

Environmental Monitoring at the La Grande Complex

Evolution of Fish Mercury Levels

Summary Report 1978-2012



OCTOBER 2013



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Evolution of Fish Mercury Levels Summary Report 1978–2012

Joint report by:

HYDRO-QUÉBEC PRODUCTION

AND

GENIVAR INC.

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EXECUTIVE SUMMARY

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Abstract:

An environmental monitoring program was established to evaluate the physical, chemical and biological changes associated with the development of the La Grande hydroelectric complex. The monitoring of fish mercury became a regular component of the program as soon as the increase in fish mercury levels was observed. The specific objectives were to evaluate the temporal evolution of the phenomenon in the different types of modified environments, inform fish consumers and improve impact prediction methods for future projects.

The main objectives of monitoring fish mercury during Phase I and II development of the La Grande complex were all achieved. The monitoring program, which involved conducting 45,000 analyses of total mercury in fish, helped establish the extent and duration of the temporary increase in fish mercury levels, the main processes at work and the physical and biological factors that control them. Reservoir impoundment caused an increase in fish mercury levels in the newly created reservoirs and the water bodies downstream of them to increase significantly, by factors generally ranging from 2 to 8 relative to the levels measured in natural environments. Levels peaked 4 to 11 years after impoundment in non-piscivorous species (0.33 to 0.72 mg/kg) and after 9 to 14 years in piscivorous species (1.65 to 4.66 mg/kg), depending on the environment. The phenomenon was temporary, however, as mercury levels generally returned to baseline values found in natural environments 10 to 20 years after impoundment in non-piscivorous species and after 20 to 30 years in piscivorous species. The Québec Crees were consistently informed of fish mercury levels in the La Grande complex, in accordance with the provisions of the two mercury-related agreements signed with the Crees of Québec in 1986 and 2001. Fish consumption guidelines for the La Grande complex were produced in 1998, 2001, 2004 and 2013 on the basis of the mercury exposure criteria established by the Cree Board of Health and Social Services of James Bay (CBHSSJB), using the data collected during the monitoring program. The development of two prediction models for fish mercury levels in reservoirs clearly demonstrates that the third objective, which was to improve impact prediction methods for future projects, was fulfilled.

For the majority of fish species in most of the modified water bodies, the average mercury levels recorded during the most recent surveys once again allow for consumption similar to that recommended for the region's natural lakes. Therefore, it has been suggested that the monitoring of mercury levels in environments modified by the La Grande complex during phases I and II be discontinued except in Lac Sakami, where it will be incorporated into the monitoring of water bodies affected by Phase III.

Keywords: Mercury / Fish / Hydroelectric complex / La Grande / Québec / Baie James / reservoir / reduced-flow environment / increased-flow environment / polynomial regression / northern pike / walleye / lake white-fish / longnose sucker

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POCKET INSERT MAP

Map A	Sampling Stations Used to Monitor Mercury	
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1. INTRODUCTION

In Northern Québec, mercury is present in the natural environment, where it has accumulated since the last ice age as a result of atmospheric deposition. The mercury in the atmosphere comes from natural sources such as the weathering of rocks in the earth's crust, forest fires and volcanoes, as well as from anthropogenic sources like coal combustion and waste incineration. Mercury of atmospheric origin exists mainly in inorganic form and is not readily assimilated by living organisms. In aquatic environments, it is converted to methylmercury by the bacteria that break down organic matter containing mercury. Methylmercury is an organic form of mercury that is readily assimilated by living organisms, travels through the food chain and accumulates in fish (Jackson, 1988; Lucotte *et al.*, 1999a).

The impoundment of hydroelectric reservoirs causes a number of chemical and biological changes, including a temporary increase in mercury levels in fish, through the flooding of land environments (Verta *et al.*, 1986; Verdon *et al.*, 1991; Strange *et al.*, 1991; Schetagne *et al.*, 2002). This is due to extensive bacterial decomposition of the newly flooded organic matter (vegetation and surface organic soil layers), which increases methylmercury production and its accumulation in fish.

The presence of mercury in the environment is a matter of concern because of the potential toxicity of methylmercury for humans. In Canada, the main source of human exposure to mercury is fish consumption. At the La Grande complex, fish mercury levels have been monitored since 1978, in both natural and modified environments. The main objectives of monitoring are to determine the temporal evolution of the increase in fish mercury levels in environments modified by development of the La Grande hydroelectric complex, to provide the necessary data to produce fish consumption guidelines and to allow for an *a posteriori* comparison of the impacts actually measured with the effects predicted by the environmental impact assessment studies, with a view to improving impact prediction methods for future projects.

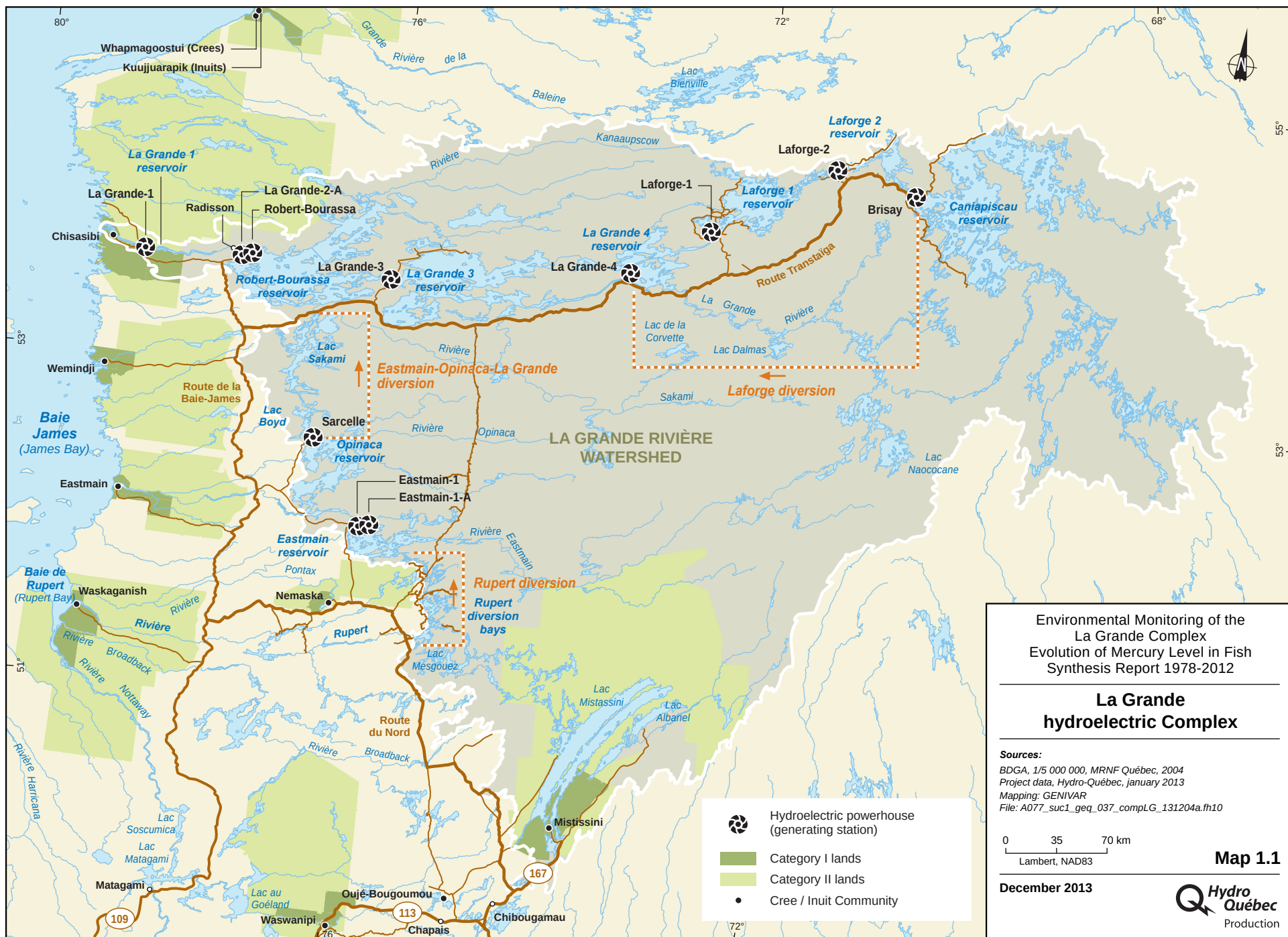
This report provides a summary of the results obtained between 1978 and 2012, during Phase I and II development of the La Grande complex. The evolution of fish mercury levels in Eastmain 1 reservoir and in the forebay and tailbay created by the Rupert diversion (Phase III) are not presented here, as these water bodies are too recent.

1.1 Project description, general commitments and obligations

1.1.1 Study area and environment

The study area for monitoring fish mercury covers the region of the La Grande hydroelectric complex, shown in Map 1.1. The main characteristics of the physical, biological and human environments in the area of the La Grande complex are as follows:

- Geology (SEBJ, 1978):
 - Rests on the Canadian Shield, which is made up of outcropping igneous and metamorphic rock
 - Contains deposits of silty clay and fine deltaic sand carried at least 200 km inland by the Tyrrell Sea (elevation 290 m; SEBJ, 1987) to where the coastal plain, 150 km wide and scattered with peatlands and clay deposits, meets the hilly central plateau with its numerous lakes
- Climate and hydrography (Roy *et al.*, 1986):
 - Cold, continental climate characteristic of the humid subarctic zone
 - Mean annual temperature of - 4°C with prevailing westerly winds
 - Precipitation increases gradually from west to east and decreases from south to north; annual average of 765 mm
 - Rivers are fed by rain and snowfall; heavy spring floods from snowmelt; summer low-water period varies in severity; fall flood due to rainfall; winter low-water period begins in November and lasts until early May (period of lake ice cover); ice-breakup and spring floods begin in May or early June
- Vegetation and land wildlife (Roy *et al.*, 1986):
 - Sparse forest of black spruce (*Picea mariana*), jack pine (*Pinus banksiana*), larch (*Larix laricina*) and aspen (*Populus tremuloides*), unsuitable for commercial harvesting; many peat bogs, especially on the coastal plain; undergrowth dominated by heath, mosses and lichens; riparian vegetation dominated by shrubby willows (*Salix* spp.)



Environmental Monitoring of the
La Grande Complex
Evolution of Mercury Level in Fish
Synthesis Report 1978-2012

La Grande hydroelectric Complex

Sources:

BDGA, 1/5 000 000, MRNF Québec, 2004
Project data, Hydro-Québec, January 2013
Mapping: GENIVAR
File: A077_suc1_geq_037_compLG_131204a.fh10

0 35 70 km
Lambert, NAD83

Map 1.1

December 2013

Hydro-Québec
Production

- Presence of 39 species of mammals, including moose (*Alces alces*), caribou (*Rangifer caribou*) and beaver (*Castor canadensis*), which are of economic and sporting interest; overall wildlife densities are lower than in more southerly regions; the eastern coast of Baie James (James Bay) is used extensively by migrating waterfowl
- Aquatic wildlife and water quality (Verdon, 2001; Therrien *et al.*, 2002; Schetagne *et al.*, 2005):
 - Twenty-eight species of fish identified, the most common of which are longnose sucker (*Catostomus catostomus*), white sucker (*Catostomus commersoni*), normal and dwarf lake whitefish (*Coregonus clupeaformis*), cisco (*Coregonus artedii*), northern pike (*Esox lucius*), lake trout (*Salvelinus namaycush*), walleye (*Sander vitreus*), brook trout (*Salvelinus fontinalis*) and burbot (*Lota lota*)
 - Slower growth than in the southern regions of the province, but greater longevity; later sexual maturity and less frequent reproduction
 - Water of relatively high transparency (1.5 to 4.0 m); very well oxygenated (80% to 100% saturation); mildly acidic (pH of 5.9 to 6.9), with relatively low buffering capacity (0.6 to 11.0 mg/L of bicarbonates), low mineral content (8 to 30 µS/cm), relatively rich in organic matter and poor in nutrients (0.004 - 0.010 mg/L total phosphorus)
- Populations (Baie-James region):
 - Cree population of around 16,000 (in 2013; Tourisme Québec, 2013) living in five villages along the coast of Baie James (Waskaganish, Eastmain, Wemindji, Chisasibi) and Baie d'Hudson (Hudson Bay) (Whapmagoostui), as well as in four inland villages (Nemaska, Waswanipi, Mistissini and Oujé-Bougoumou)
 - Non-Native population of about 15,000 (in 2013; Tourisme Québec, 2013) concentrated mainly in the southern part of the Baie-James region (over 90%)
 - Visited by approximately 98,000 tourists a year (in 2007; Tourisme Québec, 2009)

1.1.2 Hydroelectric developments in the La Grande complex

The La Grande complex hydroelectric developments (Map 1.1 and tables 1.1 and 1.2), located within the new watershed of the Grande Rivière (Figure 1.1), were built in three phases. Phase I (1973–1985) comprised three generating stations: Robert-Bourassa (5,328 MW), La Grande-3 (2,304 MW) and La Grande-4 (2,651 MW), each having its own reservoir.

Two additional reservoirs, Caniapiscou and Opinaca, which were formed by two partial river diversions, feed the other three. Located at the eastern extremity of the complex, Caniapiscou reservoir acts as an interannual flow regulator by providing a mean annual input of 790 m³/s. Opinaca reservoir, the most southerly of the Phase I and II reservoirs in the complex, channels a mean annual flow of 845 m³/s into Robert-Bourassa reservoir. As a result of these inflows, the mean annual flow at the mouth of the Grande Rivière has doubled, going from about 1,700 m³/s to approximately 3,400 m³/s.

Phase II of the La Grande complex called for the construction of five generating stations: La Grande-1 (1,368 MW), La Grande-2-A (1,998 MW), Laforge-1 (838 MW), Laforge-2 (304 MW) and Brisay (447 MW). The work was carried out from 1987 to 1996. For Phase II, new reservoirs (la Grande 1 and Laforge 1) only had to be created for the La Grande-1 and Laforge-1 generating stations, as the other stations used the reservoirs impounded during Phase I.

During Phase III, the partial diversion of the Rivière Rupert into the Grande Rivière brought the flow at the mouth of the latter to about 3,800 m³/s. In addition, three more generating stations were built: Eastmain-1 powerhouse (507 MW) and Eastmain-1-A powerhouse (768 MW), which are fed by Eastmain 1 reservoir, and Sarcelle powerhouse (150 MW), which gets its flow from Opinaca reservoir. The work was carried out from 2002 to 2013.

1.1.3 General commitments and obligations

Under the *James Bay and Northern Québec Agreement* (JBNQA) (Éditeur officiel du Québec, 1976), the Société d'énergie de la Baie James (SEBJ) was given a mandate to implement an environmental monitoring program that included an assessment of the impacts of hydroelectric development in the Baie-James region and any necessary remedial measures, subject to review by SEBJ's Environmental Expert Committee. The Environmental Monitoring Network (EMN), which was established by SEBJ in 1977 and continued by Hydro-Québec until 2000, focused primarily on water quality and fish communities and the monitoring of fish mercury as a complementary activity.

Table 1.1 Characteristics of La Grande Complex Reservoirs at Maximum Level

Reservoir	Mean annual drawdown observed ^a (m)		Maximum reservoir area (km ²)	Maximum land area flooded ^b (km ²)		Mean depth (m)	Maximum water volume ^c (km ³)	Theoretical residence time (months)	Mean annual flow (m ³ /s)	Impoundment period	Phase
Robert-Bourassa	3.3	(7.7)	2,835	2,630	(92%)	22.0	61.7	6.9	3,374	78-11 to 79-12	I
La Grande 3 ^d	5.5	(12.2)	2,420	2,175	(90%)	24.4	60.0	11.0	2,064	81-04 to 84-08	I
La Grande 4	8.0	(11.0)	765	700	(89%)	29.4	19.5	4.8	1,534	83-03 to 83-11	I
Opinaca	3.6	(4.0)	1,040	740	(71%)	8.2	8.4	3.8	845	80-04 to 80-09 ^h	I
Caniapiscau	2.1	(12.9)	4,275	3,430	(80%)	16.8	53.8	25.8	790	81-10 to 84-09	I
Laforge 1 ^e	4.0	(8.0)	1,288	923	(72%)	6.2	8.0	3.2	938	93-08 to 93-10	II
Laforge 2 ^f	1.5	(1.5)	286	171	(60%)	6.3	1.8	0.8	804	83-08 to 84-04	II
La Grande 1	0.9	(1.5)	70	40	(57%)	18.6	1.3	0.15	3,400	93-10 to 93-11	II
Eastmain 1	7.7	(9.0)	603	478	(79%)	14.4	6.9	2.6	1,015, ^g	05-11 to 06-05	III
Total			13,556	11,287	(83%)						

a Maximum drawdown shown in parentheses.

b Percentage of maximum area made up of flooded lands shown in parentheses.

c Values include dead storage.

d Impoundment was interrupted for 13 months.

e The impoundment of Vincelotte basin (1982) flooded a land area of 125 km² and the increase in level resulting from the creation of Laforge 1 reservoir (1993) resulted in the flooding of an additional land area of 798 km².

f Fontanges basin was impounded during Phase I and became Laforge 2 reservoir in Phase II.

g Includes the Rupert diversion.

h A small local area was flooded when the Petite Rivière Opinaca was cut off in July 1979, but the bulk of impoundment began in April 1980 with the cut-off of the Rivière Opinaca.

Table 1.2 **Characteristics of La Grande Complex Generating Stations**

Generating station	Generating units	Capacity (MW)	Design flow (m ³ /s)	Rated head (m)	Commissioning	Phase
Robert-Bourassa	16	5,328	4,300	137.2	1979–1981	I
La Grande-2-A	6	1,998	1,620	138.5	1991–1992	II
La Grande-1	12	1,368	5,950	27.5	1994–1995	II
La Grande-3	12	2,304	3,260	79.2	1982–1984	I
La Grande-4	9	2,651	2,520	116.7	1984–1985	I
Laforge-1	6	838	1,613	57.3	1993–1994	II
Laforge-2	2	304	1,200	27.4	1996	II
Brisay	2	447	1,130	37.5	1993	II
Eastmain-1	3	507	840	63.0	2006	III
Eastmain-1-A	3	768	1,344	63.0	2011–2012	III
Sarcelle	3	150	1,380	10.8	2013	III
Total	74	16,463				

In addition, monitoring programs focused on the main land and avian wildlife resources and their habitat, as well as on some components of the social environment. Studies were also done on the estuaries of rivers modified by the hydroelectric developments and along the northeast coast of Baie James. Twenty summary reports were published in 1985 and 1986. In 1986, SEBJ transferred its environmental monitoring obligations for Phase I to Hydro-Québec.

With the exception of the Laforge-1 project, environmental monitoring activities related to Phase II development of the La Grande complex were subject to the conditions of the projects' certificates of authorization.

The parties agreed on an administrative procedure for implementing the environmental monitoring program for the La Grande-2-A and La Grande-1 projects. Filed in 1994, the master plan for the program incorporated the request by the Ministère de l'environnement du Québec (MENV) (provincial Department of the Environment) that the proponent focus on the main issues raised in the impact assessment studies and harmonize monitoring of the two projects. In September 1993, a proposal for harmonizing aquatic and riparian environmental monitoring programs was drawn up jointly by SEBJ and Hydro-Québec for the Laforge-1, Laforge-2 and Brisay generating station projects. The proposal was accepted by the MENV, as was a proposal for optimizing fish population monitoring programs for the La Grande complex as a whole. The monitoring programs also encompassed land use and economic and social impacts.

In 1996, SEBJ transferred its environmental monitoring obligations for Phase II to Hydro-Québec. The schedule set out in the monitoring master plans was completed in 2000. The summary supports on the various environmental components marked the conclusion of these monitoring programs.

Seven summary reports were published and distributed in 2001 and 2002. The reports focused on the following components: 1) hydrology and ice regime on the Grande Rivière, 2) bank dynamics on the Grande Rivière, 3) riparian and aquatic vegetation in the La Grande complex, 4) eelgrass on the northeast coast of Baie James, 5) the Grande Rivière freshwater plume, 6) evolution of fish mercury levels in the La Grande complex, and 7) changes in fish communities in the La Grande complex. An eighth summary report on water quality was published in 2005.

1.2 Commitments and obligations specific to mercury

Prior to the construction of Phase I of the La Grande complex, very little was known about mercury in reservoirs. The discovery in the early 1980s that fish mercury had increased in the La Grande complex reservoirs led the Crees of Québec,

the Québec government, SEBJ and Hydro-Québec to sign the *James Bay Mercury Agreement (1986)*. The agreement comprised three components—the environment, health and sociocultural aspects—and set out studies, monitoring activities and mitigation measures for each component. Hydro-Québec was responsible for the monitoring of fish mercury, which was carried under the environment component of the agreement.

The *James Bay Mercury Agreement (1986)* was renewed and became the *Mercury Agreement (2001)*. The non-profit Niskamoon Corporation was created to apply the new agreement, the main focus being on monitoring the Cree communities' exposure to mercury and restoring the Cree fisheries. Since the new agreement came into effect, fish mercury monitoring no longer falls under the corporation's activities but is still carried out by Hydro-Québec, which informs the Cree Board of Health and Social Services of James Bay (CBHSSJB) in this regard. The CBHSSJB is still responsible for drawing up fish consumption guidelines for the Crees.

The Master Plan for the Eastmain-1 Environmental Monitoring Program (PSE-EM1, April 2005) was filed with the Ministère du Développement durable, de l'Environnement et des Parcs (MDDEP) (Québec Department of Sustainable Development, Environment and Parks), after it was approved by the Crees. A Follow-up Methodologies document was produced in June 2006 to go with the Master Plan. These documents describe the objectives, study area, proposed methods, schedule and source of the commitments for the various components to be monitored.

The *Boumhounan Agreement* was signed by the Cree Regional Authority (CRA), the Grand Council of the Crees (Eeyou Istchee) [GCC (EI)], the Cree nations of Mistissini, Nemaska, Waskaganish and Eastmain, Hydro-Québec and SEBJ to provide a framework for the Eastmain-1-A/Sarcelle/Rupert project. This agreement and the *Monitoring Committee Agreement* both stipulated that the project's environmental monitoring program was to be implemented in cooperation with the Crees. Consequently, a Monitoring Committee was set up with representatives from the Niskamoon Corporation, the six Cree communities affected by the project, SEBJ and Hydro-Québec. The Committee acts as the main advisory body through which the Crees participate in the development and implementation of the environmental monitoring program.

The monitoring program for this project is governed by the *Boumhounan Agreement*, the commitments resulting from the Environmental Impact Statement (EIS) and its supplement, and the conditions set out in all government approvals issued (Hydro-Québec, 2007a).

The program meets the following conditions of the Certificate of Authorization issued by the MDDEP under section 164 of the EQA (ref. 3214-10-17):

- Condition 5.9: The proponent shall submit to the Administrator for authorization a detailed follow-up program on mercury levels in fish flesh for the sectors of the Rupert diversion bays. These stations must notably make it possible to measure the phenomenon of bioaccumulation in fish.
- Condition 5.27: The proponent shall submit to the Administrator for authorization a detailed follow-up program on mercury levels in fish meat for the Rivière Rupert, Rivière Lemare and Rivière Nemiscau sectors downstream from the control works. The proponent shall make provision in its follow-up program on mercury levels in fish flesh for stations downstream from the Eastmain-1-A powerhouse and control works. These stations must notably make it possible to measure the phenomenon of bioaccumulation in fish and to evaluate the extent of mercury export downstream from the structures.
- Condition 5.34: The proponent shall submit to the Administrator for authorization a detailed follow-up program on mercury levels in fish meat for the increased flow sector. The proponent shall make provision in its follow-up program on mercury levels in fish flesh for stations downstream from the Eastmain-1-A powerhouse and control works. These stations must notably make it possible to measure the phenomenon of bioaccumulation in non-piscivorous fish and to evaluate the extent of mercury exports downstream from the structures.

In addition, in the agreement with the Crees signed in June 2007, Hydro-Québec agreed to monitor mercury contamination in fish in a lake flowing into the Rivière Misticawissich in response to concerns raised by the tallyman of trapline M26.

The 2002 summary report on the monitoring of fish mercury in the La Grande complex clearly showed that all of Hydro-Québec's commitments relating to fish mercury monitoring were met. Nevertheless, Hydro-Québec recommended that additional analyses of mercury levels in piscivorous fish in the La Grande complex be carried out with a view to managing the potential health risk to fish consumers. This would also make it possible to more accurately establish the time required for mercury in these species to return to natural levels. In addition, monitoring programs were implemented for the Eastmain-1, Eastmain-1-A, Sarcelle and Rupert diversion developments and will continue until mercury concentrations return to levels that allow for consumption of fish from the reservoirs equivalent to that recommended for natural lakes, i.e., less than 0.5 mg/kg for non-piscivorous species and less than 1.99 mg/kg for piscivorous species.

1.3 Review of prior studies

As part of the EMN implemented by SEBJ, fish mercury levels have been monitored in both natural and modified environments in the La Grande complex since 1978. When Hydro-Québec took over management of the EMN in 1986, the La Grande complex was split into two sectors (East and West) and alternately sampled every two years, then every four. Fish mercury levels in the West sector were generally analyzed every two years from 1982 to 2000 inclusively and then in 2004 and 2008 (Schetagne *et al.*, 2002; Therrien and Schetagne, 2005a, 2009). In the East sector, fish mercury levels were measured in 1980 and 1984, every two years from 1987 to 1999 inclusively, and then in 2003 and 2007 (Schetagne *et al.*, 2002; Therrien and Schetagne, 2004, 2008a). The 2012 surveys targeted both sectors for the first time since 1984. Optimization of the monitoring program in 2004 made it possible to reduce the number of survey stations by nearly 50% with no significant loss of data (Therrien and Schetagne, 2005 b). The optimized version of the program has been used ever since. It should be noted that Opinaca reservoir was normally monitored at the same time as the other reservoirs in the West sector. However, since it was subsequently monitored at the same time as Eastmain 1 reservoir, Opinaca reservoir was sampled for fish mercury in 2007, 2009 and 2011 (Therrien et Schetagne, 2008 b, 2010, 2012). Opinaca reservoir was not included in the 2012 surveys.

1.4 Objectives

The objectives of monitoring were to evaluate the temporal evolution of the phenomenon in the different types of modified environments, inform fish consumers and improve impact prediction methods for future hydroelectric development projects. The report by Schetagne *et al.* (2002) showed that the main objectives of the monitoring program were fully achieved and clearly established the extent and duration of the phenomenon, the main processes involved and the underlying physical and biological factors that control it.

The Crees of Québec were consistently informed of fish mercury levels in the La Grande complex. Fish consumption guidelines for the La Grande complex were produced on the basis of exposure criteria established by the CBHSSJB, using data collected during monitoring. Anglers were also kept informed of fish mercury levels in the complex, as the monitoring data was regularly incorporated into Québec's freshwater sport fish consumption guidelines. The two models developed to predict fish mercury levels in reservoirs clearly show that the third objective, which was to improve impact methods for future hydroelectric development projects, was met.

The health component of the mercury issue, which involves managing the potential risks posed to consumers' health by the temporary increase in fish mercury levels, remains the responsibility of the CBHSSJB. In regard to non-Native anglers from the Baie-James region, Hydro-Québec works in close cooperation with the Centre régional de santé et de services sociaux de la Baie-James (CRSSSBJ).

In this context, Hydro-Québec provides technical assistance by conducting fish mercury studies, carrying out statistical analyses, calculating the maximum safe number of fish meals per month and providing financial support for the production and dissemination of fish consumption guidelines.

After several guidelines had been produced under the *James Bay Mercury Agreement (1986)*, a first edition of the Northern Fish Nutrition Guide – La Grande Complex was produced in French and English in 2004, using fish mercury data collected up to the year 2000. The guide was intended for use by the Crees and other Baie-James residents. The data collected during the 2011 and 2012 surveys was used to revise the information and produce the Northern Fish Nutrition Guide – Baie-James Region in 2013. The new version included guidelines for the new developments, i.e., Eastmain 1 reservoir, the Rupert diversion bays (forebay and tailbay), and the Rupert and Nemiscau rivers downstream of the diversion bays.

This report provides a summary of the results obtained between 1978 and 2012 at the La Grande complex and describes the changes that have occurred in mercury levels in the main fish species since the environments were modified. The report incorporates data taken from a number of previous reports and summary articles (Messier *et al.*, 1985; Messier and Roy, 1987; Brouard *et al.*, 1990; Verdon *et al.*, 1991; Entraco, 1996; Schetagne *et al.*, 1996; Lucotte *et al.*, 1999; Doyon and Schetagne, 2000; Schetagne *et al.*, 2002; Therrien and Schetagne, 2004, 2005a et b, 2008a et b, 2009, 2010, 2012).

The report is divided into four chapters, which cover the following topics:

- 1) A description of the environment and hydroelectric developments, commitments and obligations, and target objectives
- 2) The methods used
- 3) The results obtained (changes in mercury levels in natural and modified environments and supplementary studies)
- 4) Risk management (including fish consumption guidelines)

In addition, an English-language executive summary is provided in Appendix 1.

Two appendices included in a separate document (GENIVAR, 2013) provide the results of the statistical analyses of fish mercury data collected in 2012. This document completes the appendices to previous reports, which record the results of the mathematical processing performed since monitoring began. All of these documents are also available at Hydro-Québec's documentation centre.

2. METHODS

This chapter presents the methodology applied to monitoring fish mercury levels at the La Grande complex from 1978 to 2012. It describes the sampling strategy, field measurements, laboratory analyses and quality control methods applied, as well as the statistical approach followed and aspects related to data presentation.

2.1 Sampling strategy, measurements and samples taken

2.1.1 Sampling strategy

Sampling stations

From 1978 to 2012, i.e., before and after development, fish were caught at 93 sampling stations distributed throughout the natural lakes (25 stations, Table 2.1) and modified water bodies (68 stations, Table 2.2) within the La Grande complex. Fish were also caught along the east coast of Baie James (19 stations, Table 2.3). Map A (in pocket) shows the locations of all the stations.

For logistical reasons, the territory of the La Grande complex was split into two sectors, East and West. The boundary between the two was based on the presence or absence of certain fish species. Walleye and cisco are only present in the West sector, while dwarf lake whitefish are found only in the East. The boundary between the two sectors lies approximately in line with La Grande-4 generating station (Map 1.1). Monitoring of the two sectors was generally carried out in alternating years.

The stations sampled in the two sectors since 2004 are those retained after the mercury component of the EMN was optimized in 2004 (Therrien and Schetagne, 2005b). Although the number of sampling stations consequently decreased from 41 to 21, the ability to manage the health risk to fish consumers was not affected. In fact, for almost all species, monitoring years and environments, the mean mercury levels measured using the reduced number of sampling stations did not differ significantly from those recorded at all stations. As was the case in 2011, sampling in 2012 took place at the 19 stations in Opinaca reservoir and the Rupert diversion bay section (Therrien and Schetagne, 2012).

Table 2.1 Stations Sampled in Natural Lakes in the La Grande Complex during Monitoring of Fish Mercury Levels (1980–2012)

Station	1980	1984	1986	1987	1988	1989	1990	1991	1992	1993	1994	1995	1996	1997	1998	1999	2000	2003	2004	2007	2008	2009	2011	2012
Lac Yasinski (C2 005)					✓																			
Lac Bruce (C2 128)					✓																			
Lac McNab (C2 129)					✓																			
Lac du Vieux Comptoir (C2 130)					✓																			
Lac Conn (C2 131)					✓																			
Lac Roggan (C3 024)					✓																			
Lac Pamigamichi (C3 025)					✓																			
Lac Craven (C3 026)					✓																			
Lac Julian (C3 027)					✓																			
Lac Intersection (C3 028)					✓																			
Lac Sérigny (CE 012)*										✓		✓				✓		✓						
Lac Hazeur (CE 034)*				✓		✓		✓		✓		✓				✓		✓		✓				✓
Lac Duxbury (EA 012)					✓																			
Lac Rond-de-Poêle/Pikutamaw (EA 302)*		✓	✓		✓		✓		✓		✓		✓		✓		✓		✓	✓		✓	✓	
Lac Village Sud (EM 203)																				✓		✓	✓	
Lac Émérillon (EM 409)							✓													✓		✓	✓	
Lac Wawa (G2 275)		✓																						
Lac Tilly (G3 437)						✓												✓						
Lac des Vœux (G4 401)*								✓		✓		✓			✓									
Lac de la Montagne du Pin (KA 014)					✓																			
Lac Nouveau (OP 412)	✓																							
Lac Frégate (PO 004)								✓																
Lac Corvette (PO 457)								✓																
Lac Detcheverry (SB 400)*							✓		✓		✓	✓	✓		✓		✓				✓			✓
Lac Kaychikutinaw (SK 200)					✓																			
Lac Anonyme (SK 201)					✓																			

* Control lakes

✓ Sampling year

Table 2.2 Stations Sampled in Developed Water Bodies in the La Grande Complex during Monitoring of Fish Mercury Levels (1978–2012)

Station	1978	1980	1981	1982	1984	1986	1987	1988	1989	1990	1991	1992	1993	1994	1995	1996	1997	1998	1999	2000	2003	2004	2007	2008	2009	2011	2012
RESERVOIRS																											
Robert-Bourassa																											
LG 2 amont (G2 400)				✓	✓	✓		✓		✓		✓		✓		✓		✓		✓		✓		✓			✓
Kanaaupscow (G2 402)				✓	✓							✓															
Bereziuk (G2 403)	O		✓	✓	✓			✓		✓		✓		✓		✓		✓		✓							
Coutaceau (G2 404)	O			✓	✓	✓		✓		✓	✓	✓		✓		✓		✓		✓		✓	✓	✓			✓
Toto (G2 405)				✓	✓	✓		✓		✓	✓	✓		✓		✓		✓		✓		✓	✓	✓			✓
LG 3 aval (G2 406)				✓	✓	✓		✓		✓		✓		✓		✓		✓		✓							
Duncan dike (G2 462)												✓				✓											
Desaulniers																											
Desaulniers (G2 129)								✓				✓		✓		✓											
Opinaca																											
Opinaca (EM 400)					✓	✓		✓		✓		✓		✓		✓				✓		✓	✓		✓	✓	
Noyé (EM 401)										✓		✓		✓		✓				✓							
Low (EM 402)	O		✓		✓					✓		✓		✓		✓				✓		✓	✓		✓	✓	
Eastmain 1 amont (EM 403)						✓		✓				✓		✓		✓				✓							
La Grande 3																											
Gavaudan (G3 071)						✓		✓		✓		✓		✓		✓		✓		✓		✓	✓	✓			✓
Grande-Pointe (G3 301)						✓		✓		✓		✓		✓		✓		✓		✓							
LG 4 aval (G3 306)					✓								✓		✓		✓		✓								

Table 2.2 (cont.) Stations Sampled in Developed Water Bodies in the La Grande Complex during Monitoring of Fish Mercury Levels (1978–2012)

Station	1978	1980	1981	1982	1984	1986	1987	1988	1989	1990	1991	1992	1993	1994	1995	1996	1997	1998	1999	2000	2003	2004	2007	2008	2009	2011	2012
La Grande 3 (cont.)																											
LG 4 aval (G3 306)					✓								✓		✓		✓		✓								
Roy (G3 307)						✓		✓		✓		✓		✓		✓		✓		✓				✓			✓
Zaidi (G3 308)						✓		✓																			
LG 3 centre (G3 449)					✓																						
La Grande 4																											
Pagé (G4 114)							✓		✓		✓		✓		✓		✓		✓		✓						
Lanouette (G4 115)							✓		✓		✓		✓		✓		✓		✓		✓			✓			✓
Polaris (G4 116)											✓																
Caniapiscau																											
Dollier (CA 411)							✓		✓		✓		✓		✓		✓		✓		✓						
Caniapiscau (CA 413)							✓		✓		✓		✓		✓		✓		✓		✓			✓			✓
Apulco (CA 414)		O																									
Delorme (CA 415)		O																									
Vermeulle (CA 416)		O					✓		✓		✓		✓		✓		✓		✓		✓						
Brisay (CA 419)							✓		✓		✓		✓		✓		✓		✓		✓			✓			✓
Duplanter (CA 713)					✓																						
Nouveau (OP 412)		O																									
La Grande 1^a																											
Laperle (G1 070)						✓		✓		✓		✓		✓		✓		✓		✓							
LG 2 aval (G1 110)						✓		✓		✓		✓		✓		✓		✓		✓			✓		✓		✓
LG 1 amont (G1 300)					✓	✓		✓		✓		✓		✓		✓		✓		✓			✓		✓		✓

Table 2.2 (cont.) Stations Sampled in Developed Water Bodies in the La Grande Complex during Monitoring of Fish Mercury Levels (1978–2012)

Station	1978	1980	1981	1982	1984	1986	1987	1988	1989	1990	1991	1992	1993	1994	1995	1996	1997	1998	1999	2000	2003	2004	2007	2008	2009	2011	2012
<i>Laforge 1^b</i>																											
Laforge (LA 115)							✓		✓		✓		✓		✓		✓		✓		✓		✓				✓
Vincelotte (LA 116)							✓		✓		✓		✓		✓		✓		✓		✓						
Lac Vaulezar (LA 095)												O															
Lac Jobert (LA 119)							O				O		✓		✓		✓		✓		✓						
Lac des Œufs (LA 134)													✓		✓		✓		✓		✓		✓				✓
LG 1 amont (G1 300)					✓	✓		✓		✓		✓		✓		✓		✓		✓		✓		✓			✓
<i>Laforge 2^c</i>																											
Fontanges (LA 901)									✓		✓		✓		✓		✓		✓		✓		✓				✓
<i>Eastmain 1</i>																											
Eastmain 1 amont (EM 212)																							✓		✓	✓	
Natel (EM 318)																							✓		✓	✓	
Downstream of Rupert diversion bays (EM 319)																							✓		✓	✓	
INCREASED-FLOW SECTIONS																											
<i>Grande Rivière</i>																											
Estuary (FG 003)						✓																					
Fort George aval (FG 006)																✓				✓							

Table 2.2 (cont.) Stations Sampled in Developed Water Bodies in the La Grande Complex during Monitoring of Fish Mercury Levels (1978–2012)

Station	1978	1980	1981	1982	1984	1986	1987	1988	1989	1990	1991	1992	1993	1994	1995	1996	1997	1998	1999	2000	2003	2004	2007	2008	2009	2011	2012
<i>Eastmain and Opinaca rivers (cont.)</i>																											
Weir 9 (EA 093)								✓				✓															
Eastmain- Opinaca (EA 300)					✓	✓		✓				✓															
Eastmain (EA 301)		O	✓		✓	✓		✓				✓															
<i>Rivière Vincelotte</i>																											
Vincelotte amont (LA 121)							✓				✓		✓														
<i>Rivière Caniapiscau</i>																											
Eaton amont (CE 007)					✓		✓		✓		✓		✓		✓												
Calcaire (CN 034)									✓		✓		✓		✓												
Cambrien (CN 048)					✓		✓		✓		✓		✓		✓												
<i>Downstream of Rupert diversion bays</i>																											
Rupert dam aval (RP 176)																										✓	
Rivière Rupert (RP 060)																										✓	
Rivière Nemiscau (RU 002)																										✓	
Lac Nemiscau (RU 813)										O																✓	

O: Sampling year under natural conditions.
 √: Sampling year under modified conditions
 a Increased-flow areas (Grande Rivière) until 1993
 b Vincelotte basin (Laforge diversion) until 1993
 c Fontanges basin (Laforge diversion) until 1993

Table 2.3 Stations Sampled along the East Coast of Baie James (James Bay) during Monitoring of Fish Mercury Levels in the La Grande Complex (1987–1996)

Station	1987	1988	1989	1990	1991	1992	1993	1994	1995	1996
COASTAL ENVIRONMENT										
Kakassituq (BJ 055)						✓				
Dead Duck (BJ 056)	✓			✓		✓				✓
Aquatuc (BJ 057)	✓			✓		✓				
Tees Bay (BJ 058)	✓			✓		✓				
Goose Bay (BJ 059)				✓						
Attikuan (BJ 060)		✓		✓						
Paul Bay (BJ 061)	✓	✓		✓		✓				✓
Bay of Many Islands (BJ 062)	✓	✓				✓				
Île Black (BJ 321)	✓									
Rivière Caillet (C2 132)		✓		✓						
Old Factory (C2 134)				✓						
Moar Bay (C2 135)				✓						
Goose Island (C2 136)				✓						
Rivière Guillaume (C3 029)		✓		✓						
Rivière Piagochioui (C3 030)		✓		✓						
Rivière Kapsaouis (C3 031)		✓		✓						
Rivière Piagochioui amont (C3 034)								✓		
Île Grass (FG 303)	✓			✓		✓				✓
Îles Loon (FG 305)	✓					✓				✓

✓ Sampling year

Note: No sampling carried out before 1987 or after 1996

Sampling strategy

At each station, the objective was to catch 30 specimens of the following target species: longnose sucker, lake whitefish (normal and dwarf), northern pike, lake trout (East sector only) and walleye (West sector only). The selection criteria for these species were: piscivorous and non-piscivorous species consumed by Native people and well distributed over the territory after reservoir impoundment. A fishing effort of up to 24 net-days was allotted to obtain the required specimens.

Incidental species, i.e., those that are less abundant in the sampled areas than target species, were also kept for reference purposes, up to a maximum of 30 specimens per species and per station. The most frequently caught incidental species were cisco, burbot, brook trout and lake sturgeon (*Acipenser fulvescens*). All lake sturgeon caught were released and only those specimens caught by Cree subsistence fishers were analyzed.

From 1993 to 1999, dwarf lake whitefish was also considered a target species. An analysis in 1993 revealed the presence of sympatric populations of dwarf and normal lake whitefish in the East sector of the La Grande complex (Doyon, 1995a; Doyon *et al.*, 1998a). Bernatchez (1996) demonstrated that these populations were genetically distinct and had significantly different mercury accumulation rates, which were higher in the dwarf population (Doyon, 1995b; Doyon *et al.*, 1998a and b). Since 2003, only normal lake whitefish have been analyzed, since the dwarf type are neither fished nor consumed for sport or subsistence.

Information on fishing gear, fish sampling strategy, and the removal and preservation of samples to determine their mercury level is detailed in Tremblay *et al.* (1996).

From 1978 to 2012, a total of 44,762 fish, including 37,645 specimens of target species (Table 2.4), were caught for the purpose of fish mercury monitoring at the La Grande complex. In addition, 4,363 fish were caught outside the La Grande complex Environmental Monitoring Network (EMN), including 1,224 specimens of target species.

2.1.2 Fish measurement and sampling

From 1978 to 2012, all specimens caught were handled according to the following procedure:

- Species identification, measurement of total length (mm) and weight (g)
- Determination of sex and sexual maturity in accordance with the Bückmann classification (1929)
- Removal, in almost all cases, of certain body parts to determine age: otoliths and scales for lake whitefish and lake trout; fin rays for longnose sucker; cleithrum and scales for northern pike; and otoliths and operculum for walleye. Since 1993, lake whitefish scales have no longer been used, because of the inaccuracy of such measurements in old specimens (Power, 1978)
- Removal of a portion of muscle tissue (20 to 50 g) free of skin and abdominal spine
- Removal, in approximately 10% of specimens, of three portions (triplicates) of muscle tissue (blind samples) for quality control
- Freezing and shipping of muscle tissue to the analyzing laboratory

Table 2.4 Distribution of Main Species of Fish Analyzed for Mercury Levels from 1978 to 2012

Year	Longnose sucker	Lake whitefish*	Northern pike	Lake trout	Walleye	Total
LA GRANDE COMPLEX ENVIRONMENTAL MONITORING NETWORK**						
1978	83	102	91	0	104	380
1980	113	137	57	106	0	413
1981	0	59	9	0	59	127
1982	151	150	147	0	145	593
1984	225	407	327	96	240	1,295
1986	417	586	562	43	295	1,903
1987	400	450	302	312	0	1,464
1988	200	846	768	99	396	2,309
1989	390	393	253	273	0	1,309
1990	185	615	411	0	222	1,433
1991	418	472	241	245	0	1,376
1992	235	495	476	0	355	1,561
1993	591	654	432	422	0	2,099
1994	306	661	612	8	377	1,964
1995	569	619	329	301	0	1,818
1996	395	676	621	9	378	2,079
1997	464	442	347	235	0	1,488
1998	257	390	409	11	178	1,245
1999	464	453	387	237	5	1,546
2000	479	663	628	7	457	2,234
2003	498	769	372	142	30	1,811
2004	122	343	336	9	286	1,096
2007	25	557	510	110	267	1,469
2008	64	290	294	0	223	871
2009	15	262	296	3	287	863
2011	14	380	466	11	470	1,341
2012	90	576	506	157	219	1,548
Total	7,170	12,447	10,189	2,836	4,993	37,645
OUTSIDE THE LA GRANDE COMPLEX ENVIRONMENTAL MONITORING NETWORK ***						
1978			153	59		212
1984			91			91
1985	29	56	116		30	231
1986			65			65
1987		32	100	34		166
1988		30	44		9	83
1989		51			80	131
1990		23			27	50
1991		32			44	76
1992			119			119
Total	29	224	688	93	190	1,224

* Normal and dwarf forms combined.

** 7,117 specimens of target species were also considered, namely, 2,507 cisco, 886 dwarf lake whitefish, 1,637 burbot, 1,078 brook trout, 81 landlocked salmon (*Salmo salar*), 151 lake sturgeon, 271 round whitefish (*Prosopium cylindraceum*), 84 white sucker, 71 yellow perch (*Perca flavescens*), 50 lake chub (*Couesius plumbeus*), 168 fourhorn sculpin (*Trigloporus quadricornis*) and 133 Greenland cod (*Gadus ogac*).

*** Fish analyzed to determine the duration of the mercury increase phenomenon in reservoirs. The 3,139 specimens of incidental species caught consisted of 990 white sucker, 354 cisco, 114 mooneye (*Hiodon tergisus*), 71 goldeye (*Hiodon alosoides*), 65 sauger (*Sander canadensis*), 461 brook trout, 209 lake sturgeon, 205 rainbow smelt (*Osmerus mordax*), 353 Arctic char (*Salvelinus alpinus*) et 317 landlocked salmon.

Over the years, the selection procedure for size classes of the specimens to be considered for analysis was changed. From 1978 to 1986, the 30 specimens per target species and per station were distributed among six length classes, determined by the longest and shortest specimen of each species, following the form of a normal distribution curve (Messier *et al.*, 1985; Brouard, 1988), i.e.:

Length Class					
1	2	3	4	5	6
Shortest specimen + _____ + Longest specimen					
2	5	8	8	5	2
Number of specimens sought by class					

Since 1987, the number of specimens to be caught has been the same for each of the size classes in order to give them equal weight (Brouard *et al.*, 1987). This approach provides greater accuracy in establishing the mercury-length relationship and analyzing spatiotemporal variations, without invalidating the earlier results. In addition, it aims for a uniform distribution of lengths within a class. In the event that a given size class cannot be filled using the fish caught, further specimens are taken from the adjoining classes. The analysis of fishing yields from 1978 to 1984 (Brouard *et al.*, 1987) was used to establish predetermined length classes per species (Table 2.5).

2.2 Analytical determination

Prior to 1989, mercury analysis was always carried out on a homogenate of a whole fillet of each fish because it is a representative sample of the fish flesh consumed by Native and sport fishers. Thereafter, the analysis was done on a small sample of flesh only, since a study had shown that mercury levels measured in various parts of the fillet, i.e., the anterior, median and posterior portions, did not show any significant variation (Brouard *et al.*, 1990).

In addition, a flesh sample is a good indicator of how much mercury there is in the fish, since mercury levels in the flesh are always higher than those in the gonads, entrails or whole fish (section 3.7.5; GENIVAR and Hydro-Québec, 2004).

After they are received at the laboratory in charge of analysis, the fish samples are thawed before they undergo acid digestion, following the procedure developed by Environment Canada (NAQUADAT Method No. 80601-2). The samples are analyzed by Cold Vapor Atomic Absorption Spectrophotometry (CVAAS).

Table 2.5 Distribution of Number of Specimens to be Caught According to Species and Size Class

Species	Size class (mm)	Number per class
Longnose sucker walleye lake whitefish landlocked salmon	100-200	6
	200-300	6
	300- 400	6
	400-500	6
	500-600	6
Total		30
Dwarf lake whitefish	<150	5
	150-175	5
	175- 200	5
	200-225	5
	225-250	5
	> 250	5
Total		30
Northern pike	300-400	4
	400-500	4
	500-600	4
	600- 700	4
	700-800	4
	800-900	5
	900-1,000	5
Total		30
Lake trout	400-500	5
	500-600	5
	600 -700	5
	700-800	5
	800-900	5
	900-1,000	5
Total		30
Burbot	100-200	5
	200-300	5
	300-400	5
	400- 500	5
	500-600	5
	>600	5
Total		30
Cisco round whitefish	100-200	7
	200-300	8
	300-400	8
	400-500	7
Total		30
Brook trout	150-200	5
	200-250	5
	250- 300	5
	300-350	5
	350-400	5
	> 400	5
Total		30

Note: Standardized lengths are shown in bold. Values are 350 mm for landlocked salmon, 150 mm for cisco and 300 mm for round whitefish.

Additional methodological details are provided in Maxxam (2013). Depending on the year, the analyses were performed by five laboratories, all of which carefully applied the same procedure (Éco-Recherches, Laboratoire S.M., Analex inc., Philip Services Analytiques inc. or Maxxam). These independent laboratories were accredited by the Québec government to analyze total mercury. The changes in laboratory did not alter the results obtained for natural water bodies. Unless otherwise indicated, all results are expressed in mg of total mercury/kg of flesh (wet weight).

The various quality control procedures conducted at the analyzing laboratory are basically intended to evaluate analytic performance by studying aspects related to analytic precision (replicability and minimum detection limit) and reliability of results (repeatability, recovery, reproducibility and accuracy). A description of each of these parameters was supplied by the laboratories, including Maxxam (2013).

According to this report, the evaluation of analytic performance (relative to repeatability), which was determined using the different control procedures, helped establish an average coefficient of variation (standard deviation/mean x 100) of 3.4% to 17.2% from 1986 to 2008 (mean of 6.2 %) and 5.2% to 14.2% since 2007, based on control procedures used by the Food Analysis Performance Assessment Scheme (FAPAS; Sand Hutton, York, U.K.) (mean of 9.0%; 14.2% in 2012), which is acceptable. In regard to replicability, a coefficient of variation for accuracy of 3.1% to 7.6% was obtained for all samples from 1986 to 2012 (mean of 55%; 6.3% in 2012), which is good. For concentrations of less than 0.30 mg/kg, the coefficient of variation for accuracy varied from 3.1% to 7.3% from 1995 to 2012 (mean of 5.5%; 6.4% in 2012), which is very good.

The detection limit varied from 0.003 to 0.028 mg/kg from 1995 to 2012 (mean of 0.013 mg/kg; 0.011 mg/kg in 2012). The limit of quantification fell within the range of 0.011 to 0.084 mg/kg from 1995 to 2012 (mean of 0.044 mg/kg; 0.037 mg/kg in 2012). This limit, which is equivalent to three times the detection limit or ten times the standard deviation obtained from the measurement of one control sample, corresponds to the threshold beyond which the measured mercury values are less accurate and hard to interpret. Because the detection limit has been lower since 1997 than in earlier years (0.01 to 0.02 mg/kg vs. 0.05 mg/kg), a number of values below 0.05 mg/kg were obtained. Since this situation may skew the results relative to earlier years, the data below 0.05 mg/kg measured since 1998 was automatically considered to be at this threshold to make it comparable to the data from previous years. Therefore, the values obtained for the limit of quantification are valid.

Six quality controls, detailed by Analex (1995), were carried out daily on the samples analyzed from 1978 to 2010:

- Seven standards covering the optimum range of measurements were used to establish the calibration curve for calculating the results. This series of standards was analyzed every 20 samples.
- Three blanks (tests without fish flesh) were used to establish the base measurements.
- One blank without reagent was measured to monitor the reagents' level of mercury contamination (comparison with the previous three blanks).
- Two control samples, one of them certified, were analyzed in triplicate per block of 45 samples.
- One fish sample out of every 15 was analyzed in triplicate to determine the replicability of the analyses.
- Eight control samples—five certified standards and three internal controls—were analyzed repeatedly to evaluate the replicability, repeatability and reproducibility of the analyses.

Since 2011, the following eight controls have been used:

- Seven standards covering the optimum range of measurements are applied to establish the calibration curve for calculating the results. A batch of roughly 60 samples is analyzed per curve. Curve calibration is verified every 20 samples by analyzing a calibration verification standard.
- Every 20 samples, a method blank (i.e., a blank which contains the reagents used in the analysis and which undergoes the entire analysis process from pretreatment to measurement of mercury levels) is run to ensure that no contamination has been introduced during the analysis process. If a blank does not meet the acceptability criteria, the analysis of these 20 samples is redone.
- Every 20 samples, an instrument blank is run to ensure that no external (instrument) contamination has been introduced during the analysis process. If a blank does not meet the acceptability criteria, the analysis of these 20 samples is redone.
- One certified control sample per batch of roughly 60 samples is analyzed in triplicate to determine accuracy. If this certified control sample does not meet the confidence interval specified in the certificate, all of the analyses for this batch are redone.

- Two internal control samples per batch of roughly 60 samples are analyzed in triplicate. If these certified control samples do not meet the acceptability criterion (coefficient of variation $\leq 10\%$), all of the analyses for this batch are redone.
- Three fish control samples per batch of roughly 60 samples are analyzed in triplicate to determine the replicability of the analysis. If these certified control samples do not meet the acceptability criterion (coefficient of variation $\leq 10\%$), only the analysis of the control samples is redone.
- Complete validation of the method is carried out once every two years, including an evaluation of replicability, repeatability and reproducibility.
- Participation in a performance audit program by a recognized organization is required.

In addition to these controls, interlaboratory validation was conducted with Fisheries and Oceans Canada's Freshwater Institute in Winnipeg until 2006 and has been carried out with FAPAS since 2007. The reproducibility (or accuracy) of the results obtained from 1986 to 2008 averages 94% and that of the results obtained from FAPAS since 2007 is 104% (102.7% in 2012), which is acceptable. The accuracy reflects the precision of the results compared to those obtained by other laboratories, using interlaboratory controls and certified samples provided by the Canadian Food Inspection Agency (CFIA). No systematic trend or bias was identified in the analytic performance control results for the entire period covered. In addition, there was no significant difference in mean annual mercury levels in northern pike in the control lake (Lac Rond-de-Poêle) from 1984 to 2012, despite an accuracy range of 90% to 115%, depending on the sampling year.

All statistics relating to these evaluations of analytic performance are compiled in a report presented annually to Hydro-Québec by the analyzing laboratory, which details the sample-management method and control procedures along with the evaluation of analytic performance.

Further quality control is performed on blind triplicates sent to the laboratory without its knowledge (10% of samples). Note that variation coefficients of blind samples are very low, averaging 6.3% and ranging from 4.1% to 9.6% from 1990 to 2012 (9.6% in 2012). It should also be noted that the lowest mercury levels measured since the last decade help increase the average variation coefficient, since these same variations exert a proportionally greater influence on low values than on high ones. The results also undergo an additional verification by plotting mercury levels relative to fish length on scattergrams. This verification identifies any samples with abnormal values.

In such cases, or if the variation coefficients for the blind triplicates are too high (>10%), reanalysis is then requested. On average, about 2% of the analyses (2.4% in 2012) were redone.

2.3 Statistical approach

2.3.1 Comparisons

The study of the spatiotemporal evolution of mercury was conducted by calculating the mean mercury level for a specimen of standardized length, for various environments and sampling years. These standardized lengths, which correspond approximately to the catches' mean lengths, were determined as follows for the main species:

Longnose sucker	: 400 mm	Northern pike	: 700 mm
Lake whitefish	: 400 mm	Walleye	: 400 mm
Lake trout	: 600 mm	Burbot	: 500 mm
Cisco	: 150 mm	Dwarf lake whitefish	: 200 mm
Brook trout	: 300 mm	Landlocked salmon	: 350 mm
Lake sturgeon	: 700 mm	Round whitefish	: 300 mm

Two types of comparisons were made to address the questions arising from monitoring: temporal (interannual) comparisons carried out for the same reservoir (all stations combined) or individually per station, and spatial comparisons carried out for a group of stations.

For the temporal comparisons, the baseline for fish mercury levels under natural conditions was established using the data collected in a total of 35 natural lakes and rivers in the La Grande complex region, which were sampled between 1978 and 1994. This approach maximizes the available data, given the substantial variability in levels from one lake to the next. For the few lakes sampled more than once, only the most recent data from 1978 to 1994 was kept; this method is justified by the absence of a temporal trend in the mercury levels measured for each target species in these lakes. For dwarf lake whitefish, more recent (1999) data was used, however, since the dwarf populations were only identified in 1993.

For all species, separate baseline values were calculated for the East and West sectors because of the differences observed in the structure of their respective fish communities, as well as the significant differences observed between the mercury levels in lake whitefish in each sector.

The mean baseline value under natural conditions for each species in each sector was calculated by grouping together the fish in all natural water bodies in that sector, as if they all came from a single environment. Thus, this mean value does not take into account the variability in mercury levels from lake to lake. Furthermore, its confidence interval (95%) is very small because of the high number of fish. In order to better judge the extent of the phenomenon in modified water bodies, mercury levels estimated in fish of standardized length were also compared with the corresponding range of mean levels observed in natural lakes. Moreover, mercury levels are considered to have returned to levels equivalent to those measured under natural conditions when the mean level in a modified water body is no longer significantly different ($p < 0.05$) from that obtained in at least one natural lake in the same sector.

Since no distinction was made between normal and dwarf lake whitefish populations prior to 1993, the temporal comparisons conducted on normal lake whitefish in the East sector used only specimens longer than 300 mm for water bodies in which dwarf populations are present. Such a procedure avoids including dwarf specimens in the analysis of normal lake whitefish, as this could skew the results.

To standardize data analysis and result presentation, reservoir age was calculated starting from the first summer after impoundment, which corresponds to Year 0, or from the year of impoundment in cases where filling was rapid and only took a few weeks (i.e., Laforge 1 and La Grande 1 reservoirs). Year 0 for increased-flow environments corresponds to the commissioning of water control structures, while that of reduced-flow environments corresponds to the date when the rivers were cut off or their flow reduced.

2.3.2 Statistical procedure

The statistical procedure followed to describe spatiotemporal changes in fish mercury levels was optimized in 1995. Until 1993, the statistical approach used was based on linear regression, covariance analysis (ANCOVA) and the SNK multiple comparison test (Brouard *et al.*, 1987). This led to certain difficulties in applying the method, mainly for data obtained shortly after reservoir impoundment, which produces a marked increase in mercury accumulation rates in fish and thus changes the curve showing the relationship between mercury level and length. The use of linear regression, which is appropriate under natural conditions, often proved inadequate in these circumstances. Moreover, the conditions for using covariance analysis were no longer met in the early years after impoundment, particularly as regards equality of slopes of the linear regression models representing mercury levels as a function of length. It was therefore no longer possible to statistically compare the mercury accumulation rate before and after impoundment. The use of the SNK multiple comparison test was also inadequate when mean fish length varied from one year to the next, as often happens soon after impoundment.

Polynomial regression analysis with indicator variables (Tremblay *et al.*, 1997), which eliminates the above-mentioned limitations, was adopted in 1995. This method allows for a statistical comparison of relationships that differ in terms of their shape (linear or curvilinear) and their position on a graph representing mercury levels as a function of fish length. It also makes it possible to statistically compare estimated mean mercury levels for a standardized length rather than mean levels for fish of all lengths.

The details of the statistical approach used, based on polynomial regression with indicator variables, are presented in a separate report (Tremblay and Doyon, 1996) which describes all stages of application and interpretation. This method was used to reanalyze the data obtained prior to 1995 in order to provide a careful analysis of all data available since monitoring began.

The conditions for applying polynomial regression with indicator variables, i.e., normality of residuals and homogeneity of variances (homoscedasticity), were verified for each analysis conducted, by a visual examination of the appropriate graphs, as illustrated in Tremblay *et al.* (1996). Moreover, this method is moderately robust to deviations from normality of data and homogeneity of variances, and is much less restrictive than covariance analysis in terms of the conditions for its use.

In addition, the Box-Cox Bartlett method was used to determine the best transformations to apply to the data in order to meet the conditions for employing polynomial regression with indicator variables. Use of this method revealed that logarithmic and square root transformations were generally the most suitable. In accordance with this observation, whichever transformation was better for each species was used throughout the analyses, i.e.:

Lake whitefish	: Logarithmic	Brook trout	: Square root
Northern pike	: Square root	Lake trout	: Logarithmic
Longnose sucker:	Square root	Walleye	: Raw data
Cisco	: Square root	Burbot	: Square root
Lake sturgeon	: Logarithmic	Landlocked salmon:	Square root

Polynomial regression with indicator variables essentially consists in defining an equation (also referred to as a model) that allows the mercury level to be estimated on the basis of a polynomial of fish length.

Length was chosen over any other fish characteristic because it is directly measurable by the prospective consumer when the fish is caught and, up to a certain point, it expresses specimen growth and age. This polynomial takes the following form:

$$[\text{Hg}] = C + (K_1 \times \text{length}) + (K_2 \times \text{length}^2) + \dots + (K_n \times \text{length}^n)$$

where C = a constant

and K_1 to K_n = the coefficient for each term.

Using the model, sub-equations are produced for each group (year or station) that differs from the model. A mean mercury level is thus estimated for each group at a standardized length. Different letters are assigned when the confidence intervals for the estimated mean level do not overlap, indicating significant differences at the 95% level of probability.

Note that the mean levels obtained for the same environment and the same year may vary slightly (2nd decimal) from one analysis to the next, depending on the database used. For example, for 700-mm northern pike at Gavaudan station in La Grande 3 reservoir, a mean mercury level of 0.97 mg/kg was obtained in 2012 in the temporal analysis of that station, which compared the mean levels from each sampling year from 1986 to 2012; however, a mean level of 0.96 mg/kg was obtained at the same station in the spatial analysis that compared the two stations in the reservoir in 2012. Since the groups of data used differ from one analysis to another, the estimated mean level may vary slightly. However, this variation is not significant and does not affect interpretation of the results.

2.4 Risk management

This section describes the manner in which Hydro-Québec has managed the potential health risk posed to anglers and subsistence fishers by the temporary increase in fish mercury levels in water bodies modified by development of the La Grande complex. Risk management comprises three parts:

- Search for mitigation measures that prevent or reduce the increase in fish mercury levels caused by reservoir impoundment
- Apply compensation measures to enable the Crees to pursue their traditional activities while limiting their exposure to mercury
- Produce fish consumption guidelines so that anglers and subsistence fishers may continue to enjoy the health benefits of eating fish on a regular basis while avoiding any mercury-related effects

2.4.1 Search for mitigation measures

Under the *Mercury Agreement* (1986), a critical review of the mitigation measures identified in the scientific literature was produced by Sbeghen (1995) and Sbeghen and Schetagne (1995), based mainly on the summaries by Roy (1984), Laperle and Schetagne (1988) and Groupe Roche (1993).

These measures can be grouped into three categories: reducing sources of mercury (by clearing land, stripping forest soils, etc.), reducing the bioavailability and production of methylmercury (through such means as liming and maintaining suspended solids) and reducing the bioaccumulation of mercury by fish (through the addition of selenium and intensive fishing, for example). All of these measures, which are described in detail in Schetagne *et al.* (2002), were rejected. Following the critical review, the Environment Subcommittee set up under the *Mercury Agreement* concluded that no mitigation measures at source could be recommended, for the following reasons: unknown effectiveness, possibility of side effects on aquatic wildlife, and technical and economic unfeasibility. Subsequently, as part of Hydro-Québec's corporate mercury research program, a more in-depth evaluation was conducted of three potential measures: intensive fishing, the controlled burning of organic material (vegetation and forest cover) and the addition of selenium.

The study by Surette *et al.* (2004) revealed that intensive fishing which, under certain conditions, can reduce mercury levels in some species of fish in natural lakes, is not effective in a reservoir because the fishing effort is too high (nearly 80% of the fish biomass is removed). The main method of reducing mercury levels would be to increase the growth rate of fish; however, fish mercury levels in the La Grande complex reservoirs was found to have increased by a factor of 3 to 7 despite a marked increase in their growth rate. Therefore, this measure is not suitable for hydroelectric reservoirs.

In regard to controlled burns, an experiment conducted by Mailman *et al.* (2006) on burning organic material (vegetation and plant cover) produced inconclusive results. Use of this measure cannot be recommended on a large scale because of the risk of losing control of the fire. The authors of the study also detected significant greenhouse gas emissions.

Hydro-Québec conducted studies on the use of selenium in cooperation with Fisheries and Oceans Canada's Freshwater Institute (Mailman, 2008). Although feasible from a technological and economic point of view (Noisel *et al.*, in preparation), this measure cannot be considered at this time because of constraints related to acceptability at the environmental, social and government levels.

2.4.2 Implementation of compensation measures

In view of the impossibility of applying mitigation measures to reduce mercury levels at source, the James Bay Mercury Committee, which oversaw the *Mercury Agreement (1986)*, proposed a new approach in 1989 aimed instead at reorienting traditional food harvesting activities in order to reduce exposure to mercury and the associated health risk. The approach advocated harvesting fish and other wildlife with low mercury levels. In some cases, subsidies were provided to fund fishing, while in others, habitat improvements were made or studies conducted to promote the harvesting or production of fish and wildlife resources. These measures are described in detail in Tremblay and Langlois (1996) and summarized in Schetagne *et al.* (2002).

Under the renewed version of the first mercury agreement, i.e., the *Mercury Agreement (2001)*, a special program was implemented with the main objective of developing and restoring the Cree fisheries through measures such as providing access to replacement fishing sites, funding community fisheries, stocking fish, evaluating fish stocks and encouraging fishing (Niskamoon Corporation, 2008).

2.4.3 Production of fish consumption guidelines

With a view to reducing the health risk and enabling fishers to continue enjoying the health benefits of eating fish, a number of fish consumption guidelines were produced in cooperation with local public health authorities. Producing the guidelines involved the following steps: establishing the recommended exposure level based on mercury toxicity thresholds in humans, determining average fish consumption lengths, predicting the maximum mercury levels that would be reached in fish of these lengths, validating the maximum levels reached, calculating the recommended number of meals per month and developing a format for the fish consumption guidelines.

2.4.3.1 Recommended exposure level and tolerable daily intake

A review of a number of studies on methylmercury toxicity made it possible to establish the relationship between methylmercury intake and its effect on adults and fetuses, as shown in Table 2.6 (Hydro-Québec, 2007b).

Table 2.6 Correspondence between Hair Mercury Concentrations and Health Effects Observed

Hair concentration (ppm)	Health effects observed	
< 10	Adult:	No effect observed.
	Fetus:	No effect observed.
10 to 15	Adult:	No effect observed.
	Fetus:	Approximate threshold at which symptoms could begin to appear in a child's development (e.g., in the results of psychomotor tests), according to various health authorities.
15 to 50	Adult:	Specialized tests revealed some slight effects on physical coordination in individuals who had been exposed to mercury concentrations for a period of years.
	Fetus:	Concentrations of 15 ppm or more are likely to affect the normal development of a child (stunted growth and developmental delays).
50 to 250	Adult:	Slight effects on the nervous systems of the most sensitive individuals.*
	Fetus:	Increased risk of developmental delays in children.
250 to 1,500	Adult:	Tremors, problems with muscle coordination, difficulty in speaking, impaired hearing and vision.
	Fetus:	High risk of congenital defects and death of the fetus during pregnancy.

* The available data establishes the appearance of the first symptoms at concentrations of about 125 ppm in hair; statistical tests showed that these symptoms would begin to appear at concentrations of 50 ppm in 5% of the most sensitive individuals.

In its latest review in 2004, the World Health Organization (WHO) set the tolerable daily intake (TDI) of methylmercury as a function of an exposure threshold of 14 ppm in the mother's hair in order to protect the fetus. The WHO believes that this level of exposure will have "no adverse effects" on the development of the fetus or the child. To ensure that most individuals would stay within this threshold of 14 ppm, the WHO first calculated the corresponding daily intake. The model used predicted that the daily intake is 1.5 µg of methylmercury per kilogram of body weight. Then, to take into account individual metabolic variations, an uncertainty factor of 6.4 was applied. This factor was arrived at by multiplying the variability in the assimilation rate of methylmercury from one individual to another by the rate of transfer between the blood and hair, which can also vary from person to person. The daily intake (1.5 µg/kg of body weight) divided by the uncertainty factor (6.4) resulted in a TDI of 0.23 µg/kg/d of methylmercury.

This exposure limit was established to protect the fetus and the child, who are considered most sensitive to the effects of mercury (WHO, 2004), and set the threshold at about 2 ppm in the mother's hair. For other adults, the WHO considers that intakes of up to twice the TDI, or as much as 0.46 µg of mercury per kilogram of body weight, would not pose any risk of neurological effects. This is in keeping with the previous recommendation calculated on the basis of an exposure threshold of 50 ppm in hair, which corresponds to a daily ingestion rate of 3.3 µg/kg for a body weight of 60 kg. An arbitrary safety factor of 7 (adjustment between daily and weekly intake) was then applied, which led to a TDI of 0.47 µg/kg/d (WHO, 1972 and 1990).

Health Canada and Québec's department of health and social services both recommend a TDI of 0.47 µg/kg/d of methylmercury, which sets the exposure threshold at 5 to 7 ppm in hair. However, Health Canada has proposed that a TDI of 0.2 µg/kg be adopted for women of childbearing age as well as for children, since fetuses and young children are very sensitive to methylmercury.

The fish consumption guidelines for the La Grande complex are based on the TDIs recommended by Health Canada and set the hair mercury exposure threshold at 5 to 7 ppm for adults and at about 2 ppm for women who are pregnant or may become pregnant and for children under 13 years of age.

2.4.3.2 Calculation of consumption lengths

Since mercury levels increase with the size of the fish, consumption guidelines are calculated on the basis of the average length of each species of fish eaten by anglers and subsistence fishers. It takes about one year for an individual's exposure to mercury to stabilize, considering the stability of mercury levels in the fish consumed, the quantity of fish consumed per meal and consumption frequency. Thus, despite the wide variations in mercury levels in fish of a given species, it is believed that over the course of a full year, a fisher will have accumulated a quantity of mercury equivalent to the mean mercury level present in the average-length fish consumed.

The average consumption lengths for the main fish species were determined on the basis of catch data registered during communal fishing carried out from 2003 to 2011 by the different Cree communities (Table 2.7), as well as harvesting data provided by the Cree Regional Authority (CRA) in 1986 (James Bay Mercury Committee, 1998).

The average consumption lengths established in cooperation with the CBHSSJB are 300 mm for brook trout, 500 mm for lake whitefish, suckers (white and longnose), walleye and burbot, 600 mm for lake trout, 800 mm for northern pike and 900 mm for lake sturgeon. The consumption guidelines calculated using these average lengths are very safe for sport anglers, as the Crees use coarse-mesh nets for communal fishing and generally catch fish that are bigger than the average-sized catches taken by anglers. For instance, the average lengths of northern pike caught by anglers in water bodies around the periphery of Eastmain 1 reservoir varied between 700 mm (in 2009) and 725 mm (in 2007) (Waska Ressources, 2010), whereas the established average consumption length was 800 mm. This difference in length also results in a significant difference in mean mercury levels; for example, the difference in northern pike in Robert-Bourassa reservoir in 2012 was 1.61 mg/kg at 700 mm vs. 2.02 mg/kg at 800 mm.

2.4.3.3 Prediction and validation of maximum levels reached

In newly created hydroelectric reservoirs, where fish mercury levels increase rapidly during the first few years after impoundment, peak and then gradually return to initial values, fish consumption guidelines are calculated using the maximum levels predicted during the impact assessment phase, but validated on the basis of the first monitoring results. This method makes it possible to avoid issuing different guidelines for several successive years during the period when mercury levels are changing rapidly, which would be confusing to consumers. Thus, the fish consumption guidelines remain valid and safe for a long period of time. They can then be adjusted once mercury levels have begun to return to initial values, thus allowing for more frequent consumption.

Prediction models

Over the years, a number of models for predicting fish mercury levels in hydroelectric reservoirs have been used to estimate the maximum levels that will be reached and the period during which additional restrictions will be placed on fish consumption. These models are briefly described in the paragraphs below.

Semi-empirical model

During Phase I, following construction of the La Grande complex reservoirs and after regular monitoring of fish mercury levels in modified water bodies had begun, SEBJ developed a model for predicting mercury levels in reservoir fish (Messier *et al.*, 1985).

Table 2.7 Average Lengths of Cree Fishery Catches from 2003 to 2011 Compared to Catches in 1986

Community	Lake whitefish		Northern pike		Walleye		Sucker		Lake trout		Lake sturgeon		Brook trout		Burbot	
	n	Average length (inches)	n	Average length (inches)	n	Average length (inches)	n	Average length (inches)	n	Average length (inches)	n	Average length (inches)	n	Average length (inches)	n	Average length (inches)
Wemindji (2003–2011)	982	17.9	341	34.2	800	18.4	206	19.4	12	19.7	324	43.5				
Chisasibi (2006–2011)	533	17.8	197	30.3	171	20.8	429	18.7	156	23.8			75	14.6		
Mistissini (2008–2010)	154	19.7	97	29.7	69	20.5	164	19.7	752	23.2			6	17.0	22	24.9
Nemaska (2008–2010)	318	18.6	261	35.0	339	20.4	285	21.3	31	29.3	41	40.4	3	21.3	4	25.3
Oujé-Bougoumou (2010)	37	17.1	13	28.9	15	20.7			17	26.4			4	17.5		
Waswanipi (2008–2010)	28	17.4	97	26.1	72	19.0	52	17.6			81	38.1				
Whapmagoostui (2008)	130	19.0	32	32.9			166	17.1	213	25.7			20	14.5	1	31.0
Global data 2003–2011																
Average length (inches)	2,182	18.2	1,038	32.4	1,466	19.3	1,302	19.3	1,181	23.9	446	42.2	108	15.0	27	25.2
Average length (mm)		461		822		490		489		608		1072		380		640
Fishing data from 1986																
Average length (inches)		20		28		20		16 - 20		24	38.1	28 - 36		12		
Average length (mm)		500		700		500		400 - 500		600	43.5	700 - 900		300		500
Average length used (mm)		500		800		500		500		600		900		300		500

References: James Bay Mercury Committee, 1998; Alliance Environnement inc., 2004; Lessard, 2006, 2007a, b and c, 2008a, b and c, 2009, 2010a-h, 2011a-e, 2012a, b and c.

This semi-empirical model, which is based on the phosphorus release model of Grimard and Jones (1982), uses the phosphorus release curve generated by the Grimard and Jones model as an indicator of the decomposition intensity of organic material, and this, in turn, reflects mercury availability for fish. It was calibrated using fish mercury levels recorded during the 1981, 1982 and 1984 monitoring surveys.

The model was used to predict changes in mercury levels in two species of fish in Robert-Bourassa and Opinaca reservoirs. Lake whitefish (non-piscivorous) and northern pike (piscivorous) were selected because of their abundance and their distribution throughout the region. The model is described in detail in Schetagne *et al.* (2002).

A second version of the SEBJ model was produced in 1992 in order to factor in new information obtained from monitoring of the La Grande complex (Hydro-Québec, 1993). Here, the mercury transfer rate from non-piscivorous fish to piscivorous fish was changed to account for the presence or absence in the reservoir of a "superpredator" behavior, in which piscivorous fish (particularly northern pike) regularly feed on other piscivorous fish. In Robert-Bourassa reservoir, analyses of fish stomach contents revealed that a few years after impoundment, northern pike were feeding on a wide variety of prey and that about 60% of their diet consisted of piscivorous fish, i.e., northern pike, walleye and burbot (Doyon *et al.*, 1996). Consequently, in reservoirs where they feed mainly on other piscivorous fish (Robert-Bourassa, Opinaca and La Grande 3), northern pike reach higher mercury levels than in reservoirs such as Caniapiscau, where they mostly feed on non-piscivorous fish.

Semi-mechanistic model

Starting in the 1990s, a semi-mechanistic model was gradually developed using the monitoring data collected in the three main reservoirs of the La Grande complex, i.e., Robert-Bourassa, Opinaca and Caniapiscau (Thérien, 2001a and b, 2005, 2006, 2010). This more complex model (HQHG) uses the following main physical and biological factors that play a role in methylmercury production and bioaccumulation:

- Physical characteristics (including water temperature) and reservoir water-level fluctuation curves
- Plant biomass (or phytomass) of the main readily decomposable components of flooded forest environments
- The above components' rates of decomposition and mercury methylation obtained through laboratory experiments under different pH, temperature and dissolved oxygen conditions

- Bioenergetic parameters of the fish species studied
- Rates of growth and methylmercury accumulation of the fish
- Diet and mercury levels of the main prey of the fish

This model uses sub-models developed for natural environments, i.e., the bioenergetic model developed by the University of Wisconsin (1997) and the mercury bioaccumulation model of Norstrom *et al.* (1976) and Rodgers (1993, 1994 and 1996). The HQHG model uses the reservoir mercury levels estimated by the HQEAU model based on the vast quantity of data from the La Grande complex EMN (Schetagne *et al.*, 2004; Thérien, 2005 and 2006). However, the HQHG model remains semi-empirical, since some of the elements that cannot be modelled, such as the diet of the fish after impoundment, must still be specified.

The HQHG model was used first in the Environmental Impact Assessment (EIA) conducted for the Eastmain-1-A and Sarcelle powerhouses and Rupert diversion project and again in the EIA carried out for the Romaine complex.

Validation of maximum levels reached

Before they can be used to produce fish consumption guidelines, the maximum mercury levels predicted by the models must be validated by the mean mercury levels of the main species of consumed fish measured during the first monitoring surveys. This validation makes it possible to verify whether the curve of values estimated by the model is in keeping with the measurements and to make any required adjustments to the predicted maximum mercury levels. For example, the mercury levels measured four and six years after the impoundment of Eastmain 1 reservoir made it possible to validate the maximum levels estimated for fish in this reservoir and adjust those predicted for Opinaca reservoir, located downstream of Eastmain 1 (Therrien and Schetagne, 2012).

The monitoring of reservoirs after impoundment must be carefully planned. On the one hand, researchers must give consumption-sized fish enough time for mercury to accumulate in order to ascertain whether the increase in mercury levels is significant; on the other hand, they must not wait too long, lest mercury exposure in people who consume a lot of fish reach levels that exceed those deemed safe by public health authorities before fish consumption guidelines can be disseminated. Conducting an initial survey during the third or fourth year after impoundment usually helps to adequately validate the predicted maximum mercury levels and produce fish consumption guidelines within an acceptable timeframe, if necessary.

2.4.3.4 Calculating the recommended number of meals per month

Based on the mean mercury levels in different species of fish and different environments, public health authorities calculate the maximum number of meals per month that can be consumed without exceeding the recommended mercury exposure level to avoid any mercury-related health risk. As previously stated in section 2.4.3.1, the exposure level established by public health authorities in the Baie-James region, i.e., the CBHSSJB for the Crees and the CRSSSBJ [Baie-James regional health and social services centre] for other Jamesian residents, is generally 5 to 7 ppm in the hair of adults, whether Cree or non-Cree. Specific guidelines apply to women who are pregnant or may become pregnant and to children under 13 years of age.

The guidelines can be qualitative (i.e., unrestricted consumption, regular consumption, occasional consumption, consumption not recommended) or quantitative (number of meals per month), depending on the particular public health authority's preference. Until recently, the CCSSSBJ preferred to issue qualitative recommendations, which are easier to follow, whereas the Guide de consommation du poisson de pêche sportive en eau douce au Québec [Québec guide for the consumption of freshwater fish from sportfishing] issues quantitative consumption guidelines.

Table 2.8 shows the equivalences between fish mercury levels and the adult consumption guidelines. The calculations take the following into consideration:

- Mean mercury levels in the fish
- A 230-g portion of fresh fish (uncooked)
- Tolerable daily intake (TDI) of 0.47 µg of mercury per kilogram of body weight
- A body weight of 60 kg

Table 2.8 Equivalence between Fish Mercury Levels and Adult Consumption Guidelines

Fish mercury level (mg/kg)	Quantitative recommendation (number of meals per month)	Qualitative recommendation
≤ 0.29	> 12	Unrestricted consumption
0.30 to 0.49	8	Regular consumption
0.50 to 0.99	4	Occasional consumption
1.00 to 1.99	2	Occasional consumption
2.00 to 3.75	1	Consumption not recommended
> 3.75	< 1	Consumption not recommended

A fish in a given environment with an average mercury level of 0.29 mg/kg or lower can be eaten more than 12 times per month, which is considered "unrestricted," based on general consumption habits. When the mean mercury level ranges from 0.30 to 0.49 mg/kg, a maximum of eight meals per month is recommended. Similarly, no more than four meals per month are recommended if the mean fish mercury level is between 0.50 and 0.99 mg/kg, and a maximum of two meals per month is recommended at an average level of 1 to 1.99 mg/kg. Lastly, the consumption of fish with an average mercury level of over 2 mg/kg is not recommended by the CCSSBJ. With a view to making these guidelines easier to follow, the CCSSBJ recommends regular consumption when the mercury levels in a fish allow for eight meals per month and occasional consumption when mercury levels allow for two to four meals per month.

2.4.3.5 Development of fish consumption guidelines

Several types of fish consumption guidelines have been produced over the years. Under the *Mercury Agreement (1986)*, a pamphlet was produced in the early 1990s and a brochure entitled *Mercure – Questions et réponses* [mercury – questions and answers] was published in 1995 by the James Bay Mercury Committee (Noël and Sbeghen, 1995). These publications provided general guidelines for natural and modified environments in the La Grande complex region. Subsequently, Volume 2 of the 1998 summary report on changes in fish mercury levels in the La Grande complex included a series of five maps showing the mercury levels measured in 1996 for the different species of fish in the natural and developed water bodies of the complex, as well as three categories of consumption guidelines, which were color-coded by fish mercury level (James Bay Mercury Committee, 1998).

In 2001, during the period between the end of the *Mercury Agreement (1986)* and the signing of the *Mercury Agreement (2001)* in February 2002, two fish consumption guides were jointly produced in map form by the public health research unit of the Université Laval hospital (CHUL) and Hydro-Québec Production (Hydro-Québec and CHUL, 2001a and b). The first publication dealt with the water bodies in the La Grande complex and the Grande and Petite rivière de la Baleine areas, while the second covered water bodies in the Nottaway, Broadback and Rupert river areas. To comply with the Québec guide for the consumption of freshwater fish from sportfishing and the guide issued by CHUL, the recommendations included in these guides fell into five quantitative categories in accordance with the first five color codes shown in Table 2.8. Both guides provided the fish mercury levels measured in 1999 and 2000 in developed environments.

In 2004, a new type of guide—the Northern Fish Nutrition Guide – La Grande Complex—was jointly produced by CHUL, the Centre hospitalier universitaire de Québec (CHUQ) [Québec university hospital], Hydro-Québec Production, the Eeyou Namess Corporation (the authority responsible for application of the *Mercury Agreement (2001)*), the Cree Outfitting and Tourism Association (COTA) and the CBHSSJB. Since fish mercury levels in the reservoirs built during Phase I of the La Grande complex were already returning to pre-impoundment values that allow for the consumption of a higher number of meals per month, the new guide focused on the health benefits of eating fish, but also provided qualitative consumption guidelines, in accordance with the four simplified consumption categories shown in Table 2.8.

A number of information tools concerning mercury and fish consumption, such as the "Fish Facts for Families" pamphlet and the poster entitled "Healthy Fish Eating in Eeyou Istchee" (Hydro-Québec *et al.*, 2013) were also produced by the CBHSSJB in the 2000s.

In response to Condition 6.4 of the Certificate of Authorization issued by the MDDEP for the Eastmain-1-A and Sarcelle powerhouses and Rupert diversion project, an evaluation of the effectiveness of the information tools on mercury and fish consumption was carried out in 2010 (GENIVAR and Waska Ressources, 2013). By means of a questionnaire and discussion groups, in which 446 Crees and 175 other Jamesians participated, five different tools were evaluated: the Northern Fish Nutrition Guide – La Grande Complex, the fish consumption guide for water bodies in the La Grande complex and the Grande and Petite rivière de la Baleine areas, the fish consumption guide for the water bodies in the Nottaway, Broadback and Rupert areas, the "Fish Facts for Families" pamphlet and "Healthy Fish Eating in Eeyou Istchee" poster. All of these tools were evaluated for readability and compliance with the guidelines provided, as well as for strong points and elements that required improvement. The revised food guide published and distributed in June 2013 includes the recommendations resulting from this evaluation. The revised guide, i.e., the Northern Fish Nutrition Guide – Baie-James Region, is provided in section 4.2.

2.5 Complementary studies

While fish mercury levels were being monitored, a number of complementary studies were being carried out. The purpose of these studies was to better understand the mechanisms that led to the observations made during monitoring, to provide the input required to develop the fish mercury prediction models, and to obtain information that would allow for better management of the health risk. The main studies focused on the following:

- Distinction between dwarf and normal lake whitefish populations
- Mercury in small fish species
- Diet of the main fish species
- Entrainment of fish from reservoirs to areas downstream of the generating stations
- Proportion of methylmercury in total mercury content of different fish parts
- Levels of the main nutrients in fish flesh, including Omega-3 fatty acids

Only the last two studies used analysis methods that differed from that used to monitor fish mercury. These methods are described in detail in GENIVAR and Hydro-Québec, 2004, Therrien and Schetagne, 2001a and Lucas *et al.*, 2003.

The main findings of the complementary studies are provided in section 3.7.

3. RESULTS

The topics addressed in this chapter are covered in the following order: natural environments, reservoirs, areas immediately downstream of reservoirs, diversions, reduced-flow rivers, the Grande Rivière estuary and the east coast of Baie James, and complementary studies.

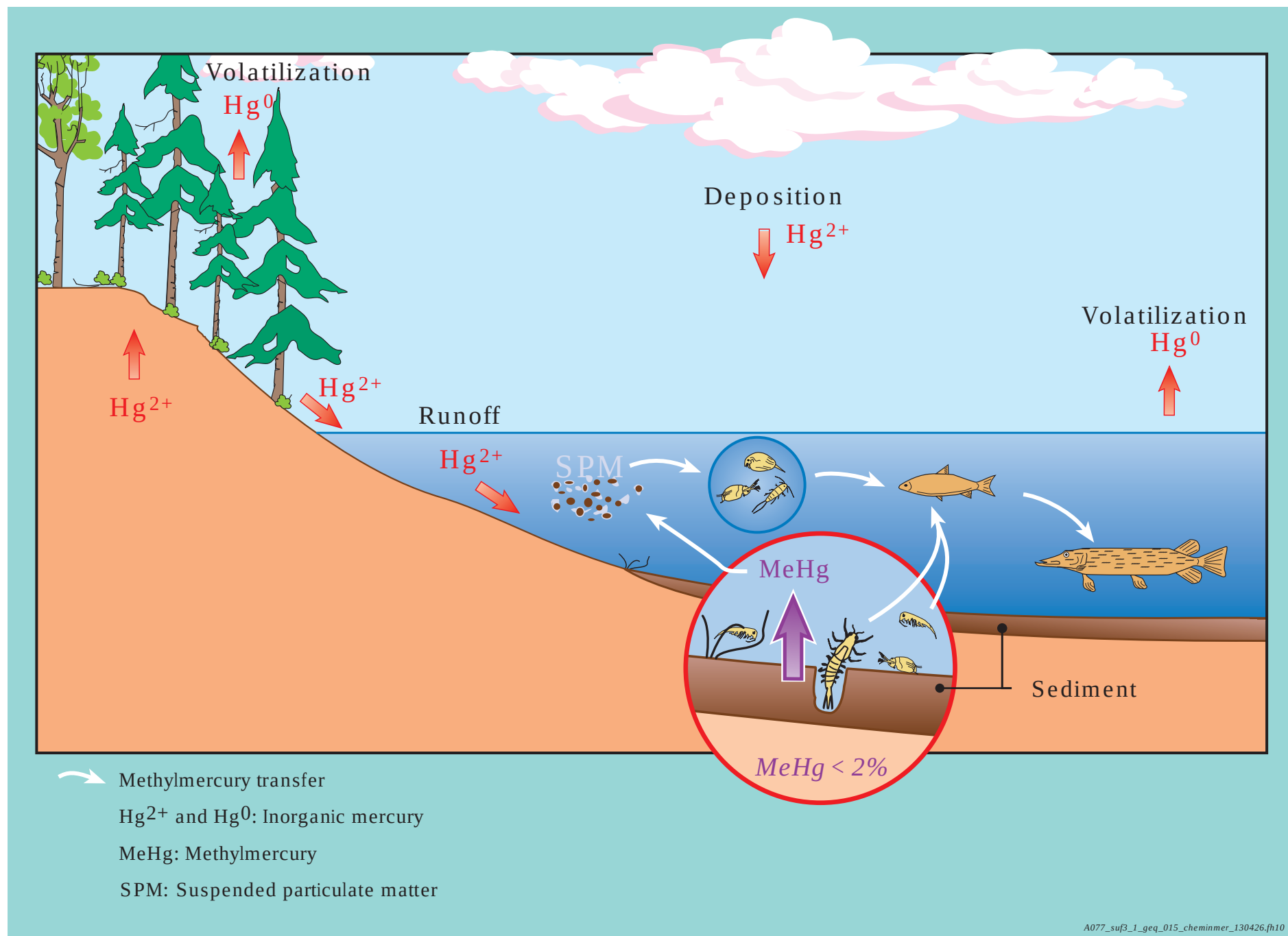
3.1 Natural environments

3.1.1 Fate of mercury in natural ecosystems in northern Québec

Inorganic mercury is found everywhere in the environment. It is in the air, vegetation and forest soil, as well as in lakes and rivers. In lake ecosystems, sediments are the main sink for mercury (Lucotte *et al.*, 1999b). It can be emitted into the air naturally or as the result of human activities such as coal combustion and waste incineration. In northern Québec, it comes mainly from transport through the atmosphere over long distances and falls into lakes and forests with dry deposition and rain. Natural airborne mercury has gradually accumulated in organic layers of soil since they began to form after the last ice age. Airborne anthropogenic mercury has been accumulating in the soil in northern Québec since the beginning of the industrial age at the end of the 19th century. Since then, atmospheric deposits of mercury in the region have doubled or tripled (Lucotte *et al.*, 1995). Between the 45th and 54th parallels, where the La Grande complex is located, airborne mercury probably comes from the industrialized Great Lakes region (Lucotte *et al.*, 1999b).

Inorganic mercury is relatively harmless, because it is not readily assimilated by living beings. Once in the lakes, rivers and reservoirs, however, it is converted by bacteria into an organic form, methylmercury, which can be easily assimilated by living organisms because of its great affinity for proteins and its low elimination rate, particularly in cold-blooded animals like fish. Methylmercury is absorbed by the plankton in the water, as well as by aquatic insects that live in mud or on aquatic vegetation. Through a process called biomagnification, the concentration of methylmercury increases as it passes through the food chain, from plankton to fish. Non-piscivorous fish such as suckers and lake whitefish contain less mercury than piscivorous species like northern pike, walleye and lake trout. Thus, although only a small fraction of the total inorganic mercury load in a lake is converted into methylmercury, its biomagnification along the food chain is such that an increase factor of about 150 can be observed between mercury concentrations in plankton at a low trophic level and concentrations recorded in large piscivorous fish (Lucotte *et al.*, 1999a). Figure 3.1 illustrates this process.

Figure 3.1 Fate of Mercury in Natural Lakes



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3.1.2 Mercury levels in fish in natural environments in the La Grande complex

3.1.2.1 Variability within a natural environment

There are wide variations in mercury levels measured in fish of the same species, of the same length and in the same environment. For example, in 1991, the mercury levels in lake trout about 750 mm long varied by a factor of 4 (between 0.59 and 2.46 mg/kg) in Lac Jobert (Figure 3.2). This may be due to differences in growth or different feeding habits between specimens.

3.1.2.2 Spatial variability between natural environments

In most fish species, there is little difference in mercury levels between the West and East sectors (Table 3.1). Note that the water quality in these two sectors is very similar, especially in regard to the parameters related to organic matter content. Only the levels in lake whitefish were found to be significantly higher in the East sector. Although the result obtained for 600-mm lake trout also indicates significantly higher levels for the East sector, the levels obtained for lengths of 400, 500 or 700 mm do not reveal any significant difference between the two sectors.

Figure 3.2 **Distribution of Mercury Levels Measured in Lake Trout in Lac Jobert in 1991**

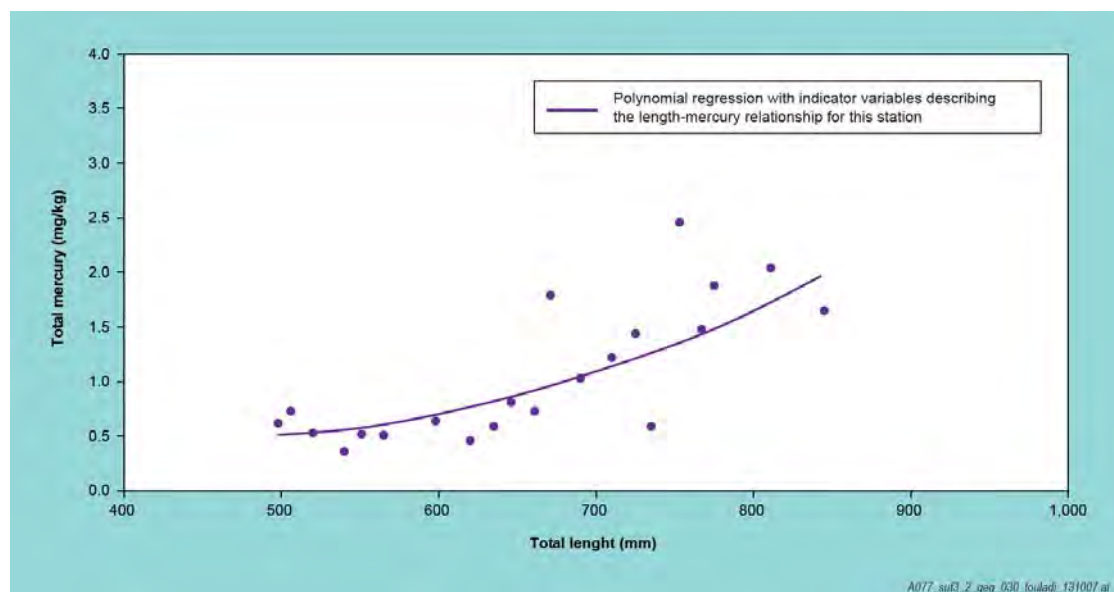


Table 3.1 Range of Mean Mercury Levels for Standardized Lengths of Main Fish Species in Natural Lakes in the West and East Sectors of the La Grande Complex

Species (Standardized length)	West sector				East sector			
	Number of fish	Number of lakes	Range of mean levels (mg/kg)	Mean total level (mg/kg)	Number of fish	Number of lakes	Range of mean levels (mg/kg)	Mean total level (mg/kg)
Lake whitefish (400 mm)	503	21	0.05 - 0.20	0.11	187	8	0.10 - 0.30	0.17
Longnose sucker (400 mm)	182	7	0.12 - 0.22	0.12	246	9	0.06 - 0.20	0.12
Northern pike (700 mm)	373	18	0.30 - 0.93	0.59	120	4	0.36 - 0.92	0.55
Walleye (400 mm)	353	13	0.30 - 1.02	0.60				
Lake trout (600 mm)	131	7	0.23 - 0.89	0.57	254	10	0.52 - 1.11	0.74
Lake trout (700 mm) ^a					254	10	0.71 - 1.44	0.93
Cisco (150 mm)	89	2 ^b	0.08 - 0.30	0.11				
Cisco (300 mm) ^c	368	6	0.09 - 0.13	0.10				
Dwarf lake whitefish (200 mm) ^d					43	2	0.17 - 0.29	0.21
Burbot (500 mm) ^e	181	5	0.49 - 0.74	0.64	181	5	0.49 - 0.74	0.64
Lake sturgeon (700 mm)	186	11	0.03 - 0.40	0.25				

a Different standardized length since 1999 owing to the absence of small specimens in modified environments at the La Grande complex.

b To increase the numbers, two different years were used for one of the two lakes. The distribution is: 1990 (n=10) and 1994 (n=39) for Lac Rond-de-Poêle (EA 302), and 1994 (n=40) for Lac Detchevery (SB 400).

c Different standardized length for the east coast of Baie James.

d The range is provided as an indication, since spatial analysis could only be carried out in two lakes.

e The two sectors are grouped together to provide the mean total level. The range was obtained from a small number of natural lakes and is only provided as an indication.

For burbot, the mean mercury level (0.64 mg/kg at a length of 500 mm) was obtained for all natural lakes in the East and West sectors combined because of the very low numbers of burbot there, particularly in the East sector. The range of mean levels obtained in natural lakes (0.49 to 0.74 mg/kg) is only provided as an indication, as there is little available data for this species.

For normal lake whitefish (400 mm), the higher mean levels in lakes in the East sector (maximum of 0.30 mg/kg) compared with those in the West sector (maximum of 0.20 mg/kg) seem to be due to the ingestion of prey containing higher mercury levels. The methylmercury and total mercury levels measured in plankton and benthic invertebrates eaten by lake whitefish are indeed two to four times higher in East sector lakes than in West sector lakes (Doyon *et al.*, 1996). These levels do not explain, however, why this east-west trend was not observed in the mean mercury levels in longnose sucker.

However, there is considerable spatial variability within the two sectors. Estimated mean levels for standardized lengths often vary significantly (by as much as a factor of 4) from one lake to another. For example, mean levels in 400-mm walleye range from 0.30 to 1.02 mg/kg for different lakes in the West sector, but only from 0.05 to 0.20 mg/kg in 400-mm lake whitefish. However, there does not appear to be any particular geographic trend. The same is true for longnose sucker, walleye and lake trout. Note that the spatial variability in fish mercury levels in natural lakes in the La Grande complex can be described using all the data collected since monitoring began, even though some of the lakes were not sampled the same year because of the absence of a temporal trend in mercury levels (Section 3.1.2.4).

Mercury levels in these natural environments, where there are no direct sources of mercury, seem to vary mostly on the basis of the physicochemical properties of the water bodies, particularly their organic matter content. A study of water quality in the Nottaway, Broadback and Rupert watersheds (SOMER inc., 1994), in which the main physical and chemical data were analyzed by principal component analysis, revealed the presence of five types of water. Type A water, from Lac Mistassini and the main stem of the Rupert, is very transparent, relatively colorless and low in phosphorus and organic matter. Types B to E water are increasingly turbid, colored, and rich in nutrients, organic matter and minerals. Mean mercury levels in lake whitefish, northern pike and walleye are lowest in type A water and increase gradually in types B to E water (Schetagne *et al.*, 2002).

Several authors also report a relationship between fish mercury levels and the level of organic matter (dissolved organic carbon and humic acids) (Mannio *et al.*, 1986; McMurtry *et al.*, 1989; Wren *et al.*, 1991; Lange *et al.*, 1993; Haines *et al.*, 1994; Simonin *et al.*, 1994; Driscoll *et al.*, 1995). For each type of water, however, the levels always vary widely from one lake to the next. Note that there are lakes in both the East and West sectors of the La Grande complex that contain type B water.

3.1.2.3 Variability of mercury levels between species

The comparison of mercury levels in the different species of fish was based on specimens of the same age. Non-piscivorous species in the West sector show similar mercury bioaccumulation levels, except for cisco (0.14 vs. 0.09–0.10 mg/kg for other species, in four-to-five-year-old specimens; Schetagne *et al.*, 1996). This difference may be due to the fact that cisco reach sexual maturity at an earlier age. Since more energy is devoted to gonad production, cisco produce proportionally less flesh. The assimilated mercury, which accumulates more in the flesh than in the gonads (Schetagne *et al.*, 1996), is therefore more concentrated.

In the East sector, mean mercury levels in normal lake whitefish are significantly higher than in longnose sucker (0.17 vs. 0.08 mg/kg for four-to-five-year-old specimens), possibly because they consume different prey.

For piscivorous species in both sectors, mean levels in northern pike are higher than in other predators (walleye and lake trout) of the same age (0.99 vs. 0.70 and 0.64 mg/kg, respectively, for 12-to-14-year-old specimens; Schetagne *et al.*, 1996). These differences may be partly explained by the more precocious piscivorous behavior of northern pike, which begins at the end of their first summer (Holland and Huston, 1984), and partly by their faster growth which enables them to consume larger fish with more mercury contamination at an earlier age than the other two piscivorous species. The examination of stomach contents supports this hypothesis, as the coregonids ingested by northern pike may be up to three times larger than those found in the stomachs of walleye in the same age group (Doyon *et al.*, 1996).

The comparison of mercury bioaccumulation levels in piscivorous and non-piscivorous species of the same age indicates that, in natural lakes in the West sector, 13-to-14-year-old northern pike have mercury levels that are about five times higher than the levels in longnose sucker and lake whitefish of the same age (0.99 vs. 0.19–0.20 mg/kg; Schetagne *et al.*, 1996). These values clearly show that mercury biomagnification is at work and indicate a biomagnification factor of 5 from one trophic level to another.

Furthermore, the data shows that the biomagnification factor obtained for these species of fish varies considerably from one lake to another; this could be explained by the different fish community structures, meaning different prey for piscivorous fish and consequently, different mercury levels (Schetagne *et al.*, 2002). Note that similar factors of around 3 were observed in lake invertebrates at different trophic levels (Lucotte *et al.*, 1999a).

3.1.2.4 Temporal variability of mercury levels in natural lakes

A few natural lakes were sampled on a regular basis from 1984 to 2012, namely, Lac Rond-de-Poêle (28 years of data) and Lac Detchevery (22 years of data) in the West sector and Lac Hazeur (26 years of data) in the East sector. Analysis of the temporal mercury-level variations in the main species of fish in these lakes did not show any particular trend over time (Figure 3.3).

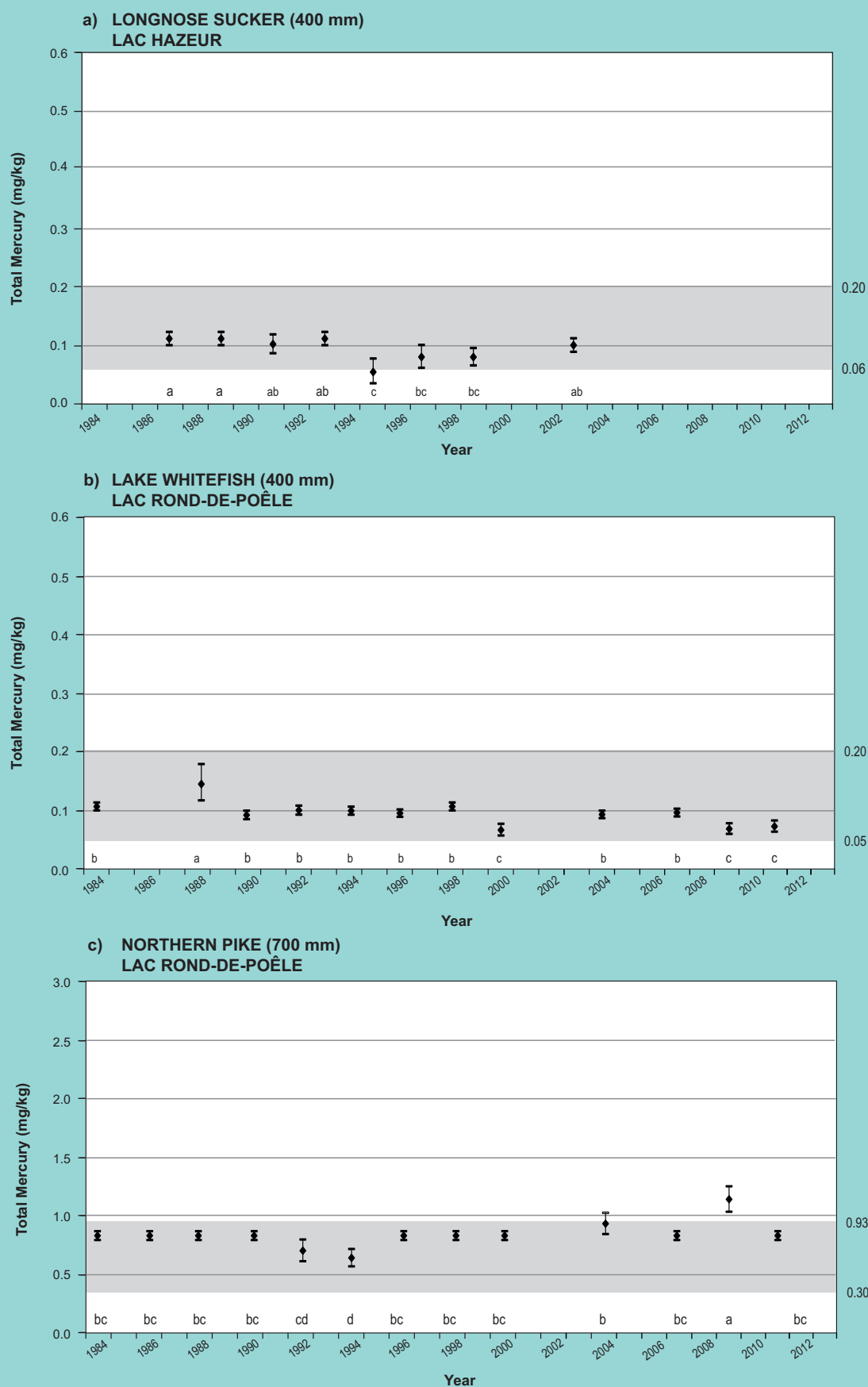
The year-to-year variations illustrated in Figure 3.3 appear to be related either to random sampling factors such as slight differences in the length distribution of the fish caught each year or in the accuracy of laboratory analyses, or to real environmental differences. It is unlikely that differences in mercury availability from one year to the next or in fish growth played a major role, because the levels were estimated for fish of standardized length and about 8 to 15 years in age, depending on the species. Such differences, therefore, would have to have occurred over sequences of several years. Variations in age-class representation for the different species of fish could have played a greater role, as these do occur over several years.

For each species, the differences observed from year to year were very small compared with the changes observed after the reservoirs were impounded. These differences consequently had no impact on the interpretation of level changes after the environments were modified. Moreover, with one exception (northern pike in Lac Rond-de-Poêle in 2009, Figure 3.3c), the mean annual levels all fall within the range of mean levels obtained for standardized lengths for all the natural lakes.

3.1.3 Other regions

Schetagne *et al.* (2002) provides comparative analyses of the La Grande complex with other regions, i.e., the Grande and Petite Rivière de la Baleine regions, the Nottaway, Broadback and Rupert regions, northern Québec, southern Québec and the rest of Canada.

Figure 3.3 Temporal Evolution of Mean Mercury Levels Calculated for Standardized Lengths in the Main Species of Fish Caught in Four Natural Lakes in the La Grande Complex

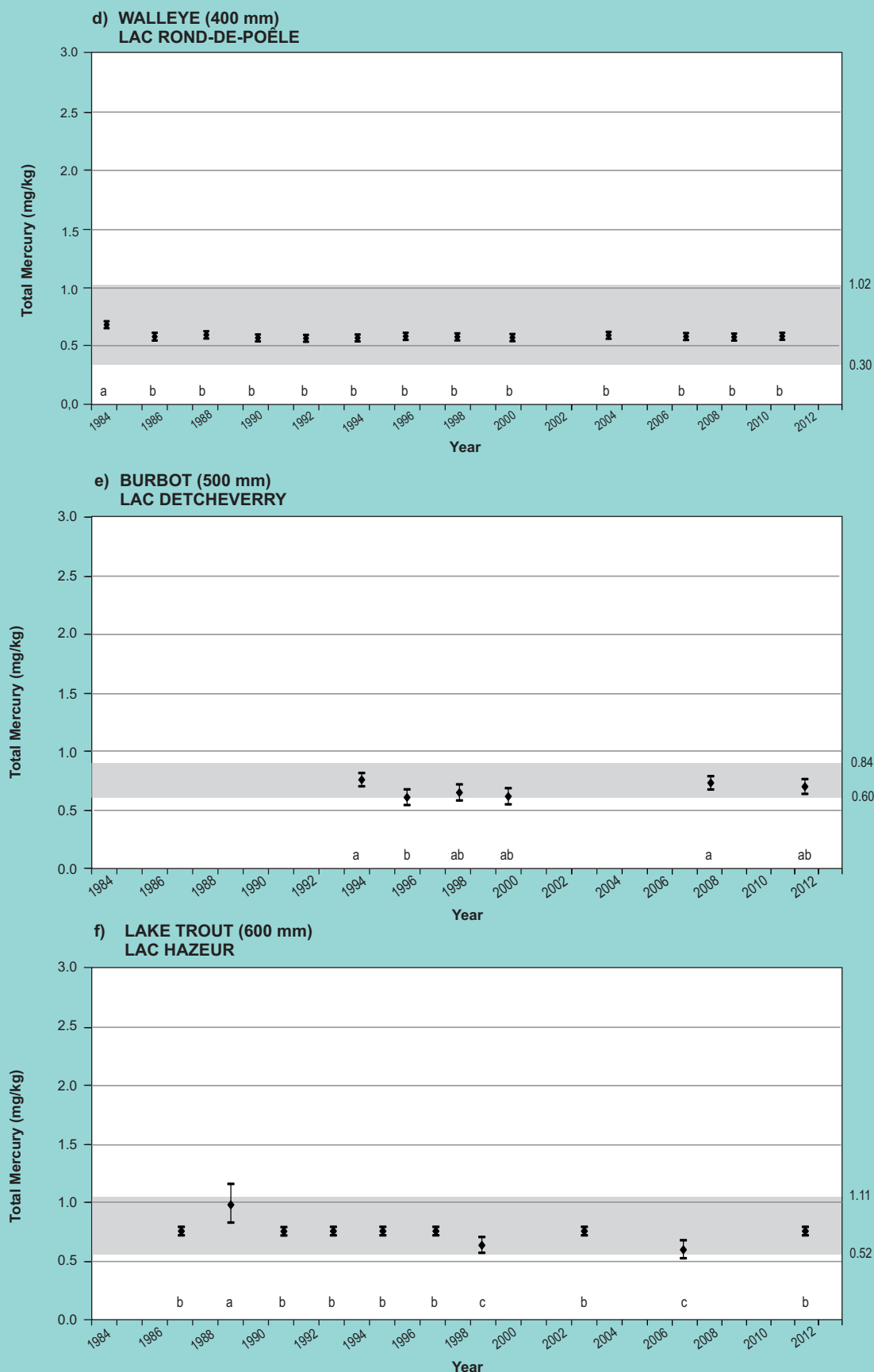


Notes: The vertical lines represent the confidence intervals (95%) for the estimated mean levels.
The different letters indicate that mercury levels are significantly different, since the confidence intervals (95%) do not overlap.

Extent of mean levels obtained for a standardized length under natural conditions

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Figure 3.3 Temporal Evolution of Mean Mercury Levels Calculated for Standardized Lengths in the Main Species of Fish Caught in Four Natural Lakes in the La Grande Complex (cont.)



Notes: The vertical lines represent the confidence intervals (95%) for the estimated mean levels.
The different letters indicate that mercury levels are significantly different, since the confidence intervals (95%) do not overlap.

Extent of mean levels obtained for a standardized length under natural conditions

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The major findings of this study component are described below.

- Fish mercury levels appear to vary according to the physical and chemical properties of the water. For most species, mercury levels are lower in the La Grande complex than in the Nottaway-Broadback-Rupert region, where they generally seem to increase from north to south, according to the five types of water identified (Section 3.1.2.2).
- Mercury levels found in non-piscivorous species in the La Grande complex are similar to those measured in lakes in various other regions of Québec, Labrador and British Columbia. However, the levels measured in lakes in the Haut-Saint-Maurice are much higher than in other regions.
- The situation is similar in piscivorous fish, with the exception of northern pike and walleye in the Abitibi and Lac-Saint-Jean regions, which contain higher levels, northern pike in the Côte-Nord region, which generally contain lower levels, and walleye in the region of South Indian Lake in Manitoba, where mercury levels are also lower. The water bodies in the Canadian Shield have a number of properties that contribute to higher fish mercury levels; they contain water that is colored and rich in organic matter, which favors a high rate of methylation, relatively acidic, unproductive water with little mineral content that leads to slow fish growth, and longer-living fish, which results in higher mercury accumulation.

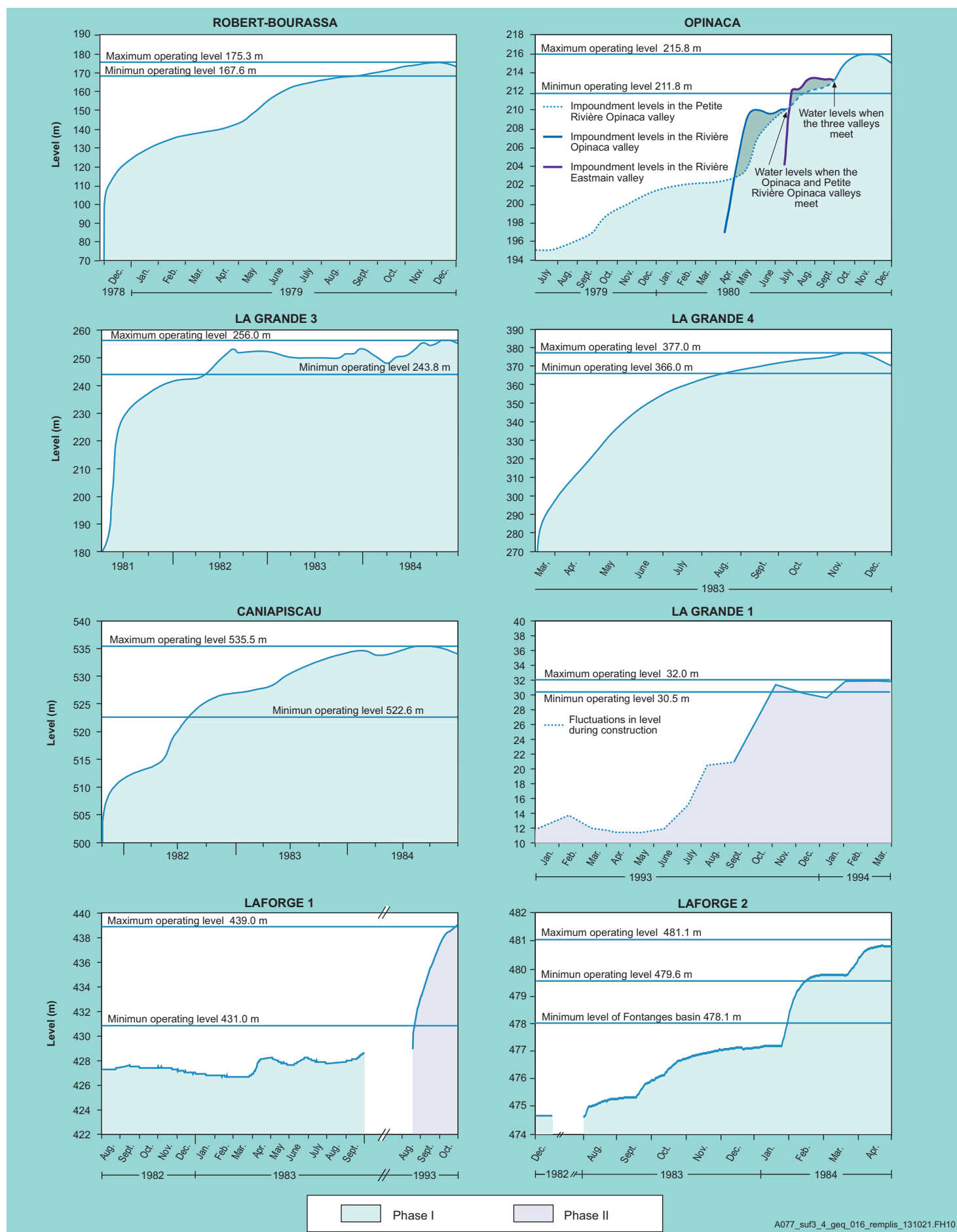
3.2 Reservoirs

3.2.1 Physical, chemical and biological changes

The main physical change caused by reservoir creation is the flooding of land. Figure 3.4 shows the filling curves for phases I and II La Grande complex reservoirs. Their physical characteristics (drawdown, area, depth, volume, etc.) were presented in section 1.1.2 (Table 1.1). Filling time varied considerably for the reservoirs, ranging from one month for La Grande 1 to nearly three years for Caniapiscou.

The three reservoirs regularly monitored for water quality between 1978 and 2000, i.e., Robert-Bourassa, Opinaca and Caniapiscou, show similar changes: a temporary decrease in the saturation rate for dissolved oxygen and pH, and a temporary increase in main ions, organic carbon and nitrogen, and total phosphorus (Schetagne *et al.*, 2005). A detailed description of the mechanisms that may explain the changes in water quality observed following impoundment is provided in Schetagne *et al.* (2002, 2005).

Figure 3.4 Filling Curves for Phases I and II La Grande Complex Reservoirs



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In Robert-Bourassa and Opinaca reservoirs, the physicochemical changes peaked quickly, two or three years after impoundment. Modifications related to decomposition of flooded organic matter were virtually over by 1988, nine to ten years after impoundment (Schetagne, 1994). In Caniapiscou reservoir, the changes were similar in scope to those observed in the other two reservoirs, but the maximum values were reached later, six to ten years after impoundment, and the return to values representative of natural conditions was nearly complete after 18 years.

The water quality recorded in the productive zone of the La Grande complex reservoirs, generally consisting of the top ten metres below the surface, has never been a constraint for aquatic organisms in general. Moreover, the nutrient levels in the water contributed to increased productivity in these areas.

Changes in phytoplankton populations were monitored by measuring chlorophyll *a*. In all three reservoirs, the increase in nutrients, especially phosphorus, caused chlorophyll *a* levels to triple. This phytoplankton increase resulted in a reduction of silica concentrations to levels which may have limited additional increases of these organisms in some parts of the reservoirs. Maximum levels of chlorophyll *a* were reached three to five years after impoundment and returned to levels comparable to those measured under natural conditions 9 to 14 years after impoundment.

The abundance and biomass of zooplankton in the La Grande complex reservoirs were clearly stimulated by the nutrient enrichment, as well as the increase in water residence time, which was very short in the rivers feeding the reservoirs. This allowed the organisms to proliferate, as more of them were able to complete their life cycle.

In reservoirs, especially during the early years, a reduction in the diversity of benthic organisms was observed (Boudreault and Roy, 1985), but the reservoir sampling stations often recorded densities and biomasses of macroinvertebrates that were higher than those found in control lakes. Moreover, one of the fish species that benefited the most from the creation of reservoirs in terms of relative abundance and growth rate was lake whitefish, which typically feeds on benthic organisms (Therrien *et al.*, 2002).

Environmental monitoring conducted between 1977 and 2000 showed that reservoir impoundment caused an initial dilution of fish populations, then an increase in overall fishing yields (catches per unit effort or CPUE) as a result of the water's enrichment (Therrien *et al.*, 2002). The growth rate and condition factor of the main fish species in the reservoirs also increased significantly after impoundment.

3.2.2 Fate of mercury in reservoirs

It was in the United States, in 1977, that the first link was established between reservoir impoundment and increased fish mercury levels (Abernathy and Cumbie, 1977). In Canada, a similar phenomenon was found in fish in Southern Indian Lake reservoir in Manitoba in 1979 (Bodaly and Hecky, 1979). These reservoirs did not receive contaminated industrial effluents, and airborne transmission of mercury alone could not explain the sudden increase in fish mercury levels.

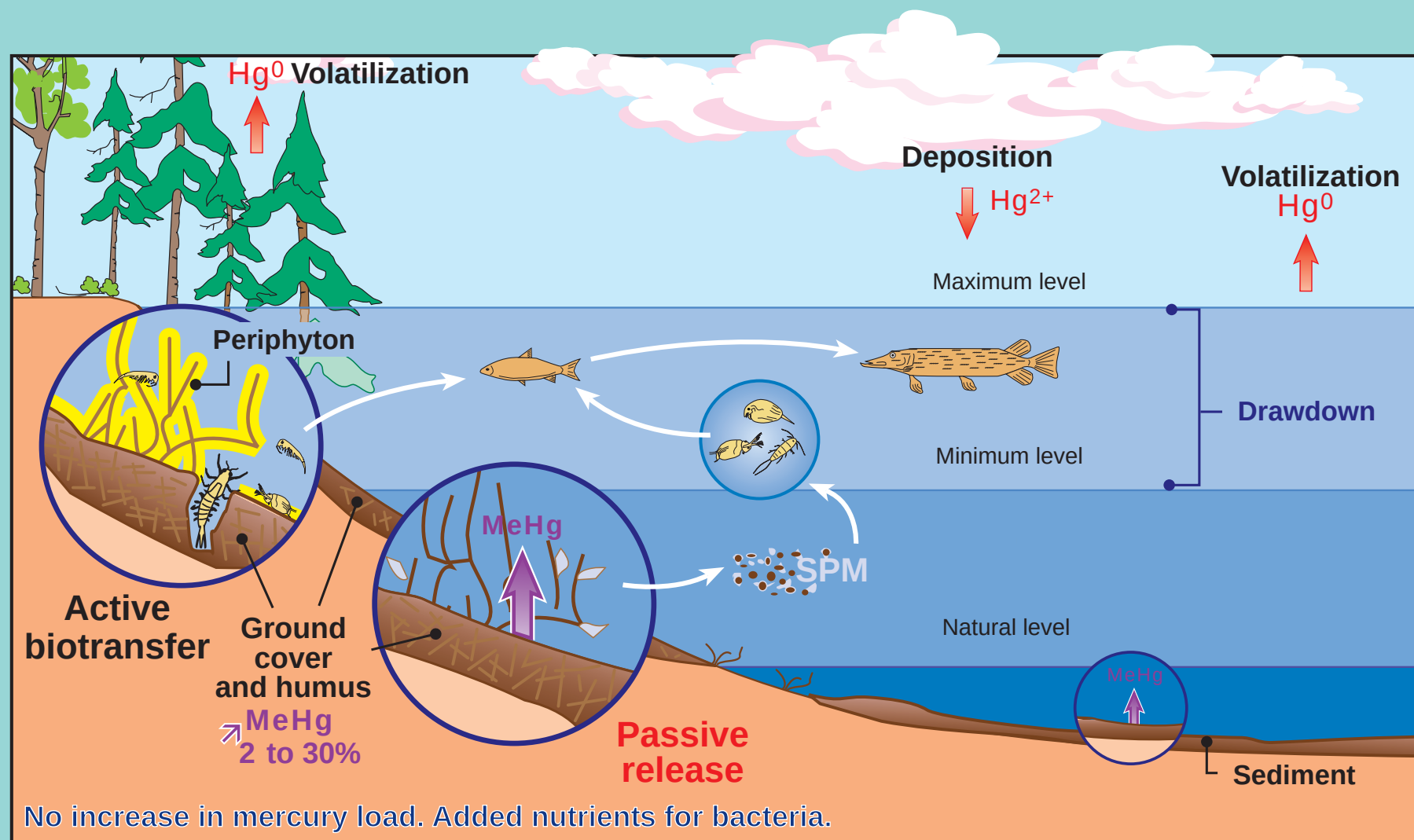
Studies in Manitoba and in the La Grande complex led to an understanding of the mechanisms responsible for the higher mercury levels in the flesh of fish in recently created reservoirs (Bodaly *et al.*, 1984; *Canada-Manitoba Mercury Agreement*, 1987; Lucotte *et al.*, 1999a). Figure 3.5 illustrates the main mechanisms in play shortly after reservoir impoundment.

Reservoir construction involves raising the water level and flooding a large quantity of terrestrial organic matter (vegetation and the surface layers of soils). During the early years of a reservoir's existence, this organic matter is subject to accelerated bacterial decomposition which increases methylation of the mercury it contains. This is, therefore, not a new source of mercury introduced by the reservoirs, but rather a conversion of the inorganic mercury already present in the flooded land environment. The production of methylmercury is largely governed by the amount and type of flooded organic matter and by biological and physical factors such as bacterial activity, water temperature, oxygen content of the water, etc.

Part of the methylmercury thus produced is released into the water column, where it may be adsorbed to suspended particles and transferred to fish via the zooplankton that filters these particles. Because of its strong affinity for organic matter, much of the methylmercury produced remains in the flooded soil. It may be transferred to the food chain by the following active biological and physical processes:

- Insect larvae feeding in the top centimetres of flooded soils can assimilate the methylmercury available and transfer it to fish.
- During the first years after reservoir impoundment, most of the flooded soils in shallow areas, exposed to the combined action of waves and ice, are gradually eroded. The largest particles of eroded soils quickly fall to the bottom. However, fine organic particles, rich in mercury, remain suspended in the water column for a short period during which they may be filtered by zooplankton and transferred to fish. These particles may also settle on the surface of flooded soil in slightly deeper water, where they may become methylmercury-rich food for the benthic organisms.

Figure 3.5 Transfer of Methylmercury to Fish shortly after Reservoir Impoundment



- Methylmercury transfer
- Hg²⁺ et Hg⁰**: Inorganic mercury
- MeHg**: Methylmercury
- SPM**: Suspended particulate matter

- The release of nutrients resulting from bacterial decomposition of flooded organic matter stimulates the growth of periphyton, a mixture of mercury-rich bacteria and algae. When it is consumed by zooplankton and insect larvae, the mercury it contains may also be transferred to fish.

3.2.3 Temporal evolution of fish mercury levels in reservoirs

The creation of reservoirs in the La Grande complex caused a significant increase in total mercury content in the flesh of all species of fish (tables 3.2 and 3.3).

The figures describing the temporal evolution of mercury levels in specimens of standardized length of the main non-piscivorous (lake whitefish and longnose sucker) and piscivorous (northern pike, walleye, lake trout and burbot) species provide detailed statistical information for the reservoir for which the longest series of data are available (Robert-Bourassa or Caniapiscau). These results can be compared with those obtained at the other reservoirs.

With the exception of La Grande 1 reservoir, which is a special case (section 3.2.3.8), all of the reservoirs show the same overall pattern of change in fish mercury levels (for species for which the time series is sufficient). Depending on the species and reservoir, mercury levels for standardized lengths increased twofold to eightfold over the levels recorded in natural environments. Concentrations in non-piscivorous species peaked 4 to 11 years after impoundment, then gradually returned to levels typical of the natural environment. In piscivorous species, levels peaked later, 9 to 14 after impoundment, and decreased significantly thereafter, returning in most cases to mean levels similar to those found in natural lakes.

This pattern of change reflects a particular situation, in which the first year classes of fish to hatch after impoundment populated the reservoirs at a time when bacterial decomposition, methylation and bioavailability of mercury were all at their peak levels. Consequently, their mercury accumulation rate was also maximized.

However, year classes born a decade after impoundment entered reservoirs where mercury methylation and bioavailability had returned to the levels of natural lakes, which means that their mercury levels are no higher than those in fish in natural lakes. The return period for fish of standardized length to levels comparable to those found in natural lakes will thus depend on the species' growth rate, which is longer in boreal regions, and on their diet; mercury levels in piscivorous species are higher for a longer period of time because they are consuming prey that does not necessarily come from cohorts born a decade after impoundment.

Table 3.2 Mercury Levels (mg/kg) in the Main Species of Fish of Standardized Length According to Reservoir Age in the West Sector of the La Grande Complex

Reservoir age (year)	Longnose sucker (400 mm)	Lake whitefish (400 mm)	Northern pike (700 mm)	Walleye (400 mm)	Cisco (150 mm)	Burbot (500 mm)
Range of values in natural lakes						
	0.12 to 0.22	0.05 to 0.20	0.30 to 0.93	0.30 to 1.02	0.08 to 0.12	0.49 to 0.74 ^a
Robert-Bourassa						
3 years (1982)	0.38 (c)	0.47 (ab)	1.45 (h)	2.03 (c)	–	–
5 years (1984)	0.61 (a)	0.53 (a)	2.77 (cd)	2.72 (a)	–	2.43 (a)
7 years (1986)	0.63 (a)	0.43 (bc)	2.29 (f)	2.32 (bc)	–	1.33 (b)
9 years (1988)	0.57 (a)	0.38 (bcd)	3.28 (ab)	2.82 (a)	–	–
11 years (1990)	0.44 (bc)	0.32 (d)	3.34 (a)	2.79 (a)	–	–
12 years (1991)	–	–	–	–	0.33 (b)	–
13 years (1992)	0.45 (b)	0.35 (cd)	3.00 (abc)	2.49 (ab)	–	–
15 years (1994)	0.39 (bc)	0.22 (e)	2.97 (bc)	2.20 (c)	0.50 (a)	0.83 (c)
17 years (1996)	0.29 (d)	0.21 (e)	2.56 (de)	1.75 (d)	0.32 (b)	0.76 (cd)
19 years (1998)	0.26 (de)	0.17 (fg)	2.28 (ef)	1.52 (de)	0.33 (b)	0.61 (d)
21 years (2000)	0.22 (e)	0.18 (efg)	2.33 (ef)	1.41 (e)	0.24 (c)	0.66 (cd)
25 years (2004)	–	0.16 (g)	1.87 (g)	1.13 (f)	0.12 (d)	0.61 (d)
29 years (2008)	–	0.16 (fg)	1.62 (gh)	1.12 (f)	–	–
33 years (2012)	–	0.21 (ef)	1.61 (gh)	1.11 (f)	–	0.61 (d)
Opinaca						
1 year (1981)	–	0.21 (def)	–	1.01 (defg)	–	–
4 years (1984)	0.72 (a)	0.43 (a)	2.25 (bc)	1.94 (ab)	–	–
6 years (1986)	0.57 (ab)	0.46 (a)	1.88 (cd)	1.74 (ab)	–	–
8 years (1988)	–	0.40 (ab)	2.13 (bc)	1.99 (ab)	–	–
10 years (1990)	–	0.39 (ab)	2.77 (a)	2.07 (a)	–	–
12 years (1992)	0.50 (b)	0.42 (a)	2.69 (a)	1.88 (ab)	–	–
14 years (1994)	–	0.29 (bc)	2.47 (ab)	1.65 (b)	0.33 (a)	0.72 (a)
16 years (1996)	0.33 (c)	0.28 (cd)	2.30 (b)	1.28 (cd)	0.22 (b)	0.69 (a)
20 years (2000)	0.27 (c)	0.22 (def)	1.53 (d)	0.76 (g)	0.17 (c)	–
24 years (2004)	0.16 (d)	0.17 (f)	1.61 (d)	0.84 (fg)	–	–
27 years (2007)	–	0.20 (ef)	1.24 (e)	1.00 (ef)	–	–
29 years (2009) ^b	–	0.20 (ef)	2.11 (bc)	1.33 (c)	–	–
31 years (2011) ^b	–	0.22 (de)	1.70 (d)	1.21 (cde)	–	–

Table 3.2 (cont.) Mercury Levels (mg/kg) in the Main Species of Fish of Standardized Length According to Reservoir Age in the West Sector of the La Grande Complex

Reservoir age (year)	Longnose sucker (400 mm)	Lake whitefish (400 mm)	Northern pike (700 mm)	Walleye (400 mm)	Cisco (150 mm)	Burbot (500 mm)
Range of values in natural lakes						
	0.12 to 0.22	0.05 to 0.20	0.30 to 0.93	0.30 to 1.02	0.08 to 0.12	0.49 to 0.74 ^a
La Grande 3						
5 years (1986)	0.30 (de)	0.34 (a)	1.51 (e)	–	1.10 (a)	–
7 years (1988)	0.40 (bc)	0.38 (a)	2.26 (d)	–	–	–
9 years (1990)	0.50 (ab)	0.31 (ab)	3.04 (c)	–	0.97 (a)	–
11 years (1992)	0.55 (a)	0.33 (ab)	4.08 (ab)	–	–	–
13 years (1994)	0.35 (cd)	0.32 (ab)	4.66 (a)	–	0.70 (b)	–
15 years (1996)	0.30 (de)	0.30 (ab)	3.71 (b)	n.r.	0.33 (c)	1.70 (a)
17 years (1998)	0.25 (ef)	0.33 (ab)	3.12 (c)	n.r.	0.26 (d)	–
19 years (2000)	0.22 (f)	0.20 (cd)	2.15 (d)	1.37 (a)	0.21 (d)	1.09 (b)
23 years (2004)	–	0.26 (bc)	1.51 (e)	1.25 (a)	0.23 (d)	0.60 (c)
27 years (2008)	–	0.20 (c)	1.37 (e)	1.24 (a)	–	0.57 (c)
31 years (2012)	–	0.14 (d)	1.08 (f)	0.93 (b)	–	0.57 (c)
La Grande 1						
1984 (5 years ^c)	0.98 (abc)	1.19 (a)	n.r.	–	–	–
1986 (7 years ^c)	1.09 (ab)	0.67 (b)	2.70 (c)	–	–	2.11 (b)
1988 (9 years ^c)	1.12 (a)	0.91 (ab)	3.47 (b)	4.31 (a)	–	–
1990 (11 years ^c)	1.29 (a)	1.13 (a)	4.27 (a)	–	–	2.64 (a)
1992 (13 years ^c)	1.31 (a)	0.59 (b)	–	–	–	–
1 year (1994)	1.10 (ab)	0.63 (b)	2.26 (c)	–	–	–
3 years (1996)	0.82 (c)	0.30 (c)	1.06 (de)	–	0.37 (a)	1.48 (c)
5 years (1998)	0.53 (d)	0.29 (c)	1.28 (d)	1.43 (bc)	0.28 (ab)	1.33 (c)
7 years (2000)	0.88 (bc)	0.18 (d)	0.92 (ef)	1.68 (b)	0.25 (b)	0.78 (d)
11 years (2004) ^d	0.40 (d)	0.17 (d)	0.94 (ef)	1.28 (cd)	–	0.77 (d)
15 years (2008) ^d	0.43 (d)	0.15 (d)	0.78 (f)	1.09 (de)	–	0.82 (d)
20 years (2012) ^d	0.43 (d)	0.17 (d)	0.82 (ef)	–	–	0.53 (e)

Notes:

n.r.: Not representative (value only available for one station or inadequate length distribution).

–: No available data or insufficient specimens (n < 10).

a: The range is only provided as an indication, as there is very little available data under natural conditions.

b: The years 2009 and 2011 also correspond to an age of 3 to 5 years for Eastmain 1 reservoir, which influences that of Opinaca reservoir.

c: The age indicated is that of Robert-Bourassa reservoir located immediately upstream (see text).

d: The only available data for longnose sucker was collected immediately downstream of Robert-Bourassa reservoir from 2004 to 2012.

Levels with a different letter are significantly different (p < 0.05). Temporal comparisons were drawn by reservoir and by species. The stations used for modified environments were generally those retained after the study was optimized in 2004, except in areas that were not sampled after 2003. By exception, the stations that were not retained were considered for the 1981–2003 period, for the rare cases where their exclusion caused a loss of data.

For burbot in Robert-Bourassa reservoir, the two maximum levels were recorded at different stations.

Table 3.3 Mercury Levels (mg/kg) in the Main Species of Fish of Standardized Length According to Reservoir Age in the East Sector of the La Grande Complex

Reservoir age (year)	Longnose sucker (400 mm)	Lake whitefish (400 mm)	Northern pike (700 mm)	Lake trout (600 mm)	Burbot (500 mm) ^a	Dwarf lake whitefish (200 mm)
Range of values in natural lakes						
	0.06 to 0.20	0.10 to 0.30	0.36 to 0.92	0.52 to 1.11	0.49 to 0.74 ^a	0.17 to 0.29 ^b
La Grande 4						
4 years (1987)	0.22 (bc)	0.20 (b)	0.55 (d)	1.34 (a)	–	–
6 years (1989)	0.34 (a)	0.33 (a)	0.89 (c)	–	–	–
8 years (1991)	0.34 (a)	0.33 (a)	1.10 (bc)	–	–	–
10 years (1993)	0.34 (a)	0.16 (cd)	1.39 (ab)	–	–	–
12 years (1995) ^c	0.24 (b)	0.16 (cd)	1.64 (a)	–	–	–
14 years (1997) ^c	0.21 (bc)	0.12 (d)	1.65 (a)	–	–	0.34 (a)
16 years (1999) ^c	0.19 (c)	0.16 (cd)	1.39 (ab)	–	–	0.31 (a)
20 years (2003) ^c	0.13 (d)	0.17 (bc)	1.42 (ab)	–	–	–
24 years (2007) ^c	–	0.16 (cd)	1.37 (ab)	–	–	–
29 years (2012) ^c	–	0.16 (cd)	0.99 (c)	0.97 (b)	–	–
Caniapiscau						
5 years (1987)	0.34 (c)	0.38 (ab)	0.79 (f)	0.82 (e)	0.49 (b)	–
7 years (1989)	0.45 (ab)	0.45 (a)	1.25 (cd)	1.56 (ab)	–	–
9 years (1991)	0.52 (a)	0.47 (a)	1.57 (abc)	1.85 (a)	–	–
11 years (1993)	0.49 (a)	0.29 (bc)	1.86 (a)	1.79 (a)	–	0.64 (a)
13 years (1995)	0.39 (bc)	0.21 (d)	1.65 (ab)	1.58 (ab)	0.76 (a)	0.48 (b)
15 years (1997)	0.24 (d)	0.24 (cd)	1.47 (bc)	1.55 (ab)	0.51 (b)	0.37 (c)
17 years (1999)	0.22 (d)	0.23 (cd)	1.51 (bc)	1.76 (a)	0.51 (b)	0.30 (d)
21 years (2003)	0.17 (e)	0.17 (e)	1.30 (c)	1.30 (bc)	n.r.	–
25 years (2007)	–	0.16 (e)	0.98 (ef)	0.92 (de)	0.49 (b)	–
30 years (2012)	–	0.16 (e)	1.05 (de)	1.12 (cd)	0.49 (b)	–

Table 3.3 (cont.) Mercury Levels (mg/kg) in the Main Species of Fish of Standardized Length According to Reservoir Age in the East Sector of the La Grande Complex

Reservoir age (year)	Longnose sucker (400 mm)	Lake whitefish (400 mm)	Northern pike (700 mm)	Lake trout (600 mm)	Burbot (500 mm) ^a	Dwarf lake whitefish (200 mm)
Range of values in natural lakes						
	0.06 to 0.20	0.10 to 0.30	0.36 to 0.92	0.52 to 1.11	0.49 to 0.74 ^a	0.17 to 0.29 ^b
Laforge 1						
3 years (1987)	0.29 (b)	0.31 (ab)	0.97 (e)	1.44 (c)	—	—
5 years (1989)	0.40 (ab)	0.36 (a)	1.14 (de)	1.89 (bc)	—	—
7 years (1991)	0.47 (a)	0.36 (a)	1.57 (ab)	2.40 (ab)	—	—
9 years (1993)	0.47 (a)	0.31 (ab)	1.76 (a)	2.63 (a)	—	—
11 years (1995) ^c	0.22 (b)	0.23 (bc)	—	1.76 (bc)	—	—
13 years (1997) ^c	0.25 (b)	0.25 (abc)	1.21 (de)	1.97 (abc)	—	0.52 (a)
15 years (1999) ^c	0.27 (b)	0.26 (ab)	1.23 (d)	1.83 (bc)	—	0.36 (b)
19 years (2003) ^c	0.26 (b)	0.23 (bc)	1.24 (d)	—	—	—
23 years (2007) ^c	—	0.20 (cd)	1.47 (bc)	—	—	—
28 years (2012) ^c	—	0.15 (d)	1.27 (cd)	—	—	—
Laforge 2						
6 years (1989)	0.44 (b)	0.47 (a)	1.66 (cde)	—	—	—
8 years (1991)	0.53 (ab)	0.48 (a)	2.14 (bc)	—	—	—
10 years (1993)	0.64 (a)	0.33 (ab)	2.73 (a)	—	—	—
12 years (1995)	0.46 (b)	0.22 (c)	2.46 (ab)	—	—	—
14 years (1997)	0.31 (c)	0.25 (bc)	1.91 (cd)	—	—	0.28 (a)
16 years (1999)	0.29 (c)	0.24 (bc)	1.62 (de)	—	—	0.28 (a)
20 years (2003)	0.21 (d)	0.15 (de)	1.48 (e)	—	0.68 (a)	—
24 years (2007)		0.16 (de)	0.85 (f)	—	—	—
29 years (2012)		0.14 (e)	0.82 (f)	—	—	—

Notes:

n.r.: Not representative (value only available for one station or inadequate length distribution).

— : No available data or insufficient specimens (n < 10).

■ : For a length of 700 mm; range of values in natural water bodies: 0.71 to 1.44 mg/kg.

a: The range is only provided as an indication, as there is very little available data under natural conditions.

b: The range is only provided as an indication, as it comes from an analysis that only involved two lakes.

c: Years 1995 to 2012 were influenced by the second impoundment of Laforge 1 reservoir in 1993.

Levels with a different letter are significantly different (p < 0.05). Temporal comparisons were drawn by reservoir and by species.

The stations used for modified environments were generally those retained after the study was optimized in 2004, except in areas that were not sampled after 2003. By exception, the stations that were not retained were considered for the 1981–2003 period, for the rare cases where their exclusion caused a loss of data.

3.2.3.1 Lake whitefish

For 400-mm lake whitefish, significant increases in mercury levels were observed in most of the reservoirs after impoundment (Figure 3.6). La Grande 4 and Laforge 1 were the only two reservoirs where peak mercury levels did not differ significantly from the levels found in some of the region's natural lakes (Figure 3.6d). Depending on the reservoir, the mean mercury level peaked at 0.36 to 0.53 mg/kg (tables 3.2 and 3.3) five to nine years after impoundment, which translates into a two- to fivefold increase. It then decreased gradually and significantly, returning to a level equivalent to those found in the region's natural lakes (i.e., which fell within the range of values recorded in natural lakes, or that did not differ significantly from the mean level found in one or more natural lakes). In reservoirs where the increase in mercury levels was significant, this return occurred 10 to 15 years after impoundment. Since then, occasional fluctuations in mean mercury levels have occurred, but have not exceeded the year-to-year variances observed in natural lakes (section 3.1.2.2 and Figure 3.3).

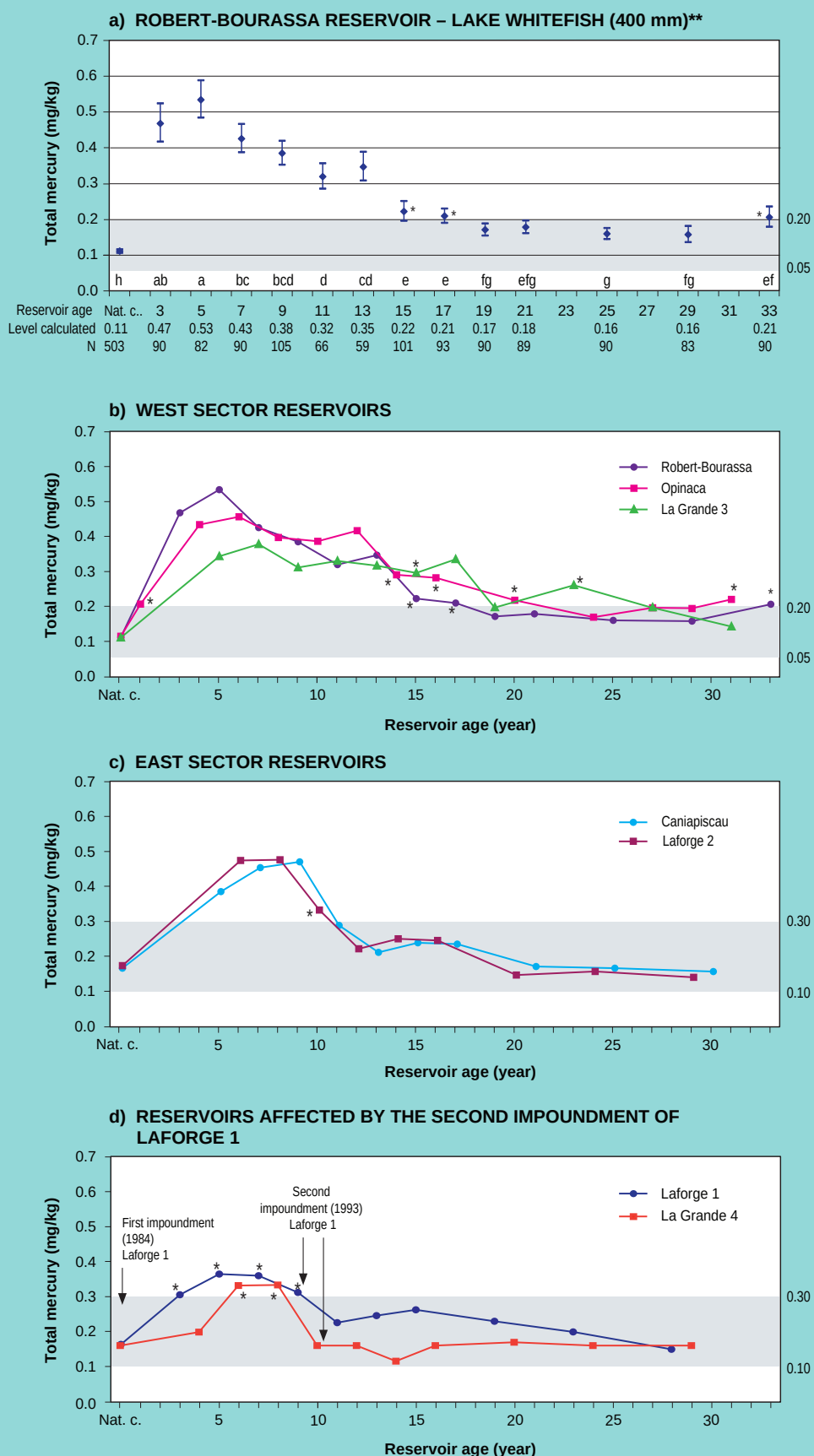
Despite the fact that Laforge 1 reservoir was flooded a second time (798 km² in 1993; Table 1.1), the mean mercury levels in Laforge 1 and La Grande 4 reservoirs, the latter being located immediately downstream of the former, remained within the range of values found in neighboring natural lakes (Figure 3.6d). In regard to La Grande 4, the transfer of mercury to the water body immediately downstream of a reservoir is covered later in this document (sections 3.2.3.3, 3.4.3 and 3.5.4).

3.2.3.2 Longnose sucker

The changes in mercury levels in 400-mm longnose sucker are similar to that in 400-mm lake whitefish. The slightly higher maximum mean levels (0.34 to 0.72 mg/kg; tables 3.2 and 3.3) were reached 4 to 11 years after impoundment (Figure 3.7), having increased by a factor of 2.5 to 6. Levels then returned to values equivalent to those in the region's natural lakes 11 to 20 years after impoundment.

The second impoundment of Laforge 1 reservoir in 1993 (Table 1.1) did not cause any significant increase in mean mercury levels in longnose sucker. It did, however, prevent the decrease noted there between 1991 and 1993 from continuing. Although there is no available data, it is likely that the mean mercury level in the reservoir had returned to a value similar to that found in natural lakes by 2012 (i.e., 19 years after the second impoundment), given the absence of a second significant increase and the duration of this phenomenon in the other reservoirs.

Figure 3.6 Temporal Evolution of Mercury Levels Calculated for 400-mm Lake Whitefish in La Grande Complex Reservoirs



Extent of mean levels obtained for a standardized length under natural conditions

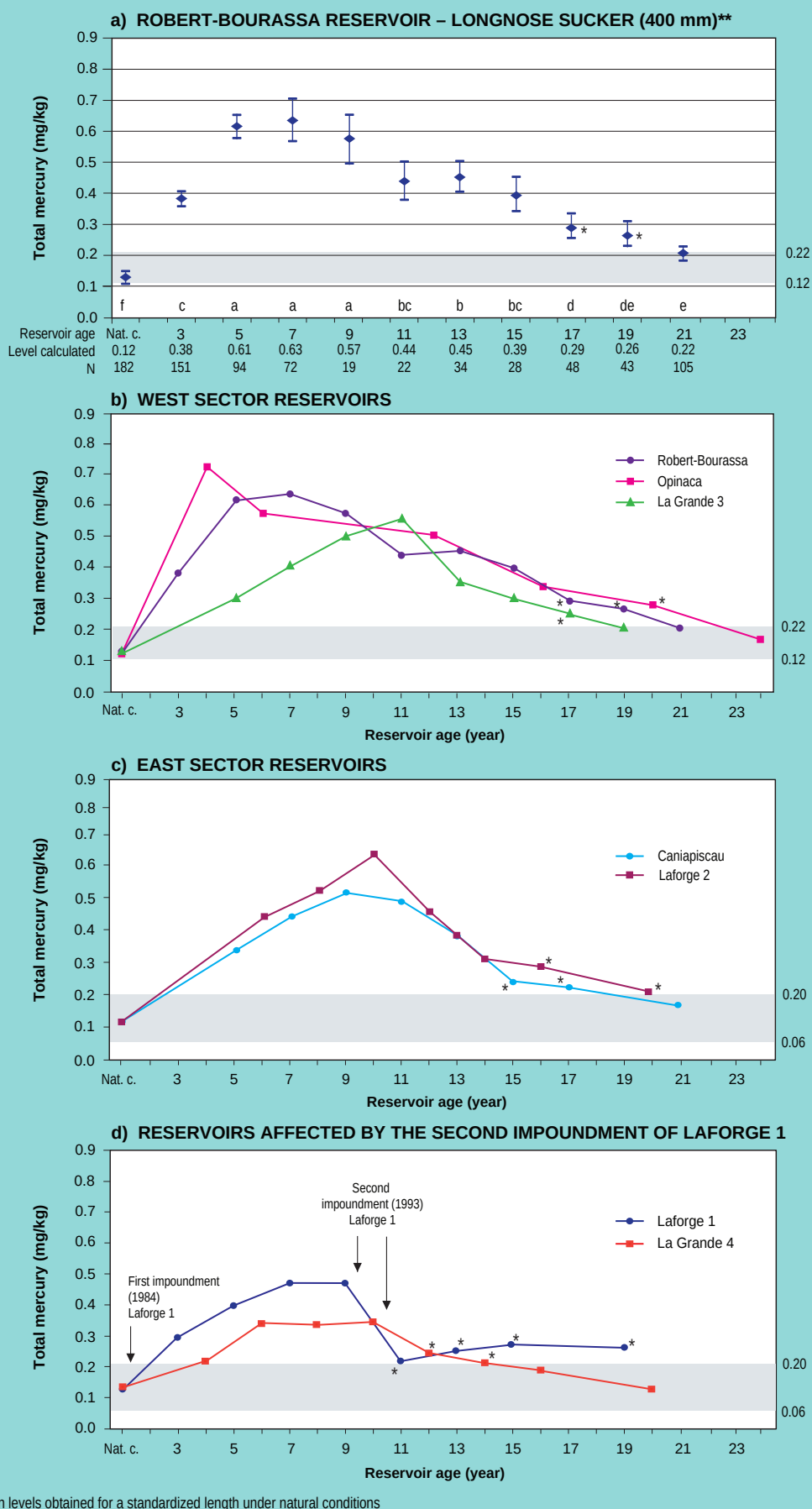
* Mean level which is higher than the range of values obtained in natural lakes but does not differ significantly from the mean level measured in at least one natural lake in the region.

** The vertical lines represent the confidence intervals (95%) for the estimated mean levels.

The different letters indicate that mercury levels are significantly different, since the confidence intervals (95%) do not overlap. Nat. c.: Natural conditions.

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Figure 3.7 Temporal Evolution of Mercury Levels Calculated for 400-mm Longnose Sucker in La Grande Complex Reservoirs



* Mean level which is higher than the range of values obtained in natural lakes but does not differ significantly from the mean level measured in at least one natural lake in the region.

** The vertical lines represent the confidence intervals (95%) for the estimated mean levels.

The different letters indicate that mercury levels are significantly different, since the confidence intervals (95%) do not overlap. Nat. c.: Natural conditions.

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No significant effect was noted in La Grande 4 reservoir, which is immediately downstream of Laforge 1. After 1993, mercury levels in longnose sucker in La Grande 4 reservoir continued to decrease gradually, reaching values within the range of those found in natural lakes by 1999, 16 years after initial impoundment.

Note that after monitoring was optimized in 2004, mercury levels in longnose sucker, which is consumed very little or not at all, were recorded only in areas immediately downstream of the reservoirs, where this species regularly exhibits piscivorous feeding behavior. This change in diet has led to higher mercury levels in longnose sucker (section 3.3).

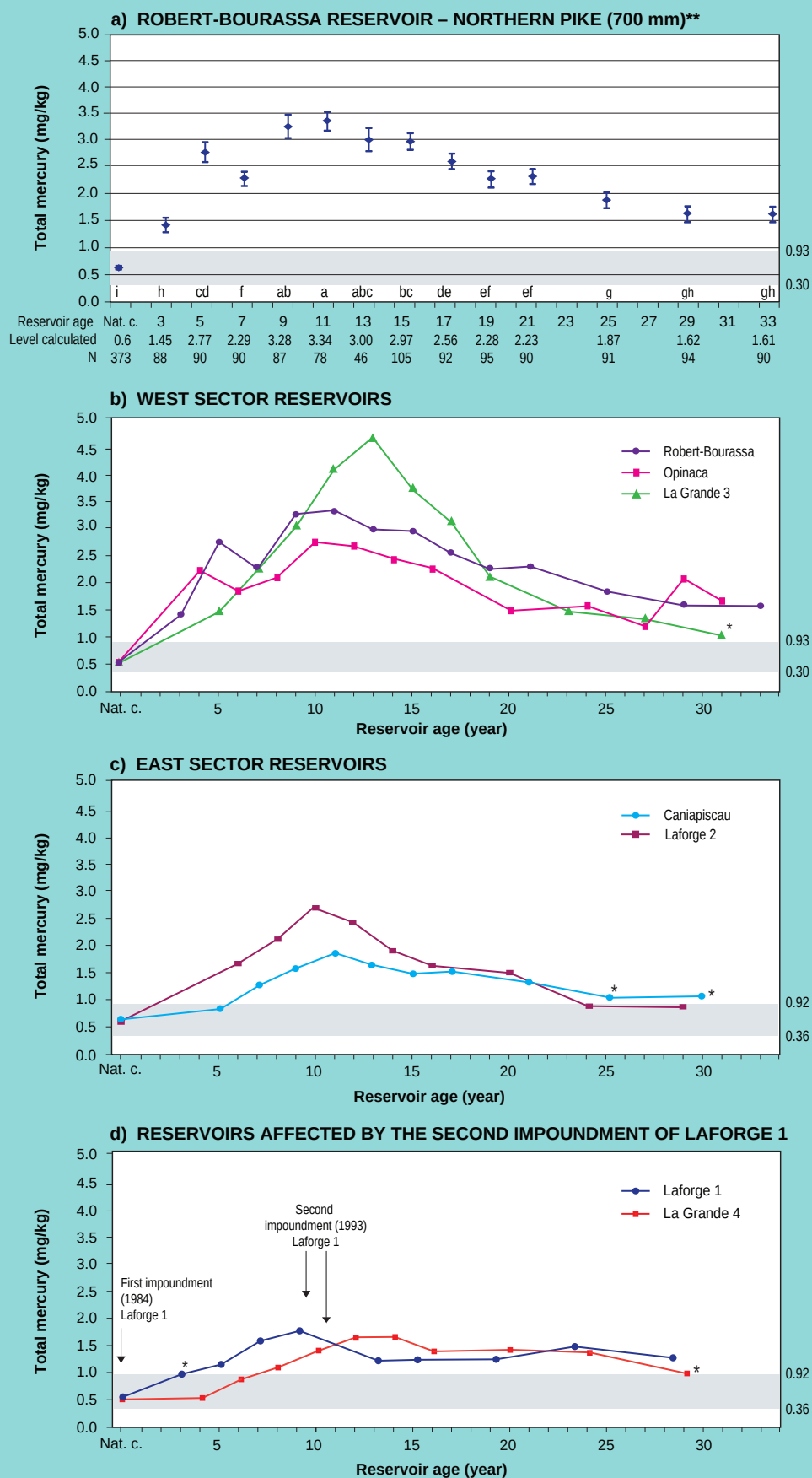
3.2.3.3 Northern pike

Mean mercury levels in 700-mm northern pike in reservoirs also increased significantly (Figure 3.8) and reached peak values of 1.57 to 4.66 mg/kg (tables 3.2 and 3.3) 9 to 14 years after impoundment, which represents a three- to eightfold increase. In reservoirs that were only impounded once (i.e., Robert-Bourassa, La Grande 3, Caniapiscau and Laforge 2), the mean levels then decreased significantly, reaching values equivalent to those found in the region's natural lakes 24 to 31 years after impoundment, with the exception of Robert-Bourassa.

For northern pike in Robert-Bourassa reservoir, the mean mercury level of 1.61 mg/kg reached in 2012, 33 years after impoundment, is still significantly higher than the levels recorded in all of the region's natural lakes. The fact that northern pike in this reservoir feed on more piscivorous fish for longer periods than elsewhere probably helped delay the return period to initial values (section 3.7.3; Therrien and Schetagne, 2009). The higher consumption of piscivorous fish increases the trophic level of predators, which in turn, leads to higher mercury levels, since mean levels increase from one trophic level to another (Lucotte *et al.*, 1999a).

In the case of Opinaca reservoir, the mean mercury levels in northern pike underwent the same changes as in other reservoirs and by 2007, 27 years after impoundment, had almost completely returned to values that did not differ significantly from those found in some natural lakes (1.24 vs. 0.93 mg/kg for Rond-de-Poêle control lake). The impoundment from November 2005 to May 2006 of Eastmain 1 reservoir, located immediately upstream of Opinaca reservoir, led to a second increase in mercury levels. The transfer of mercury, mainly through particulate matter and zooplankton, clearly demonstrated the effect that impoundment of a reservoir can have on the water body immediately downstream of it (Schetagne *et al.*, 2000, 2002).

Figure 3.8 Temporal Evolution of Mean Mercury Levels Calculated for 700-mm Northern Pike in La Grande Complex Reservoirs



Extent of mean levels obtained for a standardized length under natural conditions

* Mean level which is higher than the range of values obtained in natural lakes but does not differ significantly from the mean level measured in at least one natural lake in the region.

** The vertical lines represent the confidence intervals (95%) for the estimated mean levels.

The different letters indicate that mercury levels are significantly different, since the confidence intervals (95%) do not overlap. Nat. c.: Natural conditions

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In Laforge 1 reservoir, the mean mercury level had almost completely returned to that of the region's natural lakes 13 years after the reservoir's initial impoundment (1.21 mg/kg). Then, another increase caused by the second impoundment in 1993 was observed. There was no new increase in La Grande 4 reservoir after Laforge 1 was impounded a second time, but the return to mean levels representative of natural lakes slowed down for nearly ten years and was only observed 29 years after impoundment.

3.2.3.4 Walleye

The mean mercury level of 400-mm walleye increased significantly in all reservoirs where the species is present (Figure 3.9) and reached peak values of 2.07 to 2.82 mg/kg (Table 3.2), nine to ten years after impoundment, which represents an increase factor of 3.5 to 5. It then decreased gradually, reaching values equivalent to those in the region's natural lakes 20 to 25 years after impoundment.

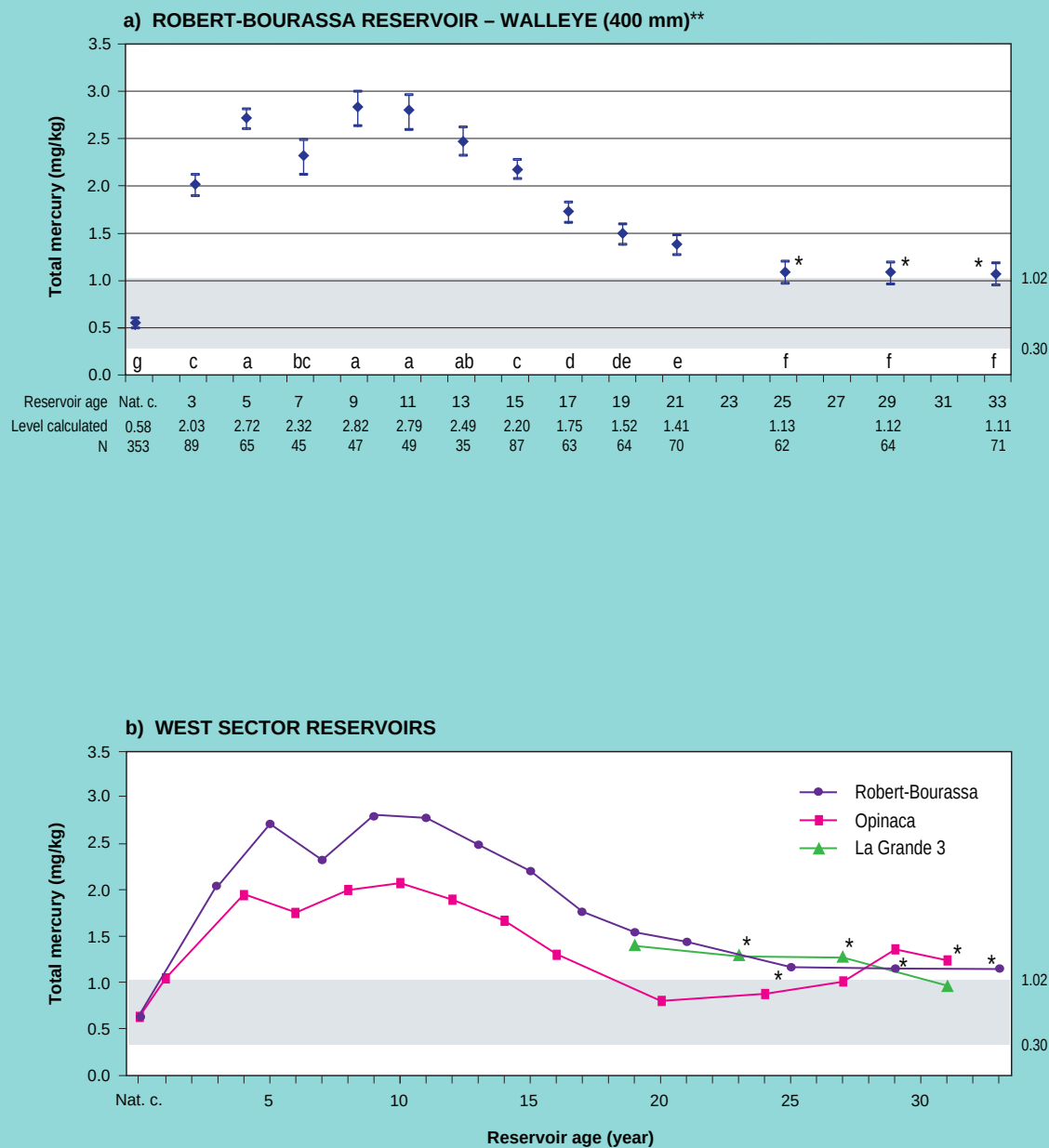
A second increase resulting from the impoundment of Eastmain 1 reservoir in 2005-2006 was observed in Opinaca reservoir in 2009. By 2011, mean mercury levels in walleye had almost completely returned to values measured in the region's natural lakes.

3.2.3.5 Lake trout

In Caniapiscau reservoir, the only one containing lake trout and having undergone only one impoundment, the mean mercury level in 600-mm lake trout increased significantly, by a factor of 2.5, and peaked at 1.85 mg/kg nine years after impoundment (Figure 3.10 and Table 3.3). Mean levels then returned to values equivalent to those in the region's natural lakes 21 years after impoundment. Subsequent fluctuations have been similar to those observed in natural lakes (section 3.1.2.2 and Figure 3.3).

The results for Laforge 1 reservoir were calculated for a standardized length of 700 mm because the study did not provide for the capture of 600-mm or smaller specimens. In this 700-mm lake trout in this reservoir, a maximum mean mercury level of 2.63 mg/kg was reached nine years after impoundment, having increased by a factor of 2.5. The mean level then decreased and reached 1.76 mg/kg after 11 years (Table 3.3). The second impoundment in fall 1993 prevented mercury levels from diminishing any further. The surveys carried out since 1999 have not produced enough catches to allow for the calculation of an accurate mean level. The changes in mercury levels in northern pike in Laforge 1 reservoir suggests that a second increase also occurred in the reservoir's lake trout population.

Figure 3.9 Temporal Evolution of Mean Mercury Levels Calculated for 400-mm Walleye in La Grande Complex Reservoirs



Extent of mean levels obtained for a standardized length under natural conditions

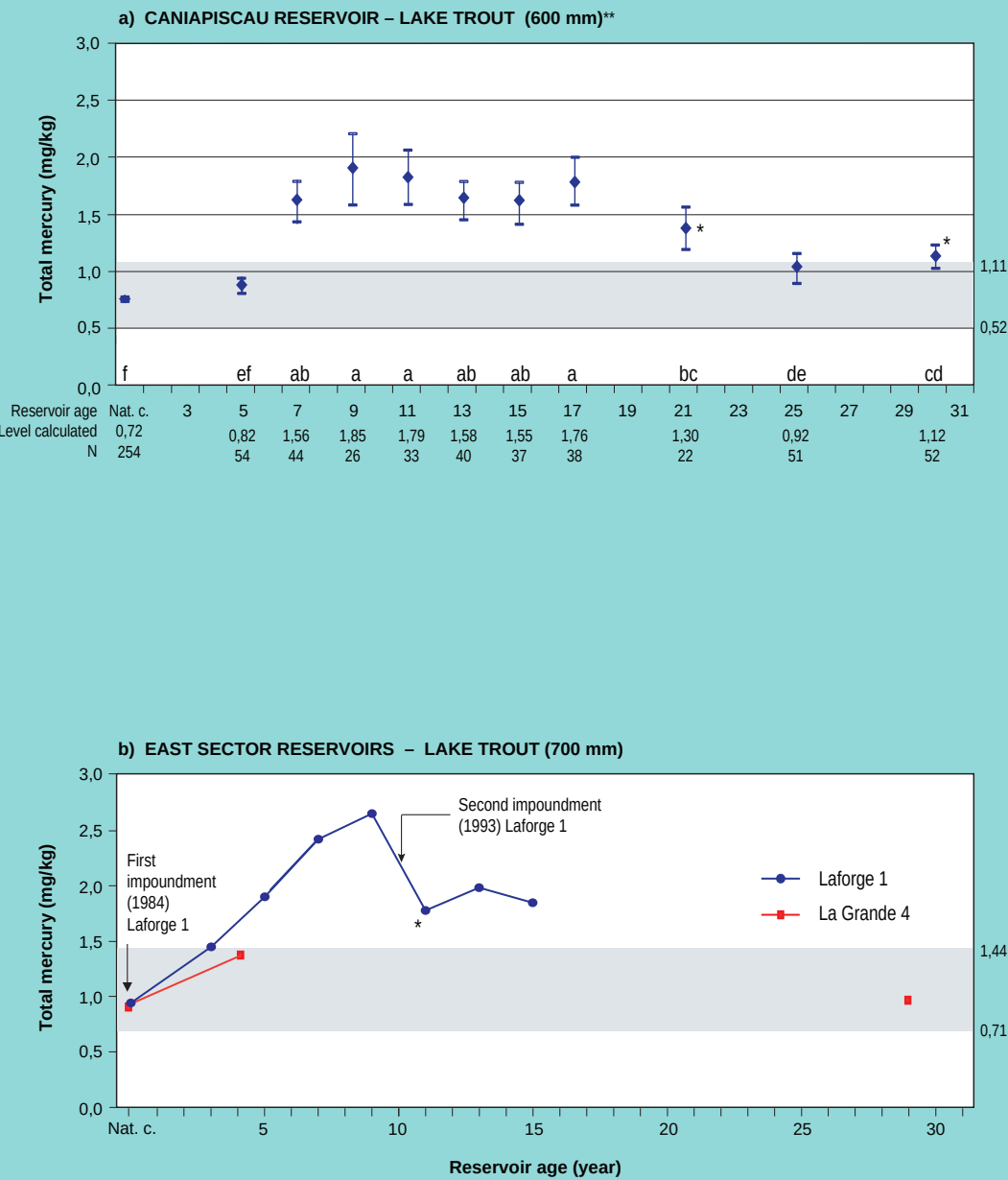
* Mean level which is higher than the range of values obtained in natural lakes but does not differ significantly from the mean level measured in at least one natural lake in the region.

** The vertical lines represent the confidence intervals (95%) for the estimated mean levels.

The different letters indicate that mercury levels are significantly different, since the confidence intervals (95%) do not overlap. Nat. c.: Natural conditions.

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Figure 3.10 Temporal Evolution of Mean Mercury Levels Calculated for 400-mm Lake Trout in La Grande Complex Reservoirs



* Mean level which is higher than the range of values obtained in natural lakes but does not differ significantly from the mean level measured in at least one natural lake in the region.
 ** The vertical lines represent the confidence intervals (95%) for the estimated mean levels.
 The different letters indicate that mercury levels are significantly different, since the confidence intervals (95%) do not overlap. Nat. c.: Natural conditions

3.2.3.6 Burbot

The maximum mean mercury levels in burbot could not be determined because catches in all reservoirs were insufficient to provide a complete series of data (Figure 3.11).

For Robert-Bourassa reservoir, the results from 1984 and 1986 were not representative of the reservoir as a whole, since most of the data came from a single station that differed from year to year. However, the maximum mean mercury level measured in 500-mm burbot in Robert-Bourassa reservoir (2.43 mg/kg) suggests that increases in mercury levels in this species may have been similar to those recorded for walleye (Table 3.2).

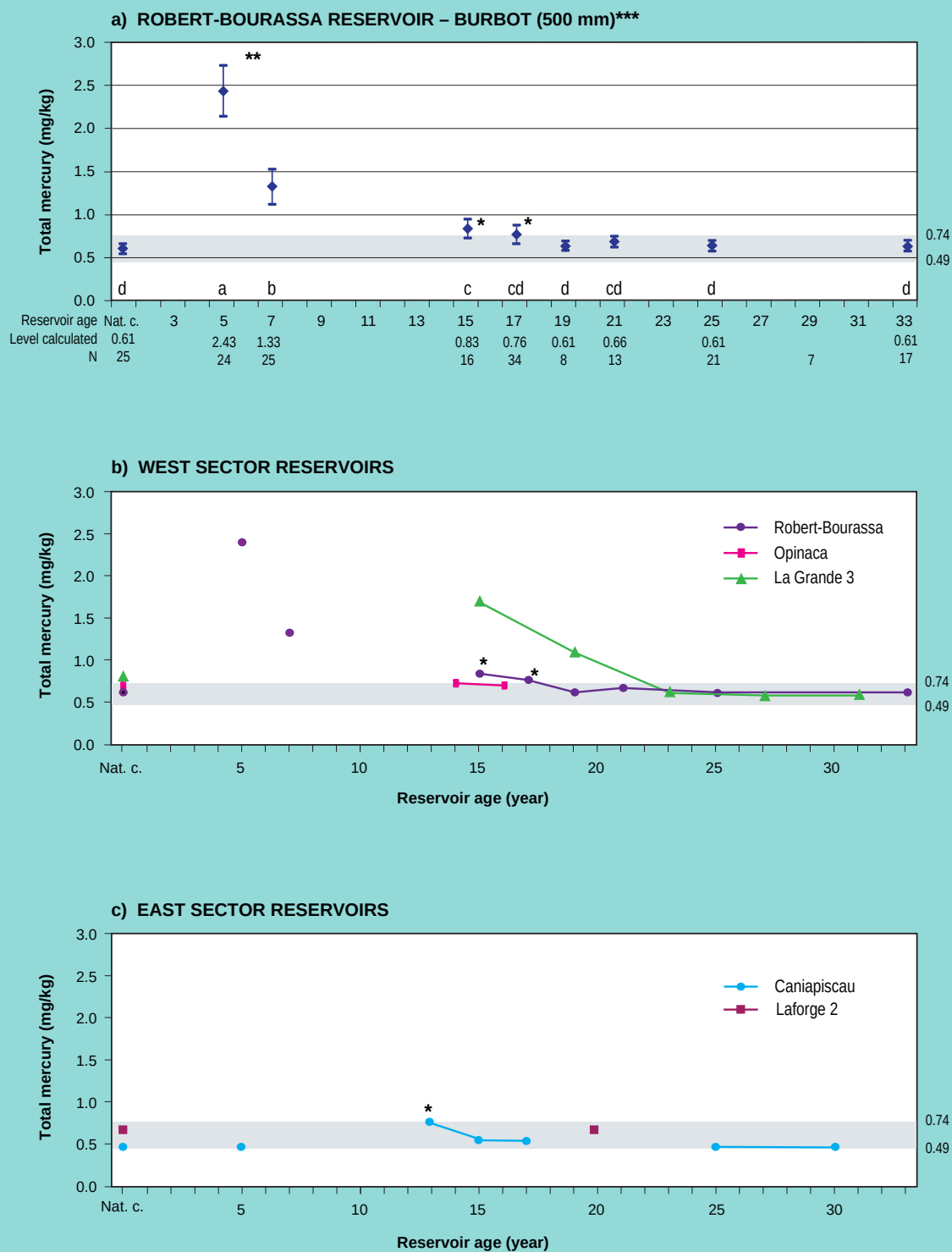
Similarly, the mean mercury level recorded in La Grande 3 in 1996, i.e., 15 years after impoundment, was not representative of the entire reservoir because most of the burbot specimens were caught at Roy station, which is located on a large bay with a low flushing rate, meaning that mercury levels were higher there than elsewhere in the reservoir (Schetagne *et al.*, 2002).

The available data indicates that for a standardized length of 500 mm, mean mercury levels probably returned to values equivalent to those found in the region's natural lakes 13 to 23 years after impoundment, depending on the reservoir.

3.2.3.7 Less abundant fish species

For cisco and dwarf lake whitefish, the small catches in some years did not allow for as conclusive an assessment (tables 3.2 and 3.3). However, the available data suggests that overall evolution of mercury levels in these species was comparable to that measured in normal lake whitefish and longnose sucker, i.e., a significant increase, followed by a gradual return to values found under natural conditions.

Figure 3.11 Temporal Evolution of Mean Mercury Levels Calculated for 500-mm Burbot in La Grande Complex Reservoirs



Extent of mean levels obtained for a standardized length under natural conditions

* Mean level which is higher than the range of values obtained in natural lakes but does not differ significantly from the mean level measured in at least one natural lake in the region.

** In reservoirs aged 5 and 7 years, the fish were caught at different stations.

*** The vertical lines represent the confidence intervals (95%) for the estimated mean levels.

The different letters indicate that mercury levels are significantly different, since the confidence intervals (95%) do not overlap. Nat. c.: Natural conditions.

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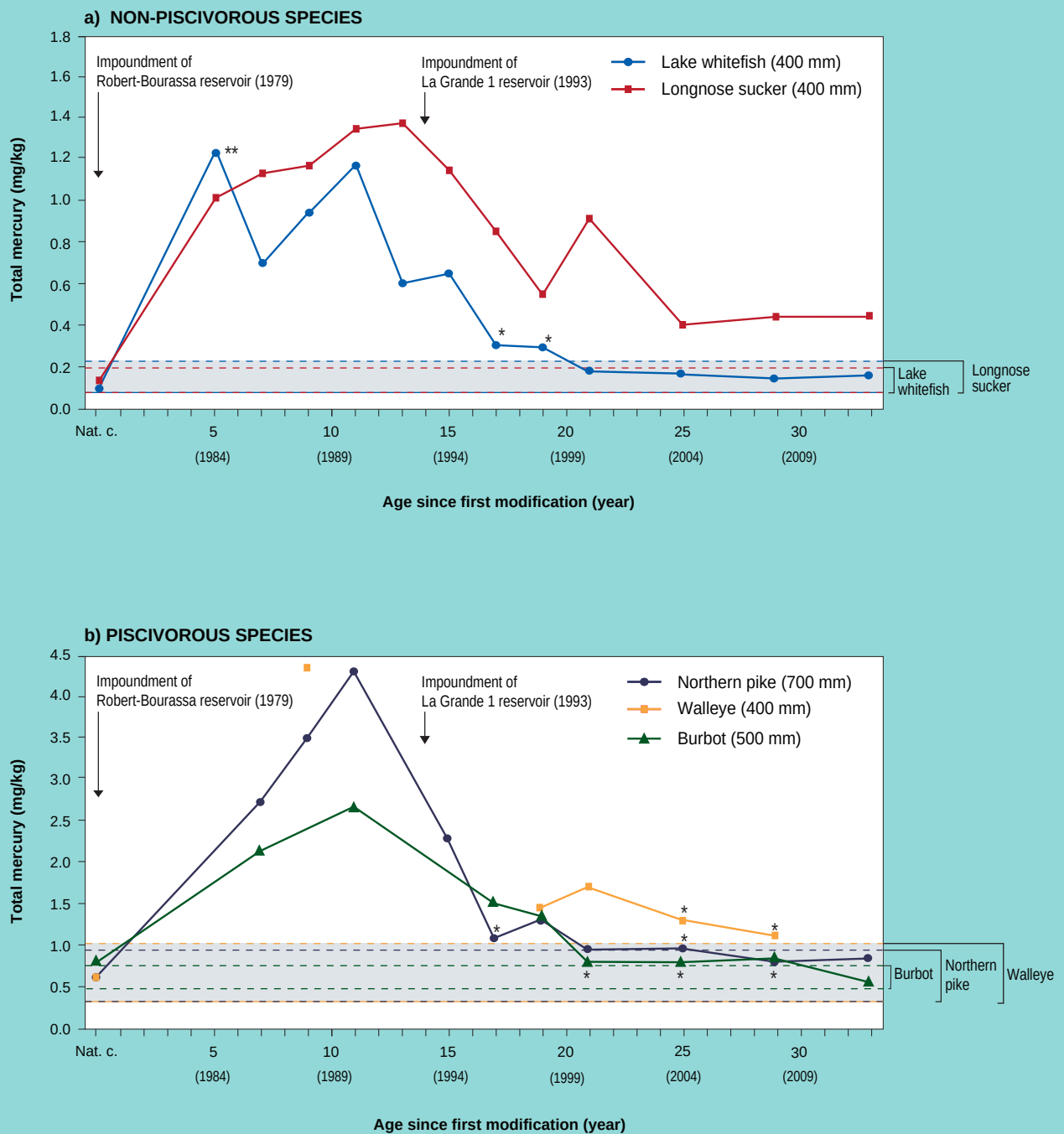
3.2.3.8 La Grande 1 reservoir

Since mercury is exported downstream from reservoirs (sections 3.4.3 and 3.5.4), the changes in fish mercury levels in La Grande 1 were mainly governed by the 1979 impoundment of Robert-Bourassa reservoir, which lies immediately upstream of it. Following impoundment, levels initially increased, then peaked after 9 to 13 years, still before the La Grande 1 reservoir was impounded in 1993 (Figure 3.12 and Table 3.2). Contrary to what was observed in other reservoirs, the impoundment of La Grande 1 reservoir did not increase fish mercury levels. In fact, the decline, which had begun a few years earlier, actually continued (Figure 3.12).

For piscivorous species, the maximum levels recorded in La Grande 1 reservoir ranged from 2.64 to 4.31 mg/kg, depending on the species. This represented a four- to sevenfold increase compared to the levels recorded in natural environments, which is comparable to the increase factor of 4 to 6 obtained for Robert-Bourassa reservoir. For suckers and lake whitefish, the recorded maximum values of 1.13 to 1.31 mg/kg corresponded to an increase factor of 10 to 11. The greater increase in this sector for usually non-piscivorous species resulted from the consumption of small fish, rendered vulnerable to predation following their passage through the turbines at Robert-Bourassa generating station, by specimens caught immediately below the generating station (section 3.3). In lake whitefish, the particularly high level recorded in 1984 is not representative of the reservoir as a whole because it reflects the sampling results from only one station, LG 1 amont, whereas in other years, three stations were sampled.

The mercury levels measured since 2000, i.e., 21 years after the impoundment of Robert-Bourassa reservoir or seven years after that of La Grande reservoir, have not differed significantly from those recorded in natural lakes in the West sector of the La Grande Complex for most species except longnose sucker and walleye. In longnose sucker, the apparent increase noted in 2000 was due to the capture of four specimens immediately downstream of Robert-Bourassa generating station that contained exceptionally high mercury levels (2.39 to 9.32 mg/kg), which point to a piscivorous diet (Therrien and Schetagne, 2001b). In 2004, 2008 and 2012, levels remained slightly higher than those observed in natural lakes (0.40 to 0.43 mg/kg vs. 0.12 to 0.22 mg/kg) and once again, a few seemingly piscivorous specimens containing relatively high mercury levels were caught downstream of Robert-Bourassa reservoir (one to four specimens per year with levels of >1.0 mg/kg). In walleye, the levels obtained since 2004, 25 years after impoundment of Robert-Bourassa reservoir, are not significantly different from those recorded in natural lakes.

Figure 3.12 Temporal Evolution of Mean Mercury Levels in the Main Fish Species in La Grande 1 Reservoir



The absence of an increase in fish mercury levels following the impoundment of La Grande 1 reservoir can be explained by the reservoir's specific characteristic, i.e., a very small land area flooded with a very large annual volume of water (Schetagne *et al.*, 2002).

3.2.3.9 Extent and duration of the increase in fish mercury levels in reservoirs

Non-piscivorous species

Depending on the species and reservoir, mercury levels in non-piscivorous fish peaked 4 to 11 years after impoundment, which represents a two- to sixfold increase over the values recorded in natural lakes. They then gradually subsided and, 10 to 20 years after impoundment, reached levels equivalent to those measured in natural lakes in the region.

This resorption period is in line with the results obtained at other reservoirs in Québec (Outardes 2, Manic 1 and Manic 5) and Labrador (Smallwood), where mercury levels in lake whitefish and other non-piscivorous species returned to values within the range of mercury levels recorded in natural lakes 10 to 20 years after the environment was modified (LGL Limited, 1993; Schetagne *et al.*, 1996, 2002). In addition, Bodaly *et al.* (2007) demonstrated that at reservoirs in Manitoba (Southern Indian Lake and Notigi), mercury levels in lake whitefish with a fork length of 350 mm generally peaked six years after impoundment and that a period of 10 to 20 years had to elapse before they returned to values akin to those recorded in nearby natural lakes.

Piscivorous fish

Depending on the species and reservoir, mercury levels in abundant piscivorous fish species in the La Grande complex (northern pike, walleye and lake trout peaked 9 to 14 years after impoundment and usually returned to values equivalent to those recorded in natural lakes 20 to 30 years after flooding, except for northern pike in Robert-Bourassa reservoir. In the latter case, the consumption of piscivorous fish by northern pike probably helped delay the return period.

In the case of burbot, the return to values representative of those in natural lakes seemed to occur more quickly, i.e., 15 to 20 years after impoundment.

Data collected at other reservoirs in Québec, Labrador and Finland also suggests that in northern pike, the return to mercury levels within the range of those found in natural lakes occurs 25 to 30 years after impoundment (Verta *et al.*, 1986; Schetagne *et al.*, 2002). At reservoirs in Manitoba, mean mercury levels in 550-mm northern pike and 400-mm walleye (fork length) peaked 2 to 8 years after impoundment and returned to values equivalent to those recorded in natural lakes 10 to 23 years after flooding (Bodaly *et al.*, 2007).

In reservoirs that were impounded twice, such as La Grande 4, Laforge 1 and Opinaca, a second increase in fish mercury levels was usually observed.

The phenomenon is temporary, because the main mechanisms involved in the production of methylmercury and its transfer to fish are intense shortly after reservoir impoundment, but gradually diminish five to eight years thereafter. The main mechanisms at work are as follows:

- Increased bacterial methylation of mercury and its passive diffusion through the water column (a trend that tapers off due to the exhaustion of labile organic components of flooded vegetation and soils).
- The release of nutrients that stimulate autotrophic production; the resulting organic matter is particularly labile and promotes additional mercury methylation (which also diminishes because of the exhaustion of easily decomposable terrigenous matter).
- Erosion of the flooded organic matter in the drawdown zone, which makes fine, mercury-rich organic particles available for aquatic filter feeders (this erosion is completed after several cycles of fluctuating water levels).
- The active transfer of mercury by aquatic insects burrowing in flooded soil that is rich in methylmercury (which decreases after a certain period of time due to the exhaustion of decomposable matter).
- Periphyton development on flooded soils and vegetation, which promotes the methylation of mercury and its active transfer to fish via aquatic insects and zooplankton feeding on it (which decreases because of the exhaustion of readily decomposable terrigenous matter).

3.2.4 Spatial variability within reservoirs

The data collected on fish mercury levels in reservoirs varies somewhat from station to station. For example, Table 3.4 illustrates the results obtained for the four main species of fish in Robert-Bourassa reservoir. For non-piscivorous species, these differences mainly occur during the first years following impoundment and then decrease.

The highest levels for the various species were not always recorded at the same station: the highest value for longnose sucker was registered at Bereziuk station in 1982, but LG 3 aval station showed the highest concentration for lake whitefish in 1982 and 1984. For piscivorous species, more significant differences were observed during the first years of sampling and then decreased in northern pike, but remained high in walleye, even 33 years after impoundment. Over the years, all stations in turn exhibited the highest levels for northern pike but there was no discernable trend, whereas for walleye, the data is too limited to detect any particular pattern. Fish movement within the reservoir, which can be extensive, may partially explain this lack of pattern.

The spatial variability observed in Robert-Bourassa reservoir is similar to that in the other reservoirs, except La Grande 3. There, Roy station displayed systematically higher levels than the other two stations. This station, which is not very representative of the reservoir as a whole, is located in a large, shallow bay where water residence time is much longer than for the rest of the reservoir, a situation that enhances mercury bioaccumulation (Schetagne *et al.*, 2002).

3.2.5 Factors that explain the differences observed between reservoirs

Although mercury levels in the main species of fish showed the same pattern of change in all reservoirs, some differences were observed between the reservoirs with regard to peak levels and the period of time required to reach them and to return to levels equivalent to those in natural environments. Note that mean mercury levels in lake whitefish and northern pike of standardized length are generally lower in East sector reservoirs (La Grande 4, Caniapiscau, Laforge 1 and Laforge 2) than in those in the West sector (Robert-Bourassa, Opinaca and La Grande 3) (tables 3.2 and 3.3).

These differences may be mainly attributable to certain physical and hydraulic characteristics of the reservoirs. The main factors that contribute to higher mercury levels are a large land area flooded, a low annual volume of water passing through the reservoir, a short filling time and a low percentage of flooded land located in the drawdown zone. Schetagne *et al.* (2002) discuss these factors in greater detail.

Table 3.4 Spatial variability of Estimated Mercury Levels (mg/kg) in the Main Species of Fish of Standardized Length in Robert-Bourassa Reservoir

Species (Standardized length)/ Reservoir age (year)	Station				
	LG 2 amont (G2 400)	Bereziuk (G2 403)	Coutaceau (G2 404)	Toto (G2 405)	LG 3 aval (G2 406)
Lake whitefish (400 mm)					
3 years (1982)	0.37 (c)	0.45 (bc)	0.52 (b)	0.49 (b)	0.67 (a)
5 years (1984)	0.56 (b)	0.47 (c)	0.56 (b)	0.56 (b)	0.65 (a)
11 years (1990)	0.38 (a)	0.35 (a)	0.38 (a)	0.38 (a)	0.33 (a)
21 years (2000)	0.15 (b)	0.21 (a)	0.15 (b)	0.22 (a)	0.15 (b)
25 years (2004)	0.15 (b)	-	0.20 (ab)	0.20 (a)	-
29 years (2008)	0.17 (a)	-	0.16 (a)	0.17 (a)	-
33 years (2012)	0.20 (a)	-	0.18 (a)	0.18 (a)	-
Longnose sucker (400 mm)					
3 years (1982)	0.37 (b)	0.46 (a)	0.37 (b)	0.35 (b)	0.37 (b)
5 years (1984)	0.60 (a)	0.60 (a)	0.70 (a)	0.60 (a)	0.74 (a)
21 years (2000)	0.21 (a)	-	0.21 (a)	0.23 (a)	0.28 (a)
Northern pike (700 mm)					
3 years (1982)	1.57 (a)	1.10 (bc)	1.22 (b)	1.52 (a)	0.99 (c)
7 years (1986)	2.86 (a)	2.86 (a)	2.22 (b)	2.21 (b)	2.33 (b)
13 years (1992)	3.19 (b)	3.19 (b)	3.19 (b)	2.64 (b)	4.46 (a)
21 years (2000)	2.32 (a)	1.78 (b)	2.26 (a)	2.32 (a)	2.32 (a)
25 years (2004)	1.61 (b)	-	2.22 (a)	1.56 (b)	-
29 years (2008)	1.34 (a)	-	1.60 (a)	1.59 (a)	-
33 years (2012)	1.30 (b)	-	1.74 (a)	1.64 (a)	-
Walleye (400 mm)					
3 years (1982)	1.68 (b)	2.15 (a)	1.87 (b)	1.87 (b)	2.44 (a)
5 years (1984)	-	2.78 (a)	2.35 (b)	2.78 (a)	2.06 (b)
13 years (1992)	-	-	2.60 (a)	2.69 (a)	-
21 years (2000)	-	N.A.	1.61 (a)	1.21 (b)	-
25 years (2004)	-	-	1.15 (a)	1.09 (a)	-
29 years (2008)	-	-	1.30 (a)	0.83 (b)	-
33 years (2012)	1.62 (a)	-	1.24 (ab)	0.97 (b)	-

Note: The different letters indicate a significant difference ($\alpha=0.05$) in mean mercury levels measured at different stations for each year and each species.

N.A. = Not applicable; the range of values is not cross-referenced with standardized length.

-.: No available data or insufficient specimens ($n < 10$).

3.2.6 Main lessons learned from monitoring reservoirs

The following conclusions result from monitoring fish mercury levels in reservoirs in the La Grande complex:

- Following reservoir impoundment, fish mercury levels increase by factors varying from two to eight compared with levels recorded in natural environments.
- Peak levels are generally reached 4 to 11 years after impoundment in non-piscivorous species and after 9 to 14 years in piscivorous species.
- In non-piscivorous species, peak values often remain lower than the Canadian marketing standard for fishery products (0.5 mg/kg of total mercury), but sometimes slightly exceed it, whereas in piscivorous species, peak levels may be two to nine times higher than the standard.
- The increases are temporary, however, and the return to levels representative of natural lakes is generally completed 10 to 20 years after impoundment in non-piscivorous species and 20 to 30 years thereafter in piscivorous species, provided there is no additional impoundment.
- All the reservoirs exhibit the same general pattern of change in fish mercury levels, and the slight variations observed may be explained by physical and hydraulic characteristics particular to each reservoir, such as the land area flooded, annual volume of water flowing through the reservoir, filling time and percentage of flooded land area located in the drawdown zone. Additional factors may be water temperature, the density and quality of decomposable organic matter, and the diet of the fish.
- Mercury levels in the main species of fish often vary significantly from one station to another in the same reservoir, but without any discernable pattern other than at certain stations that have specific characteristics.
- Fish mercury level changes in La Grande 1 reservoir, where the land area flooded is relatively small compared with the annual volume of water, are strongly influenced by mercury input from Robert-Bourassa reservoir immediately upstream.

3.3 **Immediately downstream of reservoirs**

The areas immediately downstream of reservoirs undergo similar physical, chemical and biological changes as the actual reservoirs, as they are influenced by the water flowing down from the reservoirs.

3.3.1 Non-piscivorous species

Particular attention was paid to areas immediately downstream of the reservoirs, where usually non-piscivorous fish may have changed their diet and begun to ingest small fish that had become more vulnerable to predation due to their passage through turbines or spillways (Brouard and Doyon, 1991; Brouard *et al.*, 1994; Schetagne *et al.*, 2002). This change in diet immediately downstream of a reservoir can sometimes result in higher mercury levels there than in the upstream section.

Figure 3.13 provides a comparison of mercury levels measured above and immediately below generating stations or control structures for a non-piscivorous species, lake whitefish. For all sampling years except the last one, mercury levels in lake whitefish were significantly higher immediately downstream of Robert-Bourassa generating station. The maximum mean level downstream for specimens of standardized length (1.16 mg/kg), and the greatest difference observed between locations above and below this generating station (0.85 mg/kg), were reached in 1990; these values subsequently declined, in accordance with the decrease in levels measured in Robert-Bourassa reservoir.

This phenomenon was observed primarily in large specimens (>450 mm) which, downstream, mainly ingest small fish from the reservoir (up to 84% of stomach volume, on average). The mercury levels recorded for these large specimens, which ranged from about 2.5 to 4.5 mg/kg, are typical of those measured in northern pike in Robert-Bourassa reservoir.

In the other reservoirs, the differences were smaller and often not significant. Greater differences were more often observed in the reservoirs of the West sector (in 50% of cases for Opinaca and 85% for La Grande 1) than in those of the East sector (20% for Caniapiscou and 45% for Laforge 1). In all cases, the differences became smaller over time and the mean mercury levels measured downstream all returned to those representative of natural lakes.

The lower mercury levels recorded immediately downstream of certain reservoirs could be mainly due to the following factors:

- The absence of turbines (as was the case downstream of Opinaca reservoir until 2013, as well as below Caniapiscou reservoir prior to 1993).
- A lower head in Opinaca, La Grande 1, Caniapiscou and Laforge 1 reservoirs (27.5 m to 37.5 m), compared with 137.2 m in Robert-Bourassa reservoir (Table 1.1; Schetagne *et al.*, 2002).

Figure 3.13 Comparison of Mercury Levels in 400-mm Lake Whitefish Immediately Above and Below Generating Stations or Control Structures

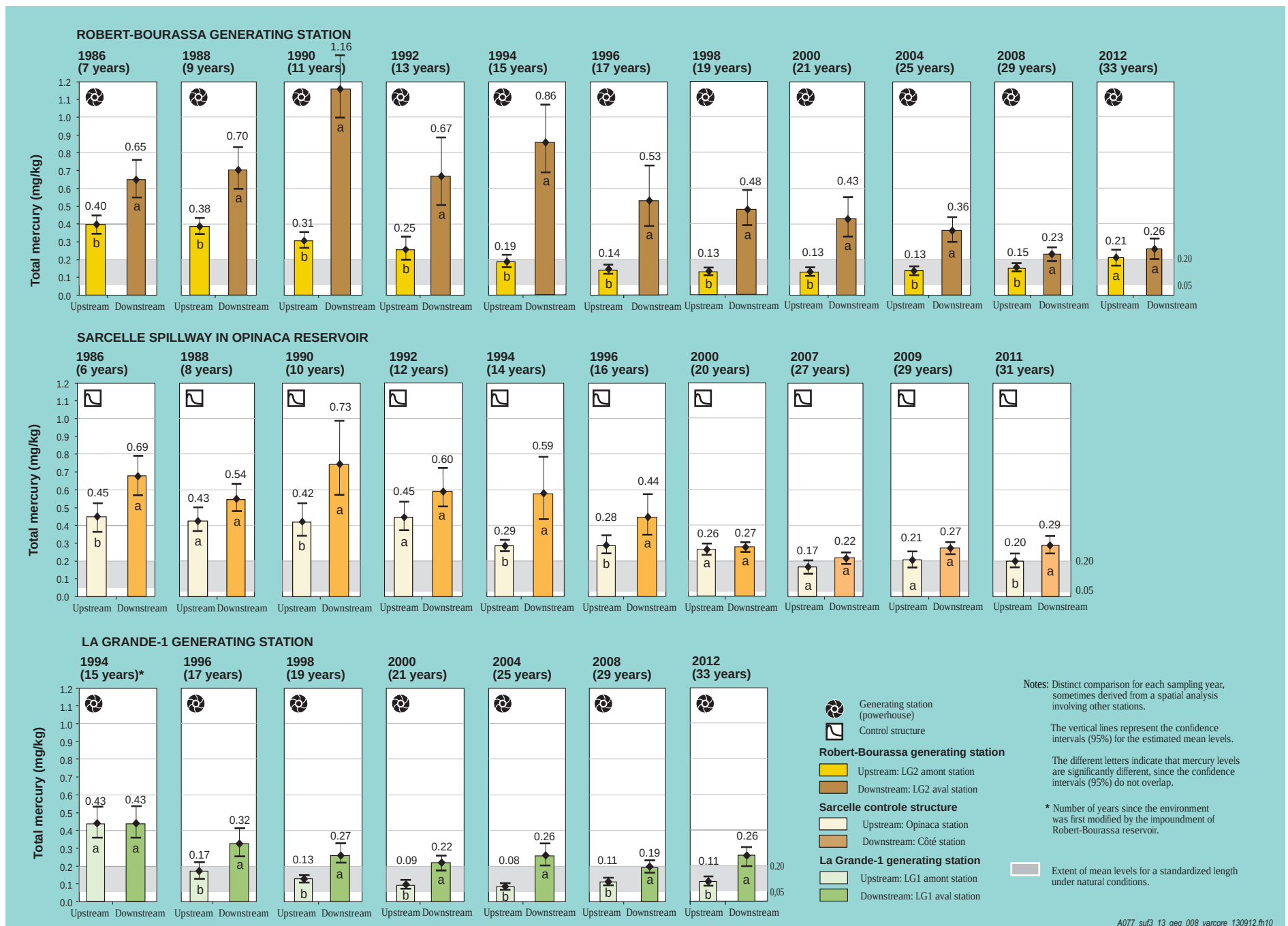
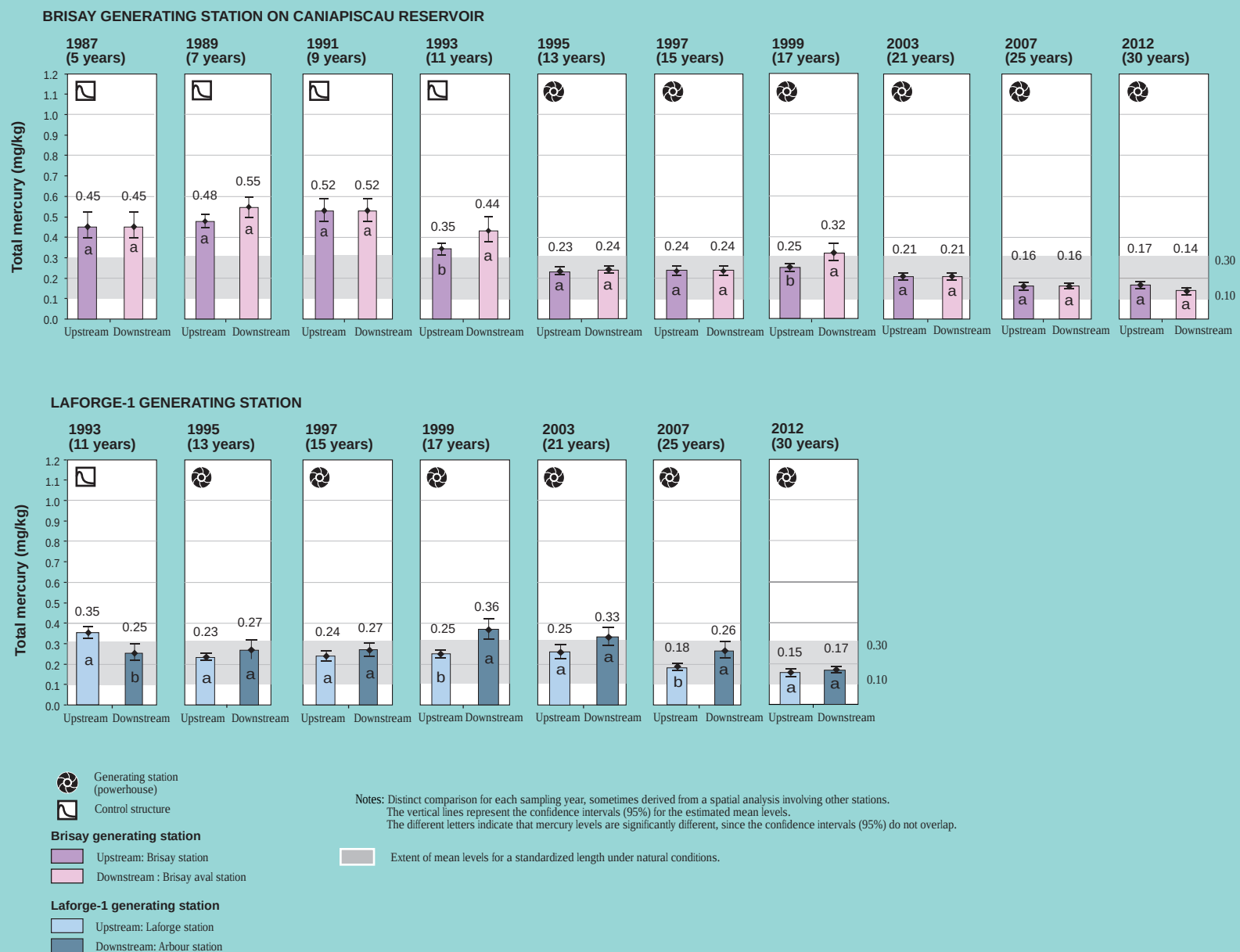


Figure 3.13 Comparison of Mercury Levels in 400-mm Lake Whitefish Immediately Above and Below Generating Stations or Control Structures
(cont.)



These two factors likely meant that the fish entrained downstream were less affected by their passage through the water transfer structures and consequently, less vulnerable to predation by usually non-piscivorous species downstream (Doyon, 1998).

Higher mercury levels below the generating stations were also observed in another non-piscivorous species, longnose sucker, but the differences between the levels measured up- and downstream were generally smaller. However, as indicated in section 3.2.3.8, the fact that a few longnose sucker containing very high mercury levels were caught on a regular basis suggests that this species occasionally preyed on other fish in the area immediately downstream of Robert-Bourassa generating station.

3.3.2 Piscivorous species

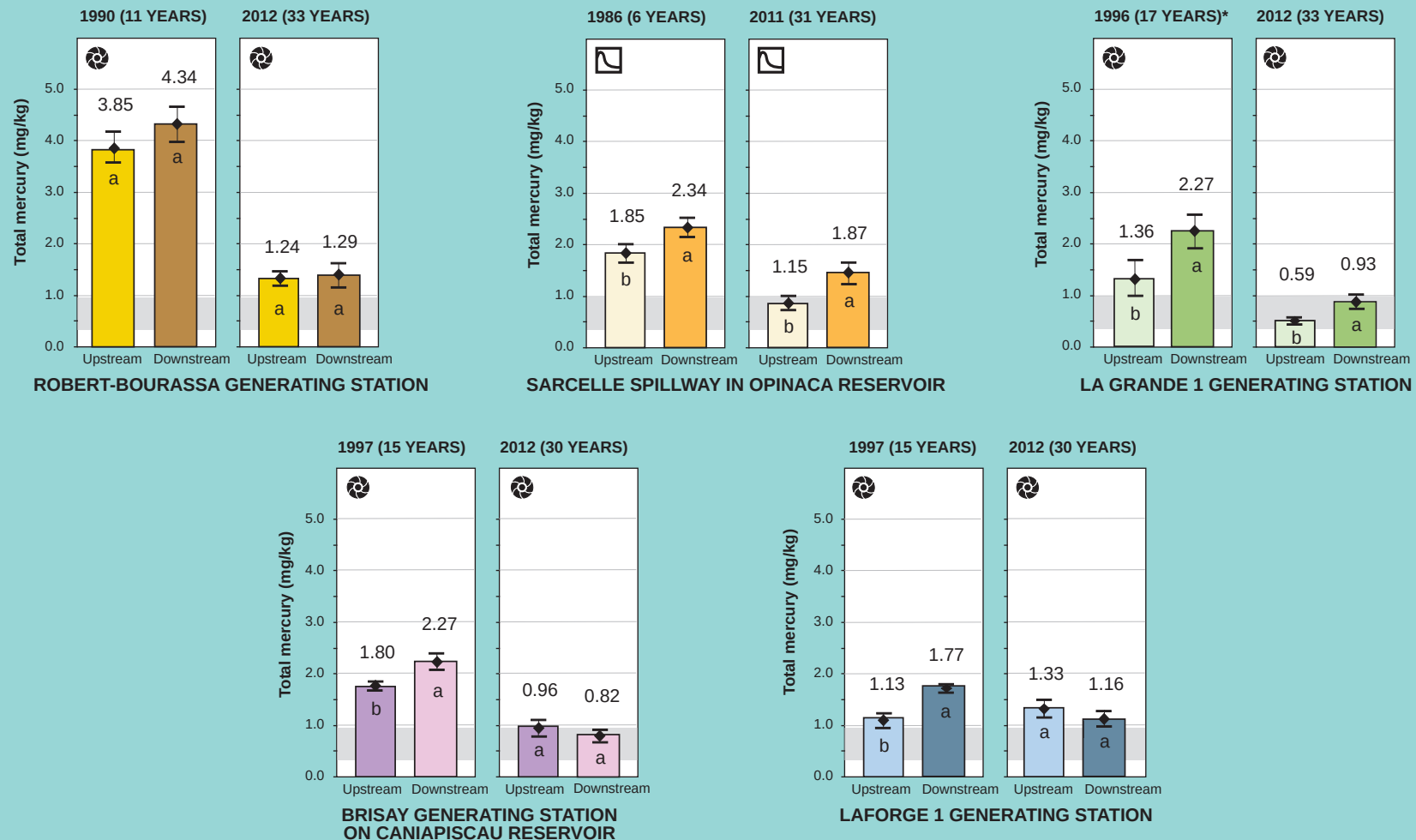
In normally piscivorous species, the increase in mercury bioaccumulation immediately downstream of the reservoirs is proportionally less pronounced than in lake whitefish. A greater bioaccumulation immediately below generating stations is less likely to occur in piscivorous species since they always have this type of diet. In addition, since the change in diet of lake whitefish is observed mainly in specimens longer than 450 mm, northern pike, even large specimens, are little affected as they mainly consume fish less than 450 mm in length (Doyon *et al.*, 1996; Doyon and Schetagne, 2000).

The three figures below provide comparisons for three piscivorous species, northern pike, walleye and lake trout, for reservoirs where such comparison was possible and for the year showing the greatest difference between the levels measured up- and downstream, and during the last sampling year.

Northern pike

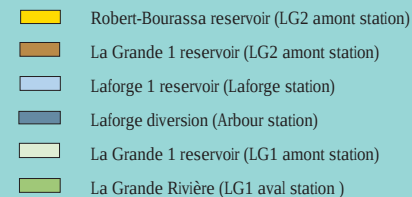
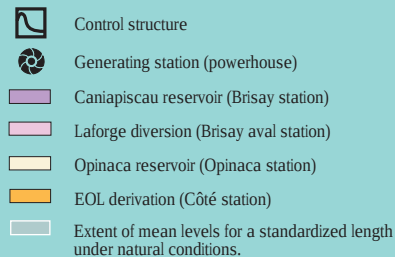
The significantly higher mercury levels sometimes measured in northern pike (Figure 3.14) immediately below certain generating stations or control structures are likely due to higher levels in their prey. Such differences were observed in all reservoirs except Robert-Bourassa. In Robert-Bourassa, Caniapiscou and Laforge 1 reservoir, no difference was recorded during the last year of sampling.

Figure 3.14 **Comparison of Mercury Levels in 700-mm Northern Pike Upstream and Immediately Downstream of Generating Stations or Control Structures**



* Number of years since the environment was first modified by the impoundment of Robert-Bourassa reservoir.

Notes: Distinct comparison for each sampling year, sometimes derived from a spatial analysis involving other stations. The vertical lines represent the confidence intervals (95%) for the estimated mean levels. The different letters indicate that mercury levels are significantly different, since the confidence intervals (95%) do not overlap. The results shown correspond to the years when the differences between levels measured upstream and downstream were greatest, and to the last sampling year.



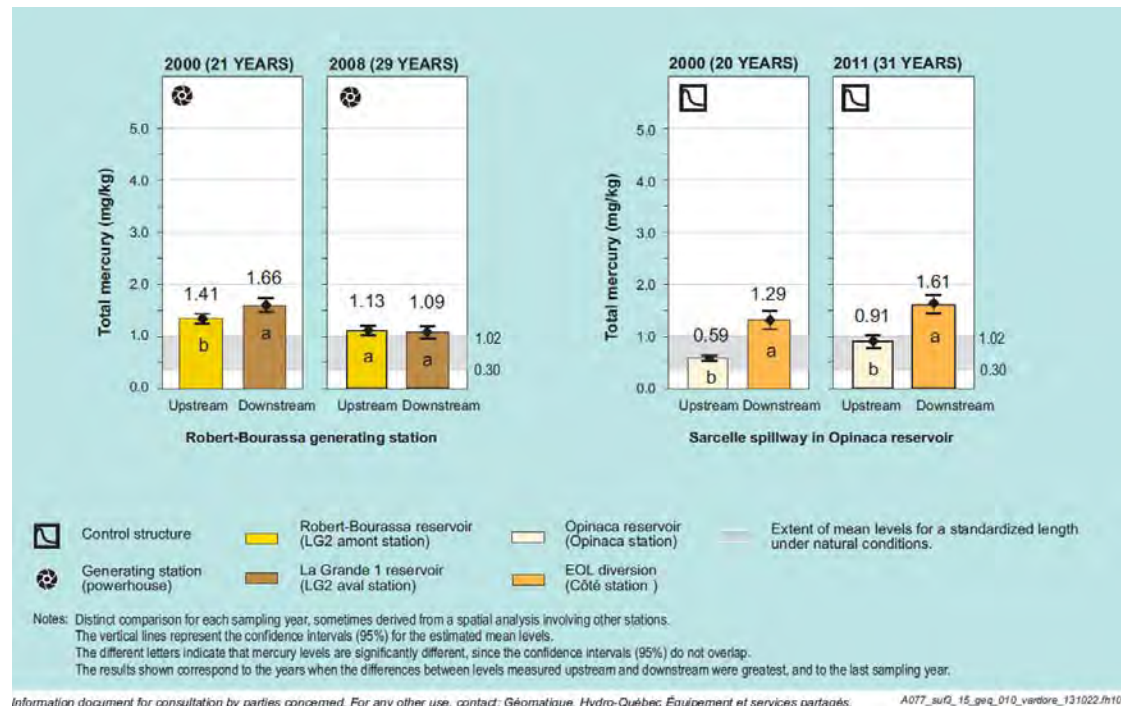
Walleye

In walleye (Figure 3.15), the mercury levels recorded at the two stations on either side of Robert-Bourassa generating station were no longer significant in 2008, 29 years after impoundment, whereas a difference was still observed in Opinaca reservoir, where the high values recorded in 2011 were associated with the recent impoundment (2005–2006) of Eastmain 1 reservoir (section 3.2.3.4).

Lake trout

The same phenomenon was observed in lake trout, i.e., significant differences between the upstream and downstream areas that decreased over time (Figure 3.16). However, a reversal was sometimes observed in this species, with upstream levels being higher than those measured downstream. This occurred once in each reservoir—in 1993 in Laforge 1 reservoir (Figure 3.16) and in 1997 in Caniapiscau (3.11 mg/kg upstream vs. 2.20 mg/kg downstream) for a length of 700 mm.

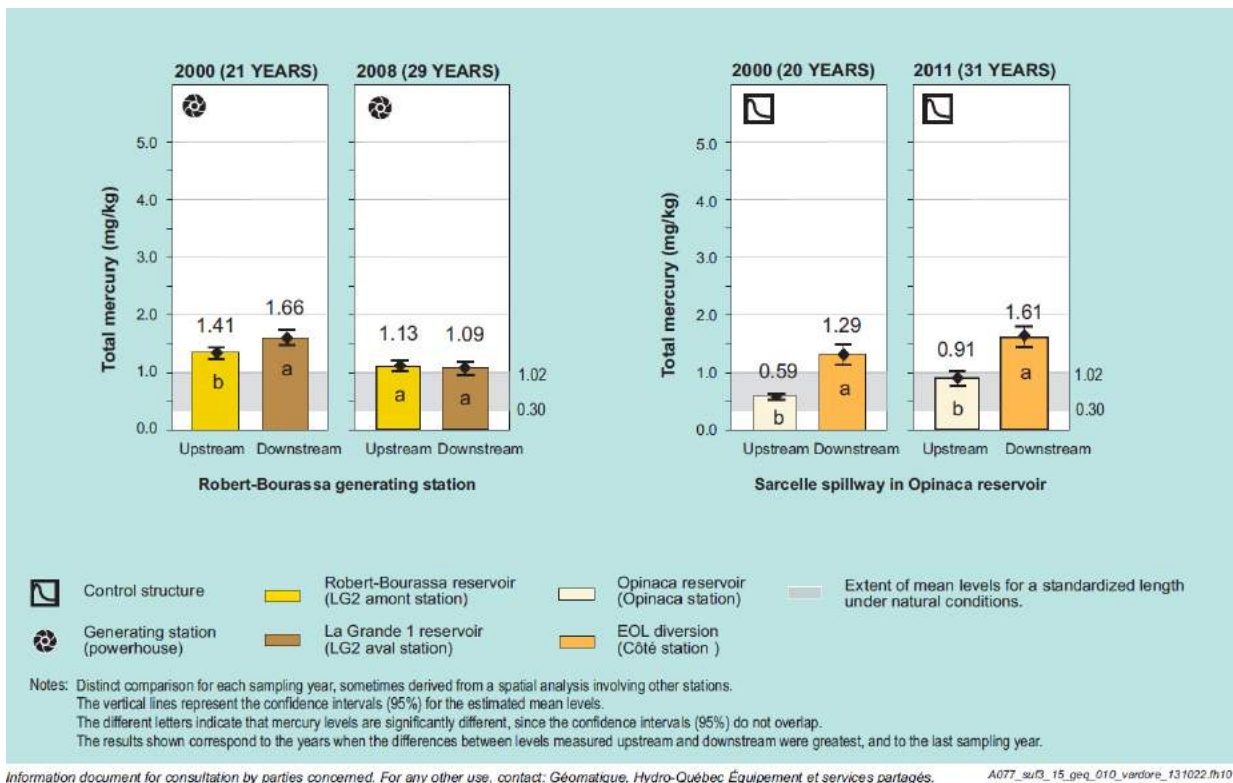
Figure 3.15 Comparison of Mercury Levels in 400-mm Walleye Upstream and Immediately Downstream of Generating Stations or Control Structures



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Figure 3.16 Comparison of Mercury Levels in 700-mm Lake Trout Upstream and Immediately Downstream of Generating Stations or Control Structures



3.3.3 Main lessons learned from monitoring immediately downstream of reservoirs

The main lessons learned from monitoring fish mercury levels immediately downstream of reservoirs in the La Grande complex are as follows:

- For lake whitefish, and sometimes also for longnose sucker, mercury levels are significantly higher immediately below generating stations and control structures than those measured in the reservoirs above these structures. This reflects a change in diet for these usually non-piscivorous species which become piscivorous as a result of the great availability of small fish made locally more vulnerable to predation by passing through the turbines or control structures.
- This change in diet occurs mainly in large specimens of lake whitefish (>450 mm).
- The difference between mercury levels measured above and below the different structures in usually non-piscivorous species appears to depend on the structures' characteristics, which make the fish passing through them more or less vulnerable to predation. The head and the presence of turbines seem to be determining factors.

- Maximum mercury levels and differences between the levels measured above and below the structures decrease at the same time as those in the reservoirs. In non-piscivorous species, the mean levels for specimens of standardized length are now equivalent to or lower than the allowable limit for unrestricted consumption (0.29 mg/kg; section 4.3) and levels in the East sector reservoirs have returned to values equivalent to those measured in the region's natural lakes.
- In piscivorous species, the differences between the mercury levels measured above and below generating stations or control structures are smaller and often not significant, as these species already have a piscivorous diet.

3.4 Diversions

3.4.1 Physical, chemical and biological changes

The following information is derived mainly from Messier *et al.* (1985), Roy *et al.* (1986), SEBJ (1987), Chartrand *et al.* (1994) and Deslandes *et al.* (1994).

The Eastmain-Opinaca-La Grande (EOL) and Laforge diversions are characterized by inflows from reservoirs and a local rise in water level, which leads to the flooding of terrestrial organic matter. The water in Boyd and Sakami lakes rose by respective average of 3.2 m and 1.6 m (Schetagne *et al.*, 2005). The flow at the outlet of Lac Sakami increased from 200 m³/s to 1,000 m³/s after the Eastmain, Opinaca and Petite Rivière Opinaca rivers were diverted in 1980, and then increased again to 1,500 m³/s following the partial diversion of the Rupert in 2009 (which did not, however, cause an increase in the maximum water level). The flow along the Laforge diversion increased from 30 m³/s to about 800 m³/s after the Rivière Caniapiscau was diverted 1982. The flooded area, which covered 125 km² at the time of diversion, increased to 798 km² with the impoundment of Laforge 1 reservoir in 1993.

The EOL diversion was marked by a number of phenomena with adverse effects on water quality: increased flow, oxygenation of water in rapids, erosion of clayey banks and flooding of forest soil. Through their combined action, the physicochemical characteristics of the water remained relatively stable, except for parameters related to erosion and nutrients. The increase in nutrients was also reflected in a temporary increase in phytoplankton biomass. Fishing yields tripled when flows increased substantially in 1981 (from 9 to 28.3 fish/net-day). They remained very high thereafter, at more than 18.4 fish/net-day (Therrien *et al.*, 2002). Walleye is especially responsible for the increase, as this species has benefited from the warmer, more turbid water.

3.4.2 Changes in fish mercury levels in the Eastmain-Opinaca-La Grande diversion

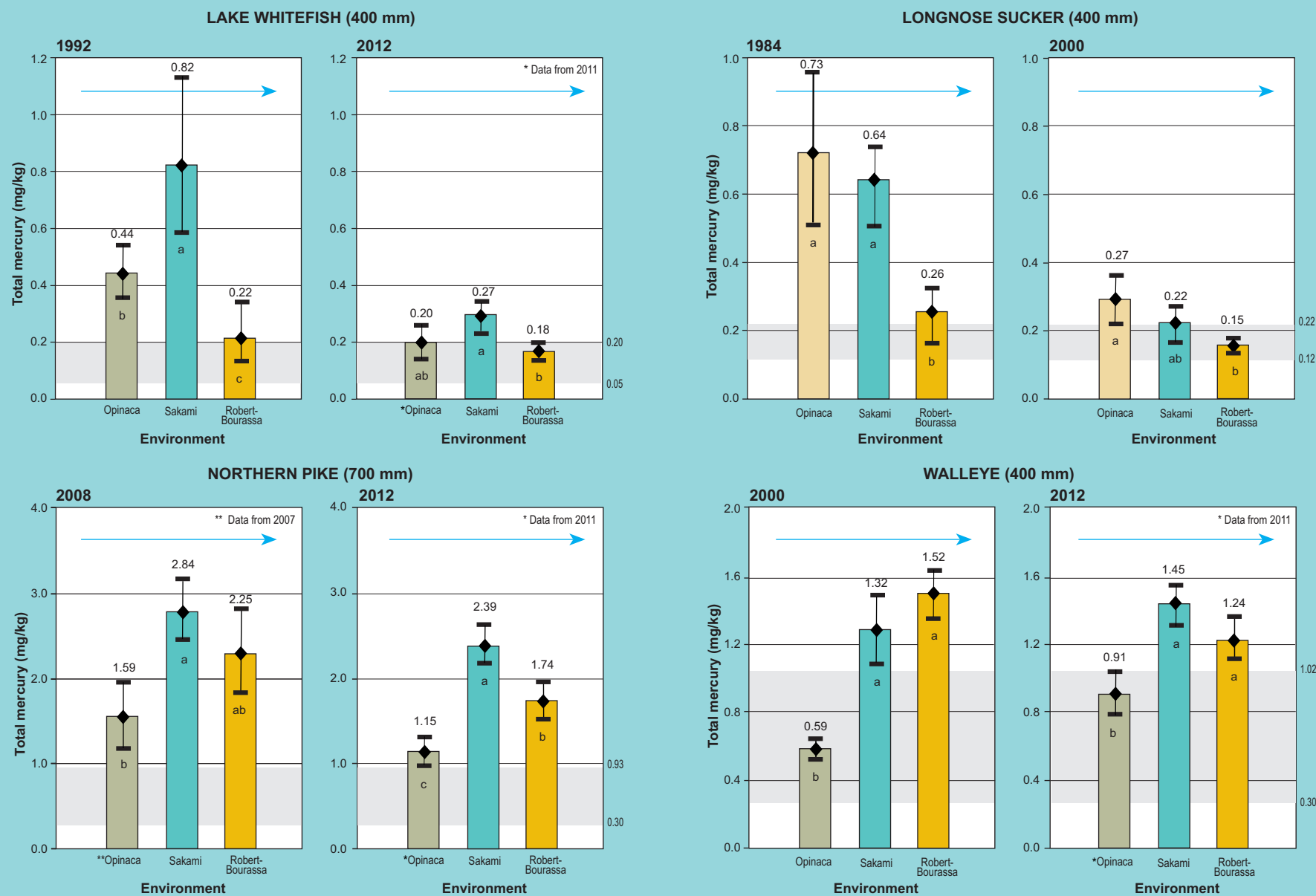
The EOL diversion channels water from the watersheds of the Eastmain, Opinaca and Petite Rivière Opinaca rivers into that of the Grande Rivière. Three stations were sampled regularly along the EOL diversion until 2000 (Map A, in pocket). Since monitoring was optimized, only Sakami station, which is located at the midpoint of the diversion, on Lac Sakami, and set back from the main flow channel, has been used (Therrien and Schetagne, 2005b). Spatial variations in mercury levels along the EOL diversion are now measured by comparing the data from Sakami station with that collected at two stations located at the up- and downstream extremities of the diversion, i.e., Opinaca station in Opinaca reservoir and Coutaceau station in Robert-Bourassa reservoir.

Figure 3.17 shows the data collected on the four main species during the year when the biggest difference was observed and during the last sampling year. Note that the comparison of the data collected over two consecutive years (2007 and 2008, then 2011 and 2012) is variable because year-to-year fluctuations are now low in these two areas, which were modified 32 years ago.

In non-piscivorous species (lake whitefish and longnose sucker), the mercury levels recorded at Sakami station are similar to or higher than those measured in Opinaca reservoir, whereas the levels recorded at Coutaceau station in Robert-Bourassa reservoir are lower. This situation, which reflects mercury transfer from the reservoir and as a result flooding of the land around Lac Sakami, was also observed in the data from the three stations along the diversion monitored until 2000 (Schetagne *et al.*, 2002). As was the case in Opinaca reservoir, mean mercury levels in lake whitefish and longnose sucker recorded at Sakami station returned to values equivalent to those found in the region's natural lakes 20 years after the environment was modified.

In piscivorous species (northern pike and walleye), the highest mercury levels were usually recorded at Sakami and Coutaceau stations. Monitoring conducted in previous years had already shown that mercury levels in fish of all species recorded at Côté and Ladouceur stations, which are located to either side of Sakami station, were usually lower than those measured at Sakami station (Schetagne *et al.*, 2002).

Figure 3.17 **Spatial Variability in Mercury Levels in the Main Species of Fish of Standardized Length Caught along the Eastmain-Opinaca-La Grande Diversion**



The generally lower mercury levels measured at Coutaceau station may be partly due to the presence of Lac Sakami, which likely caused mercury levels to increase over those recorded in Opinaca reservoir because of additional local flooding, and partly due to the following phenomena:

- Sedimentation of a portion of the mercury-rich suspended particulate matter from Opinaca reservoir or from the erosion of the flooded banks of lakes Boyd and Sakami
- Assimilation of mercury by the lake's zooplankton, which filtered this particulate matter
- Consumption by the lake's fish of zooplankton and other aquatic organisms that play a role in mercury transfer, such as insect larvae

These three processes may have resulted in reduced mercury transfer downstream of Lac Sakami, just as the presence of Lac Cambrien may have led to a decrease in mercury transfer farther downstream in the Rivière Caniapiscau (section 3.5.4).

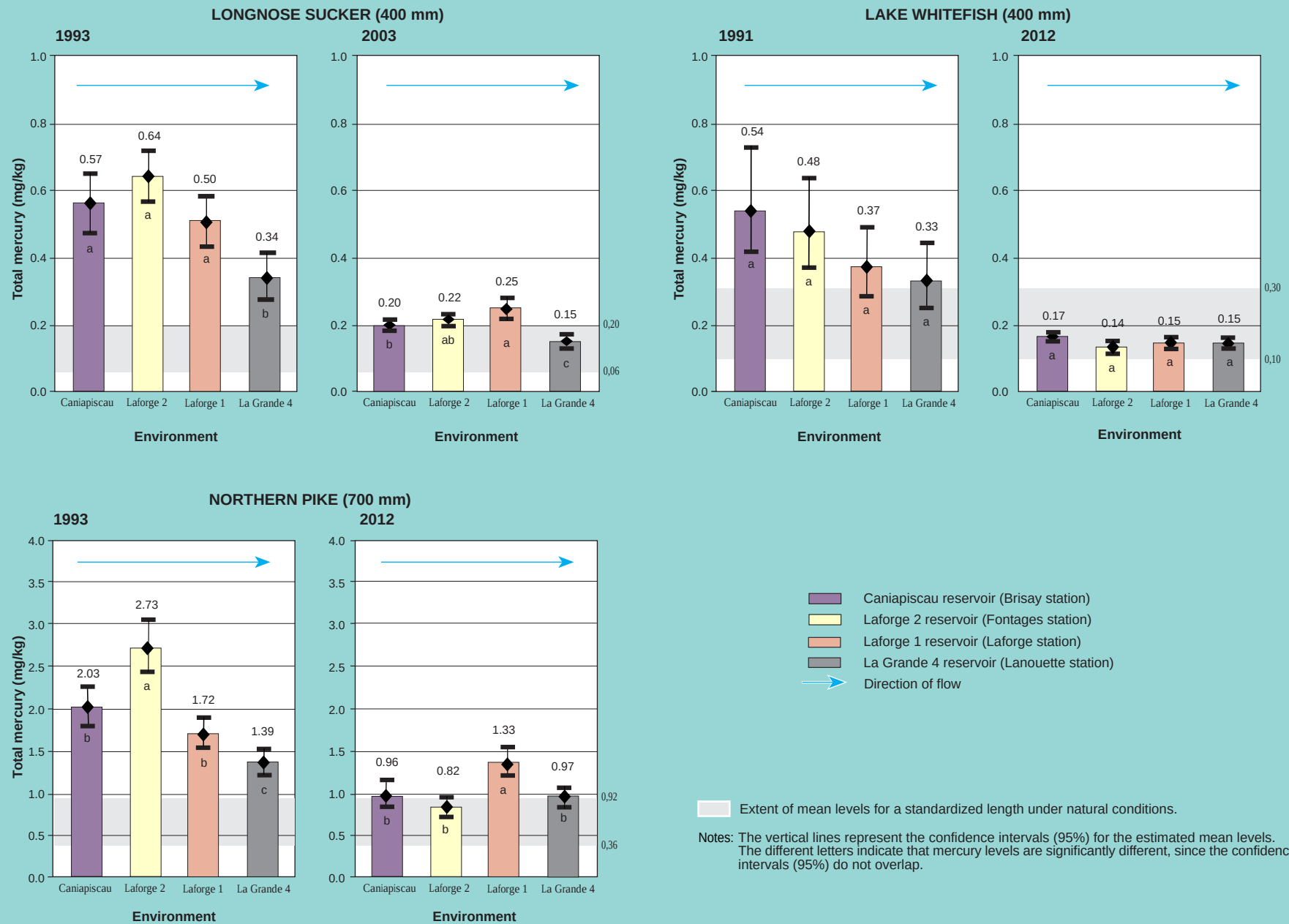
3.4.3 Changes in fish mercury levels in the Laforge diversion

The Laforge diversion channels water from the Rivière Caniapiscau watershed into that of the Grande Rivière. Along this diversion, the water flows successively through Caniapiscau, Laforge 2, Laforge 1 and La Grande 4 reservoirs, all of which were impounded around 1982 (Map 1.1 and insert pocket Map A).

Figure 3.18 illustrates the spatial evolution of mean mercury levels recorded in the main species of fish during the year when the greatest difference was observed (usually corresponding to the years when levels were highest) and during the last sampling year, from upstream to downstream, at the stations in each reservoir.

For the three sufficiently abundant species, there was usually a decrease from up- to downstream when the differences between mean mercury levels were high, and very few significant differences between the stations during the last sampling year. As was the case for the results obtained in previous years (Doyon and Schetagne, 2000), which are summarized in Schetagne *et al.* (2002) and Therrien and Schetagne (2004, 2005b, 2008a), there was no cumulative effect in mercury bioaccumulation in fish throughout the reservoirs impounded in series. Indeed, the lowest mercury levels were usually found in the last reservoir in the series, La Grande 4.

Figure 3.18 **Spatial Variability in Mercury Levels in the Main Species of Fish of Standardized Length Caught along the Laforge Diversion**



This absence of any cumulative effect corroborates the results obtained downstream of lakes Cambrien (on the Rivière Caniapiscau; section 3.5.4) and Sakami (EOL diversion; section 3.4.2), and shows that the presence of a large body of water (lake or reservoir) greatly reduces the downstream distance over which mercury export has a significant effect. Note that the increase observed in northern pike in 2012 between Laforge 2 and Laforge 1 reservoirs was likely due to the second impoundment of Laforge 1 in 1993.

Lastly, the mean mercury levels recorded in all species during the last sampling year no longer differ significantly from those measured in certain natural lakes in the region.

3.4.4 Main lessons learned from monitoring the diversions

The main lessons learned from monitoring fish mercury levels in the EOL and Laforge diversions in the La Grande complex are:

- The pattern of change in fish mercury levels in the diversions confirms that mercury is exported from the reservoirs and transferred to fish downstream.
- In some bodies of water along these flow routes, mercury levels may be higher than those in the reservoir providing the inter-basin transfer because of the combined effect of mercury export downstream of the reservoir and additional mercury production from the local flooding of land areas.
- The presence of a large, slow-flowing body of water (lake or reservoir) along the diversion route greatly reduces mercury transfer to fish farther downstream, because it favors sedimentation of the methylmercury adsorbed to suspended particulate matter, as well as local predation on plankton, insects and small fish descending from upstream.
- There is no cumulative increase in fish mercury levels when a series of reservoirs is built along the same flow route, as the influence of a given reservoir is confined to the reservoir located immediately downstream of it.

3.5 **Reduced-flow rivers**

3.5.1 Physical, physicochemical and biological changes

The following information is derived mainly from Lalumière *et al.* (1985), Roy *et al.* (1986), Belzile (1990), Groupe Environnement Shooner inc. (1993), Chartrand *et al.* (1994), Deslandes *et al.* (1994) and Waska Ressources and Biofilia (2013).

Development of the La Grande complex involved diverting eight rivers: the Caniapiscou and Vincelotte in the East sector and the Eastmain, Opinaca, Petite Rivière Opinaca, Lemare, Nemiscou and Rupert in the West sector. The diversions created six reduced-flow stretches, three of which (the Eastmain, Opinaca and Petite Rivière Opinaca) received no inflows from above the cutoff point.

Since impoundment of the Rupert diversion bays, the Lemare and Nemiscou rivers have received 100% of their baseline flow from the tailbay by way of four instream flow release structures. The Rupert now receives about 30% of its baseline flow, which is modulated over the hydrological seasons, via the Rupert forebay. In the reduced-flow stretch of the Vincelotte, an instream flow of 8 m³/s was maintained from 1982 to 1992. Between June and October 1984 and in June and July 1985, the reduced-flow stretch of the Caniapiscou received inflows of approximately 800 m³/s, i.e., about the same as those recorded before diversion, from Caniapiscou reservoir via the Duplanter spillway. The Eastmain and Opinaca rivers and the Petite Rivière Opinaca, which empties into the Opinaca, were completely and permanently cut off.

The reduction of flow in the rivers caused the following physical changes, whose intensity varied depending on the hydrological characteristics:

- A more or less pronounced reduction in water level. The banks of the Caniapiscou were exposed over a stretch of about 70 km below the cutoff point. In the Eastmain and Rupert, the cutoff respectively represents 90% and 30% of the baseline flow at the river mouth.
- A more or less marked reduction in area, depth and volume of aquatic habitat. Four weirs were constructed in certain stretches of the Eastmain to maintain a water level, over a certain distance above the weirs, comparable to the average summer level observed before diversion. Eight weirs were also built in the Rupert for the same purpose.
- A more or less substantial increase in water residence time. For example, residence time in the slowest sections of the Eastmain rose from less than a day to around 20 days after the cutoff, then to over 40 days after the weirs were added.

The quality of the water in the reduced-flow sections of the Eastmain and Opinaca now depends mainly on the small tributaries that bring in water with neutral pH and more minerals, organic matter and nutrients than the water upstream of the cutoff points. As a result of the initial erosion of the newly exposed clayey banks, turbidity increased, as did the concentration of suspended solids and mineral content.

Residence time also increased, prolonging the contact between sediment and water, and helping to dissolve minerals and nutrients. This general enrichment of the water in turn favored biological production. Water quality in the Caniapiscou and Vincelotte rivers changed very little.

In the reduced-flow sections of the Eastmain and Opinaca rivers, the reduction in turbulence and the increase in nutrients promoted phytoplankton growth, despite substantial increases in turbidity. In reaction to the increase in water residence time, zooplankton changed from the lower density and biomass typical of rivers to the higher levels characteristic of lakes. In the stretch of the Caniapiscou between Duplanter dam and Canyon Eaton, the main change was a decrease in phytoplankton populations caused by the loss of inflows from the many large lakes upstream of the closure point.

Water quality changed very little in the reduced-flow stretches of the Lemare and Nemiscau. Organic matter content increased only slightly, as these rivers were now getting their inflows from the Rupert diversion bays, where the waters of the Lemare and Nemiscau (10% of total flow) mix with those of the Rupert (90% of total flow). This means that most of the flow to the Lemare and Nemiscau now consists mainly of water from the Rupert, which is rich in organic matter. In the reduced-flow section of the Rupert, the slight increases in turbidity and suspended solids observed near the river mouth were due to erosion of the newly exposed clayey banks following the drop in water level in the sections not controlled by weirs or spur dikes.

The reduction in aquatic habitats resulted in increases in fishing yields shortly after the closure of the Eastmain, Opinaca and Caniapiscou rivers. In the Eastmain and Opinaca, the main species favored were cisco and white sucker in the lentic (or lake) sections, and longnose sucker in the lotic (or river) sections. However, lake sturgeon in the Eastmain and Opinaca gradually decreased in abundance due to very low recruitment, likely caused by losses of reproductive habitat as well as possible overfishing prompted by the reduction in flow (Doyon and Belzile, 2000). In the Caniapiscou, particularly the upstream section, longnose and white sucker increased significantly in abundance, while landlocked salmon and brook trout left the area altogether. In addition, the condition factors of the majority of fish species increased.

3.5.2 Changes in fish mercury levels in the Eastmain and Opinaca rivers

After the flow was reduced in the Eastmain and Opinaca rivers, mercury levels changed very little in all species monitored. Figure 3.19 shows that mean levels for standardized lengths of all species generally remained within the range of mean levels measured in natural lakes in the West sector of the La Grande complex. Unlike reservoir impoundment, the reduction in the rivers' flow did not lead to the flooding of organic matter, which stimulates mercury methylation. In some cases, such as for longnose sucker at the confluence of the Eastmain and Opinaca and for lake sturgeon and walleye in the Eastmain (Figure 3.19), mean levels rose slightly relative to the overall mean values obtained for all natural water bodies combined, but did not differ significantly from those measured in certain natural lakes. In these cases, the increase in dissolved organic matter caused by inflows from tributaries in the rivers' remaining watersheds may have meant that fish mercury levels became typical of natural water bodies rich in dissolved organic matter, which yielded the highest levels obtained under natural conditions (section 3.1.3).

3.5.3 Changes in fish mercury levels in the Rivière Vincelotte

It was only in 1987 that the first survey was conducted to determine fish mercury levels in this river, which received inflows from Vincelotte reservoir from 1984 to 1992; the lack of prior data made it impossible to establish the short-term effect of the compensation flow of 8 m³/s from Vincelotte reservoir. However, measurements taken in 1987 and 1991 revealed that mercury levels in the sampled species stayed within the range of mean levels measured in natural lakes in the region, despite a significant increase in northern pike (Table 3.5). The fact that the release of instream flows ceased in 1992 may have prevented any subsequent increase.

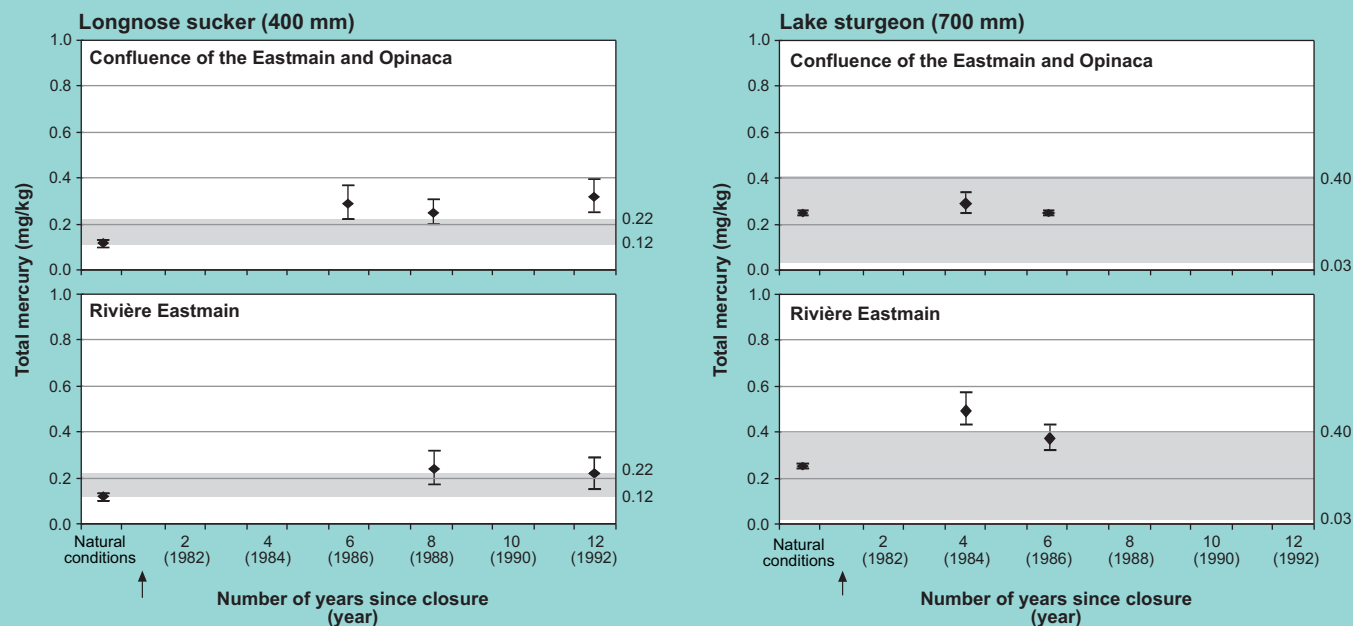
Table 3.5 Mercury Levels (mg/kg) Measured in Four Species Caught in the Rivière Vincelotte (1987–1991)

	Longnose sucker (400 mm)*	Lake whitefish (400 mm)	Northern pike (700 mm)	Lake trout (600 mm)
Range of values in natural water bodies (East sector)	0.06 to 0.20	0.10 to 0.30	0.36 to 0.92	0.52 to 1.11
Natural water bodies combined	0.12 (a)	0.14 (b)	0.56 (b)	0.74 (a)
1987	0.12 (a)	0.20 (ab)	0.58 (b)	0.88 (a)
1991	0.16 (a)	0.26 (a)	0.92 (a)	—

*: Levels are estimated for a standardized length (shown in parentheses).

Note: For each species, the different letters shown after the years indicate that their mercury levels differ significantly ($p < 0.05$).

Figure 3.19 Temporal Evolution of Mercury Levels in the Main Species of Fish of Standardized Length in the Eastmain and Opinaca Rivers



Confluence of the Eastmain and Opinaca

Number of years since closure (year)	Natural conditions	6 1986	8 1988	12 1992
	b	a	a	a
Estimated level	0.12	0.29	0.25	0.32
Lower limit	0.104	0.221	0.201	0.247
Upper limit	0.130	0.372	0.306	0.398
N	182	22	19	11

Confluence of the Eastmain and Opinaca

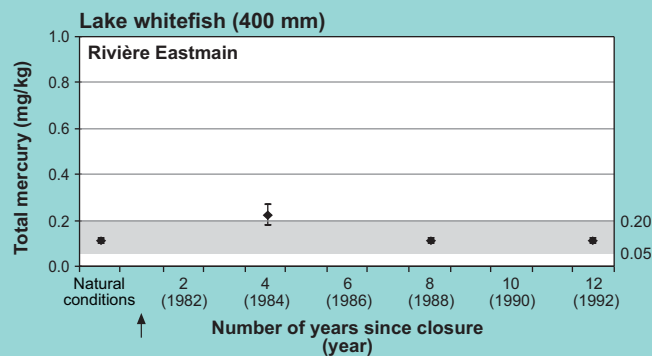
Number of years since closure (year)	Natural conditions	4 1984	6 1986
	a	a	a
Estimated level	0.25	0.29	0.25
Lower limit	0.229	0.252	0.229
Upper limit	0.267	0.343	0.267
N	186	30	12

Rivière Eastmain

	b	-	a	a
Estimated level	0.12	-	0.24	0.22
Lower limit	0.103	-	0.172	0.15
Upper limit	0.129	-	0.320	0.302
N	182	-	10	9310

Rivière Eastmain

	b	a	a
Estimated level	0.25	0.49	0.37
Lower limit	0.229	0.425	0.323
Upper limit	0.267	0.570	0.429
N	186	29	30



Rivière Eastmain

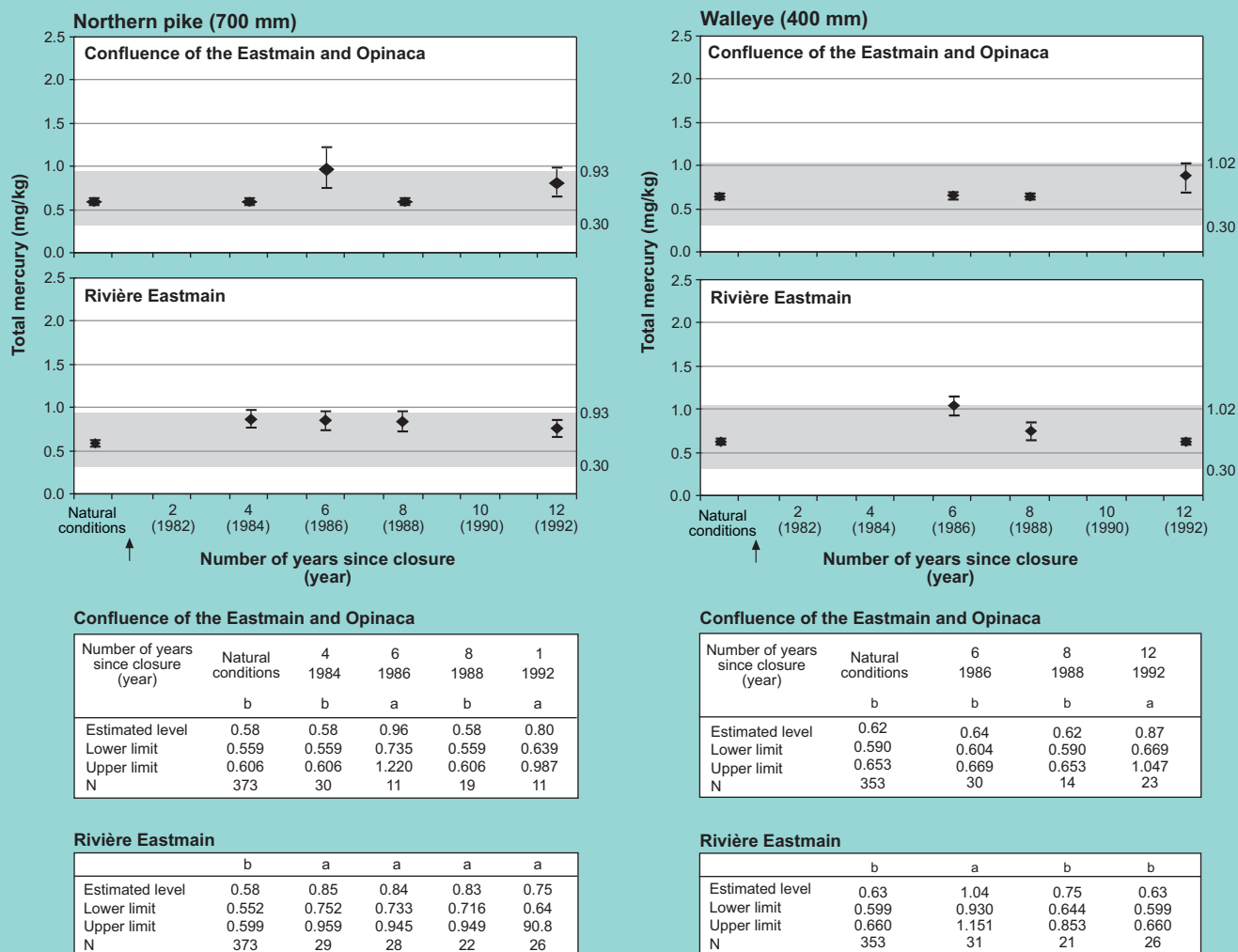
Number of years since closure (year)	Natural conditions	4 1984	8 1988	12 1992
	b	a	b	b
Estimated level	0.11	0.22	0.11	0.11
Lower limit	0.107	0.183	0.107	0.107
Upper limit	0.119	0.268	0.119	0.119
N	503	25	11	11

↑ Closure (1980)

Extent of mean levels for a standardized length under natural conditions.

Notes: The vertical lines represent the confidence intervals (95%) for the estimated mean levels. The different letters indicate that mercury levels are significantly different, since the confidence intervals (95%) do not overlap.

Figure 3.19 Temporal Evolution of Mercury Levels in the Main Species of Fish of Standardized Length
(cont.) in the Eastmain and Opinaca Rivers



Notes : The vertical lines represent the confidence intervals (95%) for the estimated mean levels.
The different letters indicate that mercury levels are significantly different, since the confidence intervals (95%) do not overlap.

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3.5.4 Changes in fish mercury levels in the reduced-flow section of the Rivière Caniapiscou

The following three stations (Map A, in pocket) were sampled in the Rivière Caniapiscou:

- Eaton amount station, located approximately 100 km downstream of the reservoir, which is representative of a river section with extensive areas of exposed riverbed and a short water residence time
- Cambrien station, located around 275 km downstream of the reservoir in a large, deep lake with a longer residence time
- Calcaire station, located downstream of Lake Cambrien, about 355 km from Caniapiscou reservoir

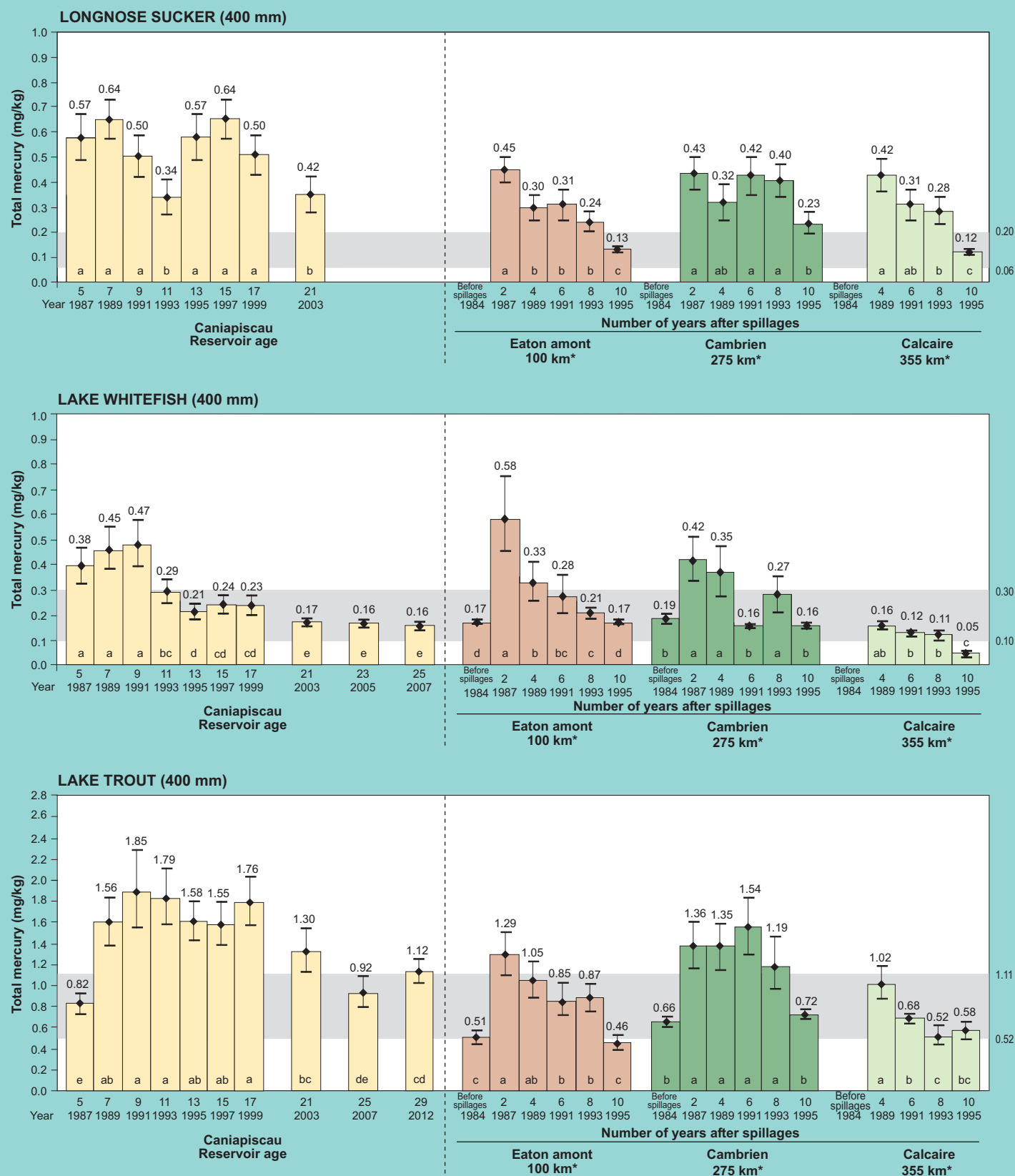
Since its closure at the end of October 1981, the Caniapiscou's mean annual flow has been reduced by about 800 m³/s, which represents respective decreases of approximately 95%, 65% and 50% at Eaton amount, Cambrien and Calcaire stations.

In 1984, three years after the river's closure, mercury levels in lake whitefish and lake trout were similar to those measured in natural lakes (Figure 3.20). However, spillages from Caniapiscou reservoir in 1984 and 1985 led to a significant increase in fish mercury bioaccumulation, which generally peaked two years later. The maximum levels reached at Eaton amount and Cambrien stations, i.e., 0.43 to 0.45 mg/kg for longnose sucker, 0.2 to 0.58 mg/kg for lake whitefish and 1.29 to 1.54 mg/kg for lake trout, were similar to those measured in Caniapiscou reservoir.

This data shows that mercury is indeed exported downstream of reservoirs by spillages and turbine discharges, and transferred to fish as quickly as in the reservoirs. The studies done by Doyon (1998) and Schetagne *et al.* (2000) revealed that the main water components responsible for methylmercury export are the dissolved phase (< 0.45 µm) and suspended solids (0.45 to 50 µm), which account for 64% and 33% of the total, respectively (Table 3.6a). Because of their low relative mass compared with the volume of turbine flow, plant debris, phytoplankton, zooplankton, benthos and fish contribute little to this export (only 3%).

However, it has been shown that fish accumulate mercury mainly through the food they ingest, and very little through the water (Hall *et al.*, 1997). Considering only the methylmercury directly transferred to downstream fish, i.e., that contained in the groups of organisms consumed by the fish, zooplankton as a food source would account for more than 90% of the total exported (Table 3.6). These groups of organisms were determined by analyzing the stomach contents of fish caught below Brisay generating station (Schetagne *et al.*, 2000).

Figure 3.20 Temporal Evolution of Mercury Levels Measured in Longnose Sucker, Lake Whitefish and Lake Trout of Standardized Length at Different Stations in the Downstream Stretch of the Rivière Caniapiscau



Extent of mean levels for a standardized length under natural conditions.

Notes: The vertical lines represent the confidence intervals (95%) for the estimated mean levels.
The different letters indicate that mercury levels are significantly different, since the confidence intervals (95%) do not overlap.

* Distance from Caniapiscau reservoir.

Table 3.6 Concentrations and Relative Proportion of Methylmercury Measured in the Different Components Exported from Caniapiscou Reservoir by Turbine Discharges from Brisay Generating Station in 1997

	Methylmercury (ng/1 000 m ³ of water)		Relative proportion (%)	
	Mean	Range	Mean	Range
a) Components in the water column				
Dissolved in the water	56,200	46,000 – 71,000	64.3	52.0 – 75.7
Suspended particulate matter	28,900	22,000 – 41,000	33.2	23.5 – 46.3
Zooplankton	1,288	245 – 4 185	1.5	0.3 – 6.4
Phytoplankton	748	79 – 2 461	0.9	0.1 – 2.8
Fish	84	0 – 574	0.1	0 – 0.7
Plant debris	8.5	0.5 – 31.9	0.01	0.0006 – 0.02
Benthic invertebrates	0.3	0 – 1.0	<0.01	0 – 0.001
Scales and bones	0.1	0 – 0.7	<0.01	0 – 0.0001
b) Group of organisms consumed by the fish				
Zooplankton	1,288	245 – 4 185	93.3	4.4 – 99.0
Fish	84	0 – 574	6.1	0 – 54.3
Plant debris	8.5	0.5 – 31.9	0.6	0 – 1.3
Benthic invertebrates	0.3	0 – 1.0	<0.1	0 – 0.1
Scales and bones	0.1	0 – 0.7	<0.1	0 – <0.1

Source: Schetagne *et al.* (2000)

At Eaton amount station, the increase to higher mercury levels was much more short-lived than in Caniapiscou reservoir, lasting four to ten years after the spillages (Figure 3.20), depending on the species. The short flow-through time at Eaton amount station, which is attributable to inflows from the tributaries in the Caniapiscou's remaining watershed, appears to explain this rapid return to levels representative of natural lakes in the sector, since the water discharged from the reservoir, which contained particles and organisms with higher mercury content, was quickly replaced by inflows from the tributaries that carried particles and organisms containing less mercury.

At Cambrien station, where the flow-through time is longer, the return to mercury levels that are not significantly different from those measured in the region's natural lakes also took four to ten years, depending on the species. This period of elevated mercury levels was also shorter than in Caniapiscou reservoir.

At Calcaire station, mercury levels in lake whitefish and lake trout did not increase significantly following spillages from the reservoir, but remained within the range of mean levels measured in natural lakes. The absence of any increase at this station, located below the large, deep Lac Cambrien, is probably attributable to the sedimentation of methylmercury-rich suspended particulate matter from Caniapiscou reservoir and to the consumption of organisms, especially zooplankton, carried downstream of the reservoir by the fish in Lac Cambrien. This lake provided zooplankton coming from upstream with a suitable lentic habitat that allowed it to complete its life cycle, with the result that very little methylmercury-rich zooplankton was exported farther downstream. The fine, methylmercury-rich suspended particulate matter from the reservoir may also have been filtered by the zooplankton in Lac Cambrien and transferred to its fish (Schetagne *et al.*, 2000).

Similar results were obtained in the region of Smallwood Reservoir in Labrador (Bruce *et al.*, 1979; LGL Limited, 1993; Anderson, 2011), i.e., an increase in fish mercury levels downstream of the reservoir, as well as a marked reduction in the phenomenon below Lake Winokapau, located about 105 km downstream.

However, levels in longnose sucker increased significantly at Calcaire station below Lac Cambrien (Figure 3.20), and the return to levels similar to those in natural lakes was spread out over 10 years. It is unlikely that this increase is related to downstream mercury export from Lac Cambrien, as the increase would also have been observed in lake whitefish, as well as in the lake trout that eat them. It therefore seems more likely attributable to downstream movements, especially before 1989, of longnose sucker themselves, as this species is particularly mobile.

3.5.5 Fish mercury levels in the Nemiscau and Rupert rivers

In the reduced-flow sections of the Nemiscau and Rupert, the data collected at four sampling stations made it possible to characterize fish mercury levels after the rivers were diverted in fall 2009. Table 3.7 shows that in the reduced-flow sections of both rivers, the mean mercury levels obtained in 2011, i.e., two years after diversion, generally remained within the range of levels recorded in the region's natural lakes.

However, in 2011, it was still too early to detect any significant increases in mercury in fish of standardized length. The increases predicted in the diversion bays and the significant increase in mercury levels in small northern pike specimens (400 to 600 mm) observed in 2011 suggest that mercury had increased significantly in all species in the reduced-flow section of the Nemiscau, which now received 100% of its flow from the Rupert tailbay (Therrien and Schetagne, 2012).

Table 3.7 Mean Mercury Levels (mg/kg) in the Main Species of Fish of Standardized Length Recorded in 2011 in the Rupert Diversion Section

Reservoir age (year)	Lake whitefish (400 mm)	Northern pike (700 mm)	Walleye (400 mm)	Lake sturgeon (900 mm)
Range of values in natural lakes (West sector)	0.05 to 0.20	0.30 to 0.93	0.30 to 1.02	0.03 to 0.40
<i>Rivière Rupert downstream</i>				
KP 314 sector		0.61	0.56	
KP 293 sector	0.21	0.61	0.47	
Lac Nemiscau (KP 188)	0.08	0.44	0.35	0.14
<i>Rivière Nemiscau downstream</i>				
Lac de la Montagne sector		0.87	0.58	
<i>Control station</i>				
Lac Émérillon	0.11	0.47	0.58	

3.5.6 Main lessons learned from monitoring reduced-flow rivers

The main lessons learned from monitoring fish mercury levels in reduced-flow rivers in the La Grande complex are as follows:

- In sections where the closure was total and permanent, no new organic matter was flooded and, consequently, additional methylmercury production was negligible. Therefore, mercury levels generally remained within the range of mean levels measured under natural conditions.
- Even if they lasted only a few months, spillages or turbine discharges from the reservoirs (if large enough to completely renew the water below them) led to a significant increase in fish mercury levels downstream, in both piscivorous and non-piscivorous species. Although shorter in duration, this increase could be as high as that observed in the reservoirs. This demonstrates a downstream export of mercury from reservoirs and a rapid transfer to fish, probably mainly by zooplankton.
- During these spillages, the extent of the mercury export, the downstream distance over which it could be felt and the duration of the increase in fish levels beyond those measured in natural environments appeared to depend on:
 - the dilution of all the components in the water column by the tributaries of the residual drainage basin;
 - the presence or absence of a large body of water allowing sedimentation of suspended particulate matter and predation on entrained zooplankton by aquatic organisms in that body of water.

3.6 Grande Rivière estuary and east coast of Baie James

3.6.1 Physical, chemical and biological changes

From 1979 to 1993, the water from Robert-Bourassa reservoir had to travel 80 km along the fluvial section of the Grande Rivière to get to La Grande-1 generating station, then 37 km through the estuarine section of the river, before it reached Baie James. La Grande 1 reservoir replaced the fluvial section in 1993, but the flow remains fairly swift and residence time is only a few days.

In the Grande Rivière, water quality was affected very little by the development of the La Grande complex. This section of river is essentially supplied by Robert-Bourassa reservoir, in which water quality underwent relatively minor changes.

Summer temperature and salinity conditions in the coastal waters of Baie James remained unchanged, since the summer flows of the Grande Rivière fall within the same range of values as under natural conditions, and spatiotemporal and even interannual variations in these parameters are caused mainly by the tide and meteorological conditions. However, since winter flows are now eight to ten times higher in the Grande Rivière, the river's freshwater plume under ice cover greatly increased in area. For winter flows greater than 4,000 m³/s, the plume occupies an area approximately three to five times larger than before the river's development (Messier, 2002).

In the Grande Rivière, phytoplankton biomass increased temporarily, as chlorophyll a levels nearly doubled then quickly returned, in the space of four years, to the values measured prior to development. The overly short water residence time in the Grande Rivière did not allow for an increase in zooplankton production.

Since 1977, longnose sucker has largely predominated in the fish community in the Grande Rivière estuary. The decrease in water temperature since Robert-Bourassa generating station began operation seems to have affected fishing yields for certain species, favoring brook trout and round whitefish, which are cold-water species, rather than cisco and walleye, which are less tolerant of cold water. Generally speaking, fish survival conditions in the Grande Rivière remain excellent and at least as good as in control lakes (Therrien and Lalumière, 2001).

3.6.2 Evolution of fish mercury levels in the Grande Rivière estuary

Mercury levels in the fish monitored in the Grande Rivière estuary have followed a pattern of change similar to that in Robert-Bourassa reservoir, with an initial increase followed by a gradual return to values found under natural conditions (Figure 3.21). As in the river section between Robert-Bourassa and La Grande 1 reservoir, fish mercury levels in the estuary are mainly determined by inflows from Robert-Bourassa reservoir.

In lake whitefish in the estuary, mean levels measured since 1994 have not differed significantly from those recorded in certain natural lakes, while for northern pike, the corresponding levels obtained in 2000 once again fall within the range of mean levels observed under natural conditions. The situation is the same for round whitefish (Table 3.8), a species caught in sufficient numbers only in the Grande Rivière and La Grande 1 reservoir.

Table 3.8 Mercury Levels (mg/kg) in Brook Trout and Round Whitefish of Standardized Length Caught in the Grande Rivière Estuary

Year	Brook trout (300 mm)	Round whitefish (300 mm)	
	LG 1 aval and Fort George	LG 1 aval	Fort George*
Natural conditions	0.13 (d)**	0.10 (a)***	0.10 (a)***
1984	1.67 (a)		
1986	0.80 (b)		
1988	0.60 (bc)		
1990	0.72 (bc)		
1992	0.77 (b)		
1994	0.54 (bc)		
1996	0.56 (bc)		0.10 (a)
1998	0.46 (c)		0.10 (a)
2000		0.10 (a)	0.10 (a)
2008	0.24 (d)		

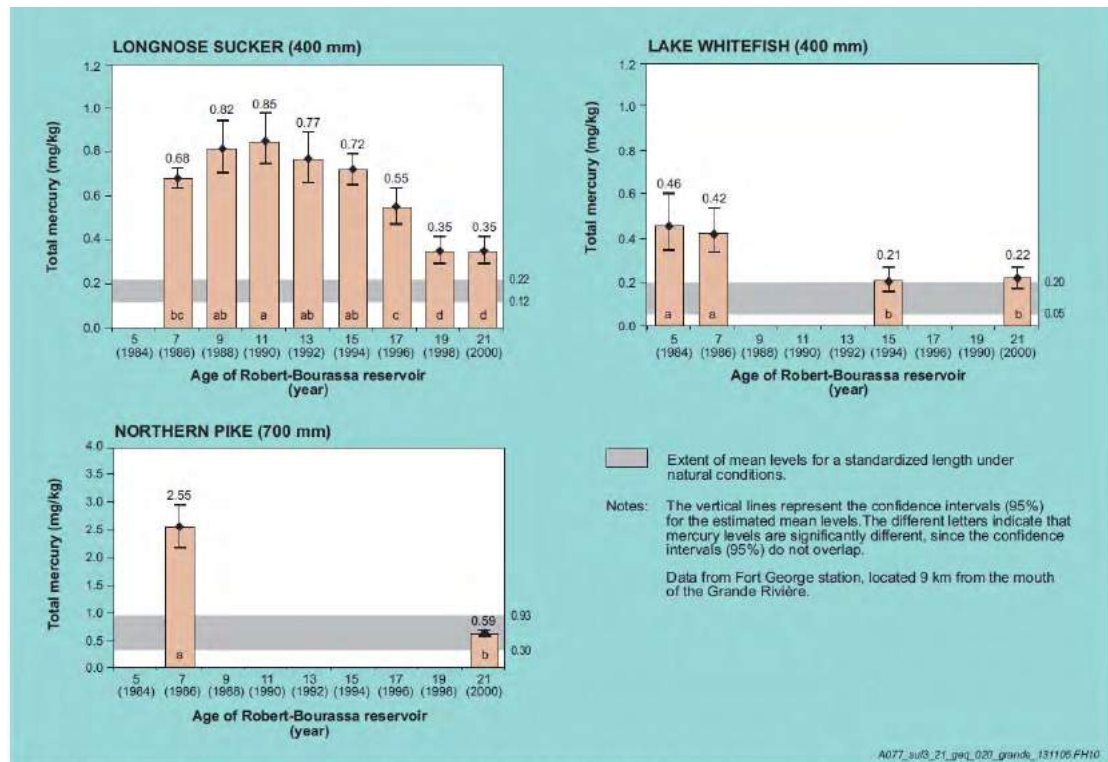
Note: Levels are estimated for a standardized length of 300 mm. The different letters after the years indicate that their mercury levels differ significantly ($p < 0.05$).

* : Combined data from FG 400, FG 006 and FG 017 stations.

** : Measured at stations located along the east coast of Baie James.

*** : Measured in natural lakes—Lac Hazeur (CE 034) and Lac Sérigny (CE 012)—in the East sector.

Figure 3.21 Temporal Evolution of Mercury Levels in Longnose Sucker, Lake Whitefish and Northern Pike of Standardized Length in the Grande Rivière Estuary



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In the case of longnose sucker, the mean level measured in 1998 at Fort George station (0.35 mg/kg), located 10 km from the river mouth, shows that it was much lower than the peak value recorded in 1990 (0.85 mg/kg), but still considerably higher than that found in the region's natural lakes. Fort George station was no longer used after monitoring was optimized, but the mean level recorded at the station immediately downstream of La Grande-1 generating station in 2008 (0.39 mg/kg), i.e., 29 years after the impoundment of Robert-Bourassa reservoir, also remained higher. This extended return period can probably be attributed to consumption by this usually non-piscivorous species of small fish that had passed through the turbines (section 3.3).

In brook trout, there was a considerable decrease in mean mercury level between the peak recorded in 1984 (1.67 mg/kg) and the level measured in 2008 (0.24 mg/kg), which no longer differs significantly from that found in certain natural lakes (Table 3.8). For this species, the population caught at LG 1 aval station seems to consist essentially of resident specimens that may also occasionally consume small fish passing through La Grande-1 generating station (Entraco, 1996; Lemieux, 1997).

3.6.3 Evolution of fish mercury levels in the coastal environment

Generally speaking, mercury levels in species of fish caught in the coastal waters of Baie James changed little between 1987 and 1994, even in specimens caught in the summer freshwater plume of the Grande Rivière (Table 3.9).

In spatial terms, mercury levels in the main species caught along the east coast of Baie James show that mercury input from the Grande Rivière had only a slight, local effect in coastal waters for most species. In fact, between 1987 and 1994, mercury levels in cisco, lake whitefish, brook trout, Greenland cod and fourhorn sculpin were only slightly higher inside the summer freshwater plume of the Grande Rivière than outside it.

In fourhorn sculpin, the data indicates a somewhat more marked effect, as specimens caught in the freshwater plume displayed mercury levels nearly three times higher than those caught outside it (0.31 to 0.55 mg/kg vs. 0.10 to 0.22 mg/kg).

3.6.4 Main lessons learned from monitoring the Grande Rivière estuary and the east coast of Baie James

The following lessons may be drawn from monitoring fish mercury levels in the Grande Rivière estuary and along the east coast of Baie James:

- Fish mercury levels in the estuary, which are determined mainly by inflows from Robert-Bourassa reservoir, show a similar pattern of change to that observed in fish in the reservoir.
- In the estuary, the levels obtained for the majority of species since 2000, 21 years after the impoundment of Robert-Bourassa reservoir, are equivalent to those measured in natural water bodies in the region.
- For longnose sucker and brook trout, the levels measured in this section in 2000 remained higher than those in natural water bodies, partly because of their occasional consumption of small fish that have passed through La Grande-1 generating station.
- In the coastal environment of Baie James, the effect on mercury of the development of the La Grande complex is confined to the summer freshwater plume of the Grande Rivière.

Table 3.9 Mercury Levels (mg/kg) in the Main Species of Fish of Standardized Length Caught in the Coastal Waters of Baie James between 1987 and 1994

Sector	Cisco (300 mm)*	Lake whitefish (400 mm)	Brook trout (300 mm)	Fourhorn sculpin (250 mm)	Greenland cod (400 mm)
SECTORS AFFECTED BY THE SUMMER FRESHWATER PLUME OF THE GRANDE RIVIÈRE					
<i>Proximal plume</i>					
Loon, Black and Grass islands	0.10 (bc)	–	–	0.44 (a)	0.42 (a)
<i>Distal plume</i>					
<i>North</i>					
Paul Bay and Rivière Piagochiou estuary	0.12 (ab)	0.15 (b)	0.20 (a)	0.55 (a)	0.38 (ab)
Goose Bay and Rivière Guillaume estuary	0.13 (ab)	0.14 (bc)	0.19 (a)	–	–
<i>South</i>					
Tees Bay	0.13 (a)	0.21 (a)	–	0.31 (b)	0.26 (bc)
<i>Mean of affected sectors</i>	<i>0.12</i>	<i>0.17</i>	<i>0.20</i>	<i>0.43</i>	<i>0.35</i>
SECTORS UNAFFECTED BY THE SUMMER FRESHWATER PLUME OF THE GRANDE RIVIÈRE					
<i>North of the Grande Rivière</i>					
Pointe Attikuan and Rivière Kapsaouis estuary	0.10 (bc)	0.15 (b)	0.14 (b)	–	–
Pointe Kakassituq and Many Islands Bay	0.09 (c)	0.08 (de)	0.09 (c)	0.10 (c)	0.14 (c)
<i>South of the Grande Rivière</i>					
Baie Aquatuc	0.10 (bc)	0.12 (bcd)	0.12 (bc)	0.22 (b)	
Dead Duck Bay and Rivière Cailliet estuary	0.10 (bc)	0.07 (e)	0.14 (b)	–	0.18 (c)
<i>Wemindji region</i>					
Goose Island	–	0.06 (e)	–	–	–
Moar Bay	0.10 (bc)	0.12 (bcd)	0.14 (b)	–	0.42 (a)
Old Factory Bay	0.10 (bc)	0.15 (b)	–	–	–
<i>Mean of unaffected sectors</i>	<i>0.10</i>	<i>0.11</i>	<i>0.13</i>	<i>0.16</i>	<i>0.26</i>

* : Mean levels estimated for a standardized length (shown in parentheses).

Note : For each species, the different letters after the sectors indicate that their mercury levels differ significantly (<0.05).

3.7 Complementary studies

Complementary studies were conducted in conjunction with the EMN to provide a better understanding of the mechanisms responsible for the changes revealed by the monitoring, as well as to provide more specific input for a semi-mechanistic model for predicting fish mercury levels in reservoirs (section 2.4.3.3).

This section presents the results of six complementary studies covering the following aspects: dwarf lake whitefish, small fish species, diet of the main fish species, entrainment of fish from reservoirs, proportion of total methylmercury in different fish parts and Omega-3 fatty acid content in fish flesh.

In addition, a laboratory study examined the release of mercury and methylmercury according to the type of flooded organic matter (Thérien and Morrison, 1999). It showed that, of the dominant species in the flooded environments of the La Grande complex, alder leaves (*Alnus* spp.) released the largest proportion of methylmercury (5 ng/g, dry weight), followed by sphagnum moss (*Sphagnum* spp., 3 ng/g) and black spruce needles (*Picea mariana*, 2 ng/g). These results allowed for methylmercury input from flooded vegetation in the La Grande complex reservoirs to be evaluated and incorporated into the mechanistic model.

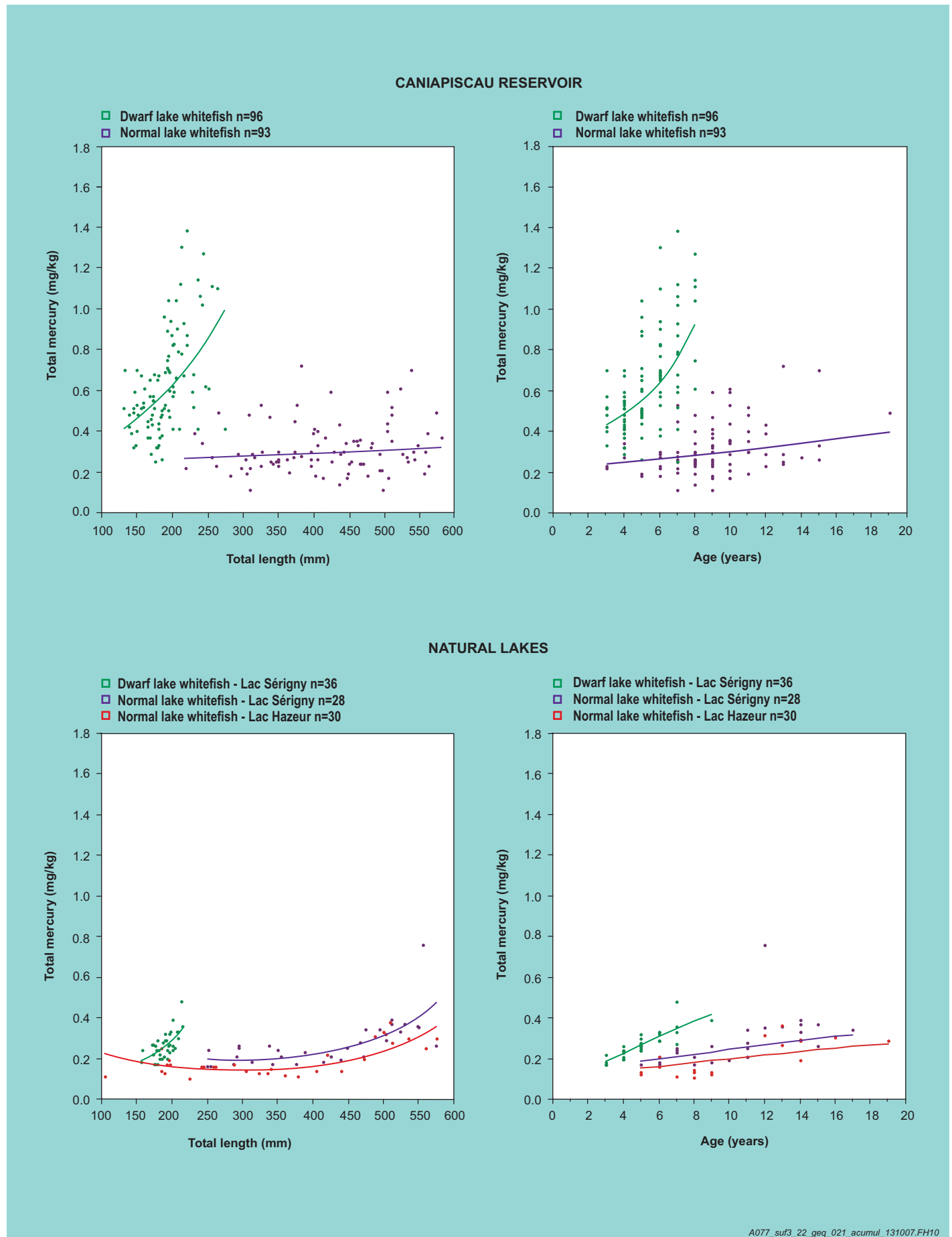
3.7.1 Dwarf lake whitefish

The monitoring of fish mercury levels showed that, unlike those in other reservoirs, small lake whitefish in Caniapiscau reservoir a few years after impoundment had higher mercury levels than large specimens. A closer examination of the data on age and sexual maturity revealed the presence of two sympatric populations of lake whitefish—normal and dwarf—in the East sector of the La Grande complex (Deslandes *et al.*, 1993; Doyon, 1995a; Doyon *et al.*, 1998a). These populations coexist in Caniapiscau reservoir as well as in some natural lakes, including lakes Sérigny and Des Voeux, and are genetically distinct (Bernatchez, 1996).

Dwarf lake whitefish in Caniapiscau reservoir accumulate mercury more rapidly than normal specimens, as a function of both age and size (Figure 3.22). The same holds true in Lac Sérigny, a natural lake, where eight-year-old dwarf specimens reach levels twice as high as normal specimens of the same age (0.38 vs. 0.22 mg/kg). In the reservoir, 11 years after impoundment (1993), the difference between bioaccumulation rates in dwarf and normal specimens is even more pronounced than in natural lakes, so that eight-year-old dwarf specimens reach bioaccumulation levels three times higher than normal specimens (0.92 vs. 0.28 mg/kg). Moreover, 11 years after impoundment, dwarf whitefish in the reservoir also had mercury concentrations 2.5 times higher than dwarf specimens in Lac Sérigny, for fish of either the same length (0.62 vs. 0.27 mg/kg at 200 mm) or the same age (0.92 vs. 0.38 mg/kg at eight years).

As is suggested by Doyon *et al.* (1998b), the difference in mercury bioaccumulation rates appears to be linked mainly to the fact that dwarf specimens mature earlier, generally at two or three years old, compared with six or seven years old for normal specimens. At seven years, dwarf specimens have generally spawned five to six times, whereas normal ones have usually spawned only once or twice. By reaching sexual maturity at an earlier age, dwarf specimens thus devote more energy to producing gonads and less to producing flesh. This has the effect of concentrating the assimilated mercury in a smaller quantity of flesh.

Figure 3.22 Mercury Accumulation Relative to Length and Age of Dwarf and Normal Lake Whitefish Caught in 1993 in Caniapiscou Reservoir and in Lakes Hazeur and Sérigny



A different diet for large specimens (> 350 mm), which are present only in the normal population, and the higher metabolic rate of dwarf specimens, a characteristic common to small species as compared with large ones (Beamish, 1964; Reinert *et al.*, 1974), are two other factors suggested to explain the differences observed (Schetagne *et al.*, 1996; Doyon *et al.*, 1998b).

3.7.2 Small fish species

The levels measured in a complementary study conducted between 1995 and 1997 (Doyon and Tremblay, 1997a, b; Doyon and Schetagne, 2000) show that small species such as lake chub (*Couesius plumbeus*), trout-perch (*Percopsis omiscomaycus*) and yellow perch (*Perca flavescens*) have mercury levels that are generally equal to or higher than those obtained in much larger species such as normal lake whitefish. In fact, specimens of these species, which average 110 to 150 mm in size, can reach mean mercury levels ranging from 0.30 to over 0.50 mg/kg in various reservoirs and natural lakes, whereas normal lake whitefish measuring 400 mm have mean levels ranging from 0.10 to 0.28 mg/kg in the same environments.

As with dwarf lake whitefish, this phenomenon would be explained by slower growth and earlier sexual maturity in small species, so that less flesh is produced for the same quantity of food ingested, resulting in the concentration of the assimilated mercury in a smaller quantity of flesh. Since piscivorous fish feed on small species, this data was used in developing the semi-mechanistic prediction model.

3.7.3 Diet of the main fish species

The diet of the main fish species in the La Grande complex was studied from 1980 to 1982, in 1990, from 1992 to 1994, then, for piscivorous species only, from 1995 to 2012, in various natural and modified water bodies in the La Grande complex (SAGE, 1983; Doyon, 1995a, b; Doyon *et al.*, 1996; Verdon and Tremblay, 1999; Doyon and Tremblay, 1997a, b; Doyon and Schetagne, 1999, 2000; Groupe conseil GENIVAR, 2002; Therrien and Schetagne, 2004, 2005a, 2008a and b, 2009, 2010, 2012). Figures 3.23 and 3.24 provide the most pertinent and representative data (i.e., high numbers) obtained from these studies, expressed as relative biomass of prey in stomach contents. Note that biomass data is not available from 1980 to 1982.

Figure 3.23 **Prey Biomass of the Main Species of Non-piscivorous Fish in the La Grande Complex**

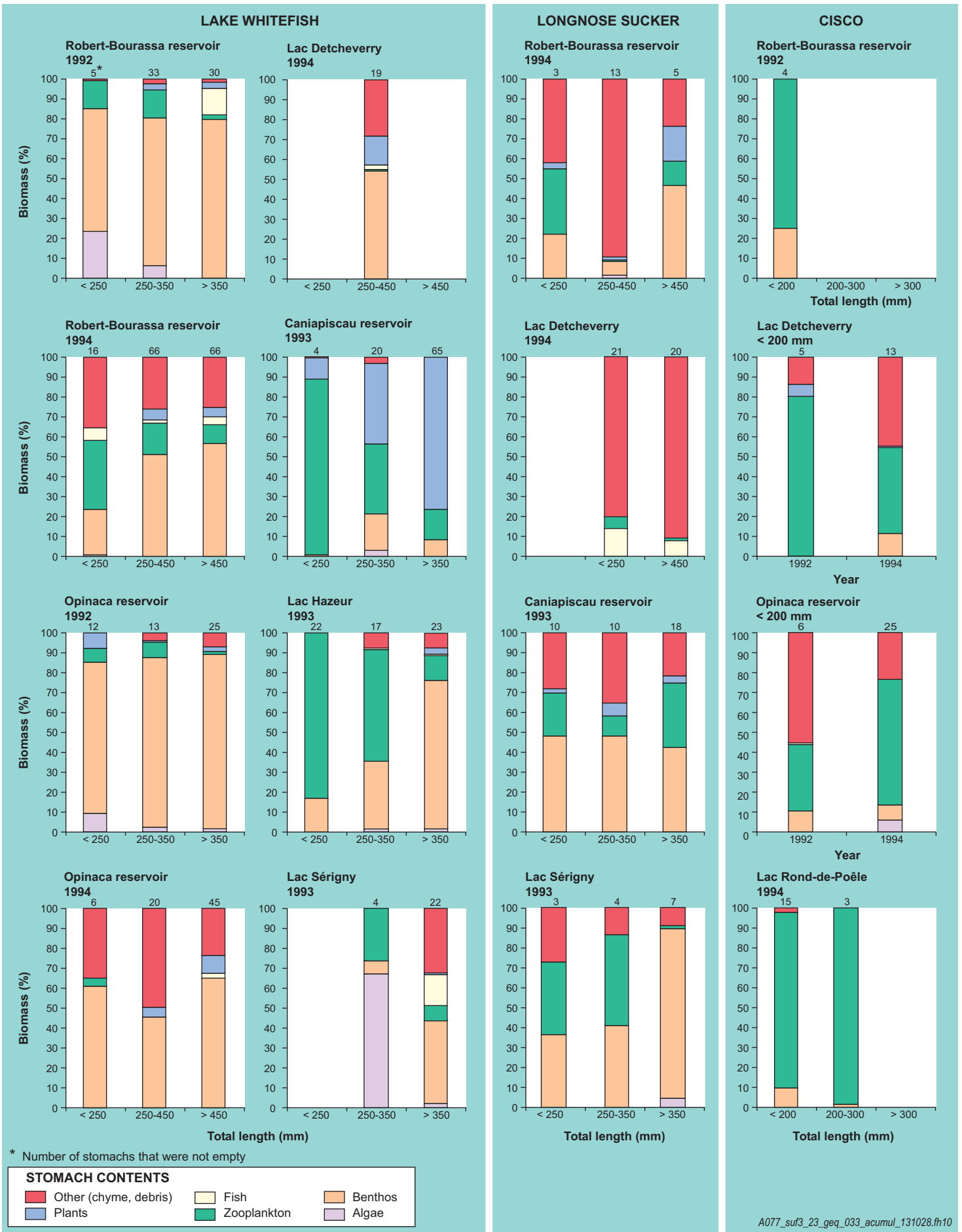
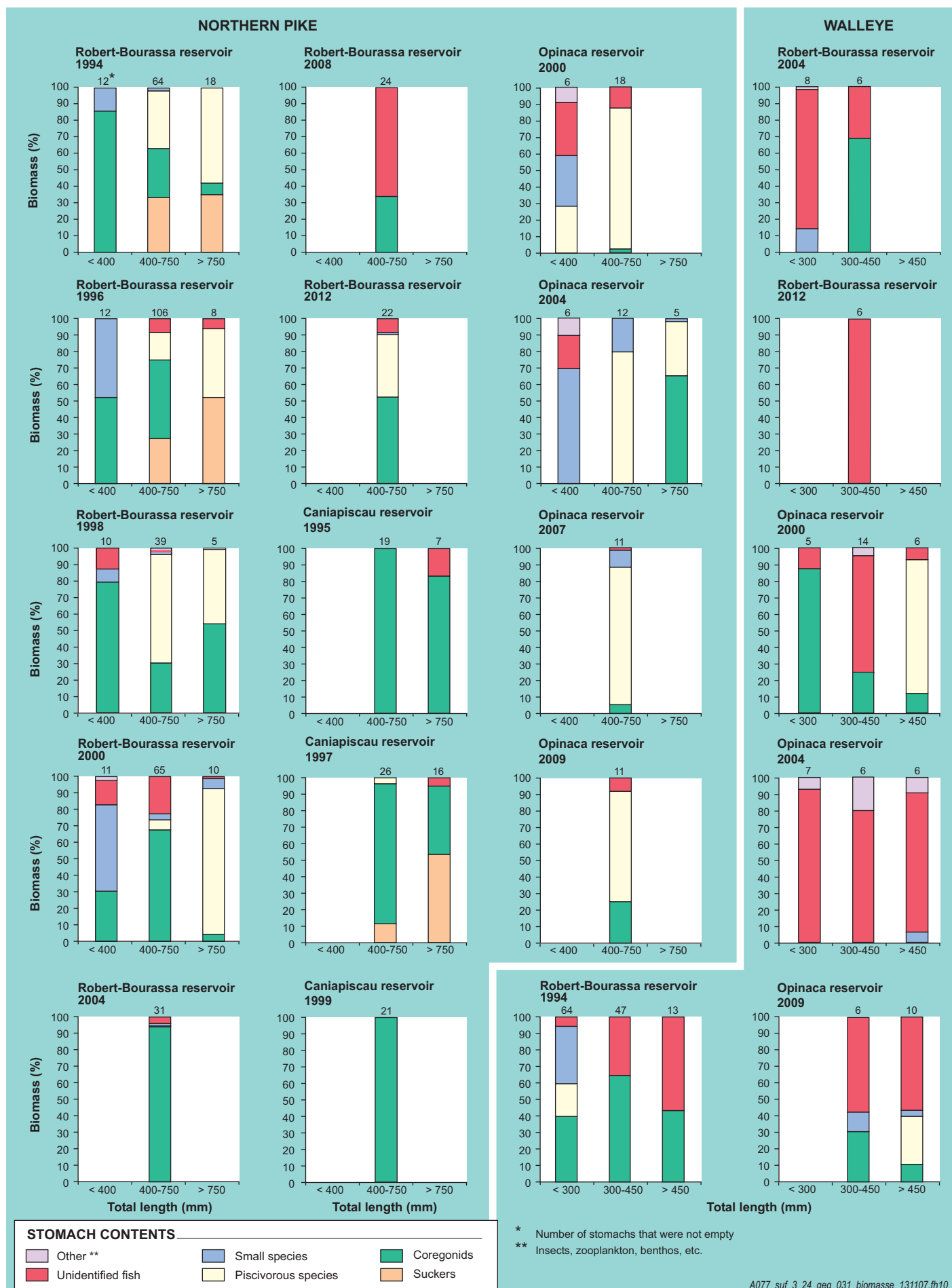
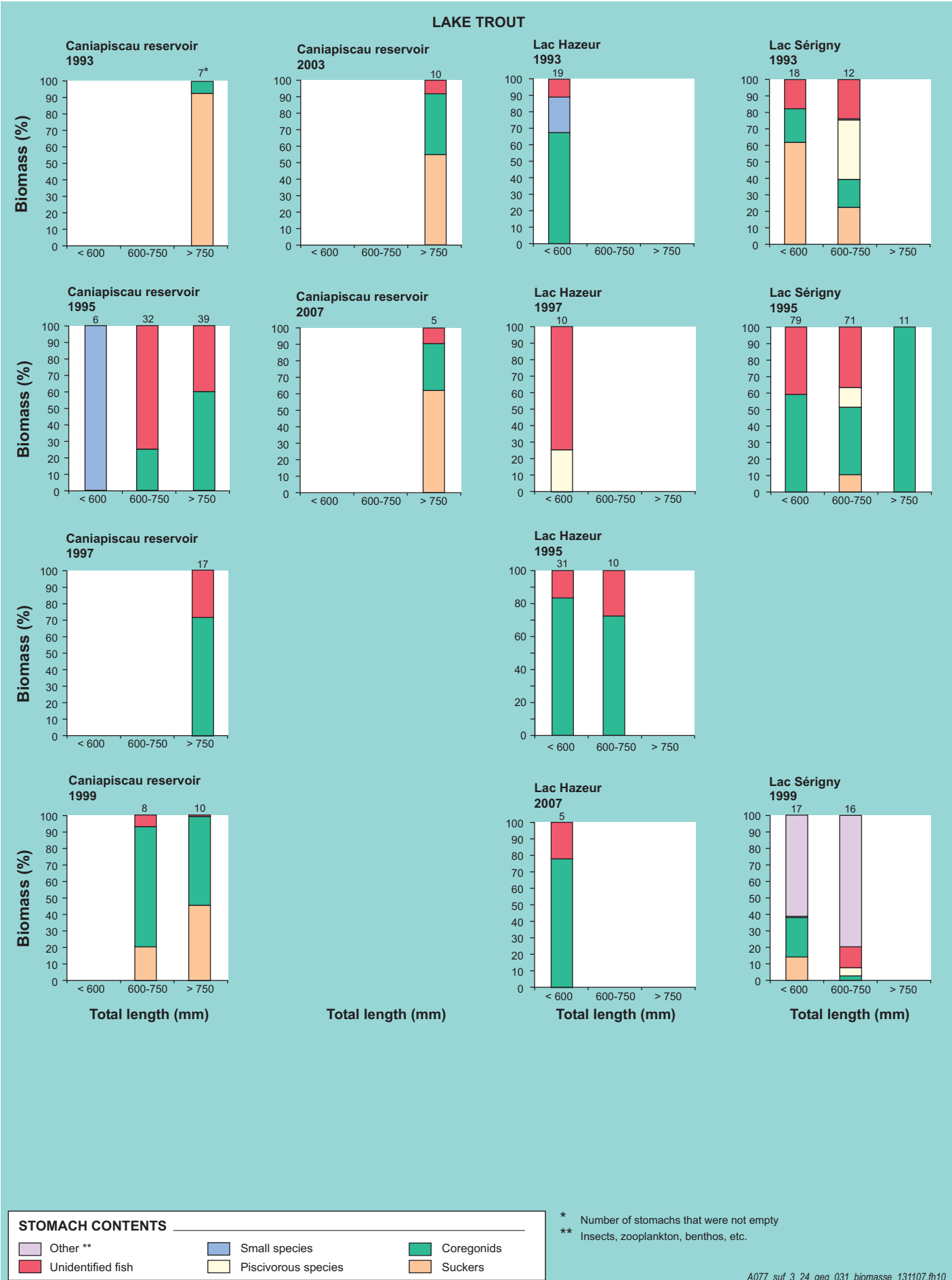


Figure 3.24 Prey Biomass of the Main Species of Piscivorous Fish in the La Grande Complex



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Figure 3.24 Prey Biomass of the Main Species of Piscivorous Fish in the La Grande Complex (cont.)



Non-piscivorous fish

The diet of non-piscivorous fish can vary from year to year and from season to season, but a fair amount of information can be derived from the results obtained. There was no significant difference in the occurrences of prey in the stomach contents of fish between the different periods (1980–1982 and 1990–1994) or sampled water bodies. This shows that the differences observed between fish mercury levels in natural water bodies and in reservoirs are related to greater availability of methylmercury after impoundment rather than a change in diet (Verdon and Tremblay, 1999).

Lake whitefish

In terms of biomass, the prey consumed most by normal lake whitefish are benthic organisms, followed by zooplankton, which can be the dominant type of prey for small specimens (Figure 3.23). In addition, the proportion of benthos in stomachs tends to increase with fish size in all environments. The proportion of plant debris in stomach contents can be high in reservoirs, but appears to be accidental, simply accompanying the ingestion of benthos on the bottom or on flooded vegetation.

The consumption of small fish by lake whitefish is generally very low, both in natural water bodies and reservoirs. However, lake whitefish can become piscivorous immediately below hydroelectric generating stations, where they take advantage of the presence of small fish stunned by their passage through the turbines, particularly cisco in the West sector (Brouard and Doyon, 1991; Brouard *et al.*, 1994) and lake whitefish in the East sector (Doyon, 1998).

Longnose sucker

Benthos is generally the type of prey consumed most by longnose sucker, whatever their size; this proportion also tends to increase with specimen size (Figure 3.23).

Cisco

Cisco's main prey, in terms of biomass, is zooplankton (Cladocera and Copepoda), although terrestrial invertebrates (Psocoptera) sometimes dominate (Figure 3.23).

Piscivorous fish

Analyses of stomach contents revealed that coregonids (cisco and lake whitefish) and small fish species were generally the main prey of piscivorous fish (Figure 3.24). However, predation on other piscivorous species, in which predators become "superpredators," is also widespread, especially in reservoirs, where it can represent up to 80% of ingested biomass. This type of predation increases with the size of piscivorous species and results in a considerable increase in mercury concentrations by adding a link to the food chain.

Northern pike

In terms of biomass, the main prey of northern pike vary according to the pike's size, ranging from coregonids for specimens smaller than 400 mm to various piscivorous species (such as northern pike, burbot and walleye) for larger specimens (Figure 3.24). However, in reservoirs in the East sector, consumption of piscivorous prey is seen less often. The diet of northern pike is varied, moreover, and may also include suckers, lake chub, stickleback (*Gasterosteidae*), trout-perch, yellow perch and sculpin (*Cottus* spp).

The situation in Robert-Bourassa reservoir is different. The numbers of fish obtained in control lakes were insufficient to reveal a greater proportion of piscivorous prey in northern pike in this reservoir compared with those in control lakes. Nevertheless, there were more occurrences of larger piscivorous prey in northern pike in Robert-Bourassa reservoir. For example, the proportion and average maximum size of piscivorous prey in northern pike specimens larger than 750 mm were 60% (n=25) and 382 mm (n=8), vs. 29% (n=7) and 295 mm (n=3) in natural lakes. "Superpredator" behavior lasted longer in this reservoir than in all other modified water bodies except Opinaca reservoir.

Walleye

The diet of walleye is similar to that of northern pike, i.e., dominance of coregonids (especially cisco) for specimens smaller than 450 mm, then a generally substantial proportion of piscivorous species (mainly burbot) for larger sizes (Figure 3.24). In natural lakes, a considerable proportion of the walleye's diet may also consist of prey other than fish (larvae and adult insects).

Lake trout

Coregonids are generally dominant in lake trout's diet, but suckers, round whitefish, brook trout, lake chub and sculpin may sometimes represent a substantial proportion of stomach content biomass (Figure 3.24). Consumption of piscivorous species is less common in lake trout, but burbot may also be ingested.

The data on the diet of fish according to their size, as well as mercury levels measured in the different types of prey (Verdon and Tremblay, 1999), were used in developing the mechanistic prediction model for fish mercury levels.

3.7.4 Entrainment of fish from reservoirs to below generating stations

Sampling conducted at the outlet of the tailrace tunnels or inside the scroll cases of the turbines at Robert-Bourassa generating station revealed that cisco is the species most often entrained through the station's turbines (Brouard, 1983; Roy *et al.*, 1986; Brouard and Doyon, 1991; Brouard *et al.*, 1994). The proportion of cisco varied from 62% to 96%, depending on the harvesting site and the season. The specimens were mainly aged 0+ (20-50 mm total length) and 1+ (90-130 mm), and were generally unharmed but temporarily stunned or knocked out. The number of entrained cisco was about 700 per hour (208 to 1,696 in five samples) in August and around 1,500 per hour (644 to 1,716 in three samples) in September (Brouard and Doyon, 1991; Brouard *et al.*, 1994). Similar results were obtained at Brisay generating station on Caniapiscau reservoir, where approximately 500 small lake whitefish were entrained per hour in August and September (Schetagne *et al.*, 2000).

The other species entrained downstream from Robert-Bourassa reservoir are lake whitefish, burbot and, less often, brook trout, lake trout, northern pike, suckers and walleye.

These observations helped provide a better understanding of changes in fish mercury levels immediately below the generating stations (section 3.3).

3.7.5 Total mercury and methylmercury levels in different fish parts

The extensive data available on fish mercury levels in the Baie-James territory concern only the flesh, which is the part usually consumed by the Crees and recreational anglers. However, a survey of Cree representatives revealed that the Crees also eat, as separate dishes, the fillet, the whole fish, the roe (gonads) and the entrails (cleaned and without the liver). Only the entrails of large species such as northern pike, lake sturgeon or lake trout are eaten as separate dishes.

For all other species, the entrails (cleaned and without the liver) are eaten with the whole scaled fish. The Crees generally do not eat the liver, except occasionally that of burbot.

In 2003, Hydro-Québec analyzed mercury concentrations in various fish parts (gonads, entrails and whole fish) to determine whether the total mercury levels in other parts of the fish that may be eaten by the Crees are underestimated in comparison with those in the flesh, and whether the consumption guidelines based on mercury levels in the flesh are also valid for other parts of the fish.

Total mercury levels in different fish parts

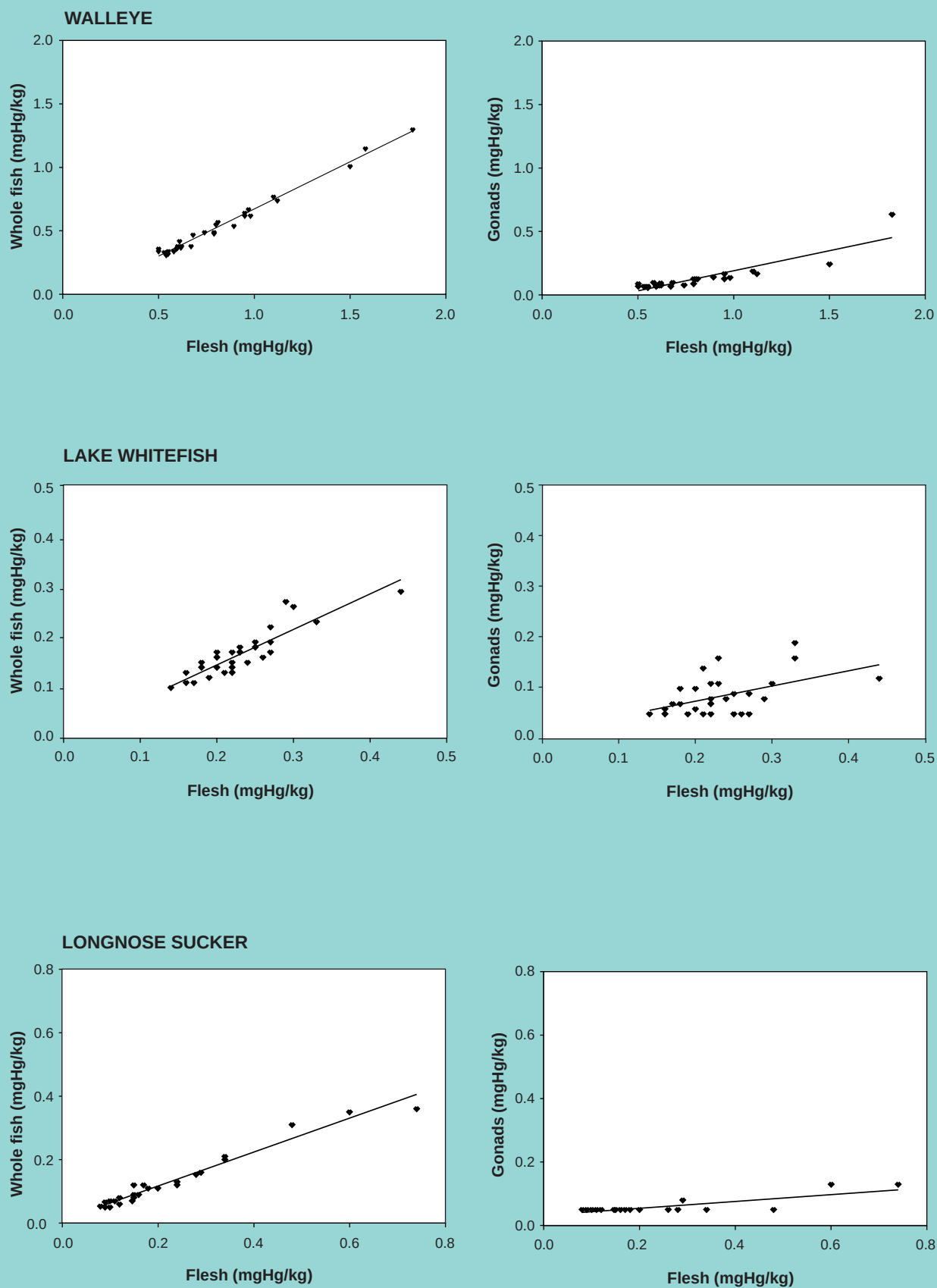
The results showed that mercury levels are always higher in flesh than in any other fish parts (Figure 3.25). The relationships between concentrations in the flesh and in other fish parts are all very significant ($p < 0.0001$).

The data shows that the evaluation of mean concentrations in the flesh can be used to estimate concentrations in other parts of the fish and that this estimate is a cautious one. In fact, basing consumption guidelines on concentrations in the flesh leads to no greater risk when other fish parts are eaten, as their levels will always be lower.

Comparison of total mercury and methylmercury in different fish parts

A comparison of total mercury and methylmercury concentrations was conducted on a subsample of various fish parts (flesh, gonads, entrails and whole fish). Table 3.10 shows that for the four species studied, the proportion of methylmercury was very high, i.e., close to 100% in all fish parts (flesh, whole fish, entrails and gonads), except in the gonads of lake whitefish (81%). This indicates that mean total mercury levels in the flesh can be used to make conservative estimates of total methylmercury levels in other fish parts and that, in the La Grande complex, the proportion of methylmercury in the flesh and other fish parts is similar to the range of values (80-99%) recorded in the related reference studies (Lindqvist, 1991; Lasorsa and Allen-Gil, 1995).

Figure 3.25 Relationship between Mercury Levels in Flesh and other Fish Parts for the Main Species in the La Grande Complex



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Figure 3.25 Relationship between Mercury Levels in Flesh and other Fish Parts for the Main Species in the La Grande Complex
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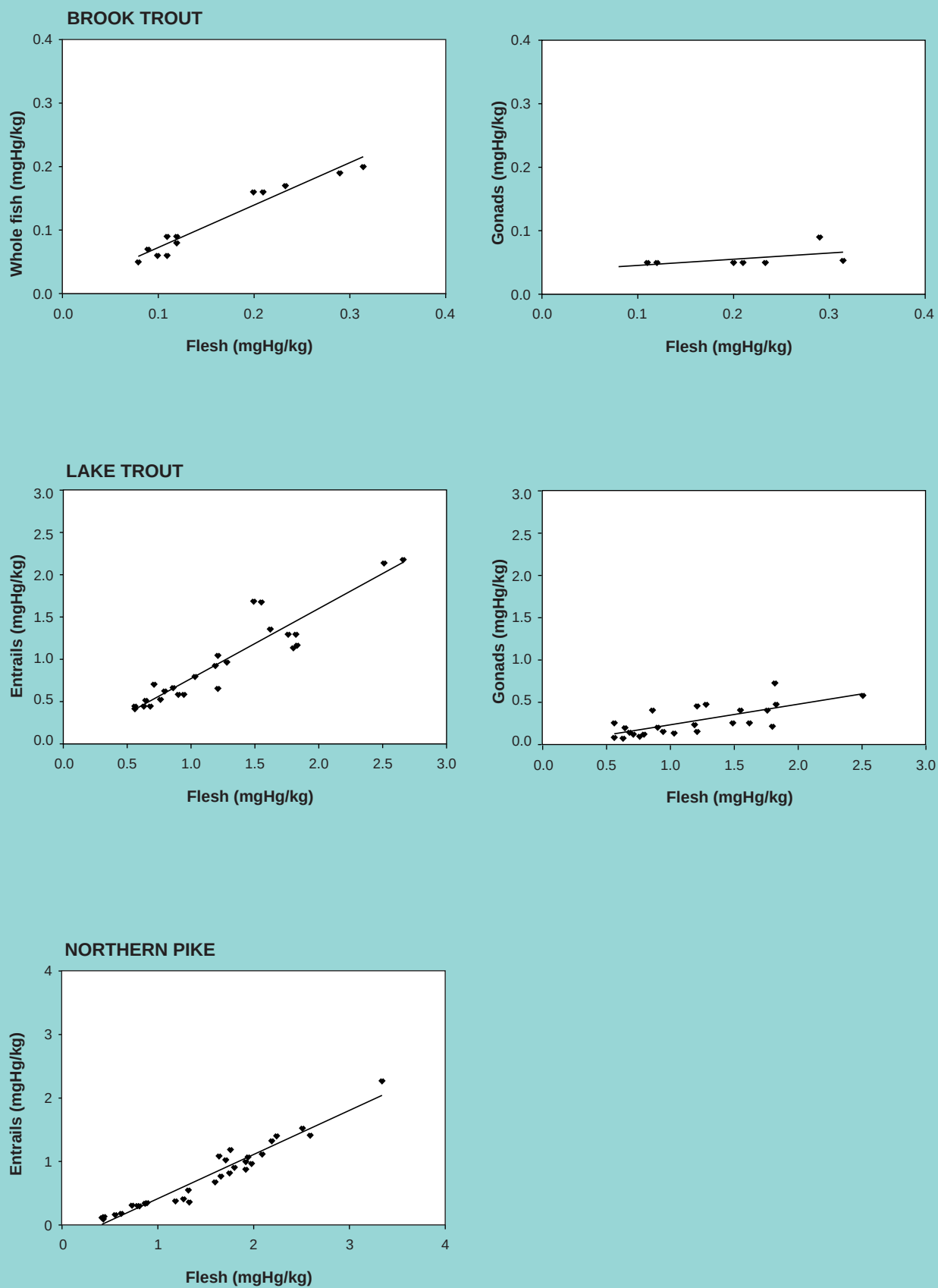


Table 3.10 Proportion of Methylmercury in Total Mercury Concentrations Measured in Flesh and other Fish Parts for the Main Species in the Eastmain and Rupert Watersheds

Species	Number	Fish part	Proportion of methylmercury (%)	C. I. ¹ (%)	Range of individual proportions (%)
Walleye	14	Flesh	100	2	106-120
Walleye	21	Gonads	97	6	66-117
Walleye	10	Whole fish	100	4	101-120
Northern pike	29	Entrails	97	6	59-119
Lake whitefish	17	Flesh	100	5	87-120
Lake whitefish	29	Gonads	81	6	51-110
Lake whitefish	6	Whole fish	100	8	98-120
Lake trout	15	Entrails	99	8	68-117

¹ C.I. = confidence interval ($p < 0.05$).

3.7.6 Nutritional profile of fish

A number of surveys to determine the content of main nutrients in the fish were conducted between 1998 and 2002 (Therrien and Schetagne, 2001a and Lucas *et al.*, 2003). Establishing the nutritional profile of fish made it possible to put the health benefits of eating fish into perspective in relation to the potential risk from the mercury they contain.

The five main species of fish in the La Grande complex that are caught recreationally or for subsistence (i.e., lake whitefish, northern pike, lake trout, walleye and brook trout) were analyzed to determine their nutrient content according to fishing season, time of spawning, environment (natural or modified) and sector (East or West). The results revealed that the nutritional value of the fish in the La Grande complex varies greatly between species, but differs very little in each species, depending on the fishing season, time of spawning, environment or sector.

Table 3.11 shows the mean concentrations of main nutrients obtained for each fish species. The nutritional content is expressed both in weight, i.e., grams or milligrams per meal (230 g portion) and as a percentage of the daily value (% DV). The DVs shown in the table correspond to the recommendations set out in Canada's Food Guide. The daily value is the amount of nutrients that we are advised to consume every day in order to supply our bodies with the essential elements they need to function properly. No daily values have been established for Omega-3 fatty acids. However, in 1999, a group of experts from the International Society for the Study of Fatty Acids and Lipids (ISSFAL) recommended a minimum adult daily intake of eicosapentanoic acid (EPA) and docosahexanoic acid (DHA) of about 440 mg.

Table 3.11 Nutritional Content of Fish Species in the La Grande Complex Expressed as an Edible Portion of 230 g and as a Percentage of the Daily Value (%DV)

Nutrient (unit)		Fish species									
		Lake whitefish		Northern pike		Brook trout		Lake trout		Walleye	
		Nutritional value in 230 g	% DV	Nutritional value in 230 g	% DV	Nutritional value in 230 g	% DV	Nutritional value in 230 g	% DV	Nutritional value in 230 g	% DV
DV for men aged 25 to 50											
Low source											
Vitamin A (IU)	2,997	21	0.7	27	0.9	27	0.9	24	0.8	21	0.7
Calcium (mg)	1,000	27	3	89	9	17	2	30	3	44	4
Iron (mg)	14	0.8	6	0.5	3	0.9	6	0.8	6	0.6	4
Sodium (mg)	< 2,400	94	4	84	3	52	2	72	3	79	3
Zinc (mg)	9	1.0	11	1.1	12	1.0	12	1.0	11	1.1	12
Magnesium (mg)	420	52	12	56	13	56	13	48	11	57	14
Total fatty acids (g)	< 65	2.0	3	1.2	2	2.6	4	6.2	10	2.6	4
Saturated fatty acids (g)	< 20	0.5	3	0.3	1	0.7	3	1.5	7	0.6	3
Medium source											
Potassium (mg)	3,500	875	25	784	22	932	27	823	24	863	25
Iodine (mg)	0.16	0.04	25	0.07	42	0.02	14	0.07	46	0.13	81*
High source											
Protein (g)	61	42	69	43	71	44	72	42	69	43	70
Selenium (mg)	0.05	0.06	124	0.06	113	0.12	236	0.08	152	0.06	126
EPA+DHA (mg)	440	500	114	411	94	544	124	955	217	687	156
Vitamin D (IU)	200	261	131	286	143	345	173	258	129	271	135

Source: CBHSSJB, CRSSSBJ and Hydro-Québec (2013).

In comparison to saltwater fish, the freshwater fish in the La Grande complex are considered thin, as they are high in proteins and low in lipids (< 5%). Eating these fish provides a healthy daily intake of protein, vitamin D, selenium, iodine and potassium. They are also an important source of Omega-3 fatty acids, especially EPA and DHA. Depending on the proportion of the DV it supplies for a given nutrient, a food can be classified as a low source (less than 20% of the DV), a medium source (between 20% and 60%) or a high source (more than 60%) of a nutrient.

The fish in the La Grande complex are thus a low source of Vitamin A, calcium, iron, sodium, zinc, magnesium, and saturated and total fatty acids. However, they constitute a medium source of potassium and iodine and a high source of vitamin D, protein, selenium and Omega-3 fatty acids (EPA and DHA).

The nutritional value of the fish in the La Grande complex compares very well to that found in the fish in Lac Saint-Pierre during the Saint-Laurent vision 2000 project (Lucas *et al.*, 2003). In fact, the analysis of two separate samples using Student's t-test revealed no significant differences in the levels of EPA and DHA, lipids, saturated fatty acids, protein, iron, zinc, magnesium and selenium in the flesh of lake whitefish, northern pike and walleye. The only significant difference found concerned vitamin D levels in lake whitefish, which were lower than those in the La Grande complex.

4. RISK MANAGEMENT

Despite the presence of mercury, consumers can now eat fish from most areas of the La Grande complex on a regular basis and thus benefit from their outstanding nutritional value (Hydro-Québec *et al.*, 2013). Based on the mean mercury levels found in the different species of fish, public health authorities issue guidelines on the maximum number of meals per month that consumers can eat without exceeding the recommended mercury exposure level and thus avoid any mercury-related health effects.

Details concerning the various methods public health authorities use to determine the safe number of meals per month are provided in section 2.4. It is important to note that for most adults, the recommended number of meals leads to long-term exposure to mercury of 5 to 7 ppm in hair, whereas the first symptoms of mercury poisoning would appear at 50 ppm in 5% of the most sensitive individuals (WHO, 1972). These recommendations are, therefore, considered very safe.

This chapter covers the following:

- Effects on fish consumption from the temporary increase in fish mercury levels in modified water bodies in the La Grande complex, based on the number of meals per month recommended by Health Canada and Santé Québec
- Consumption guidelines currently in effect as a result of fish mercury levels measured in 2012

4.1 Effects on fish consumption

Table 4.1 and figures 4.1 to 4.4 illustrate the extent and duration of the effects on fish consumption from the increase in mercury levels observed in the different modified water bodies in the La Grande complex, i.e., reservoirs, areas immediately downstream of reservoirs, diversions and reduced-flow rivers. For each type of environment, the figures show the maximum effects on consumption of the main species of fish by recreational anglers and subsistence fishers; thus, they depict the water bodies that were only impounded once and reached the highest mercury levels by species and by sector.

Table 4.1 Consumption Guidelines for the Main Fish Species According to Mean Mercury Levels Measured in Modified Water Bodies in the La Grande Complex

Environment	Lake whitefish (500 mm)					Northern pike (800 mm)					Walleye (500 mm)				Lake trout (600 mm)			
	Range in natural lake	Maximum	Last survey	Return		Range in natural lake	Maximum	Last survey	Return		Range in natural lake	Maximum	Last survey	Return	Range in natural lake	Maximum	Last survey	Return
Reservoir																		
Robert-Bourassa	0.08 - 0.34	0.69	0.26	Yes		0.37 - 1.22	4.19	2.02	No		0.55 - 1.47	3.61	1.65	Yes				
Opinaca	0.08 - 0.34	0.60	0.31 ²	Yes		0.37 - 1.22	3.50	2.04 ²	No		0.55 - 1.47	2.93	1.75 ²	Yes				
La Grande 3	0.08 - 0.34	0.60	0.37	Yes		0.37 - 1.22	5.47	1.59	Yes		0.55 - 1.47	2.55 ⁶	1.54	Yes				
La Grande 4	0.15 - 0.41	0.32	0.22	Yes		0.59 - 1.28	1.97	1.44	Yes						0.52 - 1.11	N/A	0.97 ⁷	Yes
Caniapiscou	0.15 - 0.41	0.39	0.25	Yes		0.59 - 1.28	2.17	1.43	Yes						0.52 - 1.11	1.85	1.12	Yes
La Grande 1	0.08 - 0.34	1.92	0.28	Yes		0.37 - 1.22	6.25	1.03	Yes		0.55 - 1.47	5.87	1.61	Yes				
Laforge 1	0.15 - 0.41	0.44	0.22	Yes		0.59 - 1.28	2.06	2.06	No									
Laforge 2	0.15 - 0.41	0.40	0.27	Yes		0.59 - 1.28	2.73	1.18	Yes									
Immediately downstream of reservoir																		
Robert-Bourassa downstream	0.08 - 0.34	2.14	0.50	No		0.37 - 1.22	5.92	1.60 ⁵	Yes		0.55 - 1.47	2.43 ⁶	1.61	Yes				
Opinaca downstream	0.08 - 0.34	1.13	0.43 ²	Yes		0.37 - 1.22	3.15	2.04 ²	No		0.55 - 1.47	3.14	1.86 ²	Yes				
Caniapiscou downstream	0.15 - 0.41	0.52	0.27	Yes		0.59 - 1.28	2.74	1.08	Yes						0.52 - 1.11	2.81	0.98	Yes
Laforge 1 downstream	0.15 - 0.41	0.46	0.33	Yes		0.59 - 1.28	2.14	1.54	Yes						0.52 - 1.11			
Diversions																		
EOL	0.08 - 0.34	0.80	0.26 ³	Yes		0.37 - 1.22	4.62	3.23	No		0.55 - 1.47	3.17	2.11	No				
Reduced-flow rivers																		
Caniapiscou ¹	0.15 - 0.41	0.58	0.05-0.17 ⁴	Yes											0.52 - 1.11	1.54	0.46-0.72 ⁴	Yes

Note: The colors indicate the consumption guidelines for the number of meals per month and the corresponding mercury levels, i.e.:

	Unrestricted (> 12 meals per month)	≤ 0.29 mg/kg
	8 meals per month	0.30 to 0.49 mg/kg
	4 meals per month	0.50 to 0.99 mg/kg
	2 meals per month	1.00 to 1.99 mg/kg
	1 meal per month	2.00 to 3.75 mg/kg
	< 1 meal per month	> 3.75 mg/kg

1: The data was collected at three sampling stations 100 km, 275 km and 355 km from Caniapiscou reservoir (section 3.5.4).

2: Sampling conducted in 2011.

3: Sampling conducted in 2008.

4: Sampling conducted in 1995. Range of values obtained at all three sampling stations (section 3.5.4).

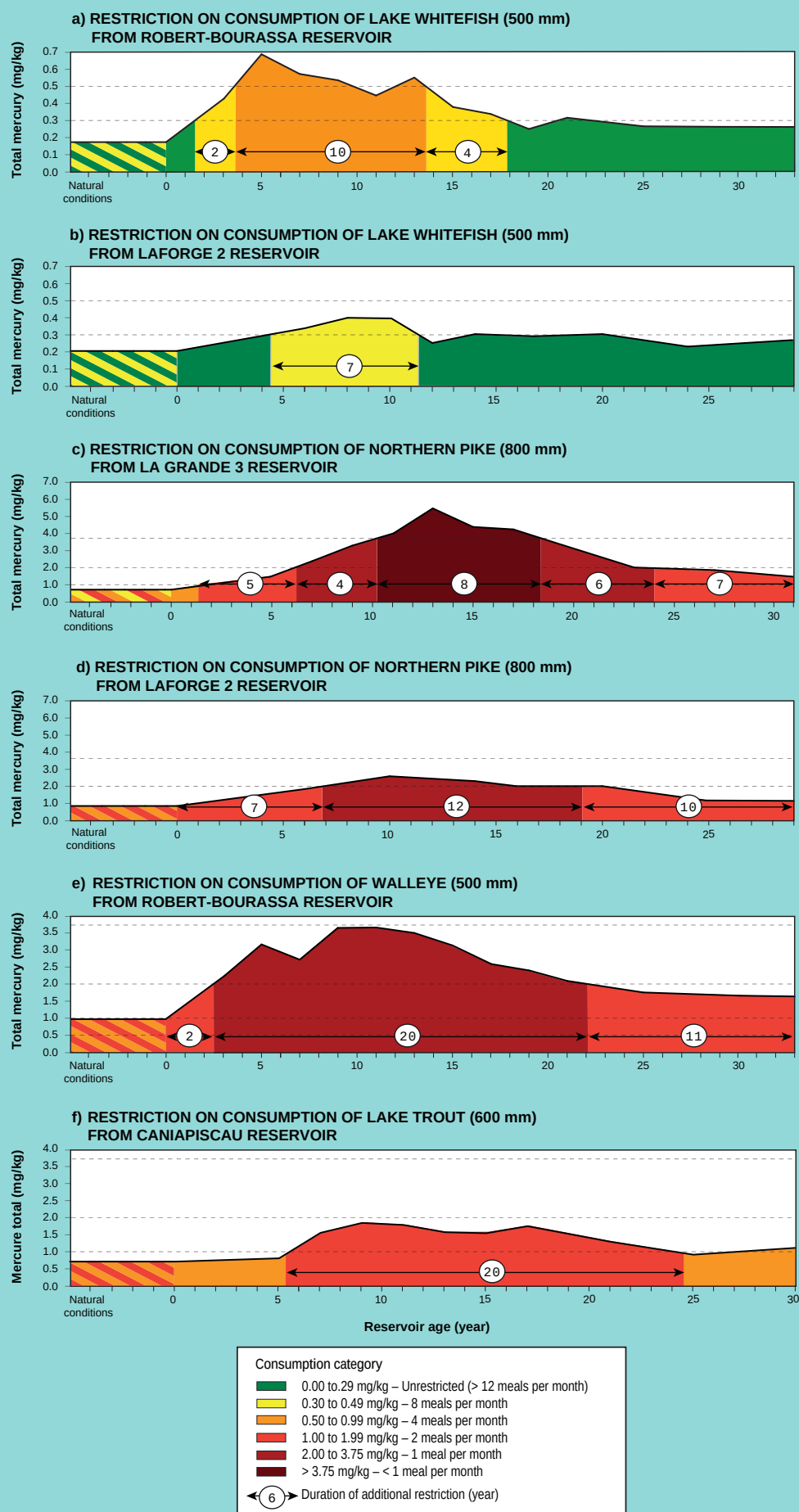
5: Probable value based on mercury level measured in 700-mm northern pike.

6: Absence of data during peak year, based on the results for other species.

7: Value calculated for a length of 700 mm.

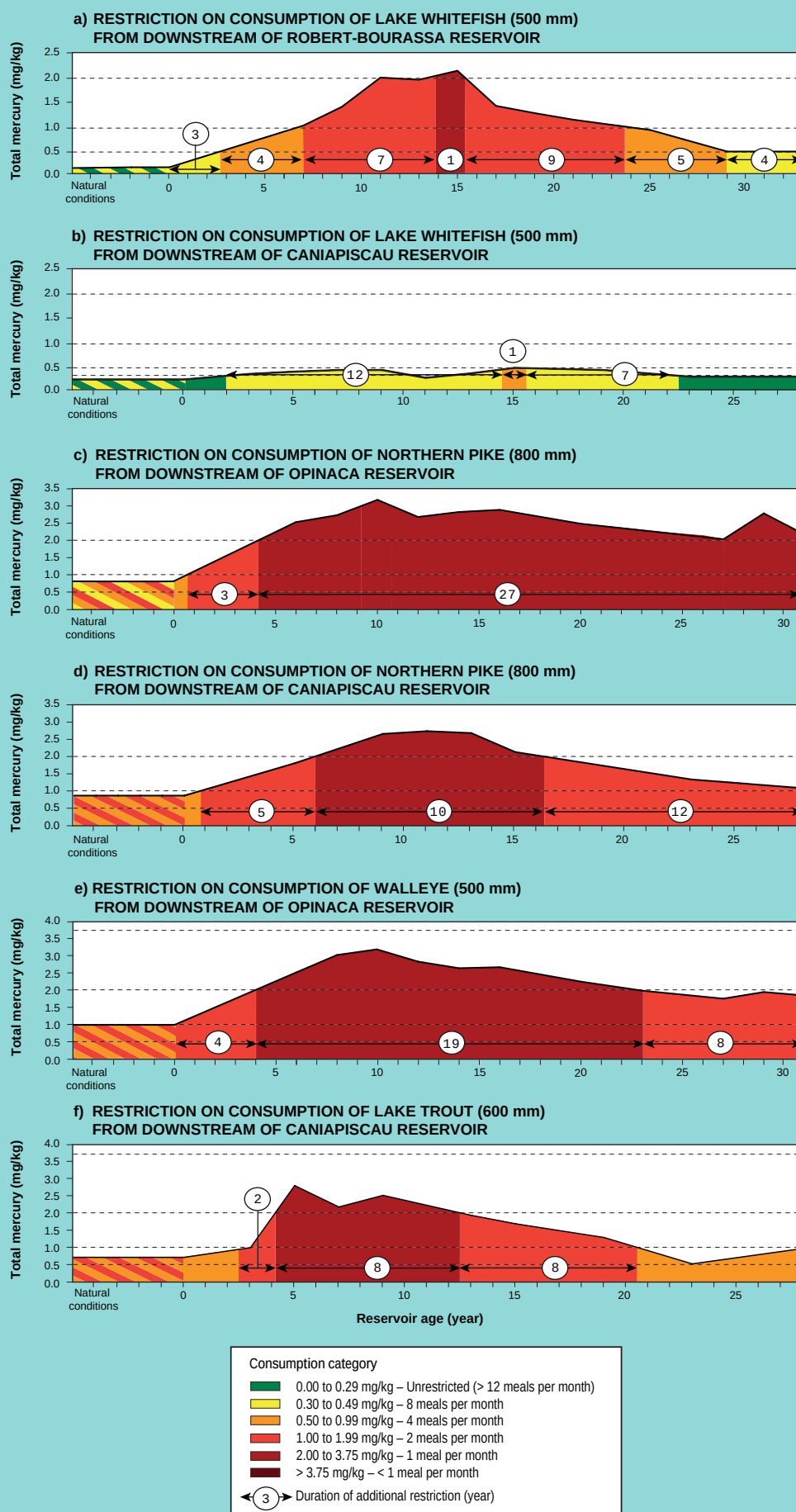
N/A: Not available; insufficient data within the time series.

Figure 4.1 Additional Restrictions on Consumption by Most Adults of the Main Species of Fish in La Grande Complex Reservoirs



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Figure 4.2 Additional Restrictions on Consumption by Most Adults of the Main Species of Fish in Areas Immediately Downstream of La Grande Complex Reservoirs



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Figure 4.3 Additional Restrictions on Consumption by Most Adults of the Main Species of Fish in the Eastmain-Opinaca-La Grande Diversion

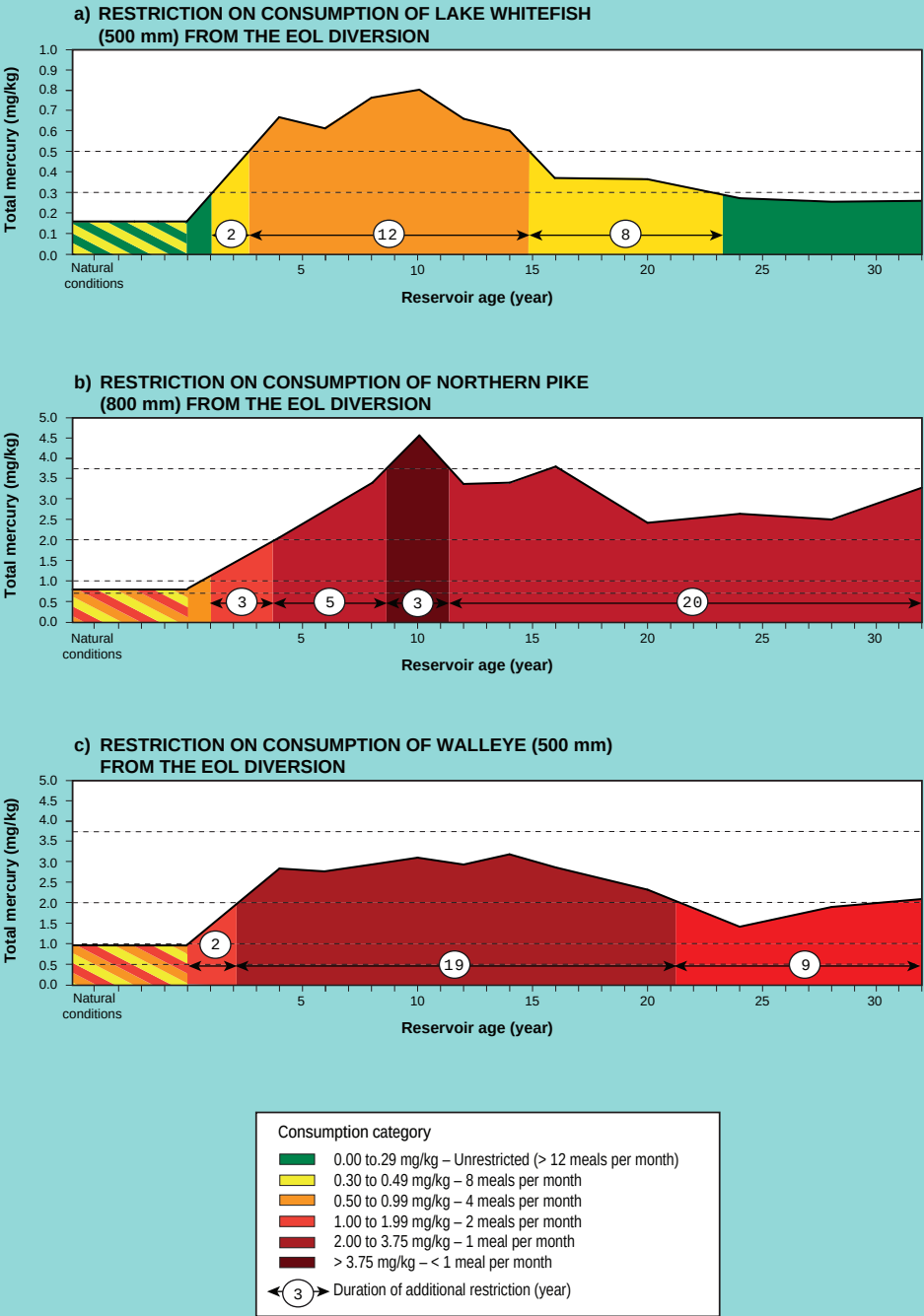
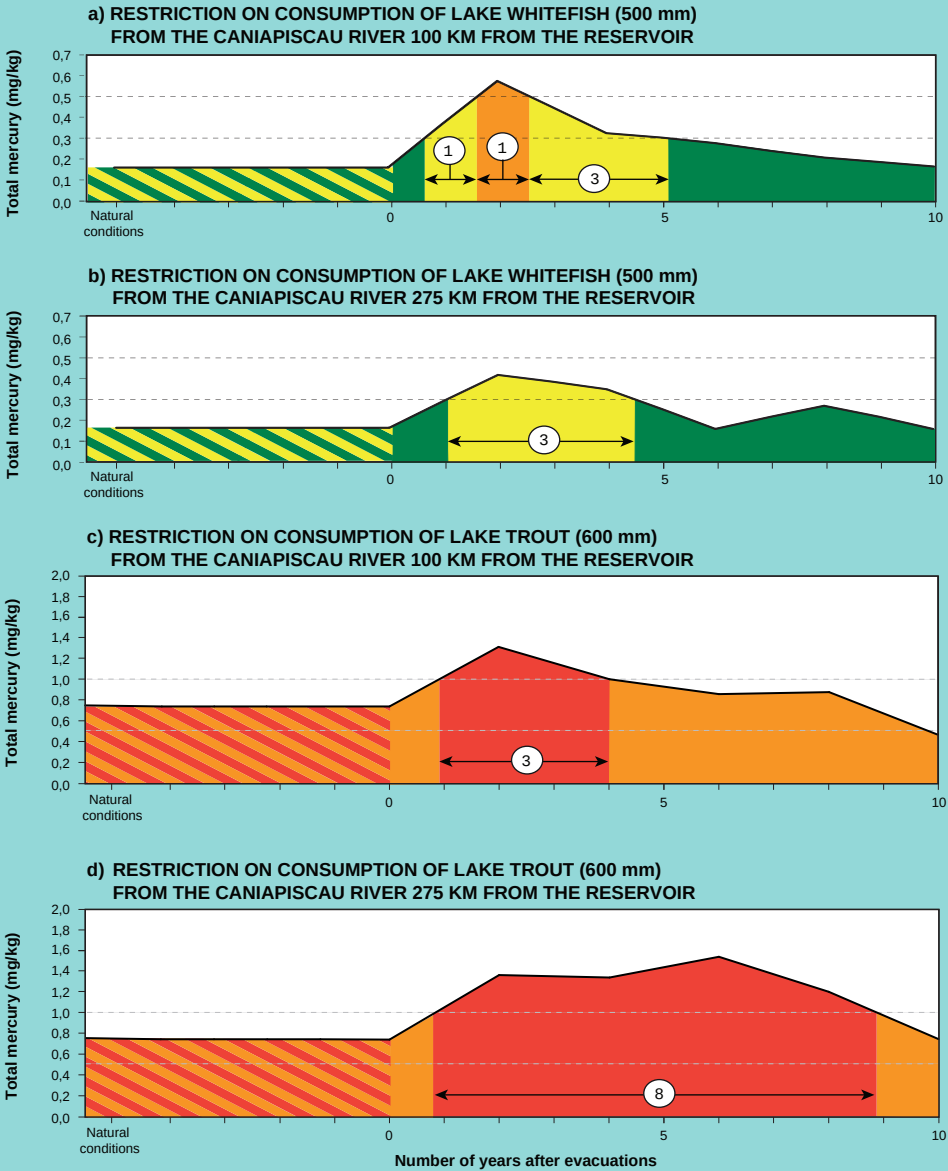


Figure 4.4 Additional Restrictions on Consumption by Most Adults of the Main Species of Fish in the Reduced-Flow Section of the Rivière Caniapiscau after Diversion



Consumption category	
	0,00 to 0,29 mg/kg – Unrestricted (> 12 meals per month)
	0,30 to 0,49 mg/kg – 8 meals per month
	0,50 to 0,99 mg/kg – 4 meals per month
	1,00 to 1,99 mg/kg – 2 meals per month
	2,00 to 3,75 mg/kg – 1 meal per month
	> 3,75 mg/kg – < 1 meal per month
3	Duration of additional restriction (year)

The consumption lengths considered in calculating the recommended number of meals per month correspond to the average lengths of the fish caught by Crees with gill nets. For most species, these fish are larger than those likely to be caught by recreational anglers, making the consumption guidelines even safer for anglers (section 2.4.3.2).

It should be noted that, because of the considerable differences in mercury levels observed in natural lakes, the consumption guidelines for each species can vary widely from one natural lake to another.

4.1.1 Reservoirs

Note that this section covers cases where the most stringent additional consumption restrictions were applied.

Lake whitefish

The guidelines for 500-mm lake whitefish in natural lakes vary from unrestricted consumption (i.e., more than 12 meals per month) to a maximum of eight meals per month, depending on the lake.

For lake whitefish in **Robert-Bourassa reservoir** (Figure 4.1a), the increase in mercury levels meant that an additional restriction was applied to the consumption guidelines for a period of 10 years, reducing the recommended number of meals to four per month. Compared to most natural lakes, where fish consumption is unrestricted, these additional restrictions remained in effect for 16 years, calling for a maximum of eight meals per month for six years (during the 3rd and 4th years after impoundment and then from years 15 to 18) and four meals per month for ten years (from years 5 to 14).

For lake whitefish in **Laforge 2 reservoir** (Figure 4.1b), no further restrictions were applied to the guidelines established for certain natural lakes (eight meals per month), but the recommendation was reduced to eight meals per month for seven years (from years 5 to 11 after impoundment) over that set out for the majority of the natural lakes in the region.

For all reservoirs in the complex, including those impounded more than once, further restrictions on the consumption of 500-mm lake whitefish for a period 0 to 15 years were applied to the guidelines established for the region's natural lakes, which varied from unrestricted consumption to a maximum of eight meals per month.

Northern pike

For 800-mm northern pike in natural lakes, the maximum recommended number of meals per month ranges from two to eight, depending on the lake.

In **La Grande 3 reservoir**, further consumption restrictions had to be applied for 18 years (Figure 4.1c). However, in comparison with most natural lakes, where the guidelines called for four meals per month, the additional restrictions on the consumption of northern pike were spread over a total of 30 years, i.e., two meals per month for 12 years (years 2 to 6 and 25 to 31 after impoundment), one meal per month for 10 years (years 7 to 10 and 19 to 24) and less than one meal per month for eight years (years 11 to 18). The mean mercury level measured during the last survey (1.59 mg/kg; Table 4.1), conducted 31 years after impoundment, corresponded to the recommendation of two meals per month that applied to certain natural lakes in the region.

In **Laforge 2 reservoir**, an additional restriction lasting 12 years was applied to the consumption guidelines for natural lakes (Figure 4.1d). However, in comparison with most of the natural lakes, the additional consumption restrictions for the reservoir were spread over a total of 29 years, i.e., two meals per month for 17 years (for the first seven years, then from years 20 to 29 after impoundment) and one meal per month for 12 years (years 8 to 19). The mean mercury level measured during the last survey (1.18 mg/kg; Table 4.1), conducted 29 years after impoundment, corresponded to the recommendation of two meals per month that applies to certain natural lakes in the region.

For all reservoirs, the additional restrictions on the consumption of 800-mm northern pike lasted 0 to 30 years, depending on the reservoir, as compared with the guidelines established for the region's natural lakes, which range from two to eight meals per month.

Walleye

For 500-mm walleye in natural lakes, the guidelines recommend two to four meals per month, depending on the lake.

In **Robert-Bourassa reservoir**, further restrictions had to be applied to the guidelines for a period of 20 years (Figure 4.1e). However, in comparison to most of the natural lakes, where the recommended number of meals was four per month, the additional restrictions on the consumption of walleye were

spread out over a total of 33 years, i.e., two meals per month for 13 years (during the first two years after impoundment and then from years 23 to 33), and one meal per month for 20 years (years 3 to 22). The mean mercury level measured during the last survey (1.65 mg/kg; Table 4.1), conducted 33 years after impoundment, corresponded to the guideline of two meals per month that applies to certain natural lakes in the region.

For all reservoirs where walleye is present, the additional restrictions on the consumption of 500-mm walleye lasted 13 to 21 years, depending on the reservoir, as compared with the recommended two to four meals per month for the region's natural lakes.

Lake trout

For 600-mm lake trout in natural lakes, the guidelines recommend two to four meals per month, depending on the lake.

In **Caniapiscou reservoir**, no further restrictions were applied to the consumption guidelines (Figure 4.1f). However, in comparison with most of the natural lakes, where the guidelines call for four meals per month, the recommendation for the reservoir was reduced to two meals per month for 20 years (year 6 to 24 after impoundment). The mean mercury levels measured as of year 25 have varied between 0.92 and 1.12 mg/kg, resulting in consumption guidelines similar to those that apply to the natural lakes in the region, i.e., two to four meals per month.

4.1.2 Immediately downstream of reservoirs

Note that this section covers cases where the most stringent additional consumption restrictions were applied.

Lake whitefish

In comparison with most of the natural lakes, which allow for unrestricted consumption, 500-mm lake whitefish caught **immediately downstream of Robert-Bourassa reservoir** were subject to additional restrictions over a period of 33 years (Figure 4.2a). The guidelines were reduced to eight meals per month for seven years (for the first three years of operation of the generating station, then from years 30 to 33), four meals per month for nine years (years 4 to 7 and 25 to 29), two meals per month for 16 years (years 8 to 14 and 16 to 24), and even one meal per month during the 15th year after impoundment.

The mean mercury levels measured during the last two surveys (0.46 and 0.50 mg/kg), conducted after 29 and 33 years of operation, correspond to the guidelines of 8 to 4 meals per month, in accordance with the recommended consumption categories.

For lake whitefish caught **immediately downstream of Caniapiscau reservoir** (Figure 4.2b), a 20-year restriction was applied over the guidelines in place for most of the natural lakes, where lake whitefish consumption is unrestricted (i.e., more than 12 meals per month). The recommendation was reduced to eight meals per month for 19 years (from years 3 to 14 after commissioning of the diversion and then from years 16 to 22) and to four meals per month during year 15. The mean mercury levels measured as of the 23rd year after commissioning now allow for unrestricted consumption of lake whitefish from this area.

In the various areas immediately downstream of the La Grande complex generating stations, additional restrictions on the consumption of 500-mm lake whitefish were applied for 0 to 26 years, depending on the case, as compared with the guidelines in effect for the region's natural lakes, which range from unrestricted consumption to a maximum of eight meals per month.

Northern pike

For the last 30 years, the consumption of northern pike from areas **immediately downstream of Opinaca reservoir** has been subject to an additional restriction over the guideline of four meals per month that applies to most of the natural lakes (Figure 4.2c). The recommendation was reduced to two meals per month for three years (years 2 to 4 after impoundment) and one meal per month for 27 years (years 5 to 31). The mean mercury level measured during the last survey, done 31 years after impoundment (2.04 mg/kg; Table 4.1), corresponds to one meal per month in accordance with the recommended consumption categories, but in reality, allows for 1.8 meals per month.

For the last 27 years, the consumption of northern pike caught **immediately downstream of Caniapiscau reservoir** has been subject to an additional restriction over the guideline of four meals per month that applies to most of the natural lakes (Figure 4.2d). The recommendation was reduced to two meals per month for 17 years (years 2 to 6 and 17 to 28 after commissioning of the diversion) and one meal per month for 10 years (years 7 to 16). The mean mercury level measured during the last survey, done 28 years after impoundment (1.08 mg/kg), corresponds to the same guidelines as those that apply to certain natural lakes in the region, i.e., two meals per month.

Walleye

For the last 31 years, the consumption of walleye caught **immediately downstream of Opinaca reservoir** has been subject to an additional restriction over the guideline of four meals per month that applies to most natural lakes (Figure 4.2e). The recommendation was reduced to two meals per month for 12 years (for the first four years, then from years 24 to 31 after impoundment) and one meal per month for 19 years (years 5 to 23). The mean mercury level measured during the last survey, conducted 31 years after commissioning (1.86 mg/kg; Table 4.1), corresponds to the same guidelines as those that apply to certain natural lakes in the region, i.e., two meals per month.

Lake trout

For 18 years, the consumption of lake trout caught **immediately downstream of Caniapiscau reservoir** was subject to an additional restriction over the guideline of four meals per month that applies to most natural lakes (Figure 4.2f). The recommendation was reduced to two meals per month for 10 years (years 4 and 5 and then years 14 to 21 after commissioning of the diversion) and to one meal per month for eight years (years 6 to 13). The mean mercury levels measured more than 21 after commissioning once again allow for consumption of four meals per month.

Thus, depending on the water body monitored, the consumption of piscivorous fish caught immediately downstream of the generating stations was subject to additional restrictions for periods of 10 to 27 years over the guidelines established for the region's natural lakes, which vary between two and eight meals per month, depending on the lake.

4.1.3 Eastmain-Opinaca-La Grande diversion

Lake whitefish

In comparison to most of the natural lakes where it is unrestricted, the consumption of 500-mm lake whitefish caught at **Lac Sakami** station, located within the EOL diversion, was subject to additional restrictions for a period of 22 years (Figure 4.3a). The recommendation was reduced to eight meals per month for 10 years (years 2 and 3 and then from years 16 to 23 after commissioning of the diversion) and to four meals per month for 12 years (year 4s to 15). The mean mercury levels recorded as of the 23rd year after commissioning once again allow for unrestricted consumption.

Northern pike

For the last 31 years, the consumption of 800-mm northern pike in **Lac Sakami** has been subjected to an additional restriction over the guidelines established for most of the natural lakes, which recommend 4 meals per month (Figure 4.3b). The recommendation was reduced to two meals per month for three years (years 2 to 4 after commissioning of the diversion), one meal per month for 25 years (years 5 to 9 and 13 to 32) and less than one meal per month from years 10 to 12. Because of the mean mercury level measured during the last survey, conducted 32 years after commissioning (3.23 mg/kg; Table 4.1), the guidelines remain at one meal per month, in accordance with the recommended consumption categories.

Walleye

For a period of 19 years, the consumption of walleye in **Lac Sakami** was subject to an additional restriction over the recommended two to four meals per month established for natural lakes (Figure 4.3c). However, additional restrictions to the consumption guideline of four meals per month for most natural lakes have been in place since the diversion was commissioned. The recommendation was reduced to two meals per month for 11 years (for the first two years after commissioning and then from years 22 to 30) and one meal per month for 19 years (years 3 to 21). The mean mercury level recorded during the last survey, done 32 after commissioning (2.11 mg/kg; Table 4.1), still corresponds to a guideline of one meal per month based on the recommended consumption categories but, in reality, allows for 1.8 meals per month.

4.1.4 Reduced-flow section of Rivière Caniapiscou

Lake whitefish

Following the spillages from Caniapiscou reservoir into the reduced-flow stretch of the Rivière Caniapiscou, very few restrictions were applied to the consumption 500-mm lake whitefish from that area. In comparison to the guidelines in place for most of the region's natural lakes, where consumption is unrestricted, restrictions lasting three to five years, respectively, were recommended for **Eaton amont** station (100 km downstream of the reservoir) and **Cambrien** station (275 km downstream). For lake whitefish caught at **Eaton amont** station (Figure 4.4a), the recommendation called for a maximum of eight meals per month for the first year after the spillages and then from the 3rd to the 5th year, and four meals per month during the 2nd year. The consumption of lake whitefish caught in **Lac Cambrien** (figure 4.4b) was restricted to eight meals per month, but only for the 2nd to 4th year after the spillages. The consumption of lake whitefish caught at **Calcaire** station, 355 km below Caniapiscou reservoir, remained unrestricted as no significant increase in mercury levels was found there.

Lake trout

Following the spillages from Caniapiscou reservoir into the reduced-flow stretch of the Rivière Caniapiscou, no further restrictions were applied to the consumption of 600-mm lake trout over the guidelines in place for the region's natural lakes, which recommended two to four meals per month. However, at **Eaton amont and Cambrien** stations, the guideline of four meals per month recommended for those caught in most of the region's natural lakes was reduced to a maximum of two meals per month for three to eight years, respectively (figures 4.4c and 4.4d). Since there was no significant increase in the mercury levels recorded at **Calcaire** station, located 355 km downstream of Caniapiscou reservoir, no further restrictions on lake trout consumption were applied to the guidelines established for the natural lakes in the region.

4.2 Fish consumption guidelines based on mercury levels measured in 2012

The mean mercury levels recorded in 2012 in fish in the modified water bodies in the La Grande complex were much lower than the maximum levels measured for the different water bodies monitored. Table 4.1 shows that the levels obtained for most of the fish species and water bodies now allow for consumption equivalent to that recommended for the region's natural lakes. Note that the most recent data on Opinaca reservoir, the area immediately downstream of it and the EOL diversion was collected in 2011.

Lake whitefish

The results of the last survey on mean mercury levels in 500-mm lake whitefish in **all water bodies monitored** allowed for consumption equivalent to that recommended for natural lakes in the region, i.e., unrestricted, or a maximum of eight meals per month (Table 4.1). The only exception concerns lake whitefish caught immediately downstream of Robert-Bourassa generating station, for which the recorded mean mercury level of 0.50 mg/kg falls within the lower range corresponding to the recommended consumption of four meals per month (0.50 to 0.99 mg/kg) but in reality, allows for a maximum of 7.5 meals per month.

Northern pike

During the last survey, the mean mercury levels recorded in 800-mm northern pike in most of the La Grande complex **reservoirs** allowed for consumption equivalent to that recommended for certain natural lakes in the region, i.e., a maximum of two meals per month (Table 4.1). The only exceptions are northern pike in Robert-Bourassa, Opinaca and Laforge 1 reservoirs, where the mean mercury levels measured in 2012 (2.02 to 2.06 mg/kg) fall within the lower range corresponding to the recommended consumption of one meal per month (2.00 to 3.75 mg/kg) but in reality, allow for a maximum of 1.8 meals per month. **Immediately downstream of the reservoirs** monitored, the mean mercury levels recorded during the last survey allow for consumption equivalent to that recommended for certain natural lakes in the region, i.e., two meals per month (Table 4.1). The only exception concerns the area immediately downstream of Opinaca reservoir, for which the mean mercury level measured in 2011 (2.04 mg/kg) corresponds to the recommended consumption of one meal per month but in reality, allows for a maximum of 1.8 meals per month. In **Lac Sakami**, the mean mercury level measured during the last survey in 2011 (3.23 mg/kg) still corresponds to a recommended consumption of one meal per month.

Walleye

The mean mercury levels recorded during the last survey on 500-mm walleye caught in **all water bodies monitored** allow for consumption equivalent to that recommended for certain natural lakes in the region, i.e., a maximum of two meals per month (Table 4.1), with the exception of those caught in Lac Sakami, for which the mean mercury level measured in 2011 (2.11 mg/kg) corresponds to the recommended consumption of one meal per month but in fact, allows for 1.8 meals per month.

Lake trout

The mean mercury levels recorded during the last survey on 600-mm lake trout caught in **all water bodies monitored** allow for consumption equivalent to that recommended for certain natural lakes in the region, i.e., a maximum of two to four meals per month (Table 4.1).

Burbot

The mean mercury levels recorded during the last survey on 500-mm burbot caught in **all water bodies monitored** allow for consumption equivalent to that recommended for certain natural lakes in the region, i.e., a maximum of four meals per month (Figure 3.11).

4.3 Northern Fish Nutrition Guide – Baie-James Region

The 2004 fish nutrition guide was revised in 2013 for two main reasons. Firstly, the decrease in fish mercury levels in modified water bodies during Phase I and II development of the La Grande complex was such that for most of the fish species and water bodies, the mean levels recorded during the most recent surveys now allow for consumption equivalent to that recommended for the region's natural lakes, meaning that people can eat more fish than the quantities recommended in 2004. Secondly, in the areas affected by Phase III development of the La Grande complex, i.e., Opinaca and Eastmain 1 reservoirs, the Rupert diversion bays and the reduced-flow stretches of the Lemare and Nemiscau rivers downstream of the diversion, overall mercury levels are still increasing and require additional restrictions on fish consumption.

Thus, the 2013 Northern Fish Nutrition Guide – Baie-James Region (Hydro-Québec *et al.*, 2013) covers the water bodies affected by phases I, II and III of the La Grande complex, as well as the natural lakes in the region. It was produced jointly by the CBHSSJB, the CRSSBJ, Hydro-Québec Production, the Institut national de santé publique du Québec [Québec's national institute of public health], the Cree Outfitting and Tourism Association and the CHU de Québec research centre, which are the public health authorities responsible for establishing fish consumption guides for recreational anglers and subsistence fishers.

Mercury in fish can affect the nervous system at high doses. However, the levels measured in the fish in the Baie-James region have led local public health authorities to consider that the health benefits of consuming them are excellent and far outweigh the risk. This is why the nutrition guide focuses on encouraging people to eat fish. It emphasizes the nutritional value and health benefits of fish and helps allay consumers' concerns about mercury and other contaminants.

The guides also contain a wealth of information likely to interest fishing buffs, such as the favorite habitats of the main fish species, their most active periods, the most effective lures, the catch record, what they each taste like and, of course, many recipes to better savor the catch. It is available in French and English and has been distributed to all Cree households, as well as to outfitters and fishing associations in the La Grande Rivière region.

4.3.1 Main messages to consumers from the 2013 nutrition guide

The nutrition guide imparts the following main messages to fish consumers.

For most adults (except women who are pregnant or may become pregnant):

- If you eat fish from the Baie-James region less than once a week, you do not need to worry about mercury. You may continue to enjoy the health benefits of eating fish.

For major consumers of fish:

- If you eat fish more than once a week throughout the year, you should exercise caution and consult the fish consumption recommendations included in this nutrition guide (maps 4.1 to 4.5). The maps in the guide will provide you with information concerning the consumption frequency recommended to avoid exceeding the mercury exposure level established by Québec public health authorities.

For women who are pregnant or may soon become pregnant and children under 13 years of age:

- Pregnant women should include a sufficient intake of Omega-3 fatty acids in their diet during and after pregnancy. Fish are rich in Omega-3s, which contribute to optimum development of the baby's brain, nervous system and eyesight. Québec public health authorities also recommend that women who are pregnant or may soon become pregnant eat at least two meals per week of low-mercury fish (identified with a green dot in the guide). Women who are pregnant or may become pregnant should avoid eating predatory fish such as northern pike, walleye, lake trout (or grey trout) and burbot.

4.3.2 Fish consumption guidelines for 2013

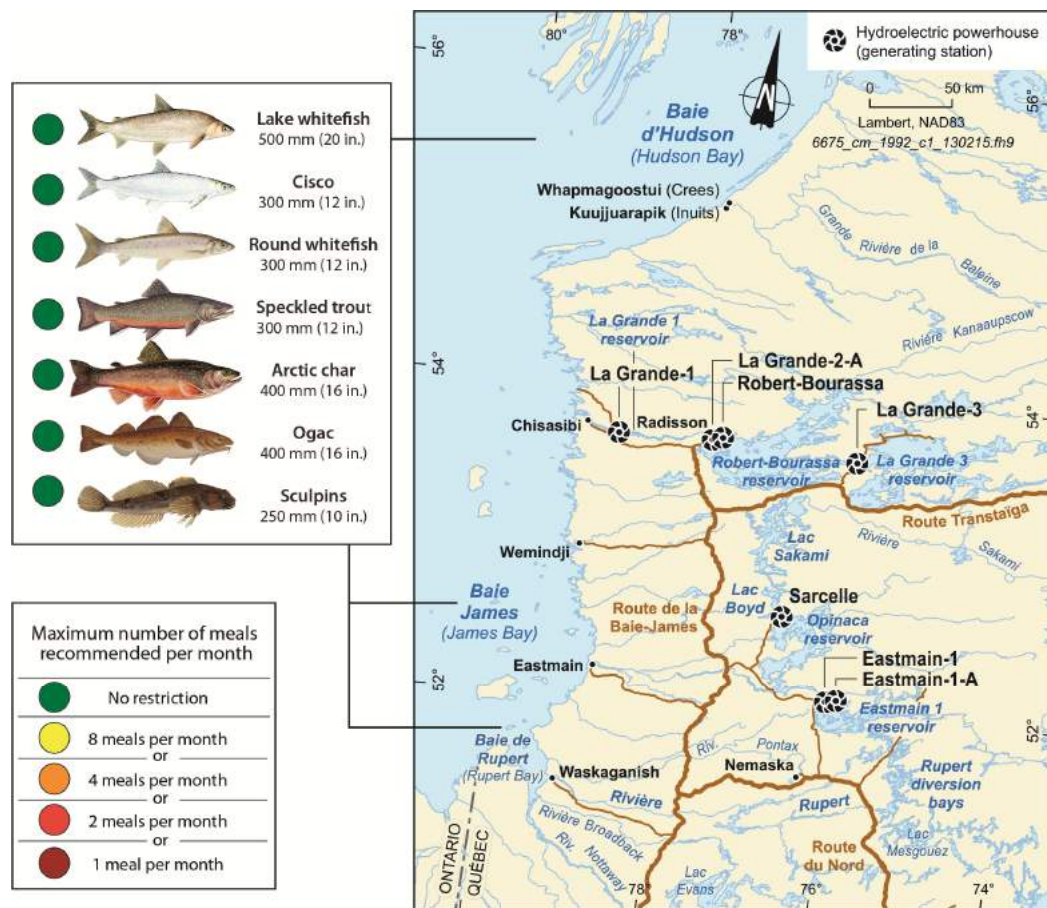
The consumption guidelines for each water body and each of the main species of fish, presented as color-coded maps, set out the maximum number of meals per month that can be consumed without exceeding the mercury exposure levels recommended by the public health authorities. The detailed calculation methods and consumption categories are provided in section 2.4.

The consumption guidelines provided are very safe, as they are based on a safety factor to ensure that all consumers remain under the recommended mercury exposure limits. For example, the consumption guidelines for predatory fish in Robert-Bourassa reservoir call for two meals per month (Map 4.2) but in fact, most consumers would have to eat these fish at least once a day for a whole year to reach a level of exposure known to cause mercury-related health effects.

Coastal regions of Baie James (James Bay) and Baie d'Hudson (Hudson Bay)

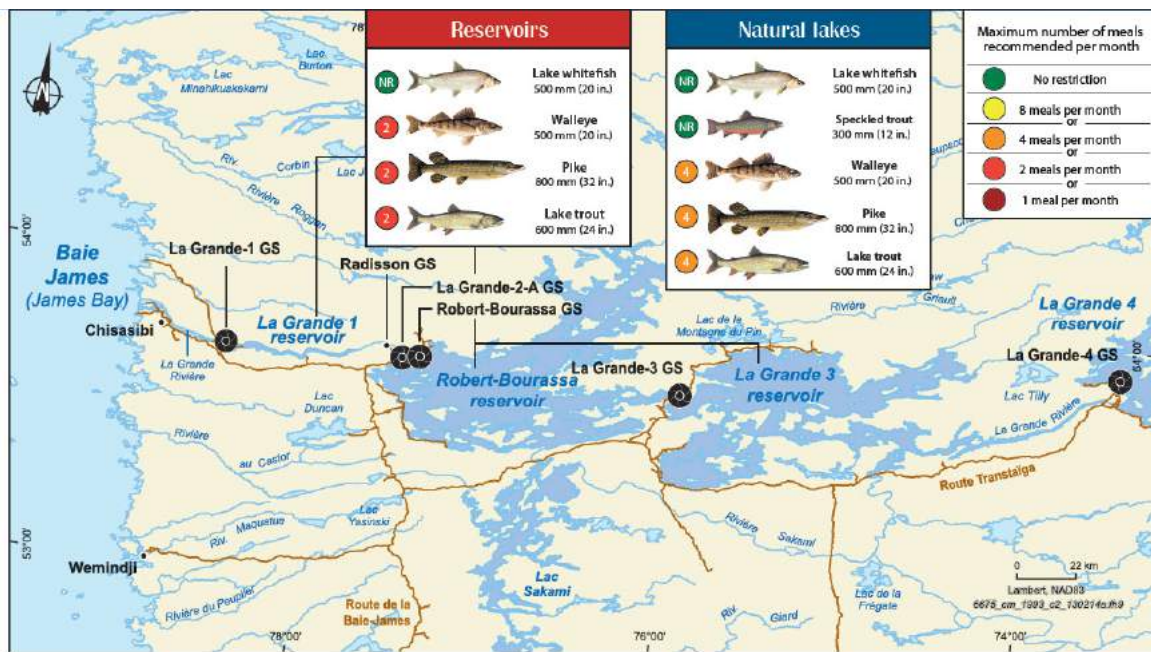
Fish along the coast of Baie James contain less mercury because of the chemical reactions that occur in salt water. There are no restrictions on the consumption of any species of fish caught along the coast of Baie James and Baie d'Hudson (Map 4.1).

Map 4.1 Fish Consumption Guidelines for the La Grande Complex for Most Adults (Baie James and Coast of Baie d'Hudson)



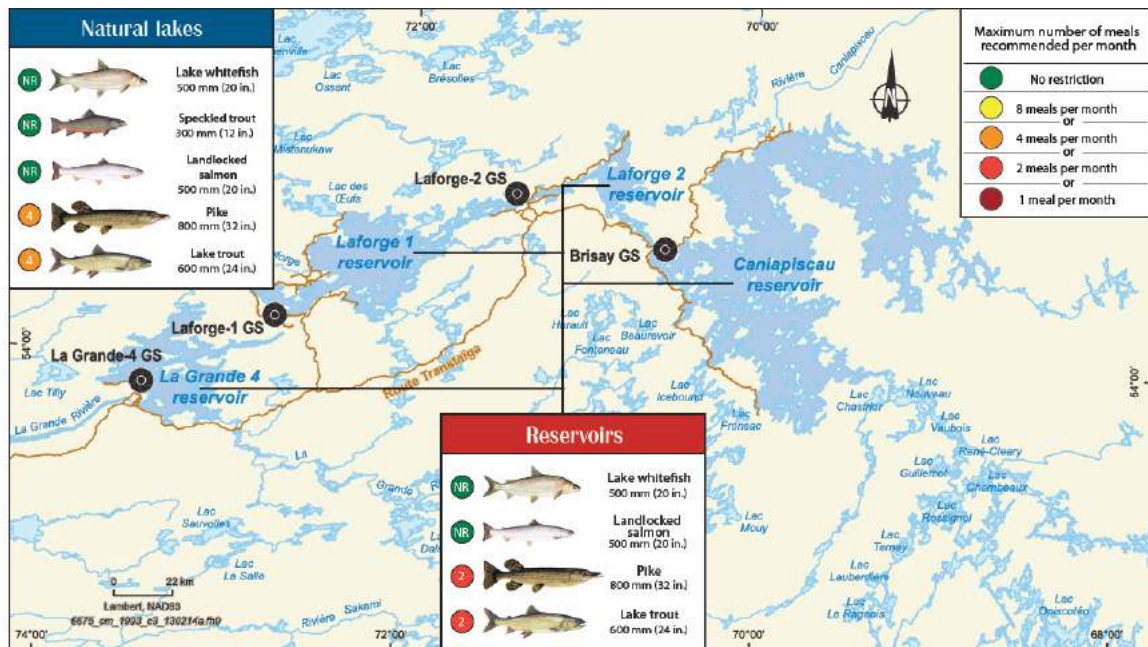
Hydro-Québec *et al.* (2013)

Map 4.2 Fish Consumption Guidelines for the La Grande Complex for Most Adults (West Sector)



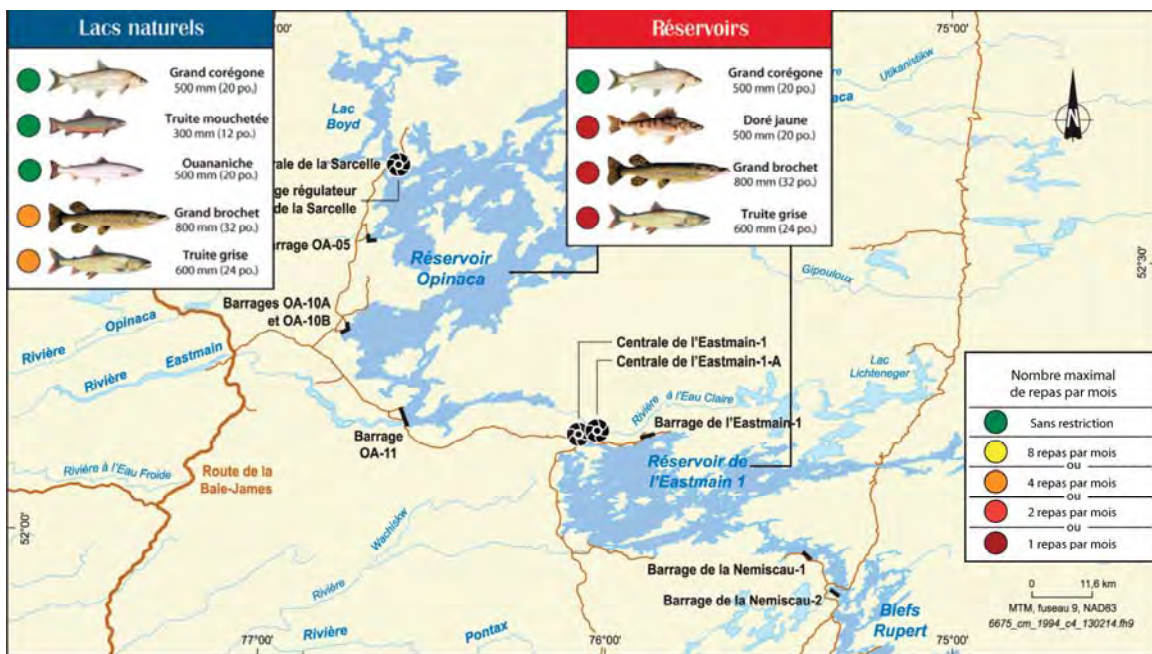
Hydro-Québec et al. (2013)

Map 4.3 Fish Consumption Guidelines for the La Grande Complex for Most Adults (East Sector)



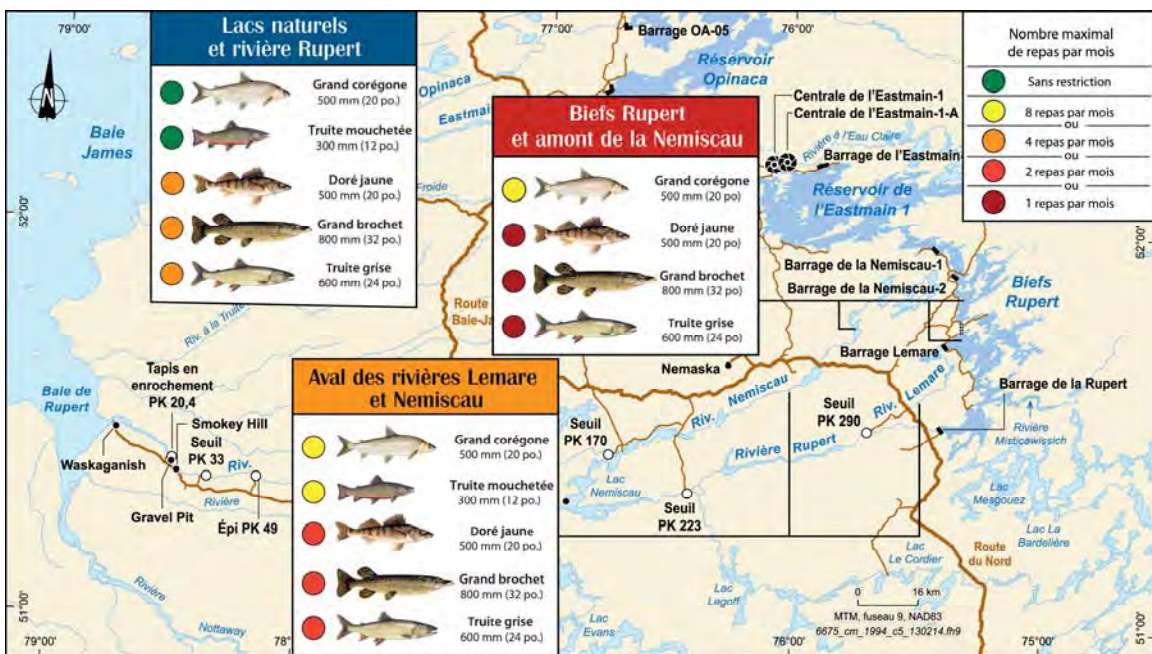
Hydro-Québec et al. (2013)

Map 4.4 Fish Consumption Guidelines for the La Grande Complex for Most Adults (Eastmain 1 Sector)



Hydro-Québec et al. (2013)

Map 4.5 Fish Consumption Guidelines for the La Grande Complex for Most Adults (Rupert Sector)



Hydro-Québec et al. (2013)

West sector of the La Grande complex

There are no restrictions on the consumption of lake whitefish or brook trout (speckled trout) caught in the natural lakes and reservoirs in the West sector of the La Grande complex (Map 4.2). The maximum recommended consumption for walleye, northern pike and lake trout (or grey trout) from the West sector of the La Grande complex is four meals per month for those caught in the natural lakes and two meals per month for those caught in reservoirs.

East sector of the La Grande complex

There are no restrictions on the consumption of lake whitefish, brook trout or landlocked salmon caught in the natural lakes and reservoirs in the East sector of the La Grande complex (Map 4.3). The maximum recommended consumption for northern pike and lake trout from the East sector of the La Grande complex is four meals per month for those caught in natural lakes and two meals per month for those caught in reservoirs.

Eastmain 1 reservoir sector

There are no restrictions on the consumption of lake whitefish or brook trout caught in the natural lakes and reservoirs in the Eastmain 1 sector of the La Grande complex (Map 4.4). The maximum recommended consumption for walleye, northern pike and lake trout from the Eastmain 1 sector is four meals per month for those caught in natural lakes and one meal per month for those caught in reservoirs.

Rupert diversion sector

There are no restrictions on the consumption of lake whitefish or brook trout caught in natural lakes and the Rivière Rupert downstream of the diversion bays, but a maximum of eight meals per month is recommended for those caught in the Rupert diversion bays and the Lemare and Nemiscau rivers downstream of them (Map 4.5). The maximum number of meals recommended for walleye, northern pike and lake trout from the Rupert sector is as follows: four meals per month for those caught in natural lakes and the Rivière Rupert downstream of the diversion bays, two meals per month for those caught in the stretch of the Lemare downstream of the diversion bays and the stretch of the Nemiscau between lakes Biggar and Nemiscau, and one meal per month for those caught in the diversion bays and the stretch of the Nemiscau between the diversion bays and Lac Biggar.

5. SUMMARY AND CONCLUSION

The development of the La Grande hydroelectric complex called for the impoundment of large reservoirs, the diversion of several rivers and the reduction in flow in several sections of river. The project also brought about major physical and hydrological modifications. A large-scale environmental monitoring program (EMN) was established to evaluate the physical, chemical and biological changes caused by these modifications, rationalize remedial measures and management of the developed bodies of water, and improve impact prediction methods for future projects.

When the La Grande complex was built, the temporary increase in fish mercury levels in reservoirs was a virtually unknown phenomenon, apart from the relatively high mercury levels that had been observed in some reservoirs in Canada and the United States. Monitoring of fish mercury levels began as an EMN complementary study before the reservoirs in the La Grande complex were impounded and became a regular component of the EMN program as soon as the increase in fish mercury levels was observed. The specific objectives of mercury monitoring were to evaluate the temporal evolution of mercury levels in the different types of modified environments, inform fish consumers and improve impact prediction methods for future projects.

Initially undertaken as a commitment by SEBJ, the study addresses Hydro-Québec's obligations related to the two signed mercury agreements (1986 and 2001), the conditions set out in the certificates of authorization issued for Phase II construction of the La Grande complex (La Grande-1, La Grande-2A, Laforge-1 and Laforge-2 generating stations) and in the certificates of authorization issued for Phase III (Eastmain-1, Eastmain-1-A and Sarcelle powerhouses and Rupert diversion).

5.1 Main lessons learned

The regular monitoring of fish mercury levels in the various natural water bodies and those modified by development of the La Grande complex made it possible to clearly establish the extent and duration of the increase in fish mercury levels and produce consumption guidelines to manage the potential health risk to recreational anglers and subsistence fishers. The main lessons learned are described below.

5.1.1 Natural lakes

Regular monitoring of mercury levels in fish of standardized length in natural lakes yielded the following findings:

- Individual fish mercury levels vary widely. They can fluctuate by a factor of four within fish of the same species, of the same length and in the same environment, but increase significantly as a function of the length and age of the fish.
- Although mean mercury levels in fish of the same species can also vary by a factor of four between two neighboring lakes, no particular geographic trend has been found. The differences are more likely due to the physical and chemical characteristics of the water bodies, particularly their organic matter content.
- Mean mercury levels in non-piscivorous species are always considerably lower than the Canadian marketing standard for fishery products (0.5 mg/kg of total mercury), whereas piscivorous species often slightly exceed the standard.
- Analysis of the temporal evolution of mercury levels in the main species of fish in natural lakes has revealed no upward or downward trend over a period of 22 to 28 years, depending on the lake studied.

5.1.2 Reservoirs

The main lessons to be drawn from the results of monitoring mercury levels in fish of standardized length in La Grande complex reservoirs are as follows:

- Following reservoir impoundment, mean mercury levels in all species of fish increase by factors of two to eight compared with levels recorded in natural lakes.
- Maximum levels are generally reached 4 to 11 years after impoundment in non-piscivorous species (0.33 to 0.72 mg/kg) and after 9 to 14 years in piscivorous species (1.65 to 4.66 mg/kg).
- In non-piscivorous species, peak values often remain lower than the Canadian marketing standard for fishery products (0.5 mg/kg of total mercury), but sometimes slightly exceed it, whereas in piscivorous species, peak levels may be two to nine times higher than the standard.

- The increases are temporary, however, and the return to levels representative of natural lakes is generally completed 10 to 20 years after impoundment in non-piscivorous species and after 20 to 30 years in piscivorous species, provided there is no additional impoundment.
- All the reservoirs exhibit the same general pattern of change in fish mercury levels, and the slight variations observed may be due to the physical and hydraulic characteristics particular to each reservoir, such as the land area flooded, the annual volume of water flowing through it, the filling time and the percentage of flooded land area located in the drawdown zone. Additional factors may be water temperature, the density and quality of flooded decomposable organic matter, and the diet of piscivorous species.
- Mercury levels in the main species of fish often vary significantly from one station to another in the same reservoir, but without any discernable pattern other than at certain stations that have specific characteristics.

5.1.3 Immediately downstream of reservoirs

The main lessons learned from monitoring mercury levels in fish of standardized length immediately downstream of La Grande complex reservoirs are as follows:

- Mercury levels in lake whitefish, and sometimes in longnose sucker, are often significantly higher immediately below generating stations and control structures than the levels measured in the reservoirs above them. This reflects a change in diet for these usually non-piscivorous species, which become piscivorous as a result of the great availability of small fish made locally more vulnerable to predation by passing through the turbines or control structures.
- In lake whitefish, this change in diet occurs mainly in large specimens (>450 mm).
- The difference between mercury levels measured above and below the different structures in usually non-piscivorous species appears to depend on the structures' characteristics, such as the head and the presence of turbines, which make the fish passing through more or less vulnerable to predation.

- Maximum mercury levels and differences between the areas above and below the structures decrease at the same time as those in the reservoirs. The mean mercury levels in non-piscivorous fish of standardized length are now at or below the limit that allows for unrestricted consumption (0.29 mg/kg).
- In piscivorous species, the differences in mercury levels between the areas above and below generating stations or control structures are smaller and often not significant, as these species already have a piscivorous diet.

5.1.4 Diversions

The main lessons learned from monitoring mercury levels in fish of standardized length in the EOL and Laforge diversions are as follows:

- The pattern of change in fish mercury levels in the diversions confirms that mercury is exported from the reservoirs and transferred to fish downstream.
- In certain water bodies located along these diversion routes, mercury levels may be higher than those in the reservoir providing the inter-basin transfer because of the combined effect of mercury export to areas downstream of the reservoirs and additional mercury production from local flooding of land areas.
- The presence of a large, slow-flowing body of water (lake or reservoir) along the diversion route greatly reduces mercury transfer to fish farther downstream because it favors sedimentation of the methylmercury adsorbed to suspended particulate matter, as well as local predation on plankton, insects and small fish descending from upstream.
- There is no cumulative increase in fish mercury levels when a series of reservoirs is built along the same flow route, as the influence of a given reservoir is confined to the reservoir located immediately downstream of it.

5.1.5 Reduced-flow rivers

The following main lessons were learned from monitoring mercury levels in fish of standardized length in reduced-flow environments in the La Grande complex:

- In environments where the closure was total and permanent, no new organic matter was flooded and, consequently, additional methylmercury production was negligible. Therefore, mercury levels generally remained within the range of mean levels measured under natural conditions.

- Even if they lasted only a few months, large spillages or turbine discharges from the reservoirs led to a significant increase in fish mercury levels downstream, in both piscivorous and non-piscivorous species. The increase could be as great as that observed in the reservoirs, though shorter in duration. This demonstrates a downstream export of mercury from reservoirs and a rapid transfer to fish, probably mainly by zooplankton.
- During these spillages, the extent of the mercury export, the downstream distance over which it could be felt and the duration of the increase in fish mercury levels beyond those measured in natural lakes appear to depend on the dilution of all the components in the water column by the tributaries of the remaining watershed, as well as on the presence or absence of a large body of water allowing sedimentation of suspended particulate matter and predation on entrained zooplankton by aquatic organisms in that body of water.

5.1.6 Effects on fish consumption

The main lessons drawn from analysis of the effects of the increase in mercury levels in consumption-length fish in water bodies modified by the development of the La Grande complex are listed below.

Because of the wide variability in fish mercury levels observed in natural lakes, the consumption guidelines for each species can vary greatly from one natural lake to another.

500-mm lake whitefish

- The guidelines for 500-mm lake whitefish caught in natural water bodies varied from unrestricted consumption (more than 12 meals per month) to a maximum of eight meals per month, depending on the lake.
- Once mean mercury levels peaked, the maximum recommended consumption for lake whitefish in the various water bodies monitored was reduced to eight, four or two meals per month, depending on the water body, compared to the unrestricted consumption recommended for most natural lakes. By exception, a recommendation of one meal per month was applied to the area immediately downstream of Robert-Bourassa reservoir.

- For 500-mm lake whitefish caught in all water bodies monitored, additional restrictions lasting 0 to 26 years were applied to the recommendations in place for the region's natural lakes, which varied from unrestricted consumption to a maximum of eight meals per month. The mean mercury levels recorded during the last survey of modified water bodies in the La Grande complex once again allow for consumption equivalent to that recommended for natural areas of the region.

800-mm northern pike

- The maximum recommended consumption of 800-mm northern pike caught in natural lakes varies from two to eight meals per month, depending on the lake.
- When mean mercury levels peaked, the maximum recommended consumption of 800-mm northern pike from the different water bodies was reduced to two, one, or less than one meal per month, depending on the water body, compared to the four meals per month recommended for most natural lakes.
- For all water bodies monitored, additional restrictions lasting 0 to 30 years, depending on the type of water body, were applied over the guidelines in place for the region's natural lakes, which called for two to eight meals per month.
- The mean mercury levels recorded during the latest survey of 800-mm northern pike in most of the modified areas of the La Grande complex once again allow for consumption equivalent to that recommended for some of the region's natural lakes, i.e., a maximum of two meals per month. The only notable exception concerns those caught in Lac Sakami, for which the recommendation of one meal per month remains in effect.

500-mm walleye

- The maximum recommended consumption of 500-mm walleye caught in natural lakes varies from two to four meals per month, depending on the lake.
- When mean mercury levels peaked, the maximum recommended consumption of walleye from the different water bodies was reduced to one meal per month depending on the water body, as compared to the four meals per month recommended for most natural lakes.

- For 500-mm walleye caught in all water bodies monitored, additional restrictions lasting 13 to 21 years, depending on the type of water body, were applied to the guidelines in place for the region's natural lakes, which called for two to four meals per month.
- The mean mercury levels recorded during the latest survey of 500-mm walleye in most of the modified areas of the La Grande complex once again allow for consumption equivalent to that recommended for some of the region's natural lakes, i.e., a maximum of two meals per month.

600-mm lake trout

- The maximum recommended consumption of 600-mm lake trout caught in natural environments varies from two to four meals per month, depending on the lake.
- When mean mercury levels peaked, the maximum recommended consumption of lake trout from the different water bodies was reduced to one or two meals per month depending on the water body, as compared to the four meals per month recommended for most natural lakes.
- For 600-mm lake trout caught in all water bodies monitored, additional restrictions lasting 0 to 8 years, depending on the type of water body, were applied to the guidelines in place for the region's natural lakes, which called for two to four meals per month. The mean mercury levels recorded during the latest survey of all modified water bodies in the La Grande complex once again allow for consumption equivalent to that recommended for the region's natural lakes.

500-mm burbot

- The mean mercury levels recorded in 500-mm burbot in the few natural lakes for which reliable data is available allow for consumption of a maximum of four meals per month.
- Catches of this species were insufficient to enable us to determine the peak mean mercury levels reached or the extent and duration of the additional consumption restrictions that could be applied. However, the mean levels recorded during the last survey of 500-mm burbot caught in all water bodies monitored allow for consumption equivalent to that recommended for those caught in the region's natural lakes, i.e., a maximum of four meals per month.

5.2 Objectives and commitments met

Phase I of the La Grande complex

The summary of the La Grande complex fish mercury monitoring program produced in 2002 clearly showed that Hydro-Québec had fully met its commitments relating to mercury monitoring during Phase I of the La Grande complex (Schetagne *et al.*, 2002).

- Monitoring the fish in the different types of modified water bodies made it possible to clearly determine the extent and duration of the temporary increase in mercury levels.
- The populations concerned were informed of fish mercury levels in the La Grande complex through the following means:
 - The Crees of Québec, by means of the two mercury agreements signed in 1986 and 2001
 - Recreational anglers, by means of the *Guide de consommation du poisson de pêche sportive en eau douce du Québec* [Québec's freshwater sport fish consumption guide], which was regularly updated with the latest monitoring data
 - A mapped fish consumption guide for water bodies in the watersheds of the Grande and Petite Rivière de la Baleine and the Nottaway, Broadback and Rupert rivers, produced in 2001, and the Northern Fish Nutrition Guide – La Grande Complex Region, published in 2004
- The development of two prediction models for fish mercury levels in reservoirs made it possible to improve prediction methods for future projects

Phase II of the La Grande complex

Hydro-Québec and its subsidiary, SEBJ, satisfied all of the mercury-related conditions stipulated in the certificates of authorization issued for Phase II projects, as follows:

- From 1991 to 2000, monitoring of the changes in mercury levels in the flesh of fish in the Grande Rivière from Robert-Bourassa reservoir to the east coast of Baie-James for the La Grande-2-A and La Grande-1 generating station projects
- From 1993 to 1999, monitoring of the changes in mercury levels in the flesh of fish in the Laforge diversion, continued modeling of methylmercury and study of the extent of downstream mercury transfer from reservoirs, for the Laforge-1, Laforge-2 and Brisay generating station projects

Despite these actions, in 2002, Hydro-Québec recommended that additional surveys be carried out to measure mercury levels in piscivorous fish in the La Grande complex until they return to levels representative of natural lakes in the region. This was done with a view to managing the potential health risk to fish consumers.

The additional surveys conducted from 2003 to 2012 in all water bodies modified by Phase I and Phase II development of the La Grande complex and the production and distribution in 2013 of the Northern Fish Nutrition Guide – Baie-James Region clearly show that the objective of managing the potential health risk was achieved.

5.3 Recommendations

The decision was made to discontinue the monitoring of fish mercury levels in water bodies modified by Phase I and Phase II development of the La Grande complex for the following reasons:

- All of the mercury-related obligations and conditions set out in the construction authorization certificates had been satisfied.
- The objective of managing the potential health risk to fish consumers was also met through the monitoring of mercury levels in piscivorous fish from 2003 to 2012.
- The mean mercury levels measured in lake whitefish in all water bodies monitored during the last surveys now allow for consumption equivalent to that recommended for natural lakes in the region.
- The mean mercury levels measured during the last surveys of consumption-length northern pike in most reservoirs, immediately downstream most generating stations and in reduced-flow rivers now allow for consumption equivalent to that recommended for natural lakes in the region.
- The mean mercury levels measured during the last surveys of consumption-length walleye, lake trout and burbot in most water bodies modified by development of the La Grande complex now allow for consumption equivalent to that recommended for natural lakes in the region.

- The fish consumption guidelines are very safe, as they are based on a safety factor to ensure that all consumers remain below the recommended mercury exposure limits. For example, the consumption guidelines for predatory fish in Robert-Bourassa reservoir call for two meals per month, but most consumers would have to eat these fish every day for a whole year to reach a mercury exposure level that could result in known mercury-related health effects.

The recommendation was also made to continue monitoring fish mercury in Lac Sakami in conjunction with the monitoring of water bodies modified by Phase III development of the La Grande complex. As stipulated in the construction authorization certificates issued for Phase III, mercury levels will continue to be monitored until they have returned to mean levels that allow for consumption equivalent to that recommended for the region's natural lakes, i.e., less than 0.5 mg/kg for lake whitefish and less than 1.99 mg/kg for piscivorous fish.

6. BIBLIOGRAPHIC REFERENCES

- ABERNATHY, A.R., CUMBIE, P.M., 1977. Mercury Accumulation by Largemouth Bass (*Micropterus salmoides*) in Recently Impounded Reservoirs. *Bulletin of Environmental Contamination and Toxicology*, Vol. 17 (1977), p. 595-602.
- ALLIANCE ENVIRONNEMENT INC., 2004. *Pêches côtières et en eaux intérieures. Wemindji 2003. Suivi de la récolte*. Report for Eeyou Namess Corporation and the Cree Nation of Wemindji. 23 p. and appendices.
- ANALEX, 1995. *Analyse de la teneur en mercure dans la chair des poissons. Rapport de contrôle de qualité 1994*. Rapport by Analex inc. for Hydro-Québec. 25 p. and appendices.
- ANDERSON, M.R., 2011. Duration and Extent of Elevated Mercury Levels in Downstream Fish following Reservoir Creation. *River Syst.* Vol. 19/3, P. 167–176.
- BEAMISH, F.W.H., 1964. Respiration of Fishes with Special Emphasis on Standard Oxygen Consumption. II – Influence of Weight and Temperature in Respiration of Several Species. *Canadian Journal of Zoology*, Vol. 42 (1964), p. 177-188.
- BELZILE, L., 1990. *Réseau de suivi environnemental du complexe La Grande, phase I (1989); étude des rendements de pêche (rivière Caniapiscau)*. Report by Groupe environnement Shooner inc. for Hydro-Québec. 28 p.
- BERNATCHEZ, L., 1996. *Caractérisation génétique des formes sympatriques naines et normales de lake whitefish du réservoir Caniapiscau et du lac Sérigny à l'aide de marqueurs microsatellites*. Report for Hydro-Québec. 33 p.
- BODALY, R.A., HECKY, R.E., 1979. Post-impoundment Increases in Fish Mercury Levels in the Southern Indian Lake Reservoir, Manitoba. Fisheries and Marine Service Manuscript Report No 1531. 15 p.
- BODALY, R.A., HECKY, R.E., FUDGE, R.J.P., 1984. Increase in Fish Mercury Levels in Lakes Flooded by the Churchill River Diversion, Northern Manitoba. *Canadian Journal of Fisheries and Aquatic Sciences*, Vol. 41 (1984), p. 682-691.

- BODALY, R.A.D., JANSEN, W.A., MAJEWSKI, A.R., FUDGE, R.J.P., STRANGE, N.E., DERKSEN, A.J., GREEN, G.J. 2007. Postimpoundment Time Course of Increased Mercury Concentrations in Fish in Hydroelectric Reservoirs of Northern Manitoba, Canada. *Archives of Environmental Contamination and Toxicology*. 53, 379-389.
- BOUDREAULT, J., ROY, D., 1985. *Macroinvertébrés benthiques. Réseau de surveillance écologique du complexe La Grande 1978–1984*. Direction Ingénierie et Environnement, Société d'énergie de la Baie James. 102 p.
- BROUARD, D., 1983. *Validation d'aménagements piscicoles réalisés dans la région de LG 2 (1982)*. Report by Gilles Shooner inc. for Société d'énergie de la Baie James. 44 p.
- BROUARD, D., 1988. *Réseau de suivi environnemental du complexe La Grande, Phase 1 (1986). Évolution du mercure dans la chair des poissons (secteur ouest)*. Report by Gilles Shooner et Associés inc. for Hydro-Québec. 53 p. and appendices.
- BROUARD, D., DOYON, J.-F., 1991. *Recherches exploratoires sur le mercure au complexe La Grande (1990)*. Report by Groupe Environnement Shooner inc. for Hydro-Québec. 33 p. and appendices.
- BROUARD, D., VERDON, R. LEGENDRE, P., 1987. *Réseau de surveillance écologique du complexe La Grande. Stratégie d'échantillonnage et processus d'analyse des données de mercure dans la chair des poissons*. Direction Environnement, Hydro-Québec. 10 p.
- BROUARD, D., DEMERS, C., LALUMIÈRE, R., SCHETAGNE, R., VERDON, R., 1990. *Rapport synthèse. Évolution des teneurs en mercure des poissons du complexe hydroélectrique La Grande, Québec (1978–1990)*. Joint report by Hydro-Québec and Groupe Environnement Shooner inc. 100 p.
- BROUARD, D., DOYON, J.-F., SCHETAGNE, R., 1994. *Amplification of Mercury Concentration in Lake Whitefish (Coregonus clupeaformis) Downstream from Robert-Bourassa Reservoir, James Bay, Québec*. In: Watras, C. and Huckabee, J.W. (Eds) *Proceedings of the International Conference on Mercury Pollution: Integration and Synthesis*, Boca Raton (FA): Lewis Publishers, CRC Press. p. 369-380.
- BRUCE, W.J., SPENCER, K.D., ARSENAULT, E., 1979. *Mercury Content Data for Labrador Fishes, 1977–1978*. Fisheries and Marine Service Data Report No. 142. 258 p.

- BÜCKMANN, A., 1929. Translated from *Die methodik fishereibiologischer untersuchungen an meeressischen. Abderhalden, handbuch der biologischen arbeitsmethoden*. Berlin: Urban and Schwarsenberg, Vol. 9. 194 p.
- CANADA-MANITOBA MERCURY AGREEMENT, 1987. *Summary Report. Canada-Manitoba Agreement on the Study and Monitoring of Mercury in the Churchill River Diversion*. 77 p.
- CCSSBJ, CRSSBJ, HYDRO-QUÉBEC, 2013. *Northern Fish Nutrition Guide – Baie-James Region*. 53 p.
- CHARTRAND, N., SCHETAGNE, R., VERDON, R., 1994. *Enseignements tirés du suivi environnemental au complexe La Grande*. 18th Congress of the International Commission on Large Dams, Durban (South Africa). Paris: Commission Internationale des Grands Barrages. p. 165-190.
- JAMES BAY MERCURY COMMITTEE, 1998. *Summary Report: Evolution of Fish Mercury Levels at the La Grande Complex. Volume 2: Regional Characterization of Fish Mercury Levels for Cree Consumers in the James Bay Region*. James Bay Mercury Committee. 40 p.
- DESLANDES, J.-C., BELZILE, L., DOYON, J.-F., 1993. *Réseau de suivi environnemental du complexe La Grande, Phase 1 (1991–1992). Étude des rendements de pêche*. Report by Groupe Environnement Shooner inc. for Hydro-Québec. 90 p. and appendices.
- DESLANDES, J.-C., GUÉNETTE, S., FORTIN, R., 1994. *Evolution of Fish Communities in Environments Affected by the Development of the La Grande Complex, Phase I (1977–1992)*. Report by Université du Québec à Montréal for Hydro-Québec. 89 p.
- DOYON, J.-F., 1995a. *Réseau de suivi environnemental du complexe La Grande, Phase I (1993). Suivi des communautés de poissons et comparaison des grands corégones nains et normaux (secteur Est)*. Report by Groupe Environnement Shooner inc. for Hydro-Québec. 57 p. and appendices.
- DOYON, J.-F., 1995b. *Réseau de suivi environnemental du complexe La Grande, Phase I (1993). Évolution des teneurs en mercure dans les poissons et études complémentaires (secteur est)*. Report by Groupe Environnement Shooner inc. for Hydro-Québec. 62 p. and appendices.

- DOYON, J.-F., 1998. *Suivi des milieux aquatiques touchés par l'aménagement des centrales Laforge-1 et Laforge-2 (1997). Étude de l'exploration du mercure en aval du réservoir Caniapiscau*. Report by Groupe conseil GENIVAR inc. For Société d'énergie de la Baie James. 40 p. and appendices.
- DOYON, J.-F., BELZILE, L., 2000. *Rivières Eastmain et Opinaca en aval des ouvrages de dérivation. Bilan du suivi des communautés de poissons (1978–1998)*. Joint report by Groupe conseil GENIVAR inc. and Hydro-Québec. 88 p. and appendices.
- DOYON, J.-F., SCHETAGNE, R., 1999. *Réseau de suivi environnemental du complexe La Grande, Phase 1 (1997–1998). Évolution des teneurs en mercure et études complémentaires*. Joint report by Groupe conseil GENIVAR inc. and Hydro-Québec. 89 p.
- DOYON, J.-F., SCHETAGNE, R., 2000. *Réseau de suivi environnemental du complexe La Grande. Évolution des teneurs en mercure des poissons et études complémentaires (1999). Secteur Est*. Joint report by Groupe conseil GENIVAR inc. and Hydro-Québec. 56 p.
- DOYON, J.-F., TREMBLAY, A., 1997a. *Réseau de suivi environnemental du complexe La Grande : suivi des teneurs en mercure des poissons et études complémentaires (1995)*. Report by Groupe conseil GENIVAR inc. for Hydro-Québec. 30 p. and appendices.
- DOYON, J.-F., TREMBLAY, A., 1997b. *Réseau de suivi environnemental du complexe La Grande (1996). Évolution des teneurs en mercure et études complémentaires (secteur Ouest)*. Joint report by Hydro-Québec and Groupe conseil GENIVAR inc. 62 p. and appendices.
- DOYON, J.-F., TREMBLAY, A., PROULX, M., 1996. *Régime alimentaire des poissons du complexe La Grande et teneurs en mercure dans leurs proies (1993–1994)*. Report by Groupe conseil GENIVAR inc. for Hydro-Québec. 105 p. and appendices.
- DOYON, J.-F., BERNATCHEZ, L., GENDRON, M., VERDON, R., FORTIN, R., 1998a. Comparison of Normal and Dwarf Populations of Lake Whitefish (*Coregonus clupeaformis*) with Reference to Hydroelectric Reservoirs in Northern Quebec. *Archiv für Hydrobiologie – Advances in Limnology*, Vol. 50 (1998), p. 97-108.

- DOYON, J.-F., SCHETAGNE, R., VERDON, R., 1998b. Different Mercury Bioaccumulation Rates between Sympatric Populations of Dwarf and Normal Lake Whitefish (*Coregonus clupeaformis*) in the La Grande Complex Watershed, James Bay, Québec. *Biogeochemistry*, Vol. 40 (1998), p. 203-216.
- DRISCOLL, C.T., BLETTE, V., YAN, C., SCHOFIELD, L., MUNSON, R., HOLSAPPLE, J., 1995. The Role of Dissolved Organic Carbon in the Chemistry and Bioavailability of Mercury in Remote Adirondack Lakes. *Water, Air and Soil Pollution*, Vol. 80 (1995), p. 499-508.
- DUSSAULT, D., BOUDREAULT, J., 1985. *Description des milieux affectés par la mise en eau des réservoirs de La Grande 2, Opinaca et Caniapiscau*. Direction Ingénierie et Environnement, Société d'énergie de la Baie James. Montréal. 25 p.
- ÉDITEUR OFFICIEL DU QUÉBEC, 1976. *James Bay and Northern Québec Agreement*. Québec: Éditeur officiel du Québec. 486 p.
- ENTRACO, 1996. *Suivi des poissons et du mercure dans les milieux affectés par l'aménagement du complexe hydroélectrique La Grande, Phase II (1986–1996)*. Report by Entraco for Société d'énergie de la Baie James. 95 p. and appendices.
- GENIVAR, 2013. *Évolution des teneurs en mercure des poissons des secteurs ouest et est du complexe La Grande (1978–2012)*. Annexe 1 : statistiques descriptives et tests de comparaisons multiples issus de la régression polynomiale avec variables indicatrices. Annexe 2 : diagrammes de dispersion et résultats bruts. Documents submitted by GENIVAR inc. to Hydro-Québec.
- GENIVAR, HYDRO-QUÉBEC, 2004. *Projet de l'Eastmain-1-A et dérivation Rupert – Mercure dans la chair des poissons*. Joint report by GENIVAR Groupe Conseil inc. and Hydro-Québec for Société d'énergie de la Baie James and Hydro-Québec. 121 p. and appendices.
- GENIVAR, WASKA RESSOURCES, 2013. *Eastmain-1-A and Sarcelle Powerhouses and Rupert Diversion – Assessment of the Effectiveness of Information Campaigns on Fish Consumption and Mercury*. Revised Report. Report submitted to Hydro-Québec Production and SEBJ. Multiple pagination and appendices.

- GRIMARD, Y., JONES, H. G., 1982. Trophic Upsurge in New Reservoirs: a Model for Total Phosphorous Concentration. *Canadian Journal of Fisheries and Aquatic Sciences*, Vol. 39 (1982). p. 1473-1483.
- GROUPE CONSEIL GENIVAR INC., 2002. *Régularisation des crues du bassin versant du lac-réservoir Kénogami. Rapport sectoriel sur le mercure dans la chair des poissons et la qualité de l'eau. Automne-été 2001 – Études d'avant-projet*. Report by Groupe conseil GENIVAR inc. for Hydro-Québec. 62 p. and appendices.
- GROUPE ENVIRONNEMENT SHOONER INC., 1993. *Étude de la communauté de poissons de l'estuaire de la rivière Eastmain, 12 ans après la réduction du débit fluvial*. Report by Groupe Environnement Shooner inc. for Hydro-Québec. 100 p. and appendices.
- HAINES, T.A., KOMOW, V.T., JAGOE, C.H., 1994. *Mercury Concentration in Perch (Perca fluviatilis) as Influenced by Lacustrine Physical and Chemical Factors in Two Regions of Russia*. In: Watras, C. and Huckabee, J.W. (Eds), *Proceedings of the International Conference on Mercury Pollution: Integration and Synthesis*. Boca Raton (FA): Lewis Publishers, CRC Press, p. 397-408.
- HALL, B.D., BODALY, R.A., FUDGE, J.W.M., ROSENBERG, D.M., 1997. Food as the Dominant Pathway of Methylmercury Uptake by Fish. *Water, Air and Soil Pollution*, Vol. 100 (1997), p. 13-24.
- HOLLAND, L.E., HUSTON, M.L., 1984. Relationship of Young-of-the-Year Northern Pike to Aquatic Vegetation Types in Backwaters of the Upper Mississippi River. *North American Journal of Fisheries Management*, Vol. 4 (1984), p. 514-522.
- HYDRO-QUÉBEC, 1993. *Complexe Grande-Baleine; avant-projet Phase II. Qualité de l'eau*. Service Ressources et Aménagement du territoire, Vice-présidence Environnement, Hydro-Québec. 132 p.
- HYDRO-QUÉBEC, 2007a. *Eastmain-1-A and Sarcelle Powerhouses and Rupert Diversion, Environmental Follow-up Program 2007–2023*. Hydro-Québec Production and Hydro-Québec Équipement, November 2007. 138 p. and appendices.
- HYDRO-QUÉBEC, 2007b. *Complexe de la Romaine: Étude d'impact sur l'environnement*. Hydro-Québec Production. 10 volumes.

- HYDRO-QUÉBEC, CHUL, 2001a. *Fish Consumption Guide for the Water Bodies of the La Grande Complex and of the Grande rivière de la Baleine and Petite rivière de la Baleine Regions*. Map by the public health research unit of the Centre hospitalier de l'Université Laval and Hydro-Québec.
- HYDRO-QUÉBEC, CHUL, 2001b. *Fish consumption Guide for the Water Bodies of the Nottaway, Broadback and Rupert Regions*. Map by the public health research unit of the Centre hospitalier de l'Université Laval and Hydro-Québec.
- HYDRO-QUÉBEC, INSQ, CCSSSBJ, 2013. *Le guide alimentaire des poissons nordiques – Région de la Baie-James/The Northern Fish Nutrition Guide – Baie-James Region*. Hydro-Québec Production, Environnement; Institut national de la santé publique du Québec; Cree Board of Health and Social Services of James Bay. Produced by Hydro-Québec. 53 p.
- JACKSON, T.A., 1988. The Mercury Problem in Recently Formed Reservoirs of Northern Manitoba (Canada): Effect of Impoundment and Other Factors on the Production of Methylmercury by Microorganisms in Sediments. *Canadian Journal of Fisheries and Aquatic Sciences*, Vol. 45 (1988), p. 97-121.
- LALUMIÈRE, R., LEJEUNE, R., BOUDREAULT, A., 1985. *Répercussions d'une réduction de débit sur les rivières Caniapiscau et Koksoak*. Report by Gilles Shooner inc. for Groupe d'étude conjoint Caniapiscau-Koksoak, Société d'énergie de la Baie James. 117 p.
- LANGE, T.R., ROYALS, H.E., CONNOR, L.L., 1993. Influence of Water Chemistry on Mercury Concentration in Largemouth Bass from Florida Lakes. *Transactions of the American Fisheries Society*, Vol. 122 (1993), p. 74-88.
- LAPERLE, M., SCHETAGNE, R., 1988. *Working Paper on Research and Development Related to the Production and Transfer of Methylmercury in Reservoirs and the Validation or Mitigating Measures*. Vice-présidence Environnement, Hydro-Québec. n.p.
- LASORSA, B., ALLEN-GIL, S., 1995. The Methylmercury to Total Mercury Ratio in Selected Marine, Freshwater and Terrestrial Organisms. *Water, Air and Soil Pollution*, Vol. 80 (1995), p. 905-913.

- LE GROUPE ROCHE LTÉE, 1993. *Aménagement hydroélectrique SM 3. Études complémentaires à la faune ichtyenne*. Report by Groupe Roche Ltée for Hydro-Québec. n.p.
- LEMIEUX, C., 1997. *Étude spéciale sur le mercure dans les poissons de La Grande Rivière, en aval de la centrale La Grande-1 (1996)*. Report by Groupe conseil GENIVAR inc. for the James Bay Mercury Committee. 65 p. and appendices.
- LESSARD, M., 2006. *Pêches côtières et en eaux intérieures. Wemindji 2005. Suivi de la récolte*. Submitted by Martin Lessard Enr. to Société Niskamoon and the Cree Nation of Wemindji. 28 p. and appendices.
- LESSARD, M., 2007a. *Pêches côtières et en eaux intérieures. Chisasibi 2006. Suivi de la récolte*. Submitted by Martin Lessard Enr. to Société Niskamoon and the Cree Nation of Chisasibi. 33 p. and appendices.
- LESSARD, M., 2007b. *Pêches traditionnelles de Nemaska. Été 2007. Suivi de la récolte*. Presentation by Martin Lessard Enr. to Niskamoon Corporation and the Cree Nation of Nemaska. 15 p. and appendices.
- LESSARD, M., 2007c. *Pêches côtières et en eaux intérieures. Wemindji 2007. Suivi de la récolte*. Submitted by Martin Lessard Enr. to the Niskamoon Corporation and the Cree Nation of Wemindji. 25 p. and appendices.
- LESSARD, M., 2008a. *Pêches traditionnelles de Nemaska. Hiver 2008. Suivi de la récolte*. Submitted by Martin Lessard Enr. to the Niskamoon Corporation and the Cree Nation of Nemaska. 15 p. and appendices.
- LESSARD, M., 2008b. *Pêches traditionnelles de Waswanipi. Suivi de la récolte 2008*. Submitted by Martin Lessard Enr. to the Niskamoon Corporation and the Cree Nation of Waswanipi. 11 p. and appendices.
- LESSARD, M., 2008c. *Pêches côtières et en eaux intérieures. Wemindji 2008. Suivi de la récolte*. Submitted by Martin Lessard Enr. to the Niskamoon and the Cree Nation of Wemindji. 26 p. and appendices.
- LESSARD, M., 2009. *Pêches traditionnelles Whapmagoostui. Suivi de la récolte 2008*. Submitted by par Martin Lessard Enr. to the Niskamoon Corporation and the Cree Nation of Whapmagoostui. 9 p. and appendices.

- LESSARD, M., 2010a. *Pêches traditionnelles de Mistissini et fumage du poisson. Suivi de la récolte 2009*. Submitted by Martin Lessard Enr. to the Niskamoon Corporation and the Cree Nation of Mistissini. 12 p. and appendices.
- LESSARD, M., 2010b. *Pêches traditionnelles de Mistissini. Suivi de la récolte d'hiver 2010*. Submitted by Martin Lessard Enr. to the Niskamoon Corporation and the Cree Nation of Mistissini. 10 p. and appendices.
- LESSARD, M., 2010c. *Pêches traditionnelles de Mistissini. Suivi de la récolte 2010*. Submitted by Martin Lessard Enr. to the Niskamoon Corporation and the Cree Nation of Mistissini. 12 p. and appendices.
- LESSARD, M., 2010d. *Pêches traditionnelles de Nemaska. Suivi de la récolte d'hiver 2010*. Submitted by Martin Lessard Enr. to the Niskamoon Corporation and the Cree Nation of Nemaska. 14 p. and appendices.
- LESSARD, M., 2010e. *Pêches traditionnelles de Waswanipi. Suivi de la récolte d'hiver 2010*. Présenté par Martin Lessard Enr. à la Société Niskamoon et à la Nation Crie de Waswanipi. 11 p. and appendices.
- LESSARD, M., 2010f. *Pêches traditionnelles de Wemindji. Suivi de la récolte 2009-2010*. Submitted by Martin Lessard Enr. to the Niskamoon Corporation and the Cree Nation of Wemindji. 28 p. and appendices.
- LESSARD, M., 2010g. *Pêches traditionnelles de Wemindji. Suivi de la récolte 2010*. Submitted by Martin Lessard Enr. to the Niskamoon Corporation and the Cree Nation of Wemindji. 24 p. and appendices.
- LESSARD, M., 2010h. *Pêches traditionnelles Whapmagoostui. Suivi de la récolte 2009*. Submitted by Martin Lessard Enr. to the Niskamoon Corporation and the Cree Nation of Whapmagoostui. 10 p. and appendices.
- LESSARD, M., 2011a. *Pêches traditionnelles de Mistissini et fumage du poisson. Suivi de la récolte 2010*. Submitted by Martin Lessard Enr. to the Niskamoon Corporation and the Cree Nation of Mistissini. 12 p. and appendices.
- LESSARD, M., 2011b. *Pêches traditionnelles de Nemaska. Suivi de la récolte d'hiver 2011*. Submitted by Martin Lessard Enr. to the Niskamoon Corporation and the Cree Nation of Nemaska. 14 p. and appendices.

- LESSARD, M., 2011c. *Pêches traditionnelles de Waswanipi. Suivi de la récolte 2010-2011*. Submitted by Martin Lessard Enr. to the Niskamoon Corporation and the Cree Nation of Waswanipi. 12 p. and appendices.
- LESSARD, M., 2011d. *Pêches traditionnelles de Wemindji. Suivi de la récolte d'été 2011*. Submitted by Martin Lessard Enr. to the Niskamoon Corporation and the Cree Nation of Wemindji. 20 p. and appendices.
- LESSARD, M., 2011e. *Pêches traditionnelles de Wemindji. Suivi de la récolte d'hiver 2011*. Submitted by Martin Lessard Enr. to the Niskamoon Corporation and the Cree Nation of Wemindji. 15 p. and appendices.
- LESSARD, M., 2012a. *Pêches traditionnelles de Chisasibi. Suivi de la récolte 2011-2012*. Submitted by Martin Lessard Enr. to the Niskamoon Corporation and the Cree Nation of Chisasibi. 32 p. and appendices.
- LESSARD, M., 2012b. *Pêches traditionnelles d'Oujé-Bougoumou et fumage du poisson. Suivi de la récolte d'automne 2010*. Submitted by Martin Lessard Enr. to the Niskamoon Corporation and the Cree Nation of Oujé-Bougoumou. 10 p. and appendices.
- LESSARD, M., 2012c. *Pêches traditionnelles Whapmagoostui. Suivi de la récolte d'automne 2010*. Submitted by Martin Lessard Enr. to the Niskamoon Corporation and the Cree Nation of Whapmagoostui. 9 p. and appendices.
- L.G.L. LIMITED, 1993. *Mercury Concentrations in Fishes within the Smallwood Reservoir-Churchill River complex, Labrador 1977–1992*. Report by L.G.L. Limited for Fisheries and Oceans Canada (St. John's NF). 56 p.
- LINDQVIST, O., 1991. Mercury in the Swedish Environment; Recent Research on Causes, Consequences and Corrective Methods. *Water, Air and Soil Pollution*, Vol. 55 (1991), p. 1-262.
- LUCAS, M., BLANCHET, C., DEWAILLY, É., SCHETAGNE, R., 2003. *Profil nutritionnel des poissons nordiques. Complexe La Grande*. Joint report by the public health research unit of the Centre de recherche du CHUL-CHUQ and Hydro-Québec Production, Direction Santé et Sécurité. 29 p. and appendices.

- LUCOTTE, M., MUCCI, A., HILLAIRES-MARCEL, C., PICHET, P., GRONDIN, A., 1995. Anthropogenic Mercury Enrichment in Remote Lakes of Northern Québec (Canada). *Water, Air and Soil Pollution*, Vol. 80 (1995), p. 467-476.
- LUCOTTE, M., SCHETAGNE, R., THÉRIEN, N., LANGLOIS, C., TREMBLAY, A., 1999a. *Mercury in the Biogeochemical Cycle: Natural Environments and Hydroelectric Reservoirs of Northern Québec*. Berlin: Springer. 334 p.
- LUCOTTE, M., MONTGOMERY, S. CARON, B., KAINZ, M., 1999b. *Mercury in Natural Lakes and Unperturbed Terrestrial Ecosystems of Northern Québec*. In: Lucotte et al. (Eds) *Mercury in the Biogeochemical Cycle: Natural Environments and Hydroelectric Reservoirs of Northern Québec*. Berlin: Springer. p. 55-87.
- MAILMAN, M., 2008, *Assessment of Mercury and Selenium Interactions in Freshwater*. Thesis submitted to the Natural Water Institute, University of Manitoba. 198 p.
- MAILMAN, M., STEPNUK, L., CICEK, N., BODALY, R.A., 2006. Strategies to Lower Methyl Mercury Concentrations in Hydroelectric Reservoirs and Lakes: A Review. *Science of the Total Environment*. 368: 224-235.
- MANNIO, J., VERTA, M., KORTELAINEN, P., REKOLAINEN, S., 1986. *The Effects of Water Quality on the Mercury Concentration of Northern Pike (Esox lucius, L.) in Finnish Forest Lakes and Reservoirs*. National Board of Waters (Finland), Publications of the Water Research Institute, No 65. p. 32-43.
- MAXXAM, 2013. *Analyses de la teneur en mercure dans la chair de poissons 2012*. Rapport de contrôle de la qualité 2012. Submitted to Hydro-Québec. 21 p. and appendices.
- MCMURTRY, M.J., WALES, D.L., SCHEIDER, W.A., BEGGS, G.L., DIMOND, P.E., 1989. Relationship of Mercury Concentrations in Lake Trout (*Salvelinus namaycush*) and Small Bass (*Micropterus dolomieu*) to the Physical and Chemical Characteristics of Ontario Lakes. *Canadian Journal of Fisheries and Aquatic Sciences*, Vol. 46 (1989), p. 426-434.

- MESSIER D., 2002. *Suivi environnemental des projets La Grande-2-A et La Grande-1. Le panache de La Grande Rivière. Rapport synthèse pour la période 1987–2000*. Direction Barrages et Environnement, Hydro-Québec Production. 73 p. and appendices.
- MESSIER, D., ROY, D., 1987. Concentrations en mercure chez les poissons au complexe hydroélectrique de La Grande Rivière (Québec). *Le Naturaliste Canadien*, Vol. 114 (1987), p. 357-368.
- MESSIER, D., ROY, D., LEMIRE, R., 1985. *Réseau de surveillance écologique du complexe La Grande 1978–1984. Évolution du mercure dans la chair des poissons*. Société d'énergie de la Baie James. 170 p. and appendices.
- NISKAMOON CORPORATION, 2008. *Niskamoon Corporation Annual Report (2007–2008)*. 163 p.
- NOËL, F., SBEGHEN, J., 1995. *Mercure : questions et réponses*. James Bay Mercury Committee. Montréal. 24 p.
- NOISEL, N., SCHETAGNE, R., THERRIEN, J., (in prep). *Document synthèse sur l'ajout de sélénium pour atténuer l'augmentation du mercure dans les poissons causée par la mise en eau des réservoirs*. Produced by WSP and Hydro-Québec Production.
- NORSTROM, R.J., MCKINNON, A.E., DEFREITAS, A.S.W., 1976. A Bioenergetics-based Model for Pollutant Accumulation by Fish: Simulation of PCB and Methylmercury Residue Levels in Ottawa River Yellow Perch (*Perca flavescens*). *J. Fish. Res. Board Can.* 33:248.
- WORLD HEALTH ORGANIZATION, 1972. *Evaluation of Certain Food Additives and Contaminants – Mercury, Lead, and Cadmium*. Joint FAO/WHO Expert Committee on Food Additives. Geneva.
- WORLD HEALTH ORGANIZATION, 1990. *Environmental Health Criteria 101; Methylmercury*. Geneva. 144 p.
- WORLD HEALTH ORGANIZATION, 2004. *Safety Evaluation of Certain Food Additives and Contaminants*. Joint FAO/WHO Expert Committee on Food Additives. WHO food additives series 52, 2004. Geneva.
- POWER, G., 1978. Fish Population Structure in Arctic Lakes. *Journal of the Fisheries Research Board of Canada*, Vol. 35 (1978). p. 53-59.

- REINERT, R.E., STONE, L.J., WILLFORD, W.A., 1974. Effect of Temperature on Accumulation of Methylmercury Chloride and p,pDDT by Rainbow Trout (*Salmo gairdneri*). *Journal of the Fisheries Research Board of Canada*, Vol. 31 (1974), p. 1649-1652.
- RODGERS, D.W., 1993. *Bioenergetics-based Models of Methylmercury Accumulation in Fish I: Model Development and Application to Yellow Perch and Lake Trout*. Ontario Hydro, report 92-273-K. 23 p.
- RODGERS, D.W., 1994. *You Are What You Eat and a Little Bit More: Bioenergetics-based Models of Methylmercury Accumulation in Fish Revisited*. In: Watras CJ & Huckabee JW (Eds) *Mercury as a Global Pollutant* (pp 427–439). Lewis Publishers.
- RODGERS, D.W., 1996. *Methylmercury Accumulation by Reservoir Fish: Bioenergetic and trophic effects*. In: Miranda LE & DeVries DR (Eds) *Multidimensional Approaches to Reservoir Fisheries Management* (pp 107–118). American Fisheries Society Symposium 16, Bethesda, Maryland.
- ROY, D., 1984. *Mesures pour diminuer les risques d'intoxication dues au mercure*. Société d'énergie de la Baie James. n.p.
- ROY, D., BOUDREAULT, J., BOUCHER, R., SCHETAGNE, R., THÉRIEN, N., 1986. *Réseau de surveillance écologique du complexe La Grande 1978–1984. Synthèse des observations*. Société d'énergie de la Baie James. 74 p.
- SAGE, 1983. *Analyse des contenus stomacaux des poissons des régions de LG 2, Opinaca et Caniapiscau. Rapport sur les travaux de 1980, 1981 et 1982*. Report by SAGE Ltée for Société d'énergie de la Baie James. 114 p. and appendices.
- SBEGHEN, J., 1995. *Revue synthèse sur les mesures d'atténuation et de compensation*. Report by Hydro-Québec for the James Bay Mercury Committee. 28 p.
- SBEGHEN, J., SCHETAGNE, R., 1995. *Mercury Mitigative Measures Related to Hydroelectric Reservoirs: The La Grande Complex Experience*. Text from a Hydro-Québec presentation to the Canadian Electrical Association.

- SCHETAGNE, R., 1994. Water Quality Modifications after Impoundment of some Large Northern Reservoirs. *Archiv für Hydrobiologie – Advances in Limnology*, Vol. 40 (1994), p. 223-229.
- SCHETAGNE, R., DOYON, J.-F., VERDON, R., 1996. *Rapport synthèse : évolution des teneurs en mercure dans les poissons du complexe La Grande (1978–1994)*. Joint report by Groupe conseil GENIVAR inc. and Hydro-Québec. 143 p. and appendices.
- SCHETAGNE, R., DOYON, J.-F., FOURNIER, J.-J., 2000. Export of Mercury Downstream from Reservoirs. *The Science of total Environment*, Vol. 260 (2000), p. 135-145.
- SCHETAGNE, R., THERRIEN, J., LALUMIÈRE, R., 2002. *Environmental Monitoring at the La Grande Complex. Evolution of Fish Mercury Levels. Summary Report 1978–2000*. Joint report by GENIVAR Groupe Conseil inc. and Direction Barrages et Environnement, Hydro-Québec Production. 193 p. and appendix.
- SCHETAGNE, R., LALUMIÈRE, R., THERRIEN, J., 2005. *Environmental Monitoring at the La Grande Complex. Water Quality Changes. Summary Report 1978–2000*. Joint report by GENIVAR Groupe conseil inc. and Direction Barrages et Environnement, Hydro-Québec Production. 168 p. and appendices.
- SEBJ, 1987. *The La Grande Rivière Hydroelectric Complex – The Environmental Challenge*. Société d'énergie de la Baie James. 199 p.
- SIMONIN, H.A., GLOSS, S.P., DRISTOLL, C.T., SCHOFIELD, C.L., KRETZER, W.A. KARCHER, R.W., SYMULA, J., 1994. *Mercury in Yellow Perch from Adirondack Drainage Lakes (New York, U.S.)*. In: Watras, C. and Huckabee, J.W. (Eds) *Proceedings of the International Conference on Mercury Pollution: Integration and Synthesis*, 1994, Boca Raton (Fa): Lewis Publishers, CRC Press. p. 457-469.
- SOMER INC., 1994. *Complexe Nottaway-Broadback-Rupert. Qualité de l'eau*. Report by SOMER inc. for Hydro-Québec. 64 p. and appendices.
- STRANGE, N.E., BODALY, R.A., FUDGE, R.J.P., 1991. *Mercury Concentrations of Fish in Southern Indian Lake and Issett Lake, Manitoba 1975–1988: the Effect of Lake Impoundment and Churchill River Diversion*. Canadian Technical Report of Fisheries Aquatic Sciences No. 1824. 30 p.

- SURETTE, C., DOIRE, J., LUCOTTE, M., 2004. Rapport annuel des activités de recherche – partie dynamique du mercure et isotopes stables, Némiscau 2002 : Étude de validation de la pêche intensive comme méthode de réduction en mercure dans les poissons. COMERN, UQAM, Montréal, Québec, Canada.
- THÉRIEN, N., 2001a. *Modèles prévisionnels du mercure et de la qualité de l'eau applicables aux réservoirs hydroélectriques du moyen-nord québécois. Mandat 2000. Volet : Modèle mercure*. Report by Université de Sherbrooke for Hydro-Québec. 245 p.
- THÉRIEN, N., 2001b. *HQHG Modèle prévisionnel du mercure dans les poissons des réservoirs hydroélectriques*. Version 2.2. Report by Université de Sherbrooke for Hydro-Québec. CD-ROM with user guide. 14 p.
- THÉRIEN, N., 2005. *Modèle prévisionnel du mercure applicable aux réservoirs hydroélectriques du moyen-nord québécois - Volet modélisation du mercure dans les poissons. Nouvelle version du logiciel HQHG; version révisée du logiciel HQEAU et création du logiciel HQRIV*. Final report submitted to R. Schetagne. October 28, 2005. 53 p. and appendices.
- THÉRIEN, N., 2006. *Modèle prévisionnel du mercure applicable aux réservoirs hydroélectriques du moyen-nord québécois. Volet modélisation du mercure dans les poissons – Validation et consolidation des logiciels HQEAU, HQHG et HQRIV*. Final report by Unité Hydraulique et environnement, Hydro-Québec. October 30, 2006. 119 p.
- THÉRIEN, N., 2010. *Modèle prévisionnel du mercure applicable aux réservoirs hydroélectriques du moyen-nord québécois. Volet modélisation du mercure dans les poissons – Révision des options de calculs des logiciels HQEAU et HQHG*. Final report by Unité Hydraulique et environnement, Hydro-Québec. December 31, 2010. 43 p.
- THÉRIEN, N., MORRISON, K., 1999. *In Vitro Release of Mercury and Methylmercury from Flooded Organic Matter*. In: Lucotte et al. (Eds) *Mercury in the Biogeochemical Cycle: Natural Environments and Hydroelectric Reservoirs of Northern Québec*. Berlin: Springer. p. 147-164.
- THERRIEN, J., LALUMIÈRE, R., 2001. *Réseau de suivi environnemental du complexe La Grande. Suivi des communautés de poissons des secteurs La Grande-2-A et La Grande-1 (1977–2000). Rapport synthèse*. Report by Groupe conseil GENIVAR inc. for Hydro-Québec. 96 p. and appendices.

- THERRIEN, J., SCHETAGNE, R., 2001a. *Teneur en acides gras de type oméga-3 chez les principales espèces de poisson du complexe La Grande et de la région du réservoir Robertson*. Joint report by Hydro-Québec, Unité Hydraulique et Environnement, and Groupe conseil GENIVAR inc. 39 p. and appendices.
- THERRIEN, J., SCHETAGNE, R., 2001b. *Réseau de suivi environnemental du complexe La Grande. Évolution des teneurs en mercure des poissons des secteurs La Grande-2-A et La Grande-1 (1977–2000). Rapport synthèse*. Joint report by Groupe conseil GENIVAR inc. and Hydro-Québec. 30 p. and appendices.
- THERRIEN, J., SCHETAGNE, R., 2004. Réseau de suivi environnemental du complexe La Grande (2003) – Évolution du mercure dans la chair des poissons dans le secteur est. Joint report by Hydro-Québec and GENIVAR Groupe Conseil inc. 56 p. and appendices.
- THERRIEN, J., SCHETAGNE, R., 2005a. *Réseau de suivi environnemental du complexe La Grande (2003–2004) – Évolution du mercure dans la chair des poissons*. Joint report by GENIVAR Groupe Conseil inc. and Hydro-Québec. 82 p. and appendices.
- THERRIEN, J., SCHETAGNE, R., 2005b. Réseau de suivi environnemental du complexe La Grande – Optimisation du suivi du mercure dans la chair des poissons. Report by GENIVAR Groupe Conseil inc. for Hydro-Québec. 43 p.
- THERRIEN, J., SCHETAGNE, R., 2008a. Réseau de suivi environnemental du complexe La Grande (2007) – Évolution du mercure dans la chair des poissons dans le secteur est. Joint report by Hydro-Québec and GENIVAR Société en commandite. 55 p. and appendices.
- THERRIEN, J., SCHETAGNE, R., 2008b. Aménagement hydroélectrique de L'Eastmain-1. Suivi environnemental en phase d'exploitation (2007). Suivi du mercure dans la chair des poissons. Joint report by Hydro-Québec and GENIVAR Société en commandite. 45 p. and appendices.
- THERRIEN, J., SCHETAGNE, R., 2009. Réseau de suivi environnemental du complexe La Grande (2008) – Évolution du mercure dans la chair des poissons dans le secteur ouest. Joint report by Hydro-Québec and GENIVAR Société en commandite. 50 p. and appendices.

- THERRIEN, J., SCHETAGNE, R., 2010. Aménagement hydroélectrique de L'Eastmain-1. Suivi environnemental en phase d'exploitation (2009). Suivi du mercure dans la chair des poissons. Rapport conjoint d'Hydro-Québec et de GENIVAR Société en commandite. 45 p. and appendices.
- THERRIEN, J., SCHETAGNE, R., 2012. Aménagement hydroélectrique de L'Eastmain-1. Suivi environnemental en phase d'exploitation (2011). Suivi du mercure dans la chair des poissons. Joint report by Hydro-Québec and GENIVAR inc. 45 p. and appendices.
- THERRIEN, J., VERDON, R., LALUMIÈRE, R., 2002. Environmental Monitoring at the La Grande Complex. Changes in Fish Communities. Summary Report (1977–2000). Report for Niskamoon Corporation. 131 p. and appendices.
- TOURISME QUÉBEC, 2009. Le tourisme dans les régions touristiques du Québec en 2007 et 2008. Ministère du Tourisme. 10 p.
- TOURISME QUÉBEC, 2013. Web site consulted October 28, 2013. <http://www.bonjourquebec.com/qc-fr/baiejames.html>.
- TREMBLAY, G., DOYON, J.-F., 1996. *Réseau de suivi environnemental du complexe La Grande. Démarche méthodologique relative au suivi des teneurs en mercure des poissons*. Report by Groupe conseil GENIVAR inc. for Hydro-Québec. 30 p. and appendices.
- TREMBLAY, A., LANGLOIS, C., 1996. *Mesures d'atténuation réalisées avec les communautés cibles de la Baie James de 1989 à 1995 dans le cadre de la Convention sur le Mercure*. Report by Hydro-Québec for the James Bay Mercury Committee. 44 p.
- TREMBLAY, G., DOYON, J.-F., SCHETAGNE, R., 1996. Réseau de suivi environnemental du complexe La Grande. Démarche méthodologique relative au suivi des teneurs en mercure des poissons. Joint report by Groupe conseil GENIVAR inc. and Hydro-Québec. 33 p. and appendices.
- TREMBLAY, G., LEGENDRE, P., VERDON, R., DOYON, J.-F., SCHETAGNE, R., 1998. Polynomial Regression Analysis with Indicator Variables for the Interpretation of Monitoring Data on Mercury Levels in Fish. *Biogeochemistry*, Vol. 40 (1998), p. 189-201.
- UNIVERSITY OF WISCONSIN, 1997. *Fish Bioenergetics 3.0*. Madison Center for Limnology and University of Wisconsin Sea Grant Institute. Madison, WI, USA. n.p.

- VERDON, R., TREMBLAY, A., 1999. *Mercury Accumulation in Fish from the La Grande Complex: Influence of Feeding Habits and Concentrations of Mercury in Ingested Prey*. In: Lucotte et al. (Eds) *Mercury in the Biogeochemical Cycle: Natural Environments and Hydroelectric Reservoirs of Northern Québec*. Berlin: Springer. p. 215-233.
- VERDON, R., BROUARD, D., DEMERS, C., LALUMIÈRE, R., LAPERLE, M., SCHETAGNE, R., 1991. Mercury Evolution (1978–1988) in Fishes of the La Grande Hydroelectric Complex, Québec Canada. *Water, Air and Soil Pollution*, Vol. 56 (1991), p. 405-417.
- VERTA, M., REKOLAINEN, S., KINNUNEN, K., 1986. *Causes of Increased Fish Mercury Levels in Finnish Reservoirs*. National Board of Waters (Finland). Publications of the Water Research Institute No. 65. p. 44-58.
- WASKA RESSOURCES, 2010. *Centrales de l'Eastmain-1-A et de la Sarcelle et dérivation Rupert – Suivi des activités de chasse et pêche sportives des travailleurs en 2009*. Report by Waska Ressources for Hydro-Québec Production.
- WASKA RESSOURCES, BIOFILIA, 2013. *Water Quality in the Rivière Rupert and the Rivière Nemiscau and Total Organic Carbon Input to Baie de Rupert – 2012 Follow-Up*. Joint report by Waska Ressources and Biofilia inc. for Hydro-Québec Production. Final version. 70 p. and 9 appendices.
- WREN, C.D., SCHEIDER, W.A., WALES, D.L., MUNCASTER, B.W., GRAY, I.M., 1991. Relation between Mercury Concentration in Walleye (*Stizostedion vitreum vitreum*) and Northern Pike (*Esox lucius*) in Ontario Lakes and Influence of Environmental Factors. *Canadian Journal of Fisheries and Aquatic Sciences*, Vol. 48 (1991), p. 132-139.

APPENDIX 1

Executive Summary in English



Environmental Monitoring at the La Grande Complex – Evolution of Mercury Levels in Fish - Summary Report 1978 - 2012

Executive Summary – October 2013





1. Background and Objectives

The development of the La Grande hydroelectric complex required the impoundment of large reservoirs, the diversion of several rivers and flow reductions in sections of rivers. It brought about major physical and hydrological modifications. A large-scale environmental monitoring network (EMN), was established to evaluate the physical, chemical and biological changes caused by these modifications, to rationalize remedial measures and management of the developed waterbodies, and to improve impact prediction methods for future projects.

When the La Grande complex was built, the temporary increase in fish mercury levels in reservoirs was a virtually unknown phenomenon, apart from the relatively high mercury levels that had been observed in some reservoirs in Canada and the United States. Monitoring of fish mercury levels began before the La Grande complex reservoirs were impounded, as an EMN complementary study, and became a regular component of the EMN program as soon as the increase in fish mercury levels was observed. The specific objectives of the mercury monitoring were to evaluate the temporal evolution of the phenomenon in the different types of modified environments, to inform fish consumers and to improve impact prediction methods for future projects.

This monitoring, initiated as a commitment of the Société d'énergie de la Baie-James (SEBJ), meets several Hydro-Québec obligations related to the Mercury Agreements of 1986 and 2001, as well as several conditions of the certificates of authorization for the construction of the La Grande Complex's Phase II (La Grande-1, La Grande-2A, Laforge-1 and Laforge-2 generating stations) and Phase III (Eastmain-1, Eastmain-1A, Sarcelle powerhouses and Rupert diversion). Map 1 shows the layout of the La Grande Complex.

2. Methods

From 1978 to 2012, namely before and after the development, fish were caught at 97 sampling stations distributed throughout natural lakes and modified environments in the La Grande complex region. Fish were also caught along the east coast of James Bay.

At each sampling station, and for each sampling campaign, the goal was to catch 30 fish, with all lengths evenly represented, from each of the following target species: lake whitefish, longnose sucker, northern pike, walleye and lake trout. Less abundant species, such as burbot, speckled trout, cisco, round whitefish and lake sturgeon, were also occasionally sampled. At most stations, sampling was usually carried out every 2 years from 1978 to 2000, then every 4 years. Over 45,000 fish flesh samples were analyzed for total mercury using the standard Cold Vapour Atomic Absorption Spectrophotometry method. The following measurements were also taken for each fish analyzed for mercury: total length, weight, sex, sexual maturity and age. The stomach contents were also examined for piscivorous species.

The statistical approach was based on the calculation of mean fish mercury levels for standardized lengths using the *Polynomial regression analysis with indicator variables*. The standardized lengths, which usually correspond to the average length caught by the multiple-mesh-size gill nets used, are the following: 400 mm (16 in) for lake whitefish, longnose sucker and walleye; 600 mm (24 in) for lake trout and 700 mm (28 in) for northern pike.

3. Main Lessons Learned

The extent and duration of the temporary increases in fish mercury levels were clearly defined. The main lessons learned are as follows.

3.1 Natural Lakes

The main lessons derived from the regular monitoring of fish mercury levels in natural lakes are:

- Mercury levels in individual fish vary greatly. They may vary by a factor of 4 for a given species, of a given length, within a given lake. They however gradually increase as a function of fish length or age;
- Mean mercury levels in fish of standardized lengths for a given species may also vary considerably (by as much as fourfold) from one lake to the next, without any particular geographic trend, but rather as a function of water quality. The highest levels are generally found in lakes with coloured water, rich in dissolved and particulate organic matter;



- Mean mercury levels in non-piscivorous species, ranging from 0.05 to 0.30 mg/kg, are always considerably lower than the Canadian marketing standard for fishery products (0.5 mg/kg of total mercury), whereas piscivorous species often slightly exceed the standard, with values ranging from 0.30 to 1.11 mg/kg;
- Regular monitoring of fish mercury concentrations in a number of natural lakes does not show any trend, either upward or downward, over periods of 22 to 28 years.

3.2 Reservoirs

The main lessons derived from the monitoring of mercury levels in standardized-length fish from reservoirs are the following:

- Reservoir impoundment leads to a significant increase of mercury levels in all fish species, by factors ranging from 2 to 8 times the levels recorded in natural environments;
- Maximum levels in non-piscivorous species (from 0.33 to 0.72 mg/kg), are generally reached 4 to 11 years after impoundment, while those in piscivorous species (1.65 to 4.66 mg/kg) are observed after 9 to 14 years;
- In non-piscivorous species, mean maximum levels often remain below the Canadian marketing standard for fishery products but sometimes slightly exceed it, whereas in piscivorous species, peak levels may be 3 to 9 times higher than the standard;
- The increases are temporary, however, and the return to levels representative of natural lakes is generally completed 10 to 20 years after impoundment for non-piscivorous species, and generally after 20 to 30 years in piscivorous species when no further flooding occurs (Figure 1);
- All the reservoirs exhibit the same general pattern of change in fish mercury levels, and the slight variations observed may be explained by physical and hydraulic characteristics particular to the reservoirs. Flooded terrestrial area, annual water

volume, filling time, and extent of drawdown are believed to be important factors, as well as water temperature, quality and density of flooded decomposable materials and fish diet;

- For a given reservoir, fish mercury levels may vary significantly from one sampling station to another, but no systematic pattern is observed, except for stations exhibiting particular characteristics.

3.3 Immediately Downstream from Reservoirs

The main lessons derived from the monitoring of mercury levels in standardized-length fish caught immediately downstream from the La Grande complex reservoirs are the following:

- Mercury levels in lake whitefish caught immediately downstream from generating stations, or flow control structures, are often significantly higher than those recorded in the upstream reservoir (Figure 2). This phenomenon is also occasionally observed in longnose sucker. These usually non-piscivorous species become piscivorous here due to the abundance of small fish made more vulnerable to predation by their passage through turbines or control structures;
- In lake whitefish, this change in diet is mainly seen in large specimens (> 400 mm in length);
- The difference in mean levels observed upstream and downstream would be a function of the characteristic of the structures, such as the water head and the presence or absence of turbines, rendering the small fish more or less vulnerable to predation;
- The maximum mercury levels reached downstream, as well the difference between upstream and downstream levels, decrease over time. Mean mercury levels recorded in the last few sampling campaigns for standardized-length lake whitefish allow unrestricted consumption (< 0.29 mg/kg);
- In piscivorous species like northern pike, the differences between areas above and below reservoirs are smaller and often not significant, as these species always have a piscivorous diet.

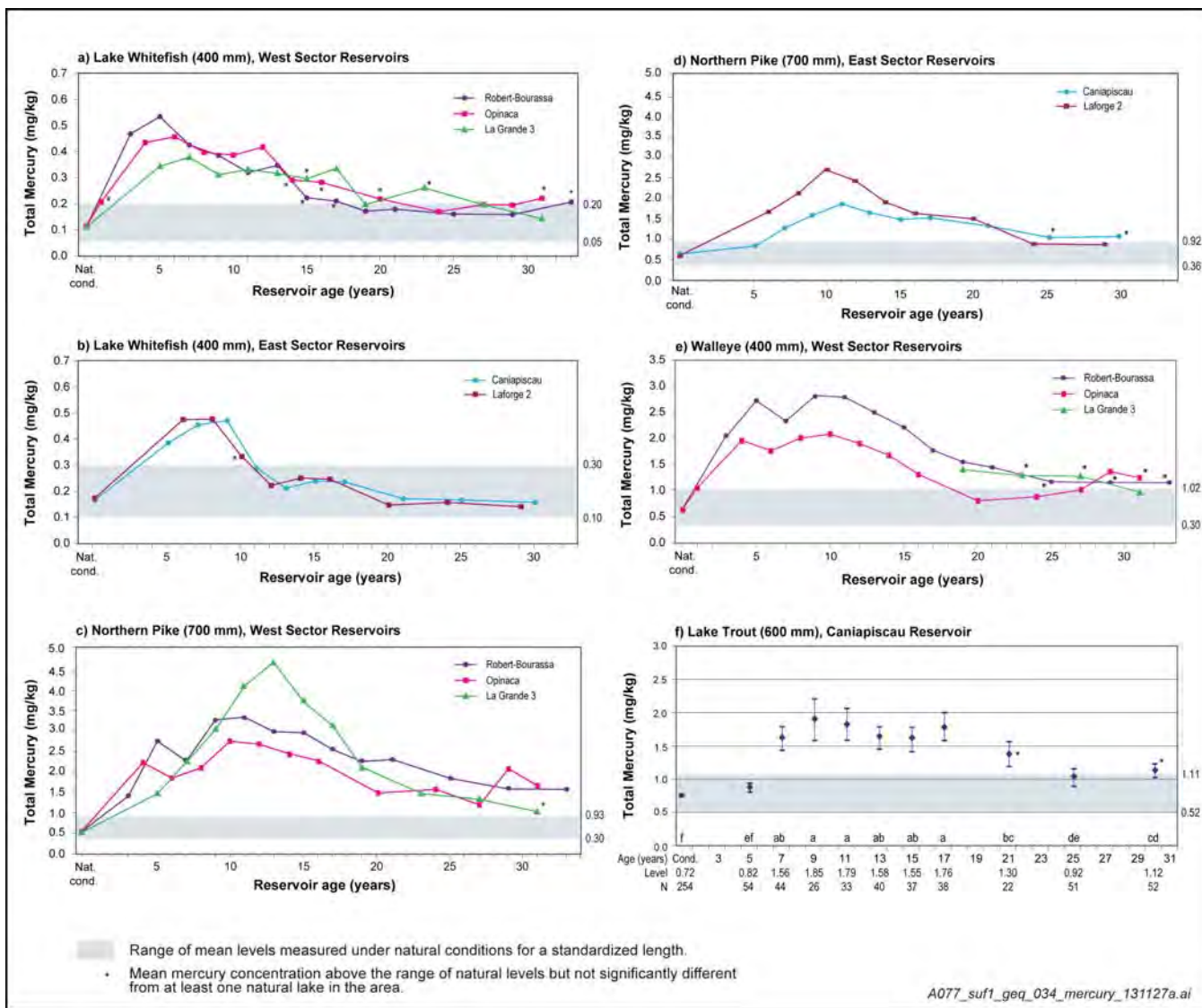


Figure 1: Temporal Evolution of Mean Mercury Levels in Standardized-Length fish in Main La Grande Complex Reservoirs

3.4 Diversion Routes

The main lessons derived from the monitoring of mercury levels in standardized-length fish caught along the Laforge and Eastmain-Opinaca-La Grande diversion routes are the following:

- The evolution of fish mercury levels recorded along diversion routes confirms that mercury is exported from reservoirs and transferred to fish living downstream;
- In some waterbodies along these flow routes, mercury levels may be higher than those in the reservoir providing the inter-basin transfer, because of the combined effect of mercury export downstream from the reservoir and additional mercury production from the local flooding of terrestrial environments;

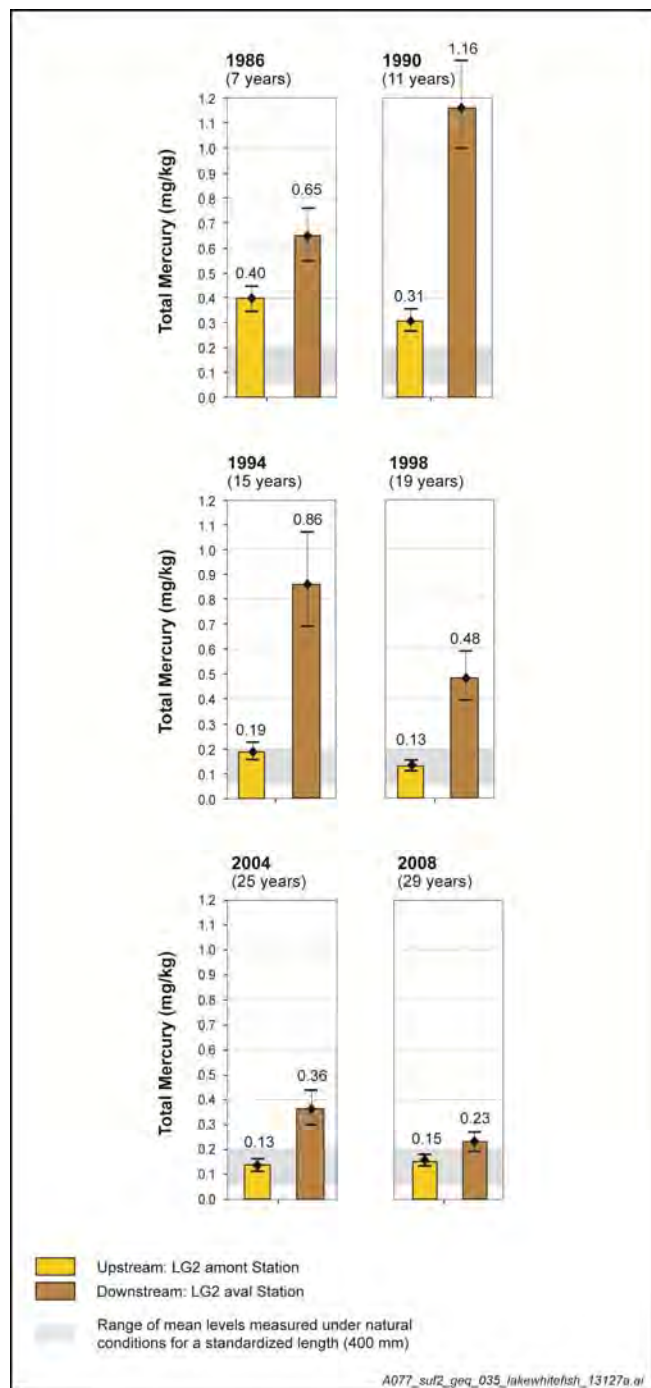


Figure 2: Comparison of Mean Mercury Levels in Lake Whitefish of Standardized Length Upstream and Immediately Downstream from the Robert-Bourassa Generating Station

- The presence of a large waterbody along a diversion route would greatly reduce the transfer of mercury to downstream fish, as it allows for the sedimentation of the mercury adsorbed onto suspended particulate matter and provides still-water conditions that greatly reduce zooplankton entrainment;
- There is no cumulative increase in fish mercury levels when a series of reservoirs is built along the same flow route (Figure 3), as the influence of a given reservoir is significant only in the reservoir located immediately downstream.

3.5 Reduced-Flow Rivers

The main lessons derived from the regular monitoring of mercury levels in standardized-length fish caught in reduced-flow rivers are the following:

- In reduced-flow rivers, where the closures were total and permanent, fish mercury levels generally remained within the range of mean levels observed under natural conditions;
- When large volumes of reservoir water are spilled into these rivers, even if only for a few months, the result is a significant increase in mercury levels in both piscivorous and non-piscivorous fish. The increase may be as great as that observed in the reservoirs, though shorter in duration. This shows that mercury is exported downstream from reservoirs and quickly transferred to downstream fish, most likely by reservoir-produced zooplankton;
- During these spillages, the extent of the mercury export, the downstream distance over which it could be felt and the duration of the increase in fish levels beyond those measured in natural environments appear to depend on the dilution of all the components in the water column by the tributaries of the residual drainage basin, as well as on the presence or absence of a large waterbody allowing sedimentation of suspended particulate matter and predation of entrained zooplankton by aquatic organisms in that waterbody.

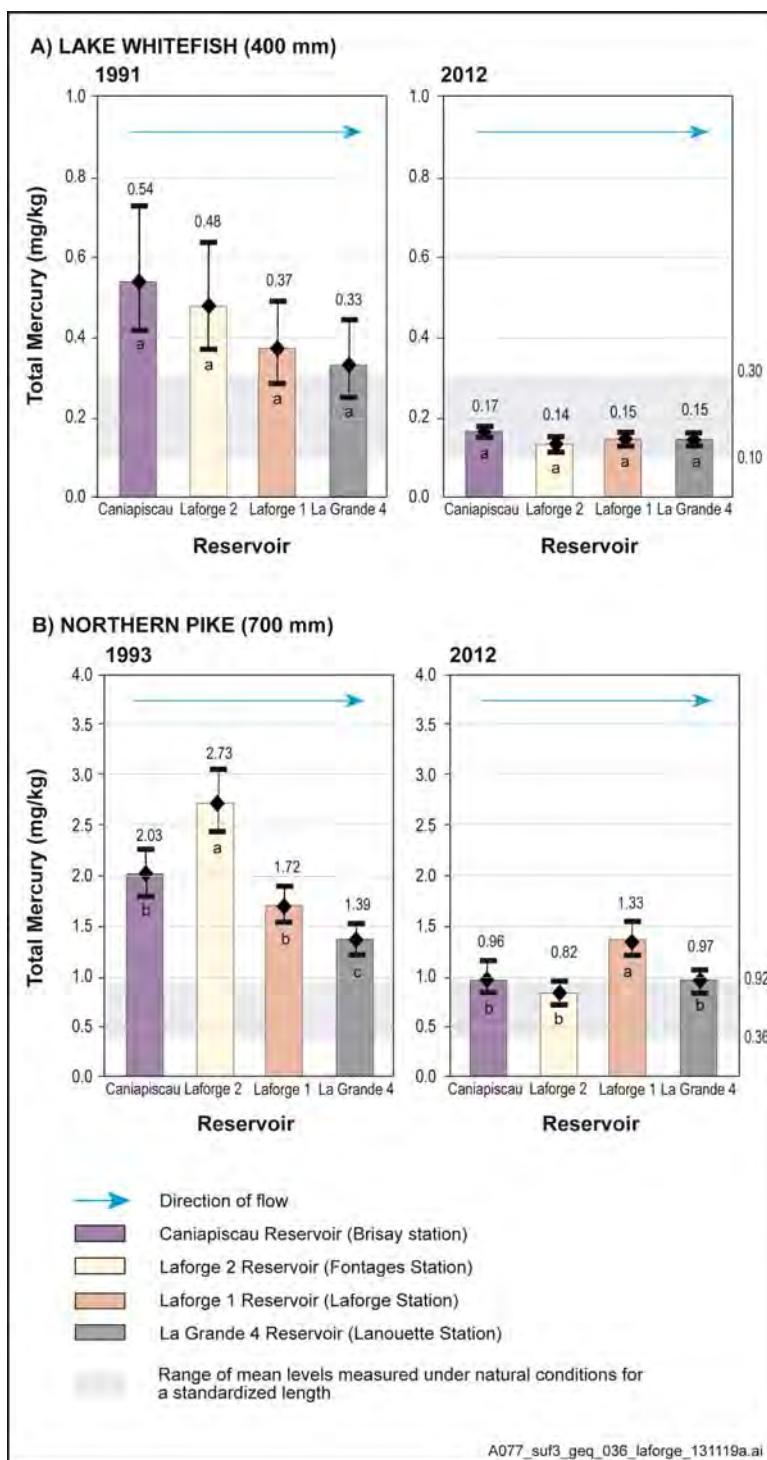


Figure 3: Spatial Comparison of Mercury Levels in Lake Whitefish and Northern Pike of Standardized Length along the Laforge Division

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3.6 Effect on Fish Consumption

The main effects of the temporary increase in mercury levels on fish consumption (Table 1) are the following:

Natural Lakes

- As a result of the great variability in mercury levels in consumption-size fish in the area's natural lakes, the consumption recommendations vary from no restriction to a maximum of 8 meals per month for non-piscivorous species, and from 2 to 8 meals per month in piscivorous species, depending on the species and the considered natural lake.

Modified Waterbodies

Lake Whitefish

- During peak mercury levels in 500-mm lake whitefish, the consumption recommendations were reduced to 2 to 8 meals per month according to the modified waterbody, compared to no restriction on consumption applying to the majority of natural lakes. Exceptionally, a maximum of one meal per month was applicable for lake whitefish caught immediately below the Robert-Bourassa generating station;
- Depending on the modified waterbody, the additional restrictions on consumption of lake whitefish lasted from 0 to 26 years, compared to the recommendations applied to natural lakes in the area, which vary from no restriction to a maximum of 8 meals per month;
- The mean mercury levels recorded for lake whitefish during the last readings, in all modified waterbodies, allow a maximum of 8 meals per month, which corresponds to the recommendation for natural lakes in the area.

Piscivorous Species

- During peak mercury levels, consumption recommendations applicable to 800-mm northern pike, 500-mm walleye and 600-mm lake trout were reduced to a maximum of 2, 1, or less than 1 meal per month depending on the species and the modified waterbody, compared to the maximum of 4 meals per month recommended for most natural lakes.

- Compared to the consumption recommendations applied to piscivorous fish in natural lakes in the area, which vary from 2 to 8 meals per month, the additional restrictions on consumption lasted from 0 to 8 years for lake trout, from 13 to 21 years for walleye, and from 0 to 30 years for northern pike, depending on the modified waterbody;
- The mean mercury levels recorded during the latest sampling campaign allow for a maximum of 2 to 4 meals per month of consumption-size piscivorous fish depending on the species and the modified waterbody, which corresponds to the recommendation applied to many lakes in the area, most of the few exceptions allowing for a maximum of 1.8 meals per month. The only true exception is northern pike caught in Lake Sakami, for which a maximum of 1 meal per month is still recommended.

4. Objectives and Obligations Met

Phase I of La Grande Complex

The synthesis report on the evolution of mercury levels in fish at the La Grande Complex – 1978 to 2000 shows that the objectives and commitments concerning mercury related to Phase I of the La Grande Complex were fully met:

- By the extensive monitoring carried out, the extent and duration of the post-impoundment increase in fish mercury levels was clearly established and the main processes involved were identified, as well as the underlying physical and biological factors;
- The concerned local populations were continuously informed of the evolution of fish mercury levels by a number of methods:
 - The Cree, via the James Bay Mercury Agreements (1986 and 2001);
 - The sport fishers, via the "Guide de consommation du poisson de la pêche sportive en eau douce du Québec", which was regularly revised with the James Bay monitoring data;

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La Grande Complex Environmental Monitoring at the La Grande Complex Evolution of Mercury Levels in Fish Summary Report 1978-2012

Table 1 Consumption Recommendations for Main Fish Species in the Modified Waterbodies of the La Grande Complex

Waterbody	Lake Whitefish (500 mm)				Northern Pike (800 mm)				Walleye (500 mm)				Lake Trout (600 mm)			
	Natural Levels	Maximum	Last Survey	Return	Natural Levels	Maximum	Last Survey	Return	Natural Levels	Maximum	Last Survey	Return	Natural Levels	Maximum	Last Survey	Return
Reservoirs																
Robert-Bourassa	0.08 - 0.34	0.69	0.26	Yes	0.37 - 1.22	4.19	2.02	No	0.55 - 1.47	3.61	1.65	Yes				
Opinaca	0.08 - 0.34	0.60	0.31 ²	Yes	0.37 - 1.22	3.50	2.04 ²	No	0.55 - 1.47	2.93	1.75 ²	Yes				
La Grande 3	0.08 - 0.34	0.60	0.37	Yes	0.37 - 1.22	5.47	1.59	Yes	0.55 - 1.47	2.55 ⁶	1.54	Yes				
La Grande 4	0.15 - 0.41	0.32	0.22	Yes	0.59 - 1.28	1.97	1.44	Yes					0.52 - 1.11	n/a	0.97 ⁷	Yes
Caniapiscou	0.15 - 0.41	0.39	0.25	Yes	0.59 - 1.28	2.17	1.43	Yes					0.52 - 1.11	1.85	1.12	Yes
La Grande 1	0.08 - 0.34	1.92	0.28	Yes	0.37 - 1.22	6.25	1.03	Yes	0.55 - 1.47	5.87	1.61	Yes				
Laforge 1	0.15 - 0.41	0.44	0.22	Yes	0.59 - 1.28	2.06	2.06	No								
Laforge 2	0.15 - 0.41	0.40	0.27	Yes	0.59 - 1.28	2.73	1.18	Yes								
Immediately downstream from reservoirs																
Robert-Bourassa downstream	0.08 - 0.34	2.14	0.50	No	0.37 - 1.22	5.92	1.60 ⁵	Yes	0.55 - 1.47	2.43 ⁶	1.61	Yes				
Opinaca downstream	0.08 - 0.34	1.13	0.43 ²	Yes	0.37 - 1.22	3.15	2.04 ²	No	0.55 - 1.47	3.14	1.86 ²	Yes				
Caniapiscou downstream	0.15 - 0.41	0.52	0.27	Yes	0.59 - 1.28	2.74	1.08	Yes					0.52 - 1.11	2.81	0.98	Yes
Laforge 1 downstream	0.15 - 0.41	0.46	0.33	Yes	0.59 - 1.28	2.14	1.54	Yes					0.52 - 1.11			
Diversion Routes																
EOL	0.08 - 0.34	0.80	0.26 ³	Yes	0.37 - 1.22	4.62	3.23	No	0.55 - 1.47	3.17	2.11	No				
Reduced Flow Rivers																
Caniapiscou ¹	0.15 - 0.41	0.58	0.05 - 0.17 ⁴	Yes									0.52 - 1.11	1.54	0.46-0.72 ⁴	Yes

Note: Colors indicate consumption recommendations in number of meal per month and associated mercury concentrations:

	No restriction (>12 meals/month)	≤ 0,29 mg/kg
	8 meals/month	0,30 à 0,49 mg/kg
	4 meals/month	0,50 à 0,99 mg/kg
	2 meals/month	1,00 à 1,99 mg/kg
	1 meal/month	2,00 à 3,75 mg/kg
	<1 meal/month	> 3,75 mg/kg

- 1: Data from 3 stations sampled at 100, 275 and 355 km from Caniapiscou reservoir.
 - 2: Sampling in 2011.
 - 3: Sampling in 2008.
 - 4: Sampling in 1995. Range of values obtained at the 3 stations sampled.
 - 5: Probable values as per the level obtained for 700-mm northern pike.
 - 6: Absence of data the peak year according to the results at a length of 400 mm.
 - 7: Level obtained for 700-mm lake trout.
- n/a: Not available, too much missing data in the time series.

- Map-type fish consumption guides were produced for the waterbodies of the La Grande Complex and of the Grande rivière de la Baleine, the Petite rivière de la Baleine and the Nottaway, Broadback and Rupert rivers regions, as well as a booklet-type guide : "The northern fish nutrition guide – La Grande complex";
- The development of two models to predict fish mercury levels in reservoirs enabled the improvement of impact prediction methods for future projects.

Phase II of La Grande Complex

The conditions related to mercury specified in the certificates of authorization for the construction of Phase II were also fully met by the monitoring and studies carried out by Hydro-Québec and its subsidiary SEBJ. These were:

- To monitor, from 1991 to 2000, mercury levels in fish in the La Grande Rivière, from the Robert-Bourassa reservoir to the shores of James Bay, for the La Grande-2A and La Grande-1 projects;



- To monitor, from 1993 to 1999, fish mercury levels along the Laforge diversion, to pursue the development of mercury modeling and to study the extent of mercury transfer downstream from the reservoirs, for the Laforge-1, Laforge-2 and Brisay projects.

Although its commitments with respect to mercury were fully met, Hydro-Québec recommended in 2002 that additional measurements be taken of mercury levels in piscivorous fish at the La Grande complex until their return to levels representative of natural lakes in the area. This activity was conducted mainly with a view to managing the potential health risk for fish consumers.

The additional monitoring campaigns carried out from 2003 to 2012 in all waterbodies modified by the development of the La Grande complex Phase I and II, as well as the production and distribution in 2013 of "The Northern Fish Nutrition Guide – James Bay Region", show that the objective of managing potential health risks for fish consumers was well met.

5. Recommendations

Considering the following reasons, it is not recommended to continue the monitoring of mercury levels in fish in the waterbodies modified by the La Grande complex Phase I and II:

- The conditions related to mercury specified in the construction certificates of authorization have been fully met;
- The objective of the additional monitoring campaigns carried out from 2003 to 2012, which was the management of the potential health risks for fish consumers, was achieved;
- The mean mercury levels obtained in lake whitefish, during the latest sampling campaigns, allow the same consumption recommendations as for natural lakes in the area;
- The mean mercury levels recorded during the latest sampling campaign in consumption-size northern pike caught in most reservoirs, immediately

downstream of most generating stations and in reduced flow rivers, allow as a whole a maximum of 2 to 4 meals per month, which corresponds to the recommendation applied to natural lakes in the area;

- The mean mercury levels measured during the latest sampling campaigns in consumption-size walleye and lake trout from most modified waterbodies, allow for a consumption of 2 to 4 meals per month, which correspond to that recommended for those caught in natural lakes in the area;
- The consumption recommendations applied are very safe, considering the built-in safety factor to make sure everybody is well protected. For example, the consumption recommendation for predatory fish from the Robert-Bourassa reservoir is 2 meals per month, but in fact, to reach the mercury level at which health symptoms may appear, most people would have to eat at least one meal per day, for a whole year.

It is also recommended that the monitoring of mercury levels in Lake Sakami fish be continued in conjunction with that of the waterbodies modified by the development of Phase III of the La Grande complex. In accordance with the certificates of authorization, this monitoring is scheduled to continue until mean mercury levels allow the same consumption rates as for those of natural lakes in the area, which means until their levels fall back below 0.5 mg/kg in non-piscivorous fish, and below 1.99 mg/kg in piscivorous fish.

APPENDIX 2

Mean Mercury Levels (mg/kg) in Main Species of Consumption Size Fish
According to Reservoir Age in the La Grande Complex

Appendix 2.1

Mean Mercury Levels (mg/kg) for a Standardized Consumption Size in Main Species of Fish, according to Reservoir Age in the West Sector of the La Grande Complex

Reservoir age (year)	Lake whitefish (400 mm)	Northern pike (700 mm)	Walleye (400 mm)	Burbot (500 mm)
Range of values in natural lakes				
	0.08 to 0.34	0.37 to 1.22	0.55 to 1.47	0.49 to 0.74 ^a
Robert-Bourassa				
3 years (1982)	0.42 (bcd)	1.57 (f)	2.25 (d)	–
5 years (1984)	0.69 (a)	2.99 (d)	3.12 (b)	2.43 (a)
7 years (1986)	0.57 (ab)	2.35 (e)	2.75 (c)	1.33 (b)
9 years (1988)	0.53 (ab)	3.62 (bc)	3.61 (a)	–
11 years (1990)	0.45 (bc)	4.19 (a)	3.61 (a)	–
12 years (1991)	–	–	–	–
13 years (1992)	0.54 (ab)	3.83 (abc)	3.47 (a)	–
15 years (1994)	0.38 (cd)	3.82 (ab)	3.17 (b)	0.83 (c)
17 years (1996)	0.32 (de)	3.31 (cd)	2.59 (cd)	0.76 (cd)
19 years (1998)	0.26 (f)	3.01 (d)	2.33 (de)	0.61 (d)
21 years (2000)	0.31 (def)	3.06 (d)	2.11 (d)	0.66 (cd)
25 years (2004)	0.27 (ef)	2.46 (e)	1.73 (f)	0.61 (d)
29 years (2008)	0.27 (ef)	2.05 (e)	1.68 (f)	–
33 years (2012)	0.26 (f)	2.02 (e)	1.65 (f)	0.61 (d)
Opinaca				
1 year (1981)	0.20 (e)	–	1.38 (f)	–
4 years (1984)	0.45 (abc)	2.63 (b)	2.57 (b)	–
6 years (1986)	0.51 (ab)	2.00 (d)	2.11 (cd)	–
8 years (1988)	0.57 (a)	2.50 (bc)	2.68 (ab)	–
10 years (1990)	0.55 (a)	3.50 (a)	2.93 (a)	–
12 years (1992)	0.60 (a)	3.18 (a)	2.65 (ab)	–
14 years (1994)	0.42 (b)	3.24 (a)	2.59 (b)	0.72 (a)
16 years (1996)	0.38 (c)	3.14 (a)	2.12 (c)	0.69 (a)
20 years (2000)	0.30 (d)	1.98 (d)	1.44 (f)	–
24 years (2004)	0.28 (d)	2.21 (cd)	1.51 (ef)	–
27 years (2007)	0.28 (d)	1.53 (e)	1.52 (ef)	–
29 years (2009) ^b	0.29 (d)	2.94 (ab)	1.91 (cd)	–
31 years (2011) ^b	0.31 (cd)	2.04 (d)	1.75 (de)	–

Appendix 2.1 (cont.) Mean Mercury Levels (mg/kg) for a Standardized Consumption Size in Main Species of Fish, according to Reservoir Age in the West Sector of the La Grande Complex

Reservoir age (year)	Lake whitefish (400 mm)	Northern pike (700 mm)	Walleye (400 mm)	Burbot (500 mm)
Range of values in natural lakes				
	0.08 to 0.34	0.37 to 1.22	0.55 to 1.47	0.49 to 0.74 ^a
La Grande 3				
5 years (1986)	0.40 (b)	1.44 (g)	–	–
7 years (1988)	0.47 (ab)	2.31 (e)	–	–
9 years (1990)	0.48 (ab)	3.23 (d)	–	–
11 years (1992)	0.43 (ab)	4.03 (bc)	–	–
13 years (1994)	0.48 (ab)	5.47 (a)	–	–
15 years (1996)	0.45 (ab)	4.30 (b)	n.r.	1.70 (a)
17 years (1998)	0.60 (a)	4.14 (b)	n.r.	–
19 years (2000)	0.45 (ab)	3.52 (cd)	2.55 (a)	1.09 (b)
23 years (2004)	0.51 (ab)	2.04 (ef)	1.95 (b)	0.60 (c)
27 years (2008)	0.42 (b)	1.89 (efg)	1.93 (b)	0.57 (c)
31 years (2012)	0.37 (b)	1.59 (fg)	1.54 (c)	0.57 (c)
La Grande 1				
1984 (5 ans ^c)	–	n.r.	–	–
1986 (7 ans ^c)	–	3.09 (b)	–	2.11 (b)
1988 (9 ans ^c)	1.52 (a)	3.66 (b)	5.87 (a)	–
1990 (11 ans ^c)	1.88 (a)	6.25 (a)	5.73 (a)	2.64 (a)
1992 (13 ans ^c)	1.92 (a)	–	–	–
1 year (1994)	1.64 (a)	–	–	–
3 years (1996)	0.81 (b)	–	–	1.48 (c)
5 years (1998)	0.58 (b)	–	2.03 (c)	1.33 (c)
7 years (2000)	0.30 (c)	0.97 (c)	2.43 (b)	0.78 (d)
11 years (2004) ^d	0.29 (c)	1.17 (c)	1.81 (cd)	0.77 (d)
15 years (2008) ^d	0.26 (c)	0.99 (c)	1.61 (d)	0.82 (d)
20 years (2012) ^d	0.28 (c)	1.03 (c)	–	0.53 (e)

Notes:

n.r.: Non-representative (data available for one station only or inadequate length distribution).

–: Absence of data or sample numbers are too low (n < 10).

a: The range is provided for information purposes only, as there is little available data under natural conditions.

b: The years 2009 and 2011 also correspond to ages of three and five years for Eastmain 1 reservoir, which influences that of Opinaca.

c: The age indicated is that of Robert-Bourassa reservoir, located immediately upstream.

d: The only data on longnose sucker was collected immediately downstream of Robert-Bourassa reservoir from 2004 to 2012.

Levels with a different letter are significantly different (p < 0.05). Temporal comparisons were made by reservoir and by species. Most of the stations used in modified water bodies were generally those retained after optimization of the monitoring program in 2004, with the exception of those water bodies not sampled after 2003. However, the stations that were not retained after optimization were included for the 1981–2003 period in the rare cases where their exclusion would result in a loss of data.

For burbot in Robert-Bourassa reservoir, the two maximum levels were measured at different stations.

Appendix 2.2

Mean Mercury Levels (mg/kg) for a Standardized Consumption Size in Main Species of Fish, according to Reservoir Age in the East Sector of the La Grande Complex

Reservoir age (year)	Lake whitefish (400 mm)	Northern pike (700 mm)	Lake trout (600 mm)	Burbot (500 mm) ^a
Range of values in natural lakes				
	0.15 to 0.41	0.59 to 1.28	0.52 to 1.11	0.49 to 0.74 ^a
La Grande 4				
4 years (1987)	0.12 (c)	0.57 (e)	1.34 (a)	–
6 years (1989)	0.28 (ab)	1.05 (d)	–	–
8 years (1991)	0.28 (ab)	1.34 (bcd)	–	–
10 years (1993)	0.22 (b)	1.63 (bc)	–	–
12 years (1995) ^c	0.22 (b)	1.91 (ab)	–	–
14 years (1997) ^c	0.20 (ab)	1.97 (a)	–	–
16 years (1999) ^c	0.22 (b)	1.91 (a)	–	–
20 years (2003) ^c	0.32 (a)	1.95 (a)	–	–
24 years (2007) ^c	0.22 (b)	1.89 (a)	–	–
29 years (2012) ^c	0.22 (b)	1.44 (cd)	0.97 (b)	–
Caniapiscau				
5 years (1987)	0.31 (ab)	0.98 (c)	0.82 (e)	0.54 (ab)
7 years (1989)	0.39 (a)	1.37 (bc)	1.56 (ab)	–
9 years (1991)	0.34 (ab)	2.02 (a)	1.85 (a)	–
11 years (1993)	0.36 (a)	2.17 (a)	1.79 (a)	–
13 years (1995)	0.27 (b)	2.11 (a)	1.58 (ab)	0.74 (a)
15 years (1997)	0.30 (ab)	1.91 (a)	1.55 (ab)	0.74 (a)
17 years (1999)	0.30 (ab)	1.95 (a)	1.76 (a)	0.76 (a)
21 years (2003)	0.26 (b)	1.60 (b)	1.30 (bc)	n.r.
25 years (2007)	0.21 (c)	1.34 (b)	0.92 (de)	0.43 (b)
30 years (2012)	0.25 (bc)	1.43 (b)	1.12 (cd)	n.r.

Appendix 2.2 (cont.) Mean Mercury Levels (mg/kg) for a Standardized Consumption Size in Main Species of Fish, according to Reservoir Age in the East Sector of the La Grande Complex

Reservoir age (year)	Lake whitefish (400 mm)	Northern pike (700 mm)	Lake trout (600 mm)	Burbot (500 mm) ^a
Range of values in natural lakes				
	0.15 to 0.41	0.59 to 1.28	0.52 to 1.11	0.49 to 0.74 ^a
Laforge 1				
3 years (1987)	0.37 (ab)	1.08 (e)	1.44 (c)	—
5 years (1989)	0.42 (a)	1.25 (cde)	1.89 (bc)	—
7 years (1991)	0.44 (a)	1.82 (ab)	2.40 (ab)	—
9 years (1993)	0.27 (bc)	1.75 (a)	2.63 (a)	—
11 years (1995) ^c	0.20 (cd)	1.11 (de)	1.76 (bc)	—
13 years (1997) ^c	0.32 (ab)	1.38 (cd)	1.97 (abc)	—
15 years (1999) ^c	0.31 (ab)	1.38 (cd)	1.83 (bc)	—
19 years (2003) ^c	0.28 (bc)	1.47 (bc)	—	—
23 years (2007) ^c	0.24 (cd)	1.97 (a)	—	—
28 years (2012) ^c	0.22 (d)	2.06 (a)	—	—
Laforge 2				
6 years (1989)	0.34 (abc)	1.92 (b)	—	—
8 years (1991)	0.40 (ab)	—	—	—
10 years (1993)	0.40 (a)	2.73 (a)	—	—
12 years (1995)	0.26 (bc)	—	—	—
14 years (1997)	0.30 (abc)	2.22 (b)	—	—
16 years (1999)	0.29 (abc)	2.11 (b)	—	—
20 years (2003)	0.31 (abc)	1.95 (b)	—	0.68 (a)
24 years (2007)	0.23 (c)	1.21 (c)	—	—
29 years (2012)	0.27 (bc)	1.18 (c)	—	—

Notes:

n.r.: Non-representative (data available for one station only or inadequate length distribution).

—: Absence of data or sample numbers are too low ($n < 10$).

■: For a length of 700 mm; range of values in natural water bodies: 0.71 to 1.44 mg/kg.

a: The range is provided for information purposes only, as there is little available data under natural conditions.

b: The range is provided for information purposes only, as the analysis only involved two lakes.

c: The years 1995 to 2012 were influenced by the second impoundment of Laforge 1 reservoir in 1993.

Levels with a different letter are significantly different ($p < 0.05$). Temporal comparisons were made by reservoir and by species.

Most of the stations used in modified water bodies were generally those retained after optimization of the monitoring program in 2004, with the exception of those water bodies not sampled after 2003. However, the stations that were not retained after optimization were included for the 1981–2003 period in the rare cases where their exclusion would result in a loss of data.

For burbot in Robert-Bourassa reservoir, the two maximum levels were measured at different stations.

