the basis of social factors, combined with environmental changes induced by climate change, and other pressures on water availability and quality. This approach is undoubtedly a promising avenue in the coming years.



Source: Adapted from Acreman 2001.

Figure 13.2 Balance between alterations to the system and preservation of the natural environment

Key Issues to be Addressed

To provide a solid foundation for a prospective approach, there are a number of issues that must be addressed. In the context of Environment Canada's activities, these issues can be grouped according to seven strategic axes:

1. capacity-building and development of integration strategies,
2. development of scenarios describing the pressures on the ecosystem and its uses,
3. study of the factors that modulate these pressures,
4. environmental assessment of the effects of water availability on wildlife resources,
5. evaluation of the ecological dynamics of the system as a whole,
6. integration of the effects on the socio-economic aspects,
7. management of the body of information.

Capacity-building and development of integration strategies

The ability to describe a system at different spatial and temporal scales suited to the problems to be resolved is a first step toward the integration of data, information, knowledge and know-how. Using modelling to integrate scientific knowledge is an approach that has been successfully used in a number of contexts to study the St. Lawrence ecosystem. This approach makes it possible to integrate the physical, biological, chemical and socio-economic aspects of the issues under study, and facilitates the synthesis of complex elements into understandable, scientifically credible indicators that support informed decision making.

Development of pressure scenarios

It is essential to establish scientifically credible water input scenarios capable of properly accounting for future pressures on the St. Lawrence system. It is important to know or to simulate with the best available tools the extent of water removals attributable to various anthropogenic uses, climatic variations (extreme temperatures, ice, heavy precipitation, wind, etc.), or to a combination of these factors. As we saw in the previous chapters, attention must be paid to variables such as frequency of the pressures, seasonality, location of impacts and size of the affected area. Physical modifications to the watercourse (navigable waterway and Seaway, dredging, etc.) must also be considered since the flow may be disrupted, patterns of erosion and sedimentation modified, and water masses displaced with effects on water quality. More detailed data on the spatial and temporal distribution of these impacts must also be obtained. This type of analysis could be helpful in setting pressure reduction objectives for ecosystem maintenance and sustainability.

Study of modulating factors

In order to improve our understanding of the relationship between water availability and the ecosystem, factors that contribute to further disturbance of the ecosystem must be considered: changes in land use, discharges of urban, industrial and agricultural waste and overexploitation of wildlife resources (e.g. overfishing). For example, if a relationship is found between a reduction in water availability and an increase in organic load in the St. Lawrence River, the quality criteria for aquatic life may need to be revised. Another example is the Canadian Council of Ministers of the Environment guideline for phosphorus (30 µg/L) aimed at maintaining aquatic life; this guideline may be too high for fluvial lakes since signs of degradation in aquatic habitats, possible nocturnal anoxia and proliferation of filamentous algae, have been observed. This type of phenomenon must be better documented in order to pinpoint the associated consequences and develop nutrient load-impact models.

Water availability and effects on wildlife resources

The conventional approach of assessing the impacts of water availability on wildlife and wildlife habitats is still necessary. Indeed, it is essential to continue to study such factors as abundance and age classes of lesser-known species (such as American shad and various amphibians and reptiles), some of which have commercial value, while others do not. In addition, by considering managed habitats (e.g. marshes for ducks or certain fish species), including the various breeding and feeding or nesting areas for birds, and identifying migration patterns (fish, wetland birds), especially in cases where knowledge is limited, we can simulate the effects on the reproductive potential of the species under study. Future research could help to refine the habitat models based on different ecological strata and permit simulations of management measures for these habitats. The habitat and productivity models need to be applied to benthic organisms and to primary productivity in order to more accurately describe the impacts on the more "visible" resources of the ecosystem. As part of a complementary avenue of research, the indirect effects on the availability of wildlife resources for the various user groups could be assessed.

Ecological dynamics of the St. Lawrence system

Another approach involves taking into account the overall dynamics of the ecosystem in a way that integrates selective processes. These processes are important since they include the dynamics governing the introduction of new or invasive species, or the endangering of rare, sensitive or geographically isolated species. These processes can be examined at the species community scale or observed in light of changes in matter-energy cycles and ecological functions. This enables us to identify trends affecting the system. One example concerns flood amplitude and duration, which, combined with the relative hydraulic isolation of coastal areas, results in these areas being less frequently flooded, and consequently more productive and more quickly clogged by dense vegetation, transforming the shoreline into a more terrestrial ecosystem, a risk that has already been identified for Lake Saint-Pierre. To address this issue, it will be necessary to examine the impact of regulation of the Ottawa River, the largest tributary of the St. Lawrence River, in order to determine the long-term consequences.

Integrated environmental assessment

The assessment of ecological processes must be supplemented by an analysis of socio-economic processes, which are also dependent on global changes and pressures from other economic agents. Socio-economic adaptations are taken into consideration in order to anticipate the cumulative effects of future environmental changes. The use of knowledge in a multidisciplinary fashion results not only in a more accurate comparison of the various outcomes, but also in a more dynamic and open environmental assessment process (Yap 2003). Much still needs to be done, however, in order to draw up an agenda of relevant research and studies for integrated and adaptive management.

Compiling and managing information

It is essential that we be able to make effective use of the body of information that is measured and simulated, the models developed as well as the general scientific literature. Achieving real-time interoperability of data will entail using automated processes and innovative technologies. Electronic processes used to record environmental data should meet the same automation requirements in order to support the maximum number of uses. A number of initiatives currently under way, such as the St. Lawrence Global Observatory project, are also converging toward this objective.

Conclusion

The research done to date on water availability has been conducted in the context of specific mandates, such as the prospective assessment of the effects of the review of regulation criteria for Lake Ontario and the St. Lawrence River. The research effort carried out under this most recent mandate was on a very significant scale and produced major advances in terms of knowledge, integrated ecosystem modelling and simulations of future hydrological conditions. Moreover, the fact that the investigation was focussed on specific problems associated with improving the management of water availability facilitated the integration of data from various sources, not to mention Canada–United States co-operation. To date, the results obtained have made it possible to determine the scope and the issues posed by upstream-downstream management which seeks the optimal compromise between uses, human aspects and ecological components (International Lake Ontario–St. Lawrence River Study Board 2006).

However, this integration process is not complete and work still remains to be done. Establishing links between research work, monitoring and modelling is still necessary for decisions that require the participation of various administrative levels and a wide range of public institutions. In the United States, a recent assessment showed that research efforts are highly fragmented and that there is a similar need for integration; however, this need is perceived differently. Three areas of research and capacity were identified as requiring integration: a) water availability and pressures, b) water uses, including ecosystem needs, and c) water management institutions (Committee on Assessment of Water Resources Research 2005).

We still need to identify avenues for future research by aiming for better integration of scientists' efforts on the one hand, but especially by facilitating their input in future decisions (Acreman 2005). That is why, from the perspective of Environment Canada's framework of competitiveness and sustainability (2004), we have proposed an integration approach that aims to more effectively combine knowledge of species, habitats and ecosystem integrity with the accompanying upstream (pressures) and downstream (effects on users) socio-economic aspects.

Finally, a quote inspired by a diversity of international cases aptly summarizes the complexity of a system such as the St. Lawrence:

> Water management cannot be reduced merely to its technical dimension and does not depend solely on climatic constraints. Water shortage situations are not necessarily attributable to an actual shortage of the resource, but very often to the weakness of the social and organizational resources devoted to water management, in the form of changes in values, establishment of standards and procedures or long-term planning (Translated from Lasserre et al. 2005, p. 563).

From the broader perspective of a major ecosystem, but also in a context of rational decision making, which is context-specific and usually incremental in nature (McCay 2002), these comments also reinforce the need to broaden the geographic perspective to encompass ecosystem links with the Great Lakes and the Gulf of St. Lawrence.

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Conclusion

As will be apparent from a reading of this document, the issue of fluctuations in St. Lawrence water flows and levels is a complex one. In addition to natural fluctuations, attributable primarily to climate (precipitation, temperature, evaporation), and water inputs from the tributaries, there are superimposed human activities (e.g. the regulation of flows and levels, overconsumption of the resource) and the effects of climate change. Addressing all the issues from an integrated approach aimed at maintaining socio-economic uses and environmental integrity continues to be a major challenge. Nevertheless, our understanding of the mechanisms associated with fluctuations has greatly improved, as has the forecasting of potential adverse impacts. In this respect, the research carried out for the International Joint Commission has undoubtedly made a significant contribution.

All the authors agree that water-level fluctuations can have harmful consequences, both socio-economic (see chapters 1, 2 and 11 in particular) and environmental (see chapters 5, 6, 7, 8, 9 and 10). Nonetheless, opinions tend to differ somewhat when it comes to assessing the impact of water-level regulation plans, which is proof that much more work still remains to be done on this topic. However, it is clear that regulation should not be increased relative to the original plan. Some authors suggest an alternative "naturalization" approach, so that the hydrological characteristics of a regulated system can approximate those of a natural system. By giving preference to an approach that minimizes anthropogenic interventions to control water flows and levels, the hydrological regime therefore becomes subject to climatic forces, which can result in fluctuations in St. Lawrence River water levels over a long-term cycle of approximately 30 years.

To conclude this report, which is devoted to the impacts of water-level variations on the flora and fauna of the St. Lawrence and to the selection and application of a plan to regulate the water levels and flows of Lake Ontario, it is worth noting the remarkable pool of scientific talent that has been brought to bear on these issues for nearly ten years by experts from various backgrounds. As we have seen, the published results of all this research have helped create an exceptionally detailed picture that will guide the work of Environment Canada for many years to come. It is interesting to note the degree of adaptive flexibility required on the part of the experts when writing this type of report to make it accessible to the layman, which is not always easy. We would therefore like to congratulate the authors for a job meticulously well done.

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