Reduction of mercury concentration in fish through intensive fishing of lakes: A preliminary testing of assumptions

N. Thérien¹, C. Surette², R. Fortin², M. Lucotte², S. Garceau², R. Schetagne³ & A. Tremblay³
¹Faculté de génie, Université de Sherbrooke, Canada
²Université du Québec à Montréal, Canada
³Department of Hydraulics and Environment, Hydro-Québec, Canada

Abstract

Intensive fishing of lakes has been indicated in the literature as a means of reducing mercury concentrations in fish. However, the controlling process by which this occurs remains unclear. Three assumptions are generally put forward to explain the reduction. The first is that intensive fishing would affect the total mercury balance of the lake and reduce the mercury bioaccumulation in fish. The second is that the fish diet would be affected, especially for piscivorous fish feeding on smaller prey fish with lower mercury concentration following intensive fishing of larger prey fish. The third assumption is that the rate of growth of the fish remaining after intensive fishing would increase since competition for food would generally be reduced. Testing of these assumptions were made using fish data from three natural lakes located in the James Bay territory of northern Quebec, Canada, where intensive fishing occurred in 1998. Dominant species of fish were considered and mass and mercury concentrations of individual fish were expressed as a function of fish age. A bioenergetics model was used to compute the rate of feeding of fish. A mercury bioaccumulation model was used to relate mercury concentration in fish to intake of
mercury by fish through food diet. Results computed for the lakes investigated have indicated the effects of these processes taken separately and the conditions under which they may be controlling the reduction of mercury concentration in fish.

1 Introduction

Mercury concentrations in fish has been observed to increase very significantly and to remain high for long periods of time following the creation of large hydroelectric reservoirs in Northern Québec [1]. The mercury concentration in piscivorous fish often exceeded limits set for commercial fishing and fish consumption in these reservoirs thus affecting the well-being of local communities and sport fishermen. Since earlier results [2, 3, 4, 5] had indicated a reduction of the mercury levels in piscivorous fish following intensive fishing of water bodies from Sweeden and Finland, intensive fishing had been suggested as a means to reduce mercury concentration in fish in large reservoirs. However, the controlling process by which the observed reduction in mercury concentration of fish occurred remains unclear. Therefore, a better knowledge of the controlling process is required in order to specify the conditions under which intensive and selective fishing in large reservoirs could lead to significant and lasting reduction of mercury levels in fish. Many processes may act concurrently to contribute effectively to the reduction of mercury concentration in fish following intensive fishing. In this work each of three main assumptions would be considered separately as the controlling process. The first assumption is that intensive fishing would affect the total mercury balance of the lake by reducing the recycling of mercury in the system and thus reducing mercury bioaccumulation in fish. The second assumption is that there would be a shift in the fish diet of the remaining fish population to include food components less contaminated in mercury [4]. More specifically, it is assumed that following intensive fishing of larger prey fish, piscivorous fish will feed on a larger fraction of smaller prey fish with lower mercury concentrations [2]. The third assumption is that the rate of growth of the fish remaining after intensive fishing would increase since competition for food would generally be reduced and mercury concentrations in fish would be reduced through a biodilution effect [2,3]. The objective of the paper is to report on the relative importance of the effect of each of these assumptions on the mercury concentration in fish as a function of time using models for bioenergetics and mercury bioaccumulation in fish.
2 Methodology

2.1 Site

Three small, shallow and oligotrophic lakes located in the Nemiscau region of the James Bay territory of northern Québec, Canada (51°30’N, 77°W) were selected for intensive fishing in 1998. Some lake characteristics are given in Table 1.

2.2 Fish data

The main non piscivorous fish species for these lakes are the White sucker (Catostomus commersonii) and Lake whitefish (Coregonus clupeaformis). The main piscivorous fish are the Northern pike (Esox lucius) and Walleye (Stizostedion vitreum). The following data were available for fish species and lake: abundance (biomass) of fish prior to fishing, the number of fish removed by fishing, fish length, fish age, fish mass and mercury concentration in fish. Fish diet and the mercury concentration of the main diet components were also reported [6].

Table 1: Lake characteristics.

<table>
<thead>
<tr>
<th>Lake volume (10^6 m^3)</th>
<th>Lake 19</th>
<th>Lake 19A</th>
<th>Lake 20</th>
</tr>
</thead>
<tbody>
<tr>
<td>Lake area (10^6 m^2)</td>
<td>7.4</td>
<td>4.0</td>
<td>17.9</td>
</tr>
<tr>
<td>Water renewal time (WRT) (year)</td>
<td>1.37</td>
<td>0.96</td>
<td>3.8</td>
</tr>
</tbody>
</table>

2.3 Fish population

The number of fish of age i, i=2,3,..., prior to intensive fishing was expressed as an exponential decay function of fish age (year) with K representing the average mortality coefficient and N_i, the initial number of fish of age 1:

\[ N_i = N_i \cdot \exp\left[-K(i-1)\right] = N_i \cdot \exp\left[-K\right] \]

From the knowledge of the initial abundance of fish of a given species and lake:

\[ \text{Abundance (biomass)} = \sum_{i=1}^{N} [N_i \cdot M_i] \]

were \( M_i \) represents the average mass for fish of age i, and \( N_i \), the number of fish of age i, which can be determined once the average mortality coefficient K is known. This coefficient was determined from the logarithm of the number of fish caught as a
function of fish age. Figure 1 illustrates the distribution of fish prior to intensive fishing and one year after. The distribution of fish the second year after fishing is considered identical to the distribution observed one year after fishing but shifted one year to the right to accommodate the aging of the fish. For the following years, construction of the fish distributions is done in a similar fashion.

2.4 Effect of a reduction in the mercury balance of the lake

First, the average mass of fish was expressed as a function of fish age and a bioenergetics model [7] was used to compute the rate of feeding of fish. A fish mercury bioaccumulation model [8] was then used with the feeding rate of fish and the average mercury concentration of the diet to compute the rate of loss of mercury (methylmercury) from fish to the lake water (excretion and egestion) as a function of fish age. From the knowledge of the population distributions of fish prior and after fishing, the change in mercury losses by the population of fish of all species to the lake water was computed. A mass balance of methylmercury for the lake was done considering the change in mercury losses by the fish to the lake water, the input of methylmercury by the affluents and the water renewal time of the lake. From this, an estimate of the change in concentration of methylmercury in the lake water $\Delta$MeHg$_{\text{Water}}$ was computed.

![Graph](image)

Figure 1: Ratio of the number of Walleye prior to and after fishing in lake 19A for a biomass reduction corresponding to 40% of the initial biomass.
The level of methylmercury in diet components for non piscivorous fish (insects, benthos) is related to the concentration of methylmercury in water [9] and the following relationship was used where F represents the degree to which these components are affected globally:

$$\frac{\Delta MeHg_{Diet}}{MeHg_{Diet}} = F \left( \frac{\Delta MeHg_{Water}}{MeHg_{Water}} \right)$$

This relationship was used to compute the change in the mercury concentration of the diet to non piscivorous fish $\Delta MeHg_{Diet}$ following intensive fishing. Then, the fish mercury bioaccumulation model was used to compute the change in the mercury concentration of non piscivorous fish as a function of fish age. Also, the resulting change in the mercury concentration of the diet to piscivorous fish was calculated from the knowledge of the diet for piscivorous fish [6]. Finally, the fish mercury bioaccumulation model was used again to compute the resulting mercury concentration in the piscivorous fish. This process was repeated for each of the years following intensive fishing.

### 2.5 Effect of a change in the fish diet of piscivorous fish

The intensive fishing of large prey fish would result in a relatively larger fraction of the population of prey fish of smaller size remaining. The assumption is that there would be a shift in the fish diet of piscivorous fish to feed proportionally on a larger fraction of smaller prey fish. Since mercury concentration of prey fish is generally lower for smaller fish, the average mercury concentration for the diet of piscivorous fish would generally be lower. Diet data for piscivorous fish include the species of fish eaten, the fraction of the total diet these species represent and the length of prey fish found in stomach of predator fish of a given length as seen in Figure 2 for Lake herring (prey fish) and Walleye (predator fish). A length-age key was constructed to relate fish length to fish age as required by the fish mercury bioaccumulation model. Note that predator fish (Northern pike, Walleye) may feed on smaller fish of their own species through superpredation.
Before intensive fishing, the mercury concentration $H_{\text{gPRED}}X_B[j]$ of the diet of predator fish $X$ of age $j$ ($X=$ Northern pike, Walleye) feeding on prey fish $Y$ of age $i$ ($Y=$ Lake Whitefish, White Sucker, Northern pike, Walleye) is given as:

$$H_{\text{gPRED}}X_B[j] = \sum_{Y} \{ \phi_{ijy} \cdot H_{\text{gPRED}}Y_B[i] \}$$

where $\phi_{ijy}$ is the fraction of the population of prey fish $Y$ of age $i$ which is part of the diet of the predator fish $X$ of age $j$. After the $k^{\text{th}}$ year after intensive fishing, the mercury concentration $H_{\text{gPRED}}X_A[j,k]$ of the diet of predator fish $X$ of age $j$ feeding on prey fish $Y$ of age $i$ is given as:

$$H_{\text{gPRED}}X_A[j,k] = \sum_{Y} \{ \phi_{ijy} \cdot H_{\text{gPRED}}Y_A[i,k] \cdot (1 - \text{FREDiky}) \} + \sum_{Y} \{ \phi_{ijy} \cdot H_{\text{gPRED}}Y_A[i-1,k] \cdot \text{FREDiky} \}$$

Where FREDiky, is defined as:

$$\text{FREDiky} = 1 - \frac{\text{Number of prey fish } Y \text{ of age } i \text{ the } k^{\text{th}} \text{ year after fishing}}{\text{Number of prey fish } Y \text{ of age } i \text{ before fishing}}$$

and represents the fraction which express the reduction of the population of prey fish $Y$ of age $i$ the $k^{\text{th}}$ year after intensive fishing. This model was used each year following intensive fishing with $H_{\text{gPRED}}X_A[j,k]$ to compute the mercury concentration of the piscivorous fish.
2.6 Effect of a change in the rate of growth of fish

The rate of growth of fish would be affected differently according to which fraction of the whole population of fish is removed through intensive fishing. First, two limiting cases are considered. (a) Intensive fishing of non piscivorous fish only. In this case food availability to non piscivorous fish would increase but food availability to piscivorous fish would generally decrease. Since food availability is expressed by parameter \( P \) in the bioenergetics model [7] the idea was to relate this parameter to the number of fish remaining after intensive fishing. The following relationship between parameters \((P)\) before and after intensive fishing for the non piscivorous fish has been used where \( \text{FRED}_{NP} \) is the fraction of non piscivorous fish removed by fishing. For piscivorous fish, the

\[
(P_{NPISC})_{AFTER} = (P_{NPISC})_{BEFORE} \cdot [1 + \alpha \cdot \text{FRED}_{NP}]
\]

relationships used to express a reduction in food availability is:

\[
(P_{PISC})_{AFTER} = (P_{PISC})_{BEFORE} \cdot [1 - \gamma \cdot \text{FRED}_{NP}]
\]

Use of the bioenergetics model with \((P_{NPISC})_{AFTER}\) would then generate an increase in the feeding rate to the non piscivorous fish with a corresponding increase in the rate of growth. Also, use of the fish mercury bioaccumulation model would indicate a reduction in the mercury concentration of non piscivorous fish. Similarly, the use of the bioenergetics model would bring a decrease in the feeding rate to piscivorous fish with a decrease of growth. These reductions, through the use of the fish mercury bioaccumulation model, would generally indicate a decrease in the mercury concentration of piscivorous fish.

(b) Intensive fishing of piscivorous fish only. In this case, food availability to piscivorous fish would increase but is considered unaffected for non piscivorous fish and the relationship for \((P_{PISC})_{AFTER}\) to the fraction of piscivorous fish removed \( \text{FRED}_{P} \) becomes:

\[
(P_{PISC})_{AFTER} = (P_{PISC})_{BEFORE} \cdot [1 + \beta \cdot \text{FRED}_{P}]
\]

When considering intensive fishing of both types of fish, the same relationship as before for \((P_{NPISC})_{AFTER}\) is used for the non piscivorous fish. However, for the piscivorous fish, the expression for \((P_{PISC})_{AFTER}\) becomes more complex and the following expression has been used:

\[
(P_{PISC})_{AFTER} = (P_{PISC})_{BEFORE} \cdot [1 - \gamma \cdot \text{FRED}_{NP} + \beta \cdot \text{FRED}_{P}]
\]

In all of the above relationships, \( \alpha, \beta \) and \( \gamma \) are parameters adjustable from data.
3 Results and discussion

3.4 Effect of a reduction in the mercury balance of the lake

The evolution of the average mercury concentration in fish as a function of fish age was computed for all lakes and fish species for 2, 5, 10 and 20 years after intensive fishing. These computations were done for lake 19A and lake 20 under fishing conditions removing from 10 % to 80 % of the initial biomass of fish according to fish species and lakes. The results indicated a reduction of the mercury concentration of fish not greater than 5 % in either lake. The reason is essentially due to the small water renewal time of these lakes (high flushing rate) attenuating any change in the mercury balance. The effect of a longer water renewal time on the mercury concentration of fish is best illustrated in Figure 3 for Lake whitefish in lake 19 (WRT = 2.58 years) when compared to the effect computed for lake 19A (WRT = 0.04 year) ten years after intensive fishing. The results were computed under comparable fishing conditions representing a uniform reduction of 40 % of the initial fish biomass for all fish species in these lakes. For these conditions, the greatest reduction in the mercury concentration in fish computed for lake 19 through a change in the mercury balance alone never exceeded 15 % of the initial mercury concentration in fish.

3.5 Effect of a change in the fish diet of piscivorous fish

The computations were done for the three lakes under fishing conditions removing from 10 % to 80 % of the initial biomass of non piscivorous fish according to fish species and lakes. In all cases, the reduction in the mercury concentration of piscivorous fish never exceeded 5 % in either lake. Figure 4 illustrates the evolution of the mercury concentration profile for Northern pike in lake 19 at different times after intensive fishing. Similar results were obtained for Walleye in the other lakes. These results are not surprising considering the small change observed of the mercury concentration of non piscivorous prey fish of young age before intensive fishing as can be observed in Figure 3 for Lake whitefish. Therefore predation of Northern pike or Walleye on Lake whitefish of a younger age in the range from 1 to 7 years old does not bring about a significant change in the mercury level of the piscivorous fish diet, especially when Lake whitefish represent a significant fraction of the piscivorous fish diet.
Figure 3: Mercury concentration in Lake whitefish considering the effect of a reduction in the recirculation of mercury 10 years after intensive fishing of 40% of initial fish biomass of lakes of different water renewal times. WRT(lake 19) = 2.58 years; WRT(lake 19A) = 0.04 year.

Figure 4: Mercury concentration in Northern pike as a function of time after intensive fishing of lake 19A considering the effect of a change in the diet of piscivorous fish.
3.6 Effect of a change in the rate of growth of fish

Results under fishing conditions similar to the above cases are shown in Figure 5 for Lake whitefish in lake 19 (representative of results obtained for other lakes). The results indicated a significant reduction in the mercury concentration of fish one year after intensive fishing. However, a rapid return towards levels of mercury concentration in fish before intensive fishing is observed afterwards. Similar results were observed for others species of fish.

![Figure 5: Mercury concentration in Lake whitefish as a function of time after intensive fishing of lake 19 considering the effect of a change in the rate of growth of fish.](image)

Conclusion

Under the assumptions made for the computations, the results indicated that a small but lasting reduction in the mercury concentration in fish may result due to a reduction in the recirculation of mercury following intensive fishing. This effect would be more pronounced for lakes having a longer water residency time. For the lakes studied, a change in the diet of piscivorous fish feeding on younger prey fish has not shown a significant reduction in the mercury concentration of piscivorous fish. However, given that the mercury concentration in prey fish in other lakes or reservoirs might be more accentuated in younger fish, the effect could be
more significant. Finally, a rapid and more significant reduction in the mercury concentration of fish appears when considering a change in the rate of growth of fish. However, this effect is not lasting and may suggest periodic intensive fishing as a strategy to achieve a sustainable reduction in the levels of mercury in fish with time. These results represent a preliminary testing only of the effects anticipated by intensive fishing based on the assumptions considered. Final testing of the effects of these assumptions are planned following the availability of new data from fishing recently done in these lakes since intensive fishing done in 1998.

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References


