Absence of noticeable mercury effects on fish populations in boreal reservoirs despite threefold to sevenfold increases in mercury concentrations

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2 Absence of noticeable mercury effects on fish populations in boreal reservoirs
3 despite threefold to sevenfold increases in mercury concentrations
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5 François Bilodeau, Roger Schetagne, Jean Therrien and Richard Verdon
6

7 **Abstract:** At the La Grande hydroelectric complex (Québec, Canada), total mercury concentrations were
8 measured in more than 25,000 fish over a 20-year period. Fish population characteristics, such as fishing
9 yield, growth rate, condition factor and recruitment, were also monitored. In reservoirs, total mercury
10 concentrations in all species increased rapidly after impoundment, peaking after 4 to 9 years in non-
11 piscivorous fish, and after 9 to 11 years in piscivorous species, at levels 3 to 7 times those measured in
12 surrounding natural lakes, then declined gradually and significantly. Despite this increase, most species
13 showed increases in fishing yields (by factors ranging from 2 to 8), growth rates and condition factors (for
14 more than a decade). The percentage of small specimens of the main species was generally maintained or
15 increased in the first years after flooding, indicating good recruitment.
16

17 **Résumé:** Au complexe hydroélectrique La Grande (Québec, Canada) des analyses de mercure total ont été
18 effectuées sur plus de 25 000 poissons sur une période de plus de 20 ans. Certaines caractéristiques
19 populationnelles de poisson ont également été suivies (succès de pêche, croissance, condition et recrutement).
20 En réservoirs, les concentrations de mercure total de toutes les espèces ont augmenté rapidement, atteignant
21 les niveaux maximums 4 à 9 ans après les mises en eau chez les espèces non piscivores et après 9 à 11 ans
22 chez les piscivores, à des niveaux 3 à 7 fois ceux mesurés initialement, puis elles ont diminué graduellement
23 et significativement. Malgré cette hausse, des augmentations ont été observées dans les succès de pêche
24 (facteurs de 2 à 8), dans les taux de croissance et dans le facteur de condition (pour plus de 10 ans) pour la
25 majorité des espèces. Le pourcentage de petits spécimens s’est généralement maintenu ou a augmenté les
26 premières années après les mises en eau, indice d’un bon recrutement.
27

28 **Keywords :** mercury, boreal reservoirs, fish populations, recruitment, growth
29 **Mots clés :** Mercure, réservoirs boréaux, populations de poisson, recrutement, croissance
30

31 **Introduction**

32 Mercury, in the organic form of methylmercury,
33 bioaccumulates in fish primarily through dietary uptake (Spry
34 and Wiener 1991; Rodgers 1994; Hall et al. 1997). The level
35 of bioaccumulation is a function of age, species and trophic
36 transfer (Birge et al. 1979; Spry and Wiener 1991). Several
37 studies have addressed the potential effect of mercury in the
38 environment and its impact on fish reproduction (Crump and
39 Trudeau 2009; Weis 2009; Depew et al. 2012). These studies
40 were primarily carried out in the laboratory, in controlled

41 environments and with methylmercury concentrations
42 generally much higher than those occurring in natural
43 environments (e.g. aqueous exposure of $\mu\text{g L}^{-1}$ in laboratory
44 vs. ng L^{-1} in natural environments), although some were done
45 in the field (Friedmann et al. 2002; Latif et al. 2001; Larose
46 et al. 2008) and some, using concentrations similar to those
47 occurring in natural environments (Friedmann et al. 1996a;
48 Mela et al. 2007).

49 Direct **mortality** due to methylmercury is observed only
50 at unusually high tissue concentrations ($6\text{--}20 \mu\text{g g}^{-1}$ wet
51 weight in muscle) in cases involving extreme, gross pollution

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52 (Wiener and Spry 1996). Effects of methylmercury on
53 **growth** of fish vary greatly in laboratory experiments, from
54 negative to positive correlations to absence of correlation,
55 with a wide range of exposure concentrations (2.4 to
56 $5.6 \mu\text{g g}^{-1}$ wet weight in carcass-whole fish minus viscera)
57 and fish species (Friedmann et al. 1996a; Hammerschmidt et
58 al. 2002; Sandheinrich and Weiner 2011). Some field
59 studies have found an inverse relationship between mercury
60 concentrations and **fish condition factor** for a number of
61 species such as walleye (*Sander vitreus*) and northern pike
62 (*Esox lucius*) at concentration below or around $1 \mu\text{g g}^{-1}$ wet
63 weight in muscle (Anderson and Newman 1996; Drevnick
64 et al. 2008; Munn and Short 1997). However, Sandheinrich
65 and Weiner (2011) mention that the relation between
66 mercury exposure and fish condition may be confounded by
67 other co-occurring contaminants or fish age. Effects of
68 mercury on **behavior** were also observed (in laboratory
69 experiments at very high or field-relevant concentrations),
70 mainly on the response to visual signs of predation threat,
71 schooling behavior, spawning onset and feeding (Scott and
72 Sloman 2004; Weis et al. 2011; Weis and Candelmo 2012).

73 Mercury-related effects on **reproduction** of fish have
74 been found in a number of laboratory experiments using
75 several reproductive endpoints, at environmentally relevant
76 concentrations, such as below 1 to $2.37 \mu\text{g g}^{-1}$ (wet weight
77 in muscle) (Drevnick and Sandheinrich 2003). Reproduction
78 effects from field studies were usually inferred from effects
79 on organs (hypothalamus, pituitary, gonads, liver) or their
80 function (gametogenesis, fertilization, reproductive
81 hormones), or on embryonic development (Crump and
82 Trudeau 2009; Weis 2009; Scheuhammer et al. 2012), but
83 no reproduction impairment was directly observed in the
84 wild. In some cases, direct effects are inconclusive despite
85 mercury concentrations above the threshold for biological
86 effects (Scheuhammer et al. 2014; Batchelar et al. 2012,
87 2013).

88 It has been well documented that reservoir impoundment
89 may cause an increase in mercury concentration along the
90 food chain and ultimately in fish (Bodaly and Fudge 1999;
91 Lucotte et al. 1999; Bodaly et al. 2004). The rate of increase
92 in mercury would depend on reservoir characteristics such
93 as annual volume of water, area of flooded land, filling time
94 and organic matter in flooded area (Schetagne and Verdon
95 1999), as well as on water quality characteristics such as
96 pH, dissolved sulphate, total organic carbon and temperature
97 (Schetagne and Verdon 1999; Wiener et al. 2006; Drevnick
98 et al. 2007). Depending on these factors, the increase may
99 be significant and may last for more than a decade in fish
100 (Schetagne and Verdon 1999; Bodaly et al. 2007).

101 As part of Phase I of the La Grande hydroelectric
102 complex, built from 1973 to 1985, 5 large reservoirs were
103 impounded, namely Robert-Bourassa, La Grande 3, La
104 Grande 4, Caniapiscou and Opinaca, and 3 generating
105 stations were constructed, namely Robert-Bourassa, La
106 Grande-3 and La Grande-4 (Fig. 1). The generating stations
107 were built along the La Grande Rivière. The reservoirs were
108 impounded from 1978 to 1984, had mean depths varying
109 from 8.2 to 29.4 m and annual drawdown varying between

110 2.1 and 8.0 m. The cumulative flooded area was $9,675 \text{ km}^2$
111 (Table 1).

112 Monitoring of fish populations focused on three large
113 reservoirs (Robert-Bourassa, Opinaca and Caniapiscou) and
114 was carried out from 1978 to 1999, including lakes in pre-
115 flooding conditions. Mercury monitoring was carried out at
116 all La Grande reservoirs because of potential health risks
117 related to fish consumption and is still ongoing because of
118 new construction phases.

119 The mercury-related effects on growth, condition factor,
120 behavior and reproduction, observed in the studies discussed
121 above, were documented for individual fish but never
122 confirmed at the fish population level, with the exception of
123 a few studies referring to cases of industrial pollution
124 (Scherer et al. 1975; Wiener and Spry 1996; Adams et al.
125 1999). This paper will focus on the three major reservoirs in
126 which fish population parameters (between 1978 and 1999)
127 and mercury levels (between 1978 and 2003) were
128 monitored on a regular basis. The main objective of this
129 paper is to determine whether the post-impoundment
130 increases in fish mercury concentrations, at levels up to 3 to
131 7 times those in natural surrounding lakes, were associated
132 with any effects in fish at the population level. The specific
133 objectives are to determine whether reduced fish condition
134 and growth rate shown in individuals in the laboratory, were
135 also observed in large reservoir populations, and also to see
136 if these populations show characteristics that would indicate
137 reproduction impairments as was observed in laboratory
138 fish.

140 Material and methods

141 Data collection

142 The data presented in this paper come from two
143 sampling programs: the fish populations monitoring and the
144 mercury in fish monitoring.

145 Fish populations monitoring

146 In the western sector of the La Grande complex (Robert-
147 Bourassa and Opinaca reservoirs, and Eastmain-Opinaca-La
148 Grande diversion, see Fig. 1), fish populations were
149 sampled annually from 1978 or 1979 to 1984, and every
150 four years afterward, from 1988 to 1996. In the eastern
151 sector (Caniapiscou reservoir), sampling was carried out
152 every year from 1980 to 1982, then every four years from
153 1987 to 1999. Sampling was done four to five times every
154 year from June to October until 1995, when the fishing
155 protocol was optimized to concentrate the sampling effort in
156 July and August (Deslandes and Fortin 1994). All sampling
157 was done with four multifilament gillnets 45.7 m in length
158 and 2.4 m in height, set in pairs, a net of uniform 7.6 or
159 10.2-cm stretched mesh attached to an experimental gillnet
160 (stretched mesh ranging from 2.5 to 10.2 cm). Each set of
161 nets was set perpendicular to and near the shore. Each
162 sampling period lasted 24 h until 1994, and was then
163 increased to 48 h until 1999. The nets were visited every
164 day, for a global fishing effort per station of 4 to 5 days. A
165 total of 16 stations were sampled: 5 in Robert-Bourassa

166 reservoir, 4 in Opinaca reservoir, 4 in Caniapiscou reservoir
167 and 3 in natural reference lakes.

168 **Mercury in fish monitoring**

169 Mercury in fish monitoring was carried out at all La
170 Grande reservoirs because of potential health risks related to
171 fish consumption. For the Robert-Bourassa, Opinaca and
172 Caniapiscou reservoirs, monitoring was done at the stations
173 sampled for the fish populations program. For the other
174 reservoirs, mercury was monitored at 3 to 5 sampling
175 stations per reservoir. In the western sector, monitoring was
176 carried out in 1978 (pre-impoundment) then every 2 years
177 from 1982 to 2000. In the eastern sector, monitoring was
178 carried out in 1980 (pre-impoundment) then every 2 years
179 from 1987 to 1999. Mercury monitoring is still ongoing
180 because of new construction phases (Phase II from 1987 to
181 1996, Eastmain 1 reservoir from 2002 to 2006, and
182 Eastmain 1A and Rupert diversion from 2007 to 2012).

183 For the years were both mercury and fish populations
184 were monitored, fish for mercury analysis were taken from
185 the fish population sampling, whereas during the years were
186 only mercury was monitored, fish were collected with
187 experimental gillnets (stretched mesh ranging from 2.5 to
188 10.2 cm) as well as with multifilament nets of uniform 2.5,
189 7.6 or 10.2-cm stretched mesh.

190 A nearby reference lake was associated with each of the
191 3 monitored reservoirs and were also sampled at the same
192 times (Detcheverry, Rond-de-Poêle and Hazeur lakes shown
193 in Fig. 1). These lakes had the same fish community as the
194 reservoirs and, having a surface area varying from 6 to 20
195 km², were large enough to support the same fishing effort
196 carried out in the reservoirs without impairing populations.
197 Water chemistry in those lakes were very similar to the
198 lakes and rivers flooded by the impoundment of the
199 reservoirs: average pH varied from 6.5 to 7.1 in lakes
200 compared to 6.1 to 6.6 in reservoirs; conductivity was very
201 low and ranged from 9 to 36 µS cm⁻¹ in lakes and 9 to
202 19 µS cm⁻¹ in reservoirs, total phosphorous values were also
203 very low, ranging from 5 to 9 µg L⁻¹ in lakes and from 5 to
204 10 µg L⁻¹ in reservoirs; as was chlorophyll a, ranging from
205 0.9 to 1.9 µg L⁻¹ in lakes and from 1.4 to 1.9 µg L⁻¹ in
206 reservoirs. In addition, a total of 31 natural lakes in the La
207 Grande complex region, were also sampled to determine
208 background mercury levels in fish.

209 For both, fish populations and mercury in fish
210 monitoring, the fish caught were identified, counted,
211 measured and weighed, and sex and maturity were
212 determined. Bone structures were also taken for age
213 determination on a subsample of fish. Samples of 50 g of
214 muscle were taken for mercury analysis on a subsample of
215 fish (usually 30 fish per species, per station, per year, well
216 distributed according to length). For mercury analysis, the
217 most abundant or consumed fish species were selected: two
218 non-piscivorous species, namely lake whitefish and
219 longnose sucker (*Catostomus catostomus*), and three
220 piscivorous species, namely northern pike, walleye and lake
221 trout.

222

223 **Data analysis**

224 Because filling time extended over more than one year
225 in some reservoirs, the first year of impoundment is
226 considered as year 0 for all of them, which is different from
227 the baseline. For the western sector of the La Grande
228 Complex (Robert-Bourassa and Opinaca reservoirs), pre-
229 impoundment data from future reservoir stations were
230 pooled for 1977 and 1978 to increase the sample size.

231

232 **Fish density**

233 Catch per unit of effort (CPUE) was used as an indicator
234 of fish density. This is adequate for temporal comparison
235 when stations, period and gears are the same (Ricker 1980),
236 which is the case in the present study. For a given water
237 body (reference lake or reservoir) and year, catches of all
238 sampling nets were averaged (N of 8 to 120 depending on
239 reservoir for each year) and expressed as fishing yields in
240 number of fish per net-day (CPUE). To obtain rigorously
241 comparable data from 1978 to 1999, only data available for
242 the months of July and August were used for the CPUE
243 calculations. For the various species, variance analysis
244 (ANOVAs) and Tukey's HSD tests ($\alpha < 0.05$) were used to
245 compare annual means in CPUE between pre-impoundment
246 and post-impoundment years, and ANOVAs and Kruskal-
247 Wallis tests ($\alpha < 0.05$) were used for the comparisons
248 between reservoir and natural lake every year.

249

250 **Growth, condition and small-size fish**
251 **proportions**

252 Age determination was used to generate growth curves
253 with the von Bertalanffy equation (Ricker 1980):

254
$$Length = L_{max}(1 - e^{(-k(t-t_0)})}$$

255 Where L_{max} = maximal length of the species,
256 k = a constant, t = age of fish (year), and t_0 = age at
257 length = 0.

258 Age was determined using the cleithrum for northern
259 pike (Massé 1979; Casselman 1979), the otoliths and
260 operculum for walleye (Pépin and Lévesque 1985), the
261 otoliths for lake whitefish and lake trout (Power 1978;
262 Morin et al. 1982; Dubois and Lagueux 1978). The first
263 pectoral fin ray was used for longnose sucker (Beamish
264 1973; Verdon and Magnin 1977). Age determination is
265 available from 1977 to 2000, using the mercury monitoring
266 data in this last year. Statistical comparison ($\alpha < 0.05$) was
267 performed with length using ANOVAs and SNK or
268 Kruskal-Wallis tests ($\alpha < 0.05$) at a given age between years.

269 The Fulton condition factor (K) was determined by the
270 following equation (Ricker 1980):

271
$$K = \frac{Weight(g) \times 10^5}{Length(mm)^3}$$

272 Changes in the condition factor in modified and
273 reference environments were compared using all the data
274 available (catches from all months and monitoring) and
275 using individuals of the most abundant length classes for
276 each species, to eliminate effects of interannual variations in

length distribution. The use of all data available is valuable because there is no significant differences between the condition factor values obtained with only July and August data compared to all months sampled (Deslandes and Fortin, 1994), and the variances were lower, allowing an easier temporal comparison between years. Length classes used were 300 to 500 mm for lake whitefish and longnose sucker, 400 to 600 mm for walleye, 600 to 800 mm for lake trout and 500 to 700 mm for northern pike. For the various species, ANOVAs and SNK or Kruskal-Wallis tests ($\alpha < 0.05$) were used to compare annual means in condition factors (minimum of five fish) for a given environment between pre-impoundment and post-impoundment years. Because the nets were not set in the same pair assemblage for mercury monitoring as for fish population monitoring, only the data collected from fish caught by the fish population sampling protocol were used to calculate CPUE, growth, and small-size fish proportions. Exceptionally, because of the selection of fish subsamples according to length classes and considering the frequent use of the same fishing gear for fish population and mercury monitoring, the condition factor was also determined for fish gathered after 1996 from complementary studies (1998, 2000) or from mercury monitoring (1986, 1989, 1990, 1994, 1997, 2000, 2003).

Trends in recruitment were inferred from the percentage of small specimens in yearly length-composition data (<250 mm for lake whitefish, longnose sucker and walleye, <350 mm for northern pike, <600 mm for lake trout). These length limits represent approximately the tenth centiles of the lengths of each species in all natural environment (all surveys together). Only the fish population monitoring data (1978-1999) were used for this aspect. Comparisons between pre-impoundment and post-impoundment years and between reservoir and natural lake each year were done with binomial or Poisson Law ($\% < 5\%$ or $\% > 95\%$) hypothesis tests ($\alpha < 0.05$), in which 0.001% replaced zero values.

Mercury analysis

The determination of total mercury ($\mu\text{g g}^{-1}$ of wet weight) was done using Cold Vapor Atomic Absorption Spectrophotometry (CVAAS), as recommended by Environment Canada (1979). All analyses were performed by independent laboratories accredited by the Québec government to analyze total mercury. The quality control included: method blanks, standard additions, 15% of fish samples measured in triplicate, certified standards from the National Research Council of Canada. Further quality control was performed on blind triplicates sent to the laboratories without their knowledge (taken from 10% of all fish analyzed for mercury).

The detection limit varied from 0.01 to $0.05 \mu\text{g g}^{-1}$ (wet weight) from 1977 to 2003. Because the detection limit has been lower since 1997 than in earlier years (0.01 to $0.02 \mu\text{g g}^{-1}$ vs. $0.05 \mu\text{g g}^{-1}$), a number of values below $0.05 \mu\text{g g}^{-1}$ were obtained. Since this situation may skew the results relative to earlier years, the data below $0.05 \mu\text{g g}^{-1}$ measured since 1997 was automatically considered to be at

this threshold to make it comparable to the data from previous years.

The evaluation of analytical performance (relative to repeatability), which was determined using the different control procedures, helped establish the yearly average coefficient of variation (standard deviation/mean $\times 100$), which ranged from 3.4% to 8.5% from 1986 to 2003 (mean of 5.8%). In regard to replicability, yearly average coefficients of variation for accuracy ranging from 3.9% to 7.6% were obtained for all samples from 1986 to 2003 (with an overall mean of 5.7%). For concentrations lower than $0.30 \mu\text{g g}^{-1}$, the yearly coefficient of variation for accuracy varied from 3.4% to 5.6% from 1989 to 2003 (overall mean of 4.7%). Average yearly coefficients of variation for the blind triplicate samples varied from 4.1% to 7.1%, from 1990 to 2003, with an overall mean of 5.9%.

All mercury data presented in this paper are reported as $\mu\text{g g}^{-1}$ of total mercury (wet weight) for muscle samples. Although the monitoring done was on total mercury and many laboratory experiments on fish use methylmercury, previous studies have well demonstrated that total mercury in fish is a good surrogate for methylmercury, as the proportion of methylmercury was found to vary from 80% to 100% depending on fish species (Bloom 1992; Watras et al. 1994; Lasorsa and Allen-Gil 1995). Statistical analysis ($\alpha < 0.05$) of temporal and spatial trends was carried out using polynomial regression analysis with indicator variables (Tremblay et al. 1998). Interannual and spatial comparisons were made using a standard length, corresponding to average lengths in the catches, namely 400 mm for lake whitefish, longnose sucker and walleye, 700 mm for northern pike and 600 mm for lake trout, which correspond, for all species, to lengths at which all individuals were mature.

The “background condition” was determined with fish mercury data coming from a total of 31 unaffected natural lakes of the La Grande complex region (respectively 21 and 10 from the western and eastern sectors), including pre-flood data from 7 lakes that were flooded during the impoundment of Robert-Bourassa (2 lakes), Opinaca (1 lake) and Caniapiscau reservoir (4 lakes). Table 2 shows for each species and each sector, the number of natural lakes sampled, the number fish analyzed, the range of mean mercury levels observed at the standard lengths, and the overall mean mercury levels obtained by pooling the data from all natural lakes. The ranges of mean levels at standard lengths obtained for natural lakes of each sector are presented in figures 2 and 3.

383

Results

Mercury in fish of natural lakes

Fish total mercury levels vary greatly from one lake to another, as mean concentrations at standard lengths for a given species may vary by factors of up to 4 between neighboring lakes (Table 2). For example, in the western sector of the La Grande complex region, 400-mm lake whitefish from 21 natural lakes show an overall mean

mercury concentration of $0.11 \mu\text{g g}^{-1}$, but mean levels range from 0.05 to $0.20 \mu\text{g g}^{-1}$ from one lake to another. A corresponding range of 0.12 to $0.22 \mu\text{g g}^{-1}$, with an overall average of $0.12 \mu\text{g g}^{-1}$, was obtained for 400-mm longnose sucker. In the same sector, mean mercury levels for 700-mm northern pike and 400-mm walleye range respectively from 0.30 to $0.93 \mu\text{g g}^{-1}$ and from 0.30 to $1.02 \mu\text{g g}^{-1}$, with overall mean levels of respectively 0.60 and $0.59 \mu\text{g g}^{-1}$. In the eastern sector, mean mercury levels in 600 mm lake trout sampled from 10 natural lakes range from 0.52 to $1.11 \mu\text{g g}^{-1}$, with an overall mean of $0.72 \mu\text{g g}^{-1}$.

Mercury levels in fish of natural lakes, monitored regularly from 1984 to 2003, show no increasing or decreasing time trend, with very little year to year variations (Fig. 2), compared to the great increases observed in reservoirs.

Mercury in fish of reservoirs

Following impoundment, significant ($\alpha < 0.05$) increases were measured in total mercury concentrations in the muscle of all fish species caught in the three monitored reservoirs. Non-piscivorous species showed increases varying by factors ranging from 3 to 7 depending on species and reservoir (Fig. 3). Mercury levels in 400-mm lake whitefish increased from an overall mean of $0.11 \mu\text{g g}^{-1}$ in background conditions to a maximum of $0.53 \mu\text{g g}^{-1}$ in Robert-Bourassa reservoir after 5 years and to $0.46 \mu\text{g g}^{-1}$ in Opinaca reservoir after 6 years, while in Caniapiscou reservoir it increased from an overall mean in natural lakes of $0.16 \mu\text{g g}^{-1}$ to $0.47 \mu\text{g g}^{-1}$ after 9 years (Table 3). In 400-mm longnose sucker, mercury concentrations increased from an overall mean of $0.12 \mu\text{g g}^{-1}$ in natural lakes to a maximum of $0.63 \mu\text{g g}^{-1}$ in Robert-Bourassa reservoir (after 7 years) and from 0.12 to $0.72 \mu\text{g g}^{-1}$ in Opinaca reservoir (after 4 years). In Caniapiscou reservoir it increased from an overall mean of $0.13 \mu\text{g g}^{-1}$ to $0.52 \mu\text{g g}^{-1}$ after 9 years (Table 4).

Piscivorous species showed similar increase factors, varying from 3 to 6 (Fig. 3). In 700-mm northern pike, total mercury levels increased from an overall mean of $0.60 \mu\text{g g}^{-1}$ in background conditions to a maximum of $3.34 \mu\text{g g}^{-1}$ in Robert-Bourassa reservoir (after 11 years) and to $2.77 \mu\text{g g}^{-1}$ in Opinaca reservoir (after 10 years) (Table 5). In Caniapiscou reservoir, the corresponding concentrations increased from an overall mean of $0.59 \mu\text{g g}^{-1}$ to $1.86 \mu\text{g g}^{-1}$ after 11 years. For walleye 400 mm in length, mercury levels increased from $0.59 \mu\text{g g}^{-1}$ in background conditions to a maximum of $2.82 \mu\text{g g}^{-1}$ in Robert-Bourassa reservoir (after 9 years) and from 0.59 to $2.07 \mu\text{g g}^{-1}$ in Opinaca reservoir (after 10 years) (Table 6). In 600-mm lake trout, the mean concentration in natural lakes was $0.72 \mu\text{g g}^{-1}$ and reached a maximum of $1.85 \mu\text{g g}^{-1}$ in Caniapiscou reservoir, 9 years after impoundment (Table 7).

Mercury levels then gradually and significantly decreased in all species, except lake trout of Caniapiscou reservoir, reaching or almost reaching the range of background levels in lake whitefish and longnose sucker

after 17 to 21 years of impoundment. (Fig. 3 and tables 3 and 4). In 1999 and 2000, the last sampling year for which both mercury levels and fish population characteristics are both available, mean mercury levels in standard-length northern pike and walleye corresponded to the following decreases compared to peak concentrations: 19 to 45 % for northern pike and 50 to 63% for walleye depending on the reservoir (Fig. 3 and tables 5 and 6).

Bodaly et al. (2007) showed that increases in fish mercury levels are temporary in Boreal reservoirs and that complete returns to the range of background levels should be expected 10 years to 30 years after impoundment, depending on species and standard-lengths used. Subsequent unpublished mercury data from 2002 to 2012 for the La Grande complex reservoirs confirmed this time frame for all species and reservoirs except for northern pike of the Robert-Bourassa reservoir (Schetagne and Therrien, 2013).

Fish density

In some cases, such as lake whitefish in Caniapiscou reservoir and walleye in Robert-Bourassa and Opinaca reservoirs, a significant decrease in fishing yields was observed for the first few years following impoundment. Then, during the periods when fish mercury levels were increasing, fishing yields also showed statistically significant ($\alpha < 0.05$) increases, compared to pre-impoundment values, in all three reservoirs for most species, the exceptions being for longnose sucker in Opinaca reservoir and lake trout in Caniapiscou reservoir (Tables 3-7).

Lake whitefish maximum mercury levels were associated with maximum CPUE in the three monitored reservoirs, in 1984 in Robert-Bourassa and Opinaca reservoirs (the 1986 mercury value in Opinaca, having the same letter in table 3 as the 1984 value, is not significantly different from the 1984 value) and, in 1991 in Caniapiscou reservoir. More specifically, lake whitefish CPUE increased ($\alpha < 0.05$) by a factor ranging from 1.4 to 3.4 in the three reservoirs. (peak CPUE compared to pre-impoundment values). For all reservoirs, lake whitefish CPUE remained, after peak mercury levels, generally comparable to or greater than those obtained before impoundment or in the natural reference lakes.

Longnose sucker CPUE in the three reservoirs also typically remained comparable ($\alpha < 0.05$) to those obtained for reference lakes (Table 4), although the post-impoundment increase was less pronounced and more variable. Indeed, longnose sucker CPUE comparable to reference lake values, were associated with high or near peak mercury levels (such as $0.61 \mu\text{g g}^{-1}$ in 1984 in Robert-Bourassa reservoir, and $0.50 \mu\text{g g}^{-1}$ in 1992 in Opinaca reservoir and $0.52 \mu\text{g g}^{-1}$ in Caniapiscou reservoir). For this species, CPUE increase factors ranged from 1.7 to 2.0. After an initial increase of longnose sucker density in Robert-Bourassa reservoir, the subsequent decrease led, for a number of years, to fishing yields below initial values or surrounding natural lake values.

Northern pike CPUE increased markedly ($\alpha < 0.05$) in all reservoirs (by factors ranging from 3.8 to 9.4), and values greater than before impoundment and reference lake values were often obtained for the years where maximum or near maximum mercury levels were measured (Table 5).

In Robert-Bourassa reservoir, after an initial significant decrease in CPUE values during the first few years after impoundment, the year-to-year **walleye** CPUE fluctuates in the same manner as in the reference lake. CPUEs not significantly different ($\alpha < 0.05$) from the pre-impoundment value were obtained from 1982 to 1988 (2.0 to 3.4) and were associated with maximum or near maximum mercury levels ($2.03 \mu\text{g g}^{-1}$ to $2.82 \mu\text{g g}^{-1}$). Moreover, a CPUE not significantly different ($\alpha < 0.05$) from the pre-impoundment value but significantly greater than in the reference lake ($\alpha < 0.05$) was obtained in the last year of monitoring (1996), after the period of higher mercury levels (Table 6). In Opinaca reservoir, a gradual significant reduction in walleye CPUE was observed before the maximum increase in mercury levels, but in 1992, shortly after the maximum mercury level of $2.07 \mu\text{g g}^{-1}$, a CPUE of 3.4, not significantly different ($\alpha < 0.05$) from the pre-impoundment value, was obtained.

Lake trout is an exception, as its CPUE in Caniapiscou reservoir gradually declined ($\alpha < 0.05$) after impoundment (from an average of 2.7 to 0.6), while mercury levels gradually increased (Table 7).

Fish growth

In the three reservoirs, growth rates in all the main species were markedly higher after impoundment (Fig. 4 to 6). These figures show the growth rates (fish length as a function of fish age) obtained for the different fish species, for years before, during and after (last year of monitoring) peak mercury levels. **Lake whitefish** growth rates were consistently higher than pre-impoundment rates, up to 16 and 21 years after impoundment in Opinaca and Robert-Bourassa reservoirs and were also higher 7 years after impoundment in Caniapiscou reservoir. For example, during peak mercury levels ($0.46 \mu\text{g g}^{-1}$ in 1986) in Opinaca reservoir, lake whitefish reached 400 mm in length at age 6 as opposed to age 11 in pre-impoundment conditions (at $0.11 \mu\text{g g}^{-1}$).

Longnose sucker growth rates were consistently higher than pre-impoundment rates, up to 19 and 21 years after impoundment in Caniapiscou and Robert-Bourassa reservoirs. For example, during near peak mercury levels ($0.61 \mu\text{g g}^{-1}$ in 1984) in Robert-Bourassa reservoir, longnose sucker reached 400 mm in length at age 8 as opposed to age 12 in pre-impoundment conditions (at $0.12 \mu\text{g g}^{-1}$).

Northern pike growth rates were higher or similar to pre-impoundment rates, up to 16 and 21 years after impoundment in Opinaca and Robert-Bourassa reservoirs. For example, during near maximum mercury levels in 700-mm fish ($2.47 \mu\text{g g}^{-1}$ in 1994) in Opinaca reservoir, northern pike reached 800 mm in length at age 8 that year, as opposed to age 14 in pre-impoundment conditions (Fig. 5).

Mean mercury levels in 800-mm northern pike were then $3.24 \mu\text{g g}^{-1}$, as opposed to $0.79 \mu\text{g g}^{-1}$ in natural conditions.

In Robert-Bourassa and Opinaca reservoirs, **walleye** growth rates were consistently higher than pre-impoundment rates, up to 21 years after impoundment (Fig. 4 and 5), before and after peak mercury levels. For example, in Opinaca reservoir in 1994, walleye reached 400 mm in length at age 8, as opposed to age 11 in pre-impoundment conditions.

In Caniapiscou reservoir, **lake trout** growth rates were higher than pre-impoundment rates, 9 years (1989) and 19 years (1999) after impoundment, which corresponds to before and after peak mercury levels (1991). In 1999, lake trout reach 600 mm in length at age 4 compared to age 7 in pre-impoundment conditions.

The number of fish available for a given year, for each specific age class (for each species, reservoir, and reference lake) is often not sufficient to perform statistical comparisons between years. Nevertheless, significant increases in the mean length at a given age ($\alpha < 0.05$), compared to natural conditions, were found at young ages for almost all the species in all reservoirs. For example, 5, 6 and 7 year-old **lake whitefish** were significantly longer in Robert-Bourassa reservoir in 1982 than in pre-impoundment conditions; the same holds true for 7 year-old lake whitefish in Opinaca reservoir in 1986 and 1996, as well as for 6 year-old lake whitefish in Caniapiscou reservoir in 1987. For **longnose sucker**, 9 and 10 year-old fish were significantly longer in Robert-Bourassa reservoir in 1982, 1984 and 2000 than in natural conditions, as were 9 year old specimens in 1987 in Caniapiscou reservoir. For **northern pike**, 6 year-old specimens were significantly longer in 1982 and 1992 in Robert-Bourassa reservoir, compared to background conditions, as well as 7 and 8 year-old specimens in 1992 in the same reservoir. For **walleye**, 5 year old fish were significantly longer in Robert-Bourassa reservoir, in 1996, as well as 6, 9 and 12 year-olds in 2000; the same holds true for 7, 8 and 14 year-olds in 1984. For **lake trout**, 10 year-old specimens were significantly longer than pre-impoundment in Caniapiscou reservoir in 1989.

Fish condition

The fish condition factor K increased significantly ($\alpha < 0.05$) after impoundment, in all species and reservoirs (Fig. 3 and Tables 3 to 7), except for northern pike of Caniapiscou reservoir. For the non-piscivorous lake whitefish and longnose sucker (Fig. 3a and b and Tables 3 and 4), condition factor patterns were fairly well synchronized with mercury concentration patterns shortly after impoundment. Indeed, for **lake whitefish** increased values of both mercury and fish condition were observed a few years after impoundment, with K values higher than pre-impoundment associated with high values of mercury from 1981 to 1986 in Robert-Bourassa reservoir, in 1984 in Opinaca, and from 1987 to 1989 in Caniapiscou (Fig. 3a and Table 3). Lake whitefish condition often remained significantly higher than pre-impoundment values after peak mercury values, such as in 1992, 1996, 1998 and 2000 in

Robert-Bourassa reservoir, in 2000 in Opinaca, and in 1993 and 1995 in Caniapiscau. **Longnose sucker** condition also increased significantly during increasing mercury concentrations the first few years after impoundment of the three reservoirs (Fig. 3b and Table 4). Significantly higher condition factors ($\alpha < 0.05$), compared to pre-impoundment values, were observed with significantly higher mercury values ($\alpha < 0.05$), in 1982, 1984 and 1988 in Robert-Bourassa reservoir, in 1984 and 1986 in Opinaca, and in 1987, 1989, 1993 and 1995 in Caniapiscau. Subsequently, longnose sucker condition often remained significantly higher than pre-impoundment after peak mercury values, such as in 1992, 1996 and 2000 in Robert-Bourassa reservoir, in 2000 in Opinaca, and in 1999 and 2003 in Caniapiscau.

The piscivorous **northern-pike** condition factor shows a different pattern in Robert-Bourassa and Opinaca reservoirs (Fig. 3c and Table 5). The initial significant increases ($\alpha < 0.05$) in condition factor are not synchronized with the increases in mercury levels, as peak condition factors (in 1981 in Robert-Bourassa reservoir and in 1982 in Opinaca reservoir) are observed well before peak mercury levels (from 1988 to 1992 in Robert-Bourassa and from 1990 to 1994 in Opinaca). However, northern pike condition factors remained higher than ($\alpha < 0.05$) or comparable to pre-impoundment or reference lake condition values during and after peak mercury levels, in both of these reservoirs. The only exception was in 1992 in Opinaca reservoir when the condition factor was similar to pre-impoundment but significantly lower than in the reference lake where the highest value in 14 years was obtained.

In Caniapiscau reservoir, a colder water body, northern pike condition factors did not show the initial post-impoundment increase, but remained within the range of condition values observed either before impoundment or in the reference lake (Fig. 3c and Table 5).

As was the case for the non-piscivorous lake whitefish and longnose sucker, the piscivorous walleye and lake trout condition factors pattern of change are fairly well synchronized with mercury concentration patterns (Fig. 2d and 2e and Tables 6 and 7). In Robert-Bourassa and Opinaca reservoirs, significant increases in **walleye** condition are observed during the period of significant increases in mercury levels (from 1981 to 1984). Subsequently, walleye condition factors, in both these reservoirs, remain significantly higher than pre-impoundment values during and after peak (or near peak) mercury levels, from 1986 to 1998 in Robert-Bourassa, and from 1986 to 2000 in Opinaca reservoirs.

For **lake trout** in Caniapiscau reservoir, the pattern of change of the condition factor closely follows the mercury concentration pattern, with higher condition values associated with higher mercury values, with the exception of the 1991 condition values which are low in both the reservoir and reference lake (Fig. 2e and Table 7). Condition factors remain noticeably higher ($\alpha < 0.05$) than pre-impoundment or reference lake values during and after the peak (or near peak), from 1993 to 2003.

681 *Fish recruitment*

Recruitment can be evaluated by the proportion of small specimens of the main species in the three reservoirs. Tables 3 to 7 show the proportion of small specimens calculated before and after impoundment of the three monitored reservoirs, as well as for the unaffected reference lakes. It does not show a relationship between mercury levels and fish recruitment at the population level, as the % of small specimens did not systematically show the same pattern of change as mercury.

Lake whitefish showed different recruitment patterns, depending on the reservoir, despite similar mercury patterns in all reservoirs (Table 3). In **Robert-Bourassa reservoir**, the % of small specimens of lake whitefish was systematically and significantly lower ($\alpha < 0.5$), compared to the pre-impoundment data (1977-78), from the third year of flooding (1981) until the last year of fish population monitoring (1996). This decrease may however not be attributed to mercury levels, as the % of small lake whitefish was also systematically lower in the reference lake (compared to 1977-78). Indeed, no small specimens were captured in this lake from 1979 to 1996, while mercury levels remained stable (table 3). These fluctuations may probably be attributed to sampling alea as the lake whitefish yields (CPUE) increased from 1983 to 1988, and then remained equivalent to pre-impoundment values despite lower percentages of small specimens. In **Opinaca reservoir**, the % of small lake whitefish increased significantly two years after impoundment (1981) and then remained not significantly different from pre-impoundment values from 1982 to 1996, thus during and after peak mercury levels (from 1984 to 1992), with the exception of the 1983 value, which was significantly lower than pre-impoundment. In **Caniapiscau reservoir**, after a significant decrease in the % of small lake whitefish 5 years after flooding (1987), values significantly higher than pre-impoundment were obtained from 1991 until 1999, thus during and after peak mercury levels (1991).

After-impoundment, **longnose sucker** recruitment patterns were less variable than for lake whitefish in the 3 monitored reservoirs (table 4). After an initial significant decrease during the filling of **Robert-Bourassa reservoir** (1979), the % of small longnose sucker remained not significantly different from pre-impoundment values from 1980 to 1996, thus during and after peak mercury levels (1984 to 1987). The same pattern was observed in **Caniapiscau reservoir** where, after an initial significant decrease during filling (1982), the % of small longnose sucker remained not significantly different from pre-impoundment values from 1987 to 1999, thus during and after peak mercury levels (1989 to 1993). In **Opinaca reservoir**, the % of small longnose sucker always remained not significantly different from pre-impoundment values, thus, before and after peak mercury levels which occurred in 1984 and 1986 (table 4).

Although small **northern pike** were seldom caught in the reference lakes during the fish population monitoring period (table 5), sufficient specimens were caught in the

reservoirs to show that recruitment was apparently not affected by mercury. In **Robert-Bourassa reservoir**, a significant increase in the % of small northern pike was observed after filling, from 1980 to 1982, followed by a significant decrease in 1984, after which values remained not significantly different from pre-impoundment values (from 1988 to the last year of monitoring in 1996), thus during and after peak mercury levels occurring from 1988 to 1992). The same pattern was observed in **Opinaca reservoir** where, a significant increase in the % of small northern pike was observed after filling (in 1981 and 1982), followed by a significant decrease in 1984, after which values remained not significantly different from pre-impoundment values (from 1988 to the last year of monitoring in 1996), thus during and after peak mercury levels occurring from 1990 to 1994). In the **Caniapiscau area**, where the near absence of aquatic vegetation does not constitute a preferred habitat for the northern pike, no small specimens were caught in pre-impoundment conditions (at 5 sampling stations) nor in the reference lake (table 5). Some small specimens were however caught in Caniapiscau reservoir in 1982, 1987, 1995 and 1999, representing a significant increase compared to pre-impoundment, before, during, and after peak mercury levels which occurred from 1991 to 1995.

For **walleye of Robert-Bourassa reservoir**, the % of small specimens decreased significantly for a number of years following impoundment (from 1980 to 1988), after which values not significantly different from pre-impoundment were obtained the last two sampling years (1992 and 1996), thus during and after peak mercury levels occurring from 1988 to 1992 (Table 6). After an initial significant decrease during filling of **Opinaca reservoir** (1980), the % of small walleye remained not significantly different from pre-impoundment values from 1981 to 1992, corresponding to before and during peak mercury levels (occurring from 1984 to 1992). A significant increase in the % of small walleye was observed for the last year of monitoring (1996), shortly after peak mercury levels.

In **Caniapiscau reservoir**, significantly lower proportions of small **lake trout** were obtained 9 years after impoundment, from 1991 to 1999, corresponding to the period of peak mercury levels occurring from 1989 to 1999 (Table 7).

In summary, with the exception of lake trout in the Caniapiscau reservoir and lake whitefish of the Robert-Bourassa reservoir, significant increases in the % of small specimens or values not significantly different from pre-impoundment conditions were obtained during and after peak mercury levels for the fish species and reservoirs monitored. These data do not indicate a systematic effect of mercury on fish recruitment at the population level.

791

792 Discussion

It has been shown that the post-impoundment increase in mercury levels is due to bacterial decomposition of flooded organic matter, such as humus, mosses, grasses and leaves

of shrubs and trees (Kelly et al., 1997; Hall et al., 2005). This bacterial activity transforms the inorganic mercury contained in this organic matter into methylmercury, a form that is highly assimilated by aquatic organisms (Bodaly et al. 1984, 2007; Lucotte et al. 1999). Methylmercury production is biomagnified through the food chain and reaches maximum concentrations in piscivorous fish (Lucotte et al. 1999). The increase is temporary, however, as readily decomposable organic matter is rapidly depleted (Lucotte et al. 1999; St-Louis et al., 2004). Such a decrease has also been observed in other reservoirs in Canada or the Amazon watershed (Anderson et al. 1995; Malm 2006).

808

809 Fish density

Despite these periods of increase in fish mercury levels, increases in lake whitefish, longnose sucker and northern pike fishing yields (tables 3 to 5), as well as increases in yields of the fish community as a whole (all species caught combined; Deslandes et al. 1995), have been observed in the three La Grande complex reservoirs. This increase in fishing yields has also been observed in more than 100 reservoirs, as stated in the review of Randall et al. (1995), and is associated with the biological boom that usually occurs after the flooding of organic matter. Indeed, the increases in both mercury levels and fishing yields were related to reservoir impoundment, as they were not observed in the reference lakes. The same decomposition of flooded organic material that causes increased mercury levels also releases nutrients into the water column; this stimulates phytoplankton production, which in turn stimulates zooplankton production, with positive effects as far up as fish populations (Schetagne 1994). Lake whitefish CPUEs in Robert-Bourassa and Opinaca reservoirs were positively correlated with total phosphorus and chlorophyll *a* concentrations, as well as with zooplankton biomass (Deslandes et al. 1994). At the same time, benthic invertebrate production, which is also strongly stimulated by the great amount of available flooded organic matter, further enhances the biological boom typical of reservoir impoundment.

Significant decreases in fishing yields of lake whitefish in the Caniapiscau reservoir and of walleye in the Robert-Bourassa and Opinaca reservoirs were observed for the first few years following impoundment, and the significant increases in yields of lake whitefish, of northern pike, and of the fish population as a whole in all 3 reservoirs were usually observed only 3 or 4 years after impoundment. This delay may be explained simply by the dilution of initial fish populations by the impoundments, as aquatic area increased by factors ranging from 3.5 to 12 (Table 1). The initial water volume of these reservoirs was roughly estimated to vary from less than 1% (Robert-Bourassa reservoir) to about 10% (Opinaca) of the after-impoundment water volume. Since CPUE reflects fish density, the increased aquatic area (and water volume) must be taken into account to properly assess the increase in reservoirs' total fish abundance. For the La Grande complex reservoirs, fish abundance must have increased greatly, and rapidly, to cause higher CPUEs,

despite such marked increases in aquatic area and volume. Indeed, increases in CPUE were usually observed as early as 3 years after flooding, and our age data show that very few fish younger than 2 or 3 years old are caught by the gill nets used.

It has been well documented that the biological boom gradually tapers off, as does the increase in mercury, because readily decomposable organic matter is rapidly depleted. Water quality changes resulting from the leaching and decomposition of flooded organic matter, such as dissolved oxygen depletion, increased phosphorus and increased chlorophyll *a* (a surrogate for phytoplankton biomass), peaked 2 to 3 years after impoundment and were virtually over after 9 to 10 years in Robert-Bourassa and Opinaca reservoirs (Schetagne 1994; Lucotte et al. 1999). In Caniapiscau reservoir, impounded over a longer period and located in a colder region, these changes peaked after 2 to 10 years and were over after 10 to 14 years (Lucotte et al. 1999).

After the initial increase in longnose sucker density in Robert-Bourassa reservoir, the subsequent decrease occurred more rapidly and led, for a number of years, to fishing yields below initial values or surrounding natural lake values. In this particular case, this species may have been subject to over-predation by walleye and northern pike, as well as to competition for benthic food by lake whitefish, three species that remained in higher relative abundance 17 years after impoundment (Deslandes and Fortin 1994).

For walleye in Robert-Bourassa and Opinaca reservoirs, although post-impoundment CPUEs increased markedly after the initial decrease caused by dilution, they did not surpass pre-impoundment CPUEs. This may have involved a redistribution of the walleye in the former beds of lakes and rivers outside the submerged-tree zone, as suggested by the results of a complementary study (Plante 1982). The results of another complementary study done in 1996 (Doyon and Belzile, 1998) showed that the use of littoral sampling stations may have led to an underestimation of relative abundance for walleye after impoundment, as this species is more pelagic. The choice of littoral stations for the monitoring was guided by benthic and fish production, which is concentrated in relatively shallow habitats in these oligotrophic northern environments (Dumont 1977; Johnson 1975).

The initial decrease in lake trout fishing yield in Caniapiscau reservoir can be related to poor recruitment, which is linked to a form of homing toward initial spawning grounds, making the after-impoundment location of new spawning sites difficult for this species (Horrall 1981; Foster 1985; Gendron and Belanger 1993). It may also be related to severe winter drawdown, which may reach 13 m in this reservoir (Deslandes et al. 1994; Doyon et al. 1998). There are many examples of drawdown that have led to a drastic reduction in egg survival (Rawson 1945; Martin 1955; DeRoche 1969; Lacasse and Gilbert 1992) or to the elimination of a lake trout population in reservoirs. One example is the 10-m drawdown that has led to the elimination of a lake trout population from Bark Lake

(Wilton 1985). A number of years after impoundment, this species may have found alternative spawning grounds in tributaries (Lemieux and Doyon 1998). This would explain why lake trout CPUE increased to 1.7 in 1999 (Table 7), while mercury levels remained at maximum values for 9 years (not significantly different mercury concentrations from 1991 to 1999). Reproduction of lake trout in this reservoir is clearly not related to mercury levels, as initial decreasing density is associated with low initial mercury levels, while subsequent increasing density is associated with maximum mercury levels. Such high mercury levels did not prevent lake trout density from increasing again after its initial decrease.

Fish growth

The data presented in Fig. 4 to 6 clearly show that in connection with reservoir impoundment, where increased nutrients produce increased biological production, threefold to sevenfold increases in mercury levels did not impair growth rates. The significant increases in growth found at young ages for almost all the species in all reservoirs is an indication that it occurred in fish born during or shortly after impoundment, as a consequence of the biological boom mentioned earlier. This phenomenon has been often seen after impoundment for piscivorous species like northern pike and walleye (Machniak 1975 a, b). The increase in prey densities is directly linked to this predator growth increase. This situation is generally temporary (Nelson 1974). For fish in the three monitored reservoirs, growth rate patterns show no relationship to mercury levels, as growth rates in all species, during and after peak mercury levels, remained comparable to or higher than those obtained before impoundment, as well as in reference lakes. Indeed, growth rates were still high 17 to 21 years after reservoir impoundment, depending on species and reservoir.

Fish condition

After the impoundment of the three monitored reservoirs, the increase in mercury levels did not prevent fish condition factors (K factor) from increasing compared to pre-impoundment or reference lake values. These increases closely followed the pattern of change in chlorophyll *a*, an indicator of the post-impoundment nutrient and phytoplankton biomass increases resulting from the decomposition of readily decomposable flooded organic matter (Lucotte et al. 1999). For the piscivorous northern pike and walleye in Robert-Bourassa and Opinaca reservoirs, peak mercury levels are observed well after peak condition factors. It has been clearly shown that, in reservoirs, mercury levels in predators peak after those in non-piscivorous species, as the mercury must first accumulate in the prey in order to be later observed in the predator (Lucotte et al. 1999; Bodaly et al. 2007). Nevertheless, condition factors remained higher than or equal to pre-impoundment or reference lake condition values.

970 *Fish recruitment*

971 The proportion of small specimens of the main species
972 in the three reservoirs, an indicator of recruitment, does not
973 show a relationship with mercury levels, as its values, for
974 most species and in most reservoirs, increased or remained
975 not significantly different from pre-impoundment values up
976 to 16 to 17 years after impoundment, thus during and after
977 peak mercury levels. The only major exception in
978 recruitment was observed for lake trout in Caniapiscou
979 reservoir, where the proportion of small specimens
980 decreased continuously after impoundment. However, this
981 pattern appears not to be linked to mercury levels, but rather
982 to severe water level fluctuations and the scarcity of
983 adequate spawning grounds (Gendron and Bélanger 1991).

984 Deslandes et al. (1995) have shown that increased
985 recruitment in the first years following impoundment
986 explains part of the rise in CPUE values for several species
987 in the La Grande complex reservoirs. For instance, year
988 class strength for lake whitefish, longnose sucker and
989 northern pike, increased noticeably in the Robert-Bourassa
990 reservoir (formerly named La Grande 2), while it increased
991 as well for lake whitefish, northern pike and walleye in the
992 Opinaca reservoir. This increased recruitment explains the
993 rise in the percentage of small specimens after
994 impoundment.

995

996 *Overall fish population health indices*

997 These results do not show mercury-related ill effects on
998 fish recruitment, fishing yields, fish growth rates and fish
999 condition factors at the population level, in connection with
1000 northern reservoir impoundments, despite temporary three
1001 to sevenfold increases in fish mercury levels compared to
1002 those of surrounding natural lakes. Although it could be
1003 argued that the observed fish condition or fishing yield data
1004 were not as high as they might have been with no mercury
1005 increase, there are no available data to confirm or infirm this
1006 hypothesis. It clearly remains that three to sevenfold
1007 increases in fish mercury levels did not prevent significant
1008 post-impoundment increases in fish population good-health
1009 indices, such as recruitment, condition factor, growth rate
1010 and fishing yield.

1011 These results thus do not support the conclusions of a
1012 number of authors cited in our introduction who have
1013 observed negative effects on fish growth, condition or
1014 reproduction at mercury concentrations representative of
1015 natural pristine environments. Our results do not indicate
1016 mercury-related ill effects at concentrations 3 to 7 times
1017 higher than those found in pristine northern water bodies.

1018 As stated by Friedmann et al. (1996 b) and Wiener and
1019 Spry (1996), mercury concentrations used in the laboratory
1020 are often not environmentally relevant and may be tenfold
1021 higher than in nature. This may lead to an overestimation of
1022 the toxicity of mercury in natural environments. By not
1023 showing effects on the same endpoints as assessed in
1024 laboratory experiments, such as fish condition and growth
1025 rates, our results tend to support the Harris et al. (2003)
1026 hypothesis that the toxicity of methylmercury is

1027 overestimated in laboratory studies that usually use
1028 methylmercury chloride as a model compound for
1029 methylmercury in fish, which is bound to cysteine and may
1030 be less active or toxic.

1031 In new reservoirs, the increase in nutrients and primary
1032 and secondary production related to the flooding of
1033 terrestrial soils and vegetation, which is also responsible for
1034 the mercury increase in fish, leads to a biological boom
1035 which has positive effects on fish populations. This
1036 biological boom may have prevented potential mercury-
1037 related ill effects.

1038

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1044

1045 **REFERENCES**

1046

1047 ADAMS, S.M., BEVELHIMER, M.S., GREELEY, M.S.,
1048 LEVINE, D.A., AND THE, S.J. 1999. Ecological risk
1049 assessment in a large river-reservoir: 6. Bioindicators
1050 of fish population health. *Environ. Toxicol. Chem.*
1051 18:628–640.

1052

1053 ANDERSON, M. R., SCRUTON, D. A., WILLIAMS, U.
1054 P., AND CURTIS, L. R. 1995. Mercury in fish in the
1055 Smallwood reservoir, Labrador, 21 years after
1056 impoundment. *Water, Air, and Soil Pollution* 80: 927-
1057 930.

1058

1059 ANDERSON, R. O., AND NEUMANN, R. M. 1996.
1060 Length, weight, and associated structural indices. In
1061 Fisheries Techniques, 2nd edition, ed. B. R. Murphy
1062 and D. W. Willis: 447-482. Bethesda, Maryland:
1063 American Fisheries Society.

1064

1065 BATCHELAR, K.L., KIDD, K.A., DREVNICK, P.E.,
1066 MUNKITTRICK, K.R., BURGESS, N.M.,
1067 ROBERTS, A.P., AND SMITH, J.D. 2012. Evidence
1068 of impaired health in yellow perch (*Perca flavescens*)
1069 from a biological mercury hotspot in northeastern
1070 North America. *Environmental Toxicology and*
1071 *Chemistry*, Vol. 32, No. 3: 627-637.

1072

1073 BATCHELAR, K.L., KIDD, K.A., MUNKITTRICK, K.R.,
1074 DREVNICK P.E., AND BURGESS, N.M. 2013.
1075 Reproductive health of yellow perch (*Perca*
1076 *flavescens*) from a biological mercury hotspot in Nova
1077 Scotia, Canada. *Science of the Total Environment*.
1078 319-327.

1079

1080 BEAMISH, R.J. 1973. Determination of age and growth of
1081 populations of the white sucker (*Catostomus*
1082 *commersoni*) exhibiting a wide range in size at
1083 maturity. *J. Fish. Res. Board Can.*, 30(5):607-616.

- 1084 BIRGE, W.J., BLACK, J.A., WESTERMAN, A.G., AND
1085 HUDSON, J.E. 1979. The effects of mercury on
1086 reproduction of fish and amphibians. In Nriagu, J. ed.
1087 The Biogeochemistry of Mercury in the Environment.
1088 Amsterdam: Elsevier/North Holland 1979:629–655.
1089
- 1090 BLOOM, N. S. 1992. On the chemical form of mercury in
1091 edible fish and marine invertebrate tissue. *Can. J.*
1092 *Fish. Aquat. Sci.* 49:1010-1017.
1093
- 1094 BODALY, R. A., AND FUDGE, R. J. P. 1999. Uptake of
1095 mercury by fish in an experimental boreal reservoir.
1096 *Arch. Environ. Contam. Toxicol.* 37:103-109.
1097
- 1098 BODALY, R.A., HECKY, R.E., AND FUDGE, R.J.P.
1099 1984. Increase in fish mercury levels in lakes flooded
1100 by the Churchill River diversion, northern Manitoba.
1101 *Canadian Journal of Fisheries and Aquatic Sciences*
1102 41:682-691.
1103
- 1104 BODALY, R. A., BEATY, K. G. HENDZEL, L. H.
1105 MAJEWSKI, A. R. PATERSON, M. J. ROLFUS, K.
1106 R. PENN, A. F. ST. LOUIS, V. L. HALL, B. D.
1107 MATTHEWS, C. J. D. CHEREWYK, K. A.
1108 MAILMAN, M. HURLEY, J. P. SCHIFF, S. L., AND
1109 VENKITESWARAN, J. J. 2004. Experimenting with
1110 hydroelectric reservoirs. *Environ. Sci. Technol.*
1111 38:346A-352A.
1112
- 1113 BODALY, R. A., JANSEN, W. A. MAJEWSKI, A. R.
1114 FUDGE, R. J. P. STRANGE, N. E. DERKSEN, A. J.,
1115 AND GREEN, D. J. 2007. Postimpoundment time
1116 course of increased mercury concentrations in fish in
1117 hydroelectric reservoirs of northern Manitoba, Canada.
1118 *Arch. Environ. Contam. Toxicol.* 53:379-389.
1119
- 1120 CASSELMAN, J.M. 1979. "The esocid cleithrum as an
1121 indicator calcified structure." *Compte rendu du 10^e*
1122 *atelier sur les poissons d'eau chaude/Proceedings of*
1123 *the 10th warm water workshop, American Fisheries*
1124 *Society, Northeast Division.* Ministère du Loisir, de la
1125 Chasse et de la Pêche du Québec. Direction de la
1126 recherche faunique, Montréal, p. 249-272.
1127
- 1128 CRUMP, K. L., AND TRUDEAU, V. L. 2009. Mercury-
1129 induced reproductive impairment in fish.
1130 *Environmental Toxicology and Chemistry* 28(5):895-
1131 907.
1132
- 1133 DEPEW, D., BASU, N., BURGESS, N., CAMPBELL, L.,
1134 DELVIN, E., DREVNICK, P., HAMMERSCHMIDT,
1135 C., MURPHY, C., SANDHEINRICH, M., AND
1136 WIENER, J. 2012. Toxicity of dietary methylmercury
1137 to fish: derivation of ecologically meaningful
1138 threshold concentrations. *Environmental Toxicology*
1139 *and Chemistry* 31,7:1536-1547.
1140
- 1141 DeROCHE, S. E. 1969. Observations of the spawning habits
1142 and early life of Lake Trout. *Prog. Fish-Cult.* 3 :109-
1143 113.
1144
- 1145 DESLANDES, J.-C., AND FORTIN, R. 1994. Optimisation
1146 du réseau de suivi environnemental des populations de
1147 poissons des milieux affectés par l'aménagement du
1148 complexe La Grande (Phase I). Département des
1149 sciences biologiques, Université du Québec à
1150 Montréal for vice-Présidence Environnement Hydro-
1151 Québec. 95 p.
1152 DESLANDES, J.-C., GUÉNETTE, S., AND FORTIN, R.
1153 1994. Évolution des communautés de poissons de
1154 milieux affectés par l'aménagement du complexe
1155 La Grande, Phase 1 (1977-1992). Département des
1156 sciences biologiques, Université du Québec à
1157 Montréal for Hydro-Québec. 89 p.
1158
- 1159 DESLANDES, J.-C., GUÉNETTE, S., PRAIRIE, Y., ROY,
1160 D., VERDON, R. AND FORTIN, R. 1995. Changes in
1161 fish populations affected by the construction of the La
1162 Grande complex (Phase I), James Bay region, Quebec.
1163 *Can. J. Zool.* 73: 1860- 1877.
1164
- 1165 DOYON, J.-F., AND BELZILE, L. 1998. Réseau de suivi
1166 environnemental du complexe La Grande (1977-
1167 1996). Suivi des communautés de poissons et étude
1168 spéciale sur le doré (secteur ouest du territoire).
1169 Groupe conseil GENIVAR inc. for Hydro-Québec.
1170 145 p. and appendices.
1171
- 1172 DOYON, J.-F., BERNATCHEZ, L., GENDRON, M.,
1173 VERDON, R., AND FORTIN, R. 1998. Comparison
1174 of normal and dwarf populations of lake whitefish
1175 (*Coregonus clupeaformis*) with reference to
1176 hydroelectric reservoirs in northern Québec. *Archiv*
1177 *für Hydrobiologie – Advances in Limnology* 50:97-
1178 108.
1179
- 1180 DREVNICK, P. E., AND SANDHEINRICH, M. B. 2003.
1181 Effects of dietary methylmercury on reproductive
1182 endocrinology of fathead minnows. *Environ. Sci.*
1183 *Technol.* 37:4390-4396.
1184 DREVNICK, P.E., CANFIELD, D.E., GORSKI, P.R.,
1185 SHINNEMAN, A.L.C., ENGSTROM, D.R., MUIR,
1186 D.C.G., SMITH, G.R., GARRISON, P.J.,
1187 CLECKNER, L.B., HURLEY, J.P., NOBLE, R.B.,
1188 OTTER, R.R., AND ORIS, J.T., 2007. Deposition and
1189 cycling of sulfur controls mercury accumulation in Isle
1190 Royale fish. *Environ. Sci. Technol.* 41:7266-7272.
1191
- 1192 DREVNICK, P.E., ROBERTS, A.P., OTTER, R.R.,
1193 HAMMERSCHMIDT, C.R., KLAPER, R., AND
1194 ORIS, J.T. 2008. Mercury toxicity in livers of northern
1195 pike (*Esox lucius*) from Isle Royale, USA. *Comp.*
1196 *Biochem. Physiol. Part C* 147:331-338.
1197

- 1198 DUBOIS, A., AND LAGUEUX, R. 1978. Étude comparée
1199 de l'âge scalaire et de l'âge otolithique du touladi
1200 (*Salvelinus namaycush*). Lac Mistassini, Québec.
1201 *Natur. Can.* 95:907-928.
1202
- 1203 DUMONT, P. 1977. Quelques aspects du cycle vital du
1204 grand corégone, *Coregonus clupeaformis* (Mitchill) de
1205 quatre lacs du territoire de la Baie James: les lacs
1206 Hélène, Nathalie, Yasinski et Alder. Masters thesis,
1207 Université du Québec à Montréal.
1208
- 1209 ENVIRONMENT CANADA. 1979. Analytical methods
1210 manual. Inland Waters Directorate, Ottawa.
1211
- 1212 FOSTER, N.R. 1985. Lake Trout Reproductive Behavior:
1213 Influence of Chemosensor Cues from Young-of-the-
1214 Year By-Products. *Trans. Am. Fish. Soc.* 114:794-
1215 803.
1216
- 1217 FRIEDMANN, A.S., WATZIN, M.C., LEITER, J.C., AND
1218 BRINCK-JOHNSON, T. 1996a. Effects of
1219 environmental mercury on gonadal function in Lake
1220 Champlain northern pike (*Esox lucius*). *Bull Environ*
1221 *Contam Toxicol* 56:486-492.
1222
- 1223 FRIEDMANN A.S., WATZIN, M.C., BRINCK-JOHNSON,
1224 T., AND LEITER, L.C. 1996b. Low levels of
1225 methylmercury inhibit growth and gonadal
1226 development in juvenile walleye (*Stizostedion*
1227 *vitreum*). *Aquat. Toxicol.* 35:265-278.
1228
- 1229 FRIEDMANN, A.S., COSTAIN, E. K. MACLATCHY, D.
1230 L. STANLEY, W., AND WASHUTA, E. J. 2002.
1231 Effect of mercury on general and reproductive health
1232 of largemouth bass (*Micropterus salmoides*) from
1233 three lakes in New Jersey. *Ecotoxicol. Environ. Safety*
1234 52:117-122.
1235
- 1236 GENDRON, M., AND BÉLANGER, B. 1991. Étude de
1237 l'effet du marnage sur la faune ichthyenne des
1238 réservoirs Pimpuacan, Outardes-4 et Manic-5, travaux
1239 de recherche autonome 1990. Le Groupe de Recherche
1240 SÉEEQ ltée, for Service ressources et aménagement
1241 du territoire, Vice-présidence Environnement, Hydro-
1242 Québec. 108 p.
1243
- 1243 GENDRON, M., AND BÉLANGER, B. 1993. Étude de
1244 l'état des populations de touladi dans les réservoirs. Le
1245 Groupe de Recherche SÉEEQ ltée, for Service
1246 ressources et aménagement du territoire, Vice-
1247 présidence Environnement, Hydro-Québec. 57 p.
1248
- 1249 HALL, B.D., BODALY, R.A., FUDGE, R.J.P., RUDD,
1250 J.W.M., AND ROSENBERG, D.M. 1997. Food as the
1251 dominant pathway of methylmercury uptake by fish.
1252 *Water Air Soil Pollut.* 100:13-24.
1253
- 1254 HALL, B.D., ST. LOUIS, V.L., ROLFHUS, K.R.,
1255 BODALY, R.A., BEATY, K.G. AND PATERSON,
1256 M.J. 2005. The impact of reservoir creation on the
1257 biogeochemical cycling methyl and total mercury in
1258 boreal upland forests. *Ecosystems* 8:248-266.
1259
- 1260 HAMMERSCHMIDT, C. R., SANDHEINRICH, M. B.
1261 WIENER, J. G., AND RADA, R. G. 2002. Effects of
1262 dietary methylmercury on reproduction of fathead
1263 minnows. *Environ. Sci. Technol.* 36:877-883.
1264
- 1265 HARRIS, H.H., PICKERING, I.J. AND GEORGE, G.N.
1266 2003. The chemical form of mercury in fish. *Science*.
1267 29: 1203
1268
- 1269 HORRALL, R.M. 1981. Behavioral Stock-Isolating
1270 Mechanisms in Great Lakes Fishes with Special
1271 Reference to Homing and Site Imprinting. *Can. J.*
1272 *Fish. Aquat. Sci.* 38: 1481 - 1496.
1273
- 1274 HOUCK, A. AND CECHE, J. J. 2004. Effects of dietary
1275 methylmercury on juvenile Sacramento blackfish
1276 bioenergetics, *Aquat Toxicol*, 69: 107-123.
1277
- 1278 JOHNSON, L. 1975. Distribution of fish species in Great
1279 Bear Lake, Northwest Territories, with reference to
1280 zooplankton, benthic invertebrates, and environmental
1281 conditions. *J. Fish. Res. Board Can.* 32: 1989-2004.
1282
- 1283 KELLY, C.A., RUDD, J.W.M., BODALY, R.A., ROULET,
1284 N.P., ST LOUIS, V.L., HEYES, A., MOORE, T.R.,
1285 SCHIFF, S., ARAVENA, R., SCOTT, K.J., DYCK,
1286 B., HARRIS, R., WARNER, B., AND EDWARDS,
1287 G. 1997. Increases in fluxes of greenhouse gases and
1288 methylmercury following flooding of an experimental
1289 reservoir. *Environ. Sci. Technol.* 31:1334-1344.
1290
- 1291 LACASSE, S. AND GILBERT, L. 1992. Évaluation de
1292 l'impact du marnage sur la reproduction du Touladi au
1293 lac Mondonac. G.D.G. Environnement ltée, Hydro-
1294 Québec. 82 p. et annexes.
1295
- 1296 LAROSE, C., CANUEL, R., LUCOTTE, M., AND DI
1297 GIULIO, R.T. 2008. Toxicological effects of
1298 methylmercury on walleye (*Sander vitreus*) and perch
1299 (*Perca flavescens*) from lakes of the boreal forest.
1300 *Comp. Biochem. Physiol. Part C* 147:139-149.
1301
- 1302 LASORSA, B., AND ALLEN-GIL, S. 1995. The
1303 methylmercury to total mercury ratio in selected
1304 marine, freshwater and terrestrial organisms. *Water,*
1305 *Air and Soil Pollution* 80:905-913.
1306
- 1307 LATIF, M.A., BODALY, R.A., JOHNSON, T.A., AND
1308 FUDGE, R.J.P. 2001. Effects of environmentally and
1309 maternally derived methylmercury on the embryonic
1310 and larval stages of walleye (*Stizostedion vitreum*).
1311 *Environ Poll.* 111:139-148.

- 1312
1313 LEMIEUX, C., AND DOYON, J.F. 1998. Suivi des
1314 tributaires aménagés du réservoir Caniapiscau (1997).
1315 Report by Groupe conseil GENIVAR inc for
1316 Hydro-Québec, 63 p. and appendices.
1317
1318 LINDQVIST, O. 1991. Mercury in the Swedish
1319 environment; recent research on causes, consequences
1320 and corrective methods. Water, Air and Soil Pollution
1321 55:1-262.
1322 LUCOTTE, M., SCHETAGNE, R., THÉRIEN, N.,
1323 LANGLOIS, C., AND TREMBLAY, A. 1999.
1324 Mercury in the Biogeochemical Cycle: Natural
1325 Environments and Hydroelectric reservoirs of
1326 Northern Québec. Berlin: Springer. 334 p.
1327
1328 MACHNIAK, K. 1975a. The effects of hydroelectric
1329 developments on the biology of northern fishes
1330 (reproduction and population dynamics) II. Northern
1331 pike *Esox lucius* (Linnaeus). A literature review and
1332 bibliography. Fish. Mar. Serv. Res. Div. Tech. Rep.
1333 No 528.
1334
1335 MACHNIAK, K. 1975b. The effects of hydroelectric
1336 developments on the biology of northern fishes
1337 (reproduction and population dynamics) III. Yellow
1338 walleye *Stizostedion vitreum vitreum* (Mitchill). A
1339 literature review and bibliography. Fish. Mar. Serv.
1340 Res. Div. Tech. Rep. No 529.
1341
1342 MALM, O. 2006. Mercury in different Amazon reservoirs,
1343 Brazil. In: Proceedings of the Eighth International
1344 Conference on Mercury as a Global Pollutant.
1345 DEStech Publications inc., Madison. WI.
1346
1347 MARTIN, N. V. 1955. The effect of drawdowns on Lake
1348 Trout reproduction and the use of artificial spawning
1349 beds. Twen. Nor. Amer. Wild. Conf., p. 263-271
1350
1351 MASSÉ, G. 1979. Identification des vrais et des faux annuli
1352 sur les écailles du Grand Brochet (*Esox lucius* L.) et sa
1353 croissance dans le fleuve Saint-Laurent, près de
1354 Montréal, Québec. Masters thesis, Université du
1355 Québec à Montréal. 186 p.
1356
1357 MELA, M., RAND, M.A.F., VENTURA, D.F.,
1358 CARVALHO, C.E.V., PELLETIER, E., AND
1359 OIVEIRA RIBEIRO, C.A. 2007. Effects of dietary
1360 methylmercury on liver and kidney histology in the
1361 neotropical fish *Hoplia malabaricus*. Ecotoxicol.
1362 Environ. Safety 6:426-435.
1363
1364 MORIN, R., DODSON, J.J., AND POWER, G. 1982. Life
1365 history variations of anadromous cisco (*Coregonus*
1366 *artedii*), lake whitefish (*C. clupeaformis*), and round
1367 whitefish (*Prosopium cylindraceum*) populations of
1368 eastern James-Hudson Bay. Can. J. Fish. Aquat. Sci.
1369 39: 958-967.
1370
1371 MUNN, M.D., AND SHORT, T.M. 1997. Spatial
1372 heterogeneity of mercury bioaccumulation by walleye
1373 in Franklin D. Roosevelt Lake and the upper Columbia
1374 River, Washington. Trans. Am. Fish. Soc. 126:477-
1375 487.
1376
1377 NELSON, W.R. 1974. Age, growth and maturity of thirteen
1378 species of fish from lake Oahe during the early years
1379 of impoundment, 1963-1968. U. S. Fish. Wild. Serv.
1380 Tech. Pap. No. 77.
1381
1382 PÉPIN, S., AND LÉVESQUE, F. 1985. Technique de
1383 détermination de l'âge des dorés applicable aux
1384 populations de cette espèce au Québec. Ministère du
1385 Loisir, de la Chasse et de la Pêche, Québec. 33 p.
1386 PLANTE, M. 1982. Résultats des activités spéciales de
1387 pêche de la saison 1981 du Réseau de surveillance
1388 écologique. Direction Environnement, Société
1389 d'énergie de la Baie James. 22 p.
1390
1391 POWER, G. 1978. Fish population structure in arctic lakes.
1392 Journal of the Fisheries Research Board of Canada
1393 35:53-39.
1394
1395 RANDALL, R.G., KELSO, J.R.M., AND MINNS, C.K.
1396 1995. Fish production in freshwaters: Are rivers more
1397 productive than lakes? Canadian Journal of Fisheries
1398 and Aquatic Sciences 52:631- 643.
1399
1400 RAWSON, D. W. 1945, Further investigation of the effect
1401 of power development on the fisheries of lake
1402 Minnewanka, Banff. Can. Dep. Mines. Resour., Nat.
1403 Parks Bur. Ms. Rep.
1404
1405 RICKER, W.E. 1980. Computation and interpretation of
1406 biological statistics of fish populations. Fisheries
1407 Research Board of Canada Bulletin 191. 400 p.
1408
1409 RODGERS, D.W. 1994. You are what you eat and a little
1410 bit more: bioenergetics-based models of
1411 methylmercury accumulation in fish revisited. In:
1412 Watras C.J., and Huckabee, J.W., eds. Mercury
1413 pollution; integration and synthesis. Boca Raton,
1414 Florida: Lewis Publishers. p.427-439.
1415
1416 SCHERER, E., ARMSTRONG, F.A.J., AND NOWAK,
1417 S.H. 1975. Effects of mercury-contaminated diet upon
1418 walleyes, *Stizostedion vitreum vitreum* (Mitchill).
1419 Can. Fish. Mar. Serv. Res. Dev. Branch, Winnipeg,
1420 Tech. Rep. No. 597. 21 pp.
1421
1422 SCHETAGNE, R. 1994. Water quality modifications after
1423 impoundment of some large northern reservoirs.
1424 Archiv für Hydrobiologie - Advances in
1425 Limnology 40:223-229.
1426

- SCHETAGNE, R., AND VERDON, R. 1999. Post-impoundment evolution of fish mercury levels at the La Grande complex, Québec, Canada (from 1978 to 1996). In: Lucotte et al., eds. *Mercury in the Biogeochemical Cycle: Natural Environments and Hydroelectric reservoirs of Northern Québec*, Berlin: Springer. p. 235-258.
- SCHETAGNE, R., AND THERRIEN, J. 2013. Suivi environnemental du complexe La Grande. Évolution des teneurs en mercure dans les poissons. Rapport synthèse 1978-2012. GENIVAR inc. et Hydro-Québec Production. 174 p.
- SCHEUHAMMER, A.M., BASU, N., EVERS, D.C., HEINZ, G.H., SANDHEINRICH, M., AND BANK, M.S. 2012. Toxicology of mercury in fish and wildlife: recent advances. In: Bank M.S., ed. *Mercury in the Environment: Pattern and Process*. Berkeley: University of California Press.
- SCHEUHAMMER, A., BRAUNE, B., CHAN, H.M., FROUIN, H., KREY, A., LETCHER, R., LOSETO, L., NOËL, M., OSTERTAG, S., ROSS, P., AND WAYLAND, M. 2014. Recent progress on our understanding of the biological effects of mercury in fish and wildlife in the Canadian Arctic. *Sci. Total Environ.*
- SCOTT, G.R., AND SLOMAN, K.A. 2004. The effects of environmental pollutants on complex fish behavior: integrating behavioural and physiological indicators of toxicity. *Aquatic Toxicology*, 68(4): 369-392.
- SPRY, D.J., AND WIENER, J.G. 1991. Metal bioavailability and toxicity to fish in low-alkalinity lakes—A critical review. *Environ Pollut.* 71:243–304.
- ST. LOUIS, V.L., RUDD, J.W.M., KELLY, C.A., BODALY, R.A., PATERSON, M.J., BEATY, K.G., HESSLEIN, R.H., HEYES, A.W. AND MAJEWSKI, A.R. 2004. The rise and fall of mercury methylation in an experimental reservoir. *Environ Sci Technol* 38:1348–1358
- TREMBLAY, G., LEGENDRE, P., VERDON, R., DOYON, J.-F., AND SCHETAGNE, R. 1998. Polynomial regression analysis with indicator variables for the interpretation of monitoring data on mercury levels in fish. *Biogeochemistry* 40:189-201.
- VERDON, R., AND MAGNIN, É. 1977. Croissance en longueur du meunier noir *Catostomus commersoni* (Lacépède) du lac Croche dans les Laurentides, Québec. *Nat. Can.* 104:187-195.
- WATRAS, C.J., BLOOM, N.S., HUDSON, R.J.M., GHERINI, S., MUNSON, R., CLAAS, S.A., MORRISON, K.A., WIENER, J.G., FITZGERALD, W.F., MASON, R., VANDAL, G., POWELL, D., RADA, R., RISLOV, L., WINFREY, M., ELDER, J., KRABBEMHOFT, D., ANDREN, A.W., BABIARZ, C., PORCELLA, D.B., AND HUCKABEE, J.W. 1994. Sources and fates of mercury and methylmercury in Wisconsin lakes. In Watras, C.J., and Huckabee, J.W., eds. *Mercury Pollution Integration and Synthesis*. Boca Raton, Florida: Lewis Publishers, p. 153-177.
- WEIS, J.S. 2009. Reproductive, developmental, and neurobehavioral effects of methylmercury in fishes. *Journal of Environmental Science & Health, Part C – Environmental Carcinogenesis & Ecotoxicology Reviews* 27(4):212-225.
- WEIS, J.S., BERGEY, L., REICHMUTH, J., AND CANDELMO, A. 2011. Living in a contaminated estuary: Behavioral changes and ecological consequences for five species. *BioScience* 61:375-385.
- WEIS, J.S. AND CANDELMO, A. 2012. Pollutants and fish predator/prey behavior: A review of laboratory and field approaches. *Current Zoology* 58 (1): 9–20.
- WIENER, J.G., AND SPRY, D.J. 1996. Toxicological significance of mercury in freshwater fish. In W.N. Beyer, G.H. Heinz, and A.W. Redmon-Norwood, eds. *Environmental contaminants in wildlife: Interpreting tissue concentrations*, 297-339. Boca Raton, Florida: CRC Press.
- WIENER, J.G., KRABBENHOFT, D.P. HEINZ, G.H., AND SCHEUHAMMER, A.M. 2003. Ecotoxicology of mercury. In D.J. Hoffman, B.A. Rattner, G.A. Burton, Jr., and J. Cairns, Jr., eds. *Handbook of ecotoxicology*, 2nd edition, 409-463. Boca Raton, Florida: CRC Press.
- WIENER, J.G., KNIGHTS, B.C., SANDHEINRICH, M.B., JEREMIASON, J.D., BRIGHAM, M.E., ENGSTROM, D.R., WOODRUFF, L.G., CANNON, W.F., AND BALOGH, S.J. 2006. Mercury in soils, lakes, and fish in Voyageurs National Park (Minnesota): importance of atmospheric deposition and ecosystem factors. *Environ. Sci. Technol.* 40:6261-6268.
- WILTON, M.L. 1985. Water drawdown and its effects on lake trout (*Salvelinus namaycush*) reproduction in three south-central Ontario lakes. *Fisheries Technical Report Series* 20. 9 p.

Table 1. Characteristics of La Grande complex reservoirs (Phase I) at their maximum levels.

Reservoir	Mean annual drawdown observed (m) *	Reservoir area(km ²)	Land area flooded (km ²) **	Mean depth (m)	Volume (km ³) ***	Theoretical residence time (month)	Mean annual flow (m ³ /s)	Filling period
Robert-Bourassa	3.3 (7.7)	2,835	2,630 (92%)	22.0	61.7	6.9	3,374	78-11 to 79-12
La Grande 3	5.5 (12.2)	2,420	2,175 (90%)	24.4	60.0	11.0	2,064	81-04 to 84-08
La Grande 4	8.0 (11.0)	765	700 (89%)	29.4	19.5	4.8	1,534	83-03 to 83-11
Opinaca	3.6 (4.0)	1,040	740 (71%)	8.2	8.4	3.8	845	80-04 to 80-09
Caniapiscau	2.1 (12.9)	4,275	3,430 (80%)	16.8	53.8	25.8	790	81-10 to 84-09

* Maximum drawdown in parentheses.
** Percentage of land area flooded in parentheses.
*** Values include dead storage.

Table 2. Range of mean total mercury levels for standardized length fish for major species in natural lakes of the La Grande complex area.

Species (standardized length)	Western Sector				Eastern Sector			
	Number of fish	Number of lakes	Range of average levels ($\mu\text{g. g}^{-1}$)	Global average level ($\mu\text{g. g}^{-1}$)	Number of fish	Number of lakes	Range of average levels ($\mu\text{g. g}^{-1}$)	Global average level ($\mu\text{g. g}^{-1}$)
Lake whitefish (400 mm)	503	21	0.05 - 0.20	0.11	187	8	0.10 - 0.30	0.16
Longnose sucker (400 mm)	182	7	0.12 - 0.22	0.12	246	9	0.06 - 0.20	0.13
Northern pike (700 mm)	373	18	0.30 - 0.93	0.60	120	4	0.36 - 0.92	0.59
Walleye (400 mm)	353	13	0.30 - 1.02	0.59				
Lake trout (600 mm)	131	7	0.23 - 0.89	0.57	254	10	0.52 - 1.11	0.72

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Table 3. Total mercury concentration ($\pm$ confidence interval[n]) at 400 mm, fishing yields (CPUE $\pm$ SD[n]), condition factor K (300-500 mm, $\pm$ SD[n]) and small specimen proportions (<250 mm, $\pm$ SD[n]) for lake whitefish in the major La Grande reservoirs and the reference lakes.

Year	Robert-Bourassa reservoir							
	Total mercury (Hg μ g g ⁻¹)		Density (CPUE)		Fulton's K		Small specimen (%)	
	Reservoir	Ref. lake (Rond-de-Poêle)	Reservoir	Ref. lake (Rond-de-Poêle)	Reservoir	Ref. lake (Rond-de-Poêle)	Reservoir	Ref. lake (Rond-de-Poêle)
1977-78	^g 0.11 $\pm$ 0.005[503]		1.7 $\pm$ 2.8[146]	^y 0.9 $\pm$ 1.1[32]	0.95 $\pm$ 0.11[289]		11.5 $\pm$ 7.4[536]	^y 25.0 $\pm$ 0.9[4]
1979			1.2 $\pm$ 2.0[120]	1.2 $\pm$ 1.9[24]	*1.01 $\pm$ 0.11[256]	1.02 $\pm$ 0.06[11]	*1.0 $\pm$ 0.1[286]	^y 0[11]
1980			1.7 $\pm$ 2.4[44]	^y 1.1 $\pm$ 1.4[16]	*1.10 $\pm$ 0.11[179]		12.7 $\pm$ 5.1[237]	^y 0[4]
1981			2.9 $\pm$ 4.7[72]	^y 0.1 $\pm$ 0.3[16]	*1.10 $\pm$ 0.13[444]	^y 0.96 $\pm$ 0.05[12]	*4.1 $\pm$ 0.2[560]	^y 0[11]
1982	^{ab} 0.47 $\pm$ 0.06[90]		*4.1 $\pm$ 4.5[74]	^y 0.8 $\pm$ 0.9[16]	*1.03 $\pm$ 0.12[717]		*8.9 $\pm$ 7.6[742]	^y 0[3]
1983			*5.2 $\pm$ 8.9[40]	^y 0.4 $\pm$ 0.7[8]	*1.03 $\pm$ 0.11[470]	0.99 $\pm$ 0.10[5]	*8.8 $\pm$ 6.8[582]	^y 0[8]
1984	^a 0.53 $\pm$ 0.05[82]		*5.8 $\pm$ 8.3[40]	^y 1.2 $\pm$ 2.7[16]	*1.00 $\pm$ 0.10[586]		*3.3 $\pm$ 0.2[639]	^y 0[8]
1985								
1986	^{bc} 0.43 $\pm$ 0.04[90]				*1.01 $\pm$ 0.12[129]			
1987								
1988	^{bcd} 0.38 $\pm$ 0.03[105]		*5.0 $\pm$ 9.3[40]	^y 0.2 $\pm$ 0.5[8]	0.97 $\pm$ 0.11[410]	^y 0.88 $\pm$ 0.09[14]	*1.2 $\pm$ 0.1[520]	^y 0[14]
1989								
1990	^d 0.32 $\pm$ 0.04[66]	^y 0.20 $\pm$ 0.02[12]			0.96 $\pm$ 0.10[51]	0.92 $\pm$ 0.06[19]		
1991								
1992	^{cd} 0.35 $\pm$ 0.04[59]	^y 0.20 $\pm$ 0.02[13]	3.1 $\pm$ 4.0[40]	^y 0.4 $\pm$ 0.6[12]	*0.99 $\pm$ 0.13[207]		*4.3 $\pm$ 0.2[303]	^y 0[5]
1993								
1994	^e 0.22 $\pm$ 0.03[101]	0.20 $\pm$ 0.02[27]			0.97 $\pm$ 0.10[85]	^y 0.90 $\pm$ 0.06[25]		
1995								
1996	^e 0.21 $\pm$ 0.02[93]	^y 0.15 $\pm$ 0.03[30]	3.1 $\pm$ 2.4[72]	^y 0.2 $\pm$ 0.7[8]	*0.99 $\pm$ 0.11[163]	^y 0.91 $\pm$ 0.08[13]	*4.8 $\pm$ 0.2[251]	^y 0[13]
1997								
1998	^f 0.17 $\pm$ 0.02[90]	0.20 $\pm$ 0.02[12]			*1.03 $\pm$ 0.10[96]	^y 0.94 $\pm$ 0.07[12]		
1999								
2000	^{ef} 0.18 $\pm$ 0.02[89]	0.15 $\pm$ 0.02[32]			*1.04 $\pm$ 0.11[29]			

Note: in grey, pre-impoundment years. *: Statistical ($\alpha<0.05$) difference from the pre-impoundment level.
y: Statistical ($\alpha<0.05$) difference between reservoir and natural lake values by year.
Letters attributed to mercury levels in reservoir indicate the results of year to year multiple comparisons of means where the letter a is given to the highest value and where levels with different letters are significantly different ($\alpha<0.05$).

Table 3 (cont.). Total mercury concentration ($\pm$ confidence interval[n]) at 400 mm, fishing yields (CPUE $\pm$ SD[n]), condition factor K (300-500 mm, $\pm$ SD[n]) and small specimen proportions (<250 mm, $\pm$ SD[n]) for lake whitefish in the major La Grande reservoirs and the reference lakes.

Year	Opinaca reservoir							
	Total mercury (Hg μ g g ⁻¹)		Density (CPUE)		Fulton's K		Small specimen (%)	
	Reservoir	Ref. lake (Detcheverry)	Reservoir	Ref. lake (Detcheverry)	Reservoir	Ref. lake (Detcheverry)	Reservoir	Ref. lake (Detcheverry)
1978	^c 0.11 $\pm$ 0.005[503]		2.6 $\pm$ 3.7[68]	^y 6.9 $\pm$ 7.7[16]	1.02 $\pm$ 0.12[303]	^y 0.98 $\pm$ 0.08[126]	9.1 $\pm$ 6.0[428]	11.5 $\pm$ 4.0[157]
1979			2.3 $\pm$ 3.7[68]	2.9 $\pm$ 4.0[16]	1.01 $\pm$ 0.13[212]	0.99 $\pm$ 0.07[63]	4.5 $\pm$ 0.2[267]	^y 1.1 $\pm$ 0.1[94]
1980			4.5 $\pm$ 10.7[60]	7.1 $\pm$ 6.0[16]	*1.05 $\pm$ 0.12[426]	^y 0.96 $\pm$ 0.08[137]	10.0 $\pm$ 7.3[594]	^y 5.9 $\pm$ 3.1[170]
1981	^d 0.21 $\pm$ 0.05[26]		2.9 $\pm$ 6.6[63]	^y 7.0 $\pm$ 6.2[16]	*1.09 $\pm$ 0.14[204]	^y 0.96 $\pm$ 0.07[181]	*41.4 $\pm$ 10.2[432]	^y 9.8 $\pm$ 4.4[215]
1982			3.4 $\pm$ 7.3[56]	4.8 $\pm$ 3.1[12]	*1.18 $\pm$ 0.15[220]	^y 0.97 $\pm$ 0.09[97]	7.7 $\pm$ 6.0[505]	^y 4.7 $\pm$ 0.2[127]
1983			*7.5 $\pm$ 11.7[36]	3.5 $\pm$ 3.6[8]	*1.12 $\pm$ 0.10[661]	^y 0.99 $\pm$ 0.07[80]	*2.3 $\pm$ 0.2[768]	^y 11.1 $\pm$ 3.1[99]
1984	^a 0.43 $\pm$ 0.07[30]	^y 0.11 $\pm$ 0.01[30]	*8.1 $\pm$ 12.0[32]	6.6 $\pm$ 5.8[16]	*1.11 $\pm$ 0.13[533]	^y 0.99 $\pm$ 0.07[78]	6.9 $\pm$ 6.5[648]	^y 13.6 $\pm$ 4.8[198]
1985								
1986	^a 0.46 $\pm$ 0.08[30]				0.98 $\pm$ 0.13[40]			
1987								
1988	^{ab} 0.40 $\pm$ 0.08[18]	^y 0.15 $\pm$ 0.03[22]	5.2 $\pm$ 8.5[32]	9.6 $\pm$ 15.0[8]	1.00 $\pm$ 0.10[267]	^y 0.97 $\pm$ 0.11[161]	9.5 $\pm$ 6.0[420]	^y 2.1 $\pm$ 0.1[189]
1989								
1990	^{ab} 0.39 $\pm$ 0.07[27]	^y 0.09 $\pm$ 0.01[22]			1.03 $\pm$ 0.09[15]	1.02 $\pm$ 0.09[12]		
1991								
1992	^a 0.42 $\pm$ 0.05[50]	^y 0.10 $\pm$ 0.01[21]	4.9 $\pm$ 4.8[40]	4.0 $\pm$ 3.1[12]	1.02 $\pm$ 0.11[194]	^y 0.99 $\pm$ 0.10[63]	12.5 $\pm$ 7.2[473]	^y 3.8 $\pm$ 0.2[79]
1993								
1994	^{bc} 0.29 $\pm$ 0.04[50]	^y 0.10 $\pm$ 0.01[36]			1.03 $\pm$ 0.12[36]	^y 0.89 $\pm$ 0.08[95]		
1995								
1996	^{cd} 0.28 $\pm$ 0.04[62]	^y 0.10 $\pm$ 0.01[32]	3.2 $\pm$ 3.4[88]	4.2 $\pm$ 2.8[16]	0.99 $\pm$ 0.12[91]	^y 0.94 $\pm$ 0.10[57]	3.3 $\pm$ 0.2[314]	^y 0[67]
1997								
1998		0.11 $\pm$ 0.01[32]						
1999								
2000	^d 0.22 $\pm$ 0.03[69]	^y 0.07 $\pm$ 0.01[32]			*1.10 $\pm$ 0.10[41]	^y 1.04 $\pm$ 0.12[14]		

Note: in grey, pre-impoundment years. *: Statistical ($\alpha < 0.05$) difference from the pre-impoundment level.

y: Statistical ($\alpha < 0.05$) difference between reservoir and natural lake values by year.

Letters attributed to mercury levels in reservoir indicate the results of year to year multiple comparisons of means where the letter a is given to the highest value and where levels with different letters are significantly different ($\alpha < 0.05$).

Table 3. (cont.) Total mercury concentration ($\pm$ confidence interval[n]) at 400 mm, fishing yields (CPUE $\pm$ SD[n]), condition factor K (300-500 mm, $\pm$ SD[n]) and small specimen proportions (<250 mm, $\pm$ SD[n]) for lake whitefish in the major La Grande reservoirs and the reference lakes.

Year	Caniapiscau reservoir							
	Total mercury (Hg μ g g ⁻¹)		Density (CPUE)		Fulton's K		Small specimen (%)	
	Reservoir	Ref. lake (Hazeur)	Reservoir	Ref. lake (Hazeur)	Reservoir	Ref. lake (Hazeur)	Reservoir	Ref. lake (Hazeur)
1980	^e 0.16 $\pm$ 0.01[174]		9.8 $\pm$ 8.5[48]		0.87 $\pm$ 0.07[560]		18.9 $\pm$ 5.3[183]	
1981			13.0 $\pm$ 11.3[48]		0.87 $\pm$ 0.06[1021]		25.9 $\pm$ 15.5[1248]	
1982			*5.1 $\pm$ 6.9[64]	6.6 $\pm$ 7.1[16]	0.88 $\pm$ 0.08[260]	^y 0.96 $\pm$ 0.07[44]	28.6 $\pm$ 10.0[490]	^y 17.2 $\pm$ 4.6[151]
1983								
1984								
1985								
1986								
1987	^{ab} 0.38 $\pm$ 0.07[35]	^y 0.16 $\pm$ 0.01[32]	*5.4 $\pm$ 7.3[40]	7.6 $\pm$ 7.4[12]	*1.01 $\pm$ 0.12[285]	^y 0.90 $\pm$ 0.08[77]	*8.4 $\pm$ 5.2[346]	^y 3.2 $\pm$ 0.2[126]
1988								
1989	^a 0.45 $\pm$ 0.08[29]	^y 0.20 $\pm$ 0.02[29]			*0.93 $\pm$ 0.13[48]			
1990								
1991	^a 0.47 $\pm$ 0.09[29]	^y 0.16 $\pm$ 0.01[30]	*17.8 $\pm$ 28.8[24]	8.2 $\pm$ 5.6[8]	0.90 $\pm$ 0.12[231]	0.88 $\pm$ 0.08[35]	*64.3 $\pm$ 16.2[1139]	^y 19.8 $\pm$ 4.2[111]
1992								
1993	^{bc} 0.29 $\pm$ 0.04[40]	^y 0.16 $\pm$ 0.01[31]	10.9 $\pm$ 9.5[48]	16.6 $\pm$ 15.4[24]	*0.96 $\pm$ 0.10[330]	^y 0.89 $\pm$ 0.09[71]	*37.5 $\pm$ 13.2[741]	40.0 $\pm$ 11.8[577]
1994								
1995	^d 0.21 $\pm$ 0.03[58]	^y 0.12 $\pm$ 0.01[33]	12.0 $\pm$ 5.9[55]	^y 2.6 $\pm$ 7.8[12]	*0.91 $\pm$ 0.09[382]	^y 0.83 $\pm$ 0.09[106]	*30.0 $\pm$ 12.7[767]	28.9 $\pm$ 8.3[339]
1996								
1997	^{cd} 0.24 $\pm$ 0.03[49]	^y 0.16 $\pm$ 0.01[31]						
1998								
1999	^{cd} 0.23 $\pm$ 0.03[39]	^y 0.17 $\pm$ 0.01[32]	*8.0 $\pm$ 4.9[48]	14.6 $\pm$ 8.4[16]	0.85 $\pm$ 0.09[260]	^y 0.90 $\pm$ 0.07[187]	*38.7 $\pm$ 11.0[511]	^y 13.9 $\pm$ 5.6[266]
2000								
2001								
2002								
2003	^e 0.17 $\pm$ 0.01[39]	0.18 $\pm$ 0.01[36]			0.86 $\pm$ 0.08[81]	^y 0.90 $\pm$ 0.07[187]		

Note: in grey, pre-impoundment years. *: Statistical ($\alpha<0.05$) difference from the pre-impoundment level.
y: Statistical ($\alpha<0.05$) difference between reservoir and natural lake values by year.
Letters attributed to mercury levels in reservoir indicate the results of year to year multiple comparisons of means where the letter a is given to the highest value and where levels with different letters are significantly different ($\alpha<0.05$).

Table 4. Total mercury concentration ($\pm$ confidence interval[n]) at 400 mm, fishing yields (CPUE $\pm$ SD[n]), condition factor K (300-500 mm, $\pm$ SD[n]) and small specimen proportions (<250 mm, $\pm$ SD[n]) for longnose sucker in the major La Grande reservoirs and the reference lakes.

Year	Robert-Bourassa reservoir							
	Total mercury (Hg μ g g ⁻¹)		Density (CPUE)		Fulton's K		Small specimen (%)	
	Reservoir	Ref. lake (Rond-de-Poêle)	Reservoir	Ref. lake (Rond-de-Poêle)	Reservoir	Ref. lake (Rond-de-Poêle)	Reservoir	Ref. lake (Rond-de-Poêle)
1977-78	^e 0.12 $\pm$ 0.01[182]		1.6 $\pm$ 3.0[146]	1.2 $\pm$ 1.5[32]	1.01 $\pm$ 0.10[230]	1.02 $\pm$ 0.16[43]	8.1 $\pm$ 6.1[506]	^y 3.7 $\pm$ 0.2[80]
1979			1.2 $\pm$ 3.6[120]	1.0 $\pm$ 1.6[24]	*1.12 $\pm$ 0.13[235]	1.11 $\pm$ 0.07[29]	*0.9 $\pm$ 0.3[232]	2.6 $\pm$ 0.2[39]
1980			*2.8 $\pm$ 2.3[44]	0.8 $\pm$ 1.1[16]	*1.20 $\pm$ 0.11[300]	^y 1.09 $\pm$ 0.06[20]	5.1 $\pm$ 4.4[392]	^y 0[22]
1981			2.1 $\pm$ 7.7[72]	^y 0.4 $\pm$ 0.7[16]	*1.21 $\pm$ 0.11[325]	^y 1.07 $\pm$ 0.09[14]	8.5 $\pm$ 5.7[412]	^y 0[16]
1982	^b 0.38 $\pm$ 0.02[151]		2.3 $\pm$ 3.7[74]	1.3 $\pm$ 1.6[16]	*1.21 $\pm$ 0.12[328]	^y 1.11 $\pm$ 0.09[34]	10.3 $\pm$ 6.2[419]	7.1 $\pm$ 1.7[43]
1983			1.7 $\pm$ 3.0[40]	0.8 $\pm$ 1.1[8]	*1.22 $\pm$ 0.10[154]	^y 1.04 $\pm$ 0.05[12]	8.6 $\pm$ 3.8[186]	^y 0[16]
1984	^a 0.61 $\pm$ 0.04[94]		1.0 $\pm$ 2.4[40]	1.0 $\pm$ 2.8[16]	*1.16 $\pm$ 0.09[88]	^y 1.10 $\pm$ 0.05[14]	4.6 $\pm$ 0.2[110]	^y 15.8 $\pm$ 2.2[38]
1985								
1986	^a 0.63 $\pm$ 0.06[72]				1.04 $\pm$ 0.10[49]			
1987								
1988	^a 0.57 $\pm$ 0.08[19]		*0.1 $\pm$ 0.3[40]	^y 0.7 $\pm$ 0.7[8]	*1.09 $\pm$ 0.05[12]	1.01 $\pm$ 0.11[13]	11.1 $\pm$ 0.9[9]	^y 0[14]
1989								
1990	^b 0.44 $\pm$ 0.06[22]	^y 0.14 $\pm$ 0.02[14]			1.02 $\pm$ 0.07[14]	1.12 $\pm$ 0.32[15]		
1991								
1992	^b 0.45 $\pm$ 0.05[34]	^y 0.14 $\pm$ 0.02[14]	0.5 $\pm$ 1.0[40]	0.8 $\pm$ 0.8[12]	*1.07 $\pm$ 0.10[45]	1.09 $\pm$ 0.07[12]	2.0 $\pm$ 0.14[50]	^y 0[20]
1993								
1994	^b 0.39 $\pm$ 0.06[28]	^y 0.14 $\pm$ 0.02[32]			1.00 $\pm$ 0.11[22]	1.01 $\pm$ 0.07[45]		
1995								
1996	^e 0.29 $\pm$ 0.04[48]	^y 0.14 $\pm$ 0.02[15]	*0.4 $\pm$ 0.8[72]	0.6 $\pm$ 0.8[8]	*1.11 $\pm$ 0.11[30]	^y 0.98 $\pm$ 0.07[7]	6.0 $\pm$ 1.4[34]	^y 0[10]
1997								
1998	^{cd} 0.26 $\pm$ 0.04[43]	^y 0.10 $\pm$ 0.02[25]			1.03 $\pm$ 0.10[29]	1.00 $\pm$ 0.08[17]		
1999								
2000	^d 0.22 $\pm$ 0.02[105]	^y 0.14 $\pm$ 0.02[31]			*1.17 $\pm$ 0.12[12]	1.12 $\pm$ 0.02[17]		

Note: in grey, pre-impoundment years. *: Statistical ($\alpha < 0.05$) difference from the pre-impoundment level.

y: Statistical ($\alpha < 0.05$) difference between reservoir and natural lake values by year.

Letters attributed to mercury levels in reservoir indicate the results of year to year multiple comparisons of means where the letter a is given to the highest value and where levels with different letters are significantly different ($\alpha < 0.05$).

Table 4. (cont.) Total mercury concentration ($\pm$ confidence interval[n]) at 400 mm, fishing yields (CPUE $\pm$ SD[n]), condition factor K (300-500 mm, $\pm$ SD[n]) and small specimen proportions (<250 mm, $\pm$ SD[n]) for longnose sucker in the major La Grande reservoirs and the reference lakes.

Year	Opinaca reservoir							
	Total mercury (Hg $\mu\text{g g}^{-1}$)		Density (CPUE)		Fulton's K		Small specimen (%)	
	Reservoir	Ref. lake (Detcheverry)	Reservoir	Ref. lake (Detcheverry)	Reservoir	Ref. lake (Detcheverry)	Reservoir	Ref. lake (Detcheverry)
1978	^d 0.12 $\pm$ 0.01[182]		0.4 $\pm$ 0.8[68]	0.2 $\pm$ 0.3[16]	1.05 $\pm$ 0.11[50]	1.08 $\pm$ 0.06[6]	6.2 $\pm$ 1.9[65]	12.5 $\pm$ 0.9[8]
1979			0.8 $\pm$ 2.3[68]	0.1 $\pm$ 0.2[16]	1.06 $\pm$ 0.07[84]		3.1 $\pm$ 0.2[96]	^y 42.9 $\pm$ 1.3[7]
1980	^a 0.72 $\pm$ 0.12[9]		*1.6 $\pm$ 2.1[60]	^y 0.1 $\pm$ 0.2[16]	1.07 $\pm$ 0.10[181]		2.5 $\pm$ 0.2[203]	^y 0[3]
1981			0.4 $\pm$ 1.2[63]	0.9 $\pm$ 1.4[16]	*1.20 $\pm$ 0.11[50]	^y 1.09 $\pm$ 0.07[14]	3.6 $\pm$ 0.2[56]	^y 21.1 $\pm$ 1.8[19]
1982			0.4 $\pm$ 0.9[56]	0.7 $\pm$ 1.2[12]	*1.24 $\pm$ 0.09[38]	^y 1.01 $\pm$ 0.09[13]	*0[59]	^y 11.8 $\pm$ 1.3[17]
1983			0.4 $\pm$ 0.8[36]	0.5 $\pm$ 1.1[8]	*1.25 $\pm$ 0.11[30]	^y 1.10 $\pm$ 0.07[5]	2.7 $\pm$ 0.2[37]	12.5 $\pm$ 0.9[8]
1984			0.3 $\pm$ 0.4[32]	0.9 $\pm$ 2.3[16]	*1.24 $\pm$ 0.12[11]	1.15 $\pm$ 0.09[6]	*0[24]	^y 25.0 $\pm$ 1.7[16]
1985								
1986					*1.12 $\pm$ 0.09[18]			
1987								
1988			0.1 $\pm$ 0.3[32]	0.1 $\pm$ 0.4[8]	1.03 $\pm$ 0.08[5]		*0[8]	^y 71.4 $\pm$ 1.7[14]
1989								
1990					1.06 $\pm$ 0.07[9]			
1991								
1992	^b 0.50 $\pm$ 0.06[27]		0.6 $\pm$ 1.8[40]	0.1 $\pm$ 0.2[12]	1.09 $\pm$ 0.08[37]		3.9 $\pm$ 0.2[51]	^y 60.0 $\pm$ 2.2[20]
1993								
1994					1.12 $\pm$ 0.10[6]			
1995	^c 0.33 $\pm$ 0.05[34]							
1996			0.3 $\pm$ 0.4[88]	0.3 $\pm$ 0.5[16]	1.08 $\pm$ 0.14[17]		*0[30]	0[10]
1997								
1998								
1999								
2000					*1.12 $\pm$ 0.08[24]			

Note: in grey, pre-impoundment years. *: Statistical ($\alpha<0.05$) difference from the pre-impoundment level.
y: Statistical ($\alpha<0.05$) difference between reservoir and natural lake values by year.
Letters attributed to mercury levels in reservoir indicate the results of year to year multiple comparisons of means where the letter a is given to the highest value and where levels with different letters are significantly different ($\alpha<0.05$).

Table 4. (cont.) Total mercury concentration ($\pm$ confidence interval[n]) at 400 mm, fishing yields (CPUE $\pm$ SD[n]), condition factor K (300-500 mm, $\pm$ SD[n]) and small specimen proportions (<250 mm, $\pm$ SD[n]) for longnose sucker in the major La Grande reservoirs and the reference lakes.

Year	Caniapiscou reservoir							
	Total mercury (Hg μ g g ⁻¹)		Density (CPUE)		Fulton's K		Small specimen (%)	
	Reservoir	Ref. lake (Hazeur)	Reservoir	Ref. lake (Hazeur)	Reservoir	Ref. lake (Hazeur)	Reservoir	Ref. lake (Hazeur)
1980	ⁱ 0.13 $\pm$ 0.01[246]		3.8 $\pm$ 5.2[48]		1.04 $\pm$ 0.09[165]		12.2 $\pm$ 6.3[376]	
1981			4.8 $\pm$ 5.7[48]		1.03 $\pm$ 0.10[240]	^y 0.90 $\pm$ 0.08[25]	22.6 $\pm$ 9.0[461]	
1982			*8.2 $\pm$ 7.5[64]	^y 0.6 $\pm$ 1.0[16]	*1.08 $\pm$ 0.10[377]	^y 0.91 $\pm$ 0.08[10]	*9.4 $\pm$ 8.2[787]	^y 85.0 $\pm$ 6.6[20]
1983								
1984								
1985								
1986								
1987	^c 0.34 $\pm$ 0.03[117]	^y 0.11 $\pm$ 0.01[32]	4.8 $\pm$ 4.5[40]	3.1 $\pm$ 4.1[12]	*1.20 $\pm$ 0.17[220]	^y 0.95 $\pm$ 0.04[38]	9.8 $\pm$ 5.2[307]	^y 84.3 $\pm$ 2.6[51]
1988								
1989	^{ab} 0.45 $\pm$ 0.04[77]	^y 0.11 $\pm$ 0.01[24]			*1.09 $\pm$ 0.11[42]			
1990								
1991	^a 0.52 $\pm$ 0.04[105]	^y 0.10 $\pm$ 0.02[22]	4.3 $\pm$ 6.6[24]	4.8 $\pm$ 2.4[8]	1.04 $\pm$ 0.09[132]	1.03 $\pm$ 0.06[11]	15.9 $\pm$ 6.1[276]	^y 6.5 $\pm$ 1.7[46]
1992								
1993	^a 0.49 $\pm$ 0.04[120]	^y 0.11 $\pm$ 0.01[29]	3.8 $\pm$ 5.3[48]	4.6 $\pm$ 4.8[24]	*1.12 $\pm$ 0.11[93]	1.12 $\pm$ 0.09[12]	23.5 $\pm$ 6.8[255]	^y 34.5 $\pm$ 5.0[110]
1994								
1995	^{bc} 0.39 $\pm$ 0.04[122]	^y 0.06 $\pm$ 0.02[30]	4.0 $\pm$ 5.1[55]	4.0 $\pm$ 5.3[12]	*1.10 $\pm$ 0.09[111]	1.02 $\pm$ 0.11[9]	19.1 $\pm$ 6.3[257]	^y 58.9 $\pm$ 3.7[56]
1996								
1997	^d 0.24 $\pm$ 0.02[126]	^y 0.08 $\pm$ 0.02[31]						
1998								
1999	^d 0.22 $\pm$ 0.02[128]	^y 0.08 $\pm$ 0.02[32]	4.0 $\pm$ 3.3[48]	3.6 $\pm$ 3.8[16]	*1.12 $\pm$ 0.09[146]	^y 1.06 $\pm$ 0.07[36]	22.8 $\pm$ 6.7[255]	^y 15.8 $\pm$ 2.8[57]
2000								
2001								
2002								
2003	^c 0.17 $\pm$ 0.02[128]	^y 0.10 $\pm$ 0.01[32]			*1.08 $\pm$ 0.09[59]	1.05 $\pm$ 0.098[40]		

Note: in grey, pre-impoundment years. *: Statistical ($\alpha < 0.05$) difference from the pre-impoundment level.

y: Statistical ($\alpha < 0.05$) difference between reservoir and natural lake values by year.

Letters attributed to mercury levels in reservoir indicate the results of year to year multiple comparisons of means where the letter a is given to the highest value and where levels with different letters are significantly different ($\alpha < 0.05$).

Table 5. Total mercury concentration ($\pm$ confidence interval[n]) at 700 mm, fishing yields (CPUE $\pm$ SD[n]), condition factor K (500-700 mm, $\pm$ SD[n]) and small specimen proportions (<350 mm, $\pm$ SD[n]) for northern pike in the major La Grande reservoirs and the reference lakes.

Year	Robert-Bourassa reservoir							
	Total mercury (Hg μ g g ⁻¹)		Density (CPUE)		Fulton's K		Small specimen (%)	
	Reservoir	Ref. lake (Rond-de-Poêle)	Reservoir	Ref. lake (Rond-de-Poêle)	Reservoir	Ref. lake (Rond-de-Poêle)	Reservoir	Ref. lake (Rond-de-Poêle)
1977-78	^h 0.60 $\pm$ 0.03[373]		1.0 $\pm$ 1.8[146]	^y 0.1 $\pm$ 0.3[32]	0.57 $\pm$ 0.05[136]		2.4 $\pm$ 0.2[327]	^y 0[6]
1979			0.2 $\pm$ 1.1[120]	0.4 $\pm$ 0.7[24]	*0.59 $\pm$ 0.05[63]	0.60 $\pm$ 0.04[10]	1.0 $\pm$ 0.1[96]	^y 0[12]
1980			0.7 $\pm$ 1.2[44]	0.2 $\pm$ 0.8[16]	*0.65 $\pm$ 0.06[62]		*8.6 $\pm$ 2.7[93]	^y 0[3]
1981			2.8 $\pm$ 4.0[72]	0.7 $\pm$ 1.2[16]	*0.67 $\pm$ 0.05[353]		*4.4 $\pm$ 0.2[549]	^y 0[4]
1982	^s 1.45 $\pm$ 0.13[88]		*5.9 $\pm$ 8.0[74]	^y 0.2 $\pm$ 0.4[16]	*0.64 $\pm$ 0.05[746]		*4.6 $\pm$ 0.2[1074]	^y 0[3]
1983			*4.7 $\pm$ 7.5[40]	^y 0.5 $\pm$ 0.5[8]	*0.64 $\pm$ 0.05[380]	^y 0.56 $\pm$ 0.03[6]	2.3 $\pm$ 0.2[526]	^y 0[6]
1984	^{cd} 2.77 $\pm$ 0.18[90]		*5.2 $\pm$ 9.9[40]	^y 0.1 $\pm$ 0.6[16]	*0.62 $\pm$ 0.04[406]		*0.2 $\pm$ 0.1[571]	^y 0[4]
1985								
1986	^f 2.29 $\pm$ 0.13[90]				0.58 $\pm$ 0.06[75]			
1987								
1988	^{ab} 3.28 $\pm$ 0.21[87]		*5.4 $\pm$ 7.9[40]	^y 1.4 $\pm$ 1.4[8]	0.58 $\pm$ 0.09[277]	0.55 $\pm$ 0.06[5]	1.3 $\pm$ 0.1[555]	^y 0[6]
1989								
1990	^a 3.34 $\pm$ 0.17[78]				0.57 $\pm$ 0.05[36]	^y 0.52 $\pm$ 0.06[8]		
1991								
1992	^{abc} 3.00 $\pm$ 0.21[46]	^y 0.81 $\pm$ 0.07[12]	1.1 $\pm$ 1.9[40]	^y 0.2 $\pm$ 0.3[12]	0.57 $\pm$ 0.06[41]		0.9 $\pm$ 0.1[110]	^y 0[5]
1993								
1994	^{bc} 2.97 $\pm$ 0.15[105]	^y 0.81 $\pm$ 0.07[17]			0.57 $\pm$ 0.07[53]	0.57 $\pm$ 0.05[13]		
1995								
1996	^{de} 2.56 $\pm$ 0.15[92]	^y 0.71 $\pm$ 0.06[29]	2.0 $\pm$ 3.3[72]	0.6 $\pm$ 0.7[8]	0.56 $\pm$ 0.06[83]		3.1 $\pm$ 0.2[162]	^y 0[2]
1997								
1998	^{ef} 2.28 $\pm$ 0.15[95]	^y 0.81 $\pm$ 0.07[17]			0.58 $\pm$ 0.07[75]	0.59 $\pm$ 0.04[15]		
1999								
2000	^{ef} 2.33 $\pm$ 0.14[90]				0.55 $\pm$ 0.04[42]	0.58 $\pm$ 0.05[6]		

Note: in grey, pre-impoundment years. *: Statistical ($\alpha<0.05$) difference from the pre-impoundment level.
y: Statistical ($\alpha<0.05$) difference between reservoir and natural lake values by year.
Letters attributed to mercury levels in reservoir indicate the results of year to year multiple comparisons of means where the letter a is given to the highest value and where levels with different letters are significantly different ($\alpha<0.05$).

Table 5. (cont.) Total mercury concentration ($\pm$ confidence interval[n]) at 700 mm, fishing yields (CPUE $\pm$ SD[n]), condition factor K (500-700 mm, $\pm$ SD[n]) and small specimen proportions (<350 mm, $\pm$ SD[n]) for northern pike in the major La Grande reservoirs and the reference lakes.

Year	Opinaca reservoir							
	Total mercury (Hg $\mu\text{g g}^{-1}$)		Density (CPUE)		Fulton's K		Small specimen (%)	
	Reservoir	Ref. lake (Detcheverry)	Reservoir	Ref. lake (Detcheverry)	Reservoir	Ref. lake (Detcheverry)	Reservoir	Ref. lake (Detcheverry)
1978	^c 0.60 $\pm$ 0.03[373]		1.7 $\pm$ 1.3[68]	2.9 $\pm$ 2.1[16]	0.54 $\pm$ 0.09[150]	0.55 $\pm$ 0.06[78]	4.0 $\pm$ 0.2[278]	^y 0[112]
1979			1.3 $\pm$ 1.7[68]	2.1 $\pm$ 2.8[16]	0.56 $\pm$ 0.05[112]	0.55 $\pm$ 0.04[50]	4.5 $\pm$ 0.2[154]	^y 0[76]
1980			1.0 $\pm$ 1.2[60]	^y 2.6 $\pm$ 1.8[16]	0.56 $\pm$ 0.04[58]	0.54 $\pm$ 0.05[51]	2.4 $\pm$ 0.2[127]	^y 1.5 $\pm$ 0.1[68]
1981			1.4 $\pm$ 1.9[63]	3.4 $\pm$ 4.1[16]	*0.62 $\pm$ 0.07[98]	^y 0.54 $\pm$ 0.05[76]	*20.9 $\pm$ 5.9[211]	^y 0[64]
1982			*3.8 $\pm$ 3.3[56]	2.7 $\pm$ 3.2[12]	*0.65 $\pm$ 0.05[254]	^y 0.56 $\pm$ 0.05[70]	*9.0 $\pm$ 6.8[564]	^y 0[99]
1983			*4.3 $\pm$ 5.4[36]	2.4 $\pm$ 1.7[8]	*0.62 $\pm$ 0.06[283]	^y 0.57 $\pm$ 0.04[58]	4.0 $\pm$ 0.2[446]	^y 0[72]
1984	^{bc} 2.25 $\pm$ 0.21[30]	^y 0.82 $\pm$ 0.04[28]	*6.1 $\pm$ 8.4[32]	4.5 $\pm$ 6.4[16]	*0.61 $\pm$ 0.05[265]	^y 0.56 $\pm$ 0.05[57]	*0.8 $\pm$ 0.1[488]	^y 0[148]
1985								
1986	^{cd} 1.88 $\pm$ 0.25[28]	^y 0.82 $\pm$ 0.04[14]			*0.58 $\pm$ 0.06[57]	0.59 $\pm$ 0.05[6]		
1987								
1988	^{bc} 2.13 $\pm$ 0.21[29]	^y 0.82 $\pm$ 0.04[26]	*6.4 $\pm$ 7.5[32]	2.4 $\pm$ 1.7[8]	0.57 $\pm$ 0.09[273]	0.57 $\pm$ 0.06[45]	1.8 $\pm$ 0.1[511]	^y 1.1 $\pm$ 0.1[94]
1989								
1990	^a 2.77 $\pm$ 0.20[46]	^y 0.82 $\pm$ 0.04[17]			0.54 $\pm$ 0.06[87]	0.56 $\pm$ 0.04[8]		
1991								
1992	^a 2.69 $\pm$ 0.23[54]	^y 0.69 $\pm$ 0.10[22]	2.2 $\pm$ 1.9[40]	2.8 $\pm$ 1.5[12]	0.57 $\pm$ 0.06[97]	^y 0.60 $\pm$ 0.03[36]	3.7 $\pm$ 0.2[214]	^y 0[62]
1993								
1994	^{ab} 2.47 $\pm$ 0.15[65]	^y 0.63 $\pm$ 0.08[35]			0.55 $\pm$ 0.07[149]	0.57 $\pm$ 0.06[51]		
1995								
1996	^b 2.30 $\pm$ 0.15[62]	^y 0.82 $\pm$ 0.04[31]	*3.4 $\pm$ 3.4[88]	3.8 $\pm$ 3.4[16]	0.53 $\pm$ 0.05[109]	0.54 $\pm$ 0.05[29]	3.8 $\pm$ 0.2[338]	^y 0[56]
1997								
1998		0.82 $\pm$ 0.04[31]				0.57 $\pm$ 0.05[28]		
1999								
2000	^d 1.53 $\pm$ 0.14[63]	^y 0.82 $\pm$ 0.04[30]			0.55 $\pm$ 0.06[46]	0.57 $\pm$ 0.03[12]		

Note: in grey, pre-impoundment years. *: Statistical ($\alpha < 0.05$) difference from the pre-impoundment level.

y: Statistical ($\alpha < 0.05$) difference between reservoir and natural lake values by year.

Letters attributed to mercury levels in reservoir indicate the results of year to year multiple comparisons of means where the letter a is given to the highest value and where levels with different letters are significantly different ($\alpha < 0.05$).

Table 5. (cont.) Total mercury concentration ($\pm$ confidence interval[n]) at 700 mm, fishing yields (CPUE $\pm$ SD[n]), condition factor K (500-700 mm, $\pm$ SD[n]) and small specimen proportions (<350 mm, $\pm$ SD[n]) for northern pike in the major La Grande reservoirs and the reference lakes.

Year	Caniapiscou reservoir							
	Total mercury (Hg μ g g ⁻¹)		Density (CPUE)		Fulton's K		Small specimen (%)	
	Reservoir	Ref. lake (Hazeur)	Reservoir	Ref. lake (Hazeur)	Reservoir	Ref. lake (Hazeur)	Reservoir	Ref. lake (Hazeur)
1980	^c 0.59 $\pm$ 0.06[120]		0.2 $\pm$ 0.8[48]		0.60 $\pm$ 0.04[7]		0[17]	
1981			0.5 $\pm$ 1.3[48]			0.52 $\pm$ 0.07[7]	0[46]	
1982			1.2 $\pm$ 1.2[64]		0.64 $\pm$ 0.05[40]	0.67 $\pm$ 0.05[10]	*0.9 $\pm$ 0.1[115]	
1983								
1984								
1985								
1986								
1987	^d 0.79 $\pm$ 0.12[55]		*4.7 $\pm$ 6.8[40]		0.62 $\pm$ 0.08[222]		*0.7 $\pm$ 0.1[301]	
1988								
1989	^c 1.25 $\pm$ 0.15[41]				0.60 $\pm$ 0.04[43]			
1990								
1991	^{abc} 1.57 $\pm$ 0.22[16]		0.7 $\pm$ 1.0[24]		0.60 $\pm$ 0.04[20]		0[44]	
1992								
1993	^a 1.86 $\pm$ 0.16[39]		1.0 $\pm$ 2.0[48]		0.61 $\pm$ 0.05[49]		0[66]	
1994								
1995	^{ab} 1.65 $\pm$ 0.16[34]		*1.9 $\pm$ 2.4[55]	^y 0.3 $\pm$ 0.5[16]	0.59 $\pm$ 0.06[36]		*0.9 $\pm$ 0.1[115]	^y 0[5]
1996								
1997	^{bc} 1.49 $\pm$ 0.11[64]				0.61 $\pm$ 0.06[46]			
1998								
1999	^{bc} 1.51 $\pm$ 0.12[59]		*2.1 $\pm$ 1.4[48]	^y 0.6 $\pm$ 1.0[16]	0.60 $\pm$ 0.05[67]		*0.8 $\pm$ 0.1[133]	^y 0[10]
2000								
2001								
2002								
2003	^c 1.30 $\pm$ 0.11[57]				0.58 $\pm$ 0.05[46]			

Note: in grey, pre-impoundment years. *: Statistical ($\alpha<0.05$) difference from the pre-impoundment level.
y: Statistical ($\alpha<0.05$) difference between reservoir and natural lake values by year.
Letters attributed to mercury levels in reservoir indicate the results of year to year multiple comparisons of means where the letter a is given to the highest value and where levels with different letters are significantly different ($\alpha<0.05$).

Table 6. Total mercury concentration ($\pm$ confidence interval[n]) at 400 mm, fishing yields (CPUE $\pm$ SD[n]), condition factor K (400-600 mm, $\pm$ SD[n]) and small specimen proportions (<250 mm, $\pm$ SD[n]) for walleye in the major La Grande reservoirs and the reference lakes.

Year	Robert-Bourassa reservoir							
	Total mercury (Hg μ g g ⁻¹)		Density (CPUE)		Fulton's K		Small specimen (%)	
	Reservoir	Ref. lake (Rond-de-Poêle)	Reservoir	Ref. lake (Rond-de-Poêle)	Reservoir	Ref. lake (Rond-de-Poêle)	Reservoir	Ref. lake (Rond-de-Poêle)
1977-78	^t 0.59 $\pm$ 0.05[353]		3.8 $\pm$ 8.0[146]	1.7 $\pm$ 1.9[32]	0.89 $\pm$ 0.09[283]	0.89 $\pm$ 0.09[46]	8.8 $\pm$ 9.8[1193]	^y 2.7 $\pm$ 0.2[110]
1979			*0.4 $\pm$ 2.1[120]	1.1 $\pm$ 1.5[24]	*0.91 $\pm$ 0.09[122]	^y 0.88 $\pm$ 0.06[59]	8.9 $\pm$ 2.5[79]	^y 0[76]
1980			*1.4 $\pm$ 6.9[44]	0.3 $\pm$ 0.6[16]	*0.99 $\pm$ 0.10[148]	^y 0.83 $\pm$ 0.08[8]	*0[195]	0[8]
1981			*2.6 $\pm$ 7.8[72]	^y 0.1 $\pm$ 0.4[16]	*1.04 $\pm$ 0.11[279]	^y 0.89 $\pm$ 0.06[54]	*0.4 $\pm$ 0.1[510]	^y 0[64]
1982	^c 2.03 $\pm$ 0.12[89]		2.7 $\pm$ 6.4[74]	^y 0.1 $\pm$ 0.5[16]	*1.03 $\pm$ 0.09[321]	^y 0.90 $\pm$ 0.07[55]	*0.2 $\pm$ 0.1[491]	^y 0[61]
1983			3.4 $\pm$ 7.2[40]	0.9 $\pm$ 1.4[8]	*1.08 $\pm$ 0.10[250]	^y 0.89 $\pm$ 0.05[36]	*1.7 $\pm$ 0.1[361]	^y 2.4 $\pm$ 0.2[41]
1984	^a 2.72 $\pm$ 0.11[65]		2.0 $\pm$ 4.5[40]	1.1 $\pm$ 1.4[16]	*1.08 $\pm$ 0.10[175]	^y 0.89 $\pm$ 0.05[29]	*4.0 $\pm$ 0.2[223]	^y 2.7 $\pm$ 0.2[75]
1985								
1986	^{bc} 2.32 $\pm$ 0.18[45]				*1.02 $\pm$ 0.10[31]			
1987								
1988	^a 2.82 $\pm$ 0.18[47]		3.1 $\pm$ 11.4[40]	5.1 $\pm$ 6.7[8]	*1.05 $\pm$ 0.15[295]	^y 0.82 $\pm$ 0.06[89]	*2.7 $\pm$ 0.2[335]	^y 1.4 $\pm$ 0.1[142]
1989								
1990	^a 2.79 $\pm$ 0.18[49]	^y 0.64 $\pm$ 0.07[24]			*0.98 $\pm$ 0.06[26]	^y 0.83 $\pm$ 0.07[41]		
1991								
1992	^{ab} 2.49 $\pm$ 0.15[35]	^y 0.40 $\pm$ 0.09[20]	*0.6 $\pm$ 3.0[40]	0.2 $\pm$ 0.5[12]	*1.04 $\pm$ 0.09[33]	^y 0.98 $\pm$ 0.05[10]	14.8 $\pm$ 7.7[61]	^y 4.6 $\pm$ 0.2[24]
1993								
1994	^c 2.20 $\pm$ 0.10[87]	^y 0.45 $\pm$ 0.07[37]			*0.98 $\pm$ 0.11[42]	^y 0.89 $\pm$ 0.05[22]		
1995								
1996	^d 1.75 $\pm$ 0.11[63]	^y 0.37 $\pm$ 0.09[31]	2.4 $\pm$ 5.5[72]	^y 0.3 $\pm$ 0.4[8]	*0.95 $\pm$ 0.09[76]		10.5 $\pm$ 4.2[191]	^y 0[5]
1997								
1998	^{de} 1.52 $\pm$ 0.11[64]	^y 0.45 $\pm$ 0.09[32]			*0.99 $\pm$ 0.24[40]	^y 0.92 $\pm$ 0.05[27]		
1999								
2000	^e 1.41 $\pm$ 0.11[70]	^y 0.44 $\pm$ 0.09[32]						

Note: in grey, pre-impoundment years. *: Statistical ($\alpha<0.05$) difference from the pre-impoundment level.

y: Statistical ($\alpha<0.05$) difference between reservoir and natural lake values by year.

Letters attributed to mercury levels in reservoir indicate the results of year to year multiple comparisons of means where the letter a is given to the highest value and where levels with different letters are significantly different ($\alpha<0.05$).

Table 6. (cont.) Total mercury concentration ($\pm$ confidence interval[n]) at 400 mm, fishing yields (CPUE $\pm$ SD[n]), condition factor K (400-600 mm, $\pm$ SD[n]) and small specimen proportions (<250 mm, $\pm$ SD[n]) for walleye in the major La Grande reservoirs and the reference lakes.

Year	Opinaca reservoir							
	Total mercury (Hg μ g g ⁻¹)		Density (CPUE)		Fulton's K		Small specimen (%)	
	Reservoir	Ref. lake (Detteverry)	Reservoir	Ref. lake (Detteverry)	Reservoir	Ref. lake (Detteverry)	Reservoir	Ref. lake (Detteverry)
1978	^h 0.59 $\pm$ 0.05[353]		5.1 $\pm$ 8.5[68]	6.1 $\pm$ 5.2[16]	0.86 $\pm$ 0.09[468]	^y 0.88 $\pm$ 0.08[102]	4.6 $\pm$ 0.2[835]	^y 19.7 $\pm$ 4.8[147]
1979			4.8 $\pm$ 7.6[68]	3.0 $\pm$ 2.4[16]	0.86 $\pm$ 0.08[373]	^y 0.89 $\pm$ 0.08[51]	1.4 $\pm$ 0.1[557]	^y 18.4 $\pm$ 3.8[98]
1980			5.6 $\pm$ 7.8[60]	2.4 $\pm$ 1.5[16]	0.87 $\pm$ 0.08[575]	^y 0.91 $\pm$ 0.07[32]	*0.4 $\pm$ 0.1[739]	^y 6.5 $\pm$ 1.9[62]
1981	^{defg} 1.01 $\pm$ 0.15[30]		*1.8 $\pm$ 3.3[63]	^y 9.8 $\pm$ 7.2[16]	*0.95 $\pm$ 0.08[217]	^y 0.89 $\pm$ 0.07[132]	0.4 $\pm$ 0.1[268]	^y 5.7 $\pm$ 3.3[200]
1982			*1.6 $\pm$ 2.4[56]	3.9 $\pm$ 3.1[12]	*0.99 $\pm$ 0.09[204]	^y 0.89 $\pm$ 0.07[47]	1.3 $\pm$ 0.2[237]	^y 2.7 $\pm$ 0.2[112]
1983			*1.3 $\pm$ 2.8[36]	^y 8.9 $\pm$ 6.6[8]	*0.98 $\pm$ 0.11[115]	^y 0.94 $\pm$ 0.11[54]	6.7 $\pm$ 2.9[134]	6.5 $\pm$ 2.9[138]
1984	^{ab} 1.94 $\pm$ 0.17[30]	^y 0.68 $\pm$ 0.03[30]	*0.8 $\pm$ 1.4[32]	^y 9.3 $\pm$ 10.3[16]	*1.07 $\pm$ 0.10[48]	^y 0.92 $\pm$ 0.07[76]	7.0 $\pm$ 1.9[57]	^y 4.1 $\pm$ 0.2[244]
1985								
1986	^{ab} 1.74 $\pm$ 0.27[9]	^y 0.58 $\pm$ 0.03[30]			*0.95 $\pm$ 0.12[39]	^y 0.83 $\pm$ 0.14[14]		
1987								
1988	^{ab} 1.99 $\pm$ 0.21[18]	^y 0.60 $\pm$ 0.03[23]	*1.1 $\pm$ 1.8[32]	^y 10.5 $\pm$ 9.2[8]	*1.08 $\pm$ 0.09[38]	^y 0.89 $\pm$ 0.09[119]	1.1 $\pm$ 0.1[88]	^y 2.4 $\pm$ 0.2[255]
1989								
1990	^a 2.07 $\pm$ 0.19[23]	^y 0.57 $\pm$ 0.03[28]			*0.97 $\pm$ 0.16[25]	^y 0.88 $\pm$ 0.04[10]		
1991								
1992	^{ab} 1.88 $\pm$ 0.12[53]	^y 0.57 $\pm$ 0.03[30]	3.4 $\pm$ 3.5[40]	^y 7.1 $\pm$ 3.4[12]	*1.02 $\pm$ 0.11[199]	^y 0.95 $\pm$ 0.07[90]	3.9 $\pm$ 0.2[330]	^y 12.5 $\pm$ 3.9[136]
1993								
1994	^b 1.65 $\pm$ 0.18[32]	^y 0.57 $\pm$ 0.03[41]			*0.95 $\pm$ 0.11[99]	^y 0.86 $\pm$ 0.07[107]		
1995								
1996	^{cd} 1.28 $\pm$ 0.15[67]	^y 0.58 $\pm$ 0.03[31]	3.9 $\pm$ 4.2[88]	5.2 $\pm$ 3.1[16]	*0.95 $\pm$ 0.08[146]	^y 0.86 $\pm$ 0.06[41]	*11.4 $\pm$ 6.2[386]	^y 9.5 $\pm$ 2.7[84]
1997								
1998		0.58 $\pm$ 0.03[32]				0.85 $\pm$ 0.06[24]		
1999								
2000	^g 0.76 $\pm$ 0.12[61]	^y 0.57 $\pm$ 0.03[32]			*0.92 $\pm$ 0.06[66]	0.93 $\pm$ 0.08[14]		

Note: in grey, pre-impoundment years. *: Statistical ($\alpha<0.05$) difference from the pre-impoundment level.
y: Statistical ($\alpha<0.05$) difference between reservoir and natural lake values by year.
Letters attributed to mercury levels in reservoir indicate the results of year to year multiple comparisons of means where the letter a is given to the highest value and where levels with different letters are significantly different ($\alpha<0.05$).

Table 7. Total mercury concentration ($\pm$ confidence interval[n]) at 600 mm, fishing yields (CPUE $\pm$ SD[n]), condition factor K (600-800 mm, $\pm$ SD[n]) and small specimen proportions (<600 mm, $\pm$ SD[n]) for lake trout in the major La Grande reservoirs and the reference lakes.

Year	Caniapiscau reservoir							
	Total mercury (Hg μ g g ⁻¹)		Density (CPUE)		Fulton's K		Small specimen (%)	
	Reservoir	Ref. lake (Hazeur)	Reservoir	Ref. lake (Hazeur)	Reservoir	Ref. lake (Hazeur)	Reservoir	Ref. lake (Hazeur)
1980	^c 0.72 $\pm$ 0.04[254]		2.9 $\pm$ 2.2[48]		0.82 $\pm$ 0.11[132]		31.2 $\pm$ 7.9[288]	
1981			2.5 $\pm$ 1.4[48]		0.82 $\pm$ 0.08[177]		48.3 $\pm$ 7.7[240]	
1982			*1.5 $\pm$ 1.1[64]	^y 6.9 $\pm$ 7.5[16]	0.83 $\pm$ 0.08[90]	0.83 $\pm$ 0.11[45]	45.8 $\pm$ 6.0[144]	^y 61.9 $\pm$ 5.6[134]
1983								
1984								
1985								
1986								
1987	^c 0.82 $\pm$ 0.09[54]	0.75 $\pm$ 0.04[31]	*1.2 $\pm$ 1.4[40]	^y 3.4 $\pm$ 2.1[12]	*0.96 $\pm$ 0.19[44]	0.87 $\pm$ 0.05[13]	27.0 $\pm$ 5.9[178]	^y 73.7 $\pm$ 3.3[57]
1988								
1989	^{ab} 1.56 $\pm$ 0.23[44]	^y 0.97 $\pm$ 0.17[19]			*0.95 $\pm$ 0.13[34]	^y 0.78 $\pm$ 0.02[6]		
1990								
1991	^a 1.85 $\pm$ 0.37[26]	^y 0.75 $\pm$ 0.04[19]	*0.6 $\pm$ 1.1[24]	^y 4.8 $\pm$ 2.3[8]	0.84 $\pm$ 0.20[22]	0.78 $\pm$ 0.08[16]	*10.8 $\pm$ 1.9[37]	^y 73.6 $\pm$ 3.2[53]
1992								
1993	^a 1.79 $\pm$ 0.28[33]	^y 0.75 $\pm$ 0.04[28]	*0.6 $\pm$ 0.9[48]	^y 3.0 $\pm$ 1.6[24]	*1.02 $\pm$ 0.15[26]	^y 0.84 $\pm$ 0.10[6]	*2.9 $\pm$ 0.2[35]	^y 83.9 $\pm$ 2.7[55]
1994								
1995	^{ab} 1.58 $\pm$ 0.20[40]	^y 0.75 $\pm$ 0.04[22]	*0.7 $\pm$ 1.3[55]	2.2 $\pm$ 2.5[12]	*1.06 $\pm$ 0.16[19]	^y 0.88 $\pm$ 0.09[8]	*4.8 $\pm$ 0.2[42]	^y 77.1 $\pm$ 2.2[27]
1996								
1997	^{ab} 1.55 $\pm$ 0.21[37]	^y 0.75 $\pm$ 0.04[28]			*1.14 $\pm$ 0.18[37]	^y 0.93 $\pm$ 0.07[13]		
1998								
1999	^a 1.76 $\pm$ 0.24[38]	^y 0.76 $\pm$ 0.07[32]	*1.7 $\pm$ 2.2[48]	^y 4.1 $\pm$ 2.1[16]	*1.03 $\pm$ 0.11[49]	^y 0.86 $\pm$ 0.08[26]	*3.7 $\pm$ 0.2[109]	^y 59.1 $\pm$ 4.0[66]
2000								
2001								
2002								
2003	^b 1.30 $\pm$ 0.22[22]	^y 0.75 $\pm$ 0.04[13]			*0.97 $\pm$ 0.14[28]			

Note: in grey, pre-impoundment years. *: Statistical ($\alpha < 0.05$) difference from the pre-impoundment level.

y: Statistical ($\alpha < 0.05$) difference between reservoir and natural lake values by year.

Letters attributed to mercury levels in reservoir indicate the results of year to year multiple comparisons of means where the letter a is given to the highest value and where levels with different letters are significantly different ($\alpha < 0.05$).

Fig. 1 La Grande hydroelectric complex

141-17244-00_Article_fig1_complex_an_150828.ai

Fig. 2 Temporal evolution of mean total mercury levels (wet weight) at standardized length of major fish species caught in the natural lakes of the La Grande complex.

141-17244-00_Article_fig2_evolution_151113.ai

Fig. 3 Temporal evolution of mean total mercury (wet weight) levels and of Fulton’s fish condition factor (K) for the major species in three reservoirs of the La Grande complex.

a) Lake whitefish

b) Longnose sucker

—●— Reservoir condition factor (K) Condition factor for length intervals (a and b = 300-500 mm, c = 500-700 mm; d = 400-600 mm, e = 600-800 mm)

—▲— Ref. lake condition factor

○ Statistical difference with pre-impoundment ($\alpha = 0.05$).

—◆— Hg Mercury at standard length (a, b and d = 400 mm, c = 700 mm, e = 600 mm)

Vertical bars represent confidence intervals ($\alpha < 0.05$) of average means.

Range of mean levels measured under natural conditions for a standardized length.

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Fig. 3 (cont'd) Temporal evolution of mean total mercury (wet weight) levels and of Fulton's fish condition factor (K) for the major species in three reservoirs of the La Grande complex.

c) Northern Pike

d) Walleye

e) Lake Trout

Fig. 4 Annual von Bertalanffy growth curves for the major species in Robert-Bourassa Reservoir

141-17244-00_Article_fig4_Bourassa_an_150929.ai

Fig. 5 Annual von Bertalanffy growth curves for the major species in Opinaca Reservoir

141-17244-00_Article_fig5_Opinaca_an_150929.ai

Fig. 6 Annual von Bertalanffy growth curves for the major species in Caniapiscau Reservoir