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Temperature, growth and dietary effects on fish mercury dynamics in two Ontario lakes

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Abstract. A bioenergetics-based model was used to investigate the effects of temperature, growth and dietary exposure on methylmercury dynamics in walleye (*Stizostedion vitreum*) and yellow perch (*Perca flavescens*) from two lakes sampled in northwestern Ontario. Orange Lake was smaller, warmer, had slower fish growth and higher mercury concentrations in yearling yellow perch and walleye (three fold difference in 40 cm walleye) than Trout Lake. The model was applied to test the hypothesis that higher water temperatures in Orange Lake increased metabolic needs, food consumption and mercury uptake in fish. The effects of different growths rates in the lakes were also considered. Temperature/metabolic effects and growth effects on internal methylmercury dynamics in walleye and perch were predicted to occur but be of secondary importance. Different dietary exposure to methylmercury was likely the dominant source of variation in fish mercury concentrations between the two lakes.

Introduction

To better understand the variability in fish mercury concentrations in natural lakes with no local point sources of mercury, Bodaly et al. (1993) investigated mercury in fish in six remote lakes in northwestern Ontario. The Northwest Ontario Lake Size Series (NOLSS) lakes varied in size from 89 to 34690 ha. Chemical and watershed characteristics were similar among the lakes and did not vary systematically with lake size. The smaller, warmer lakes had higher mercury concentrations in yearling yellow perch (*Perca flavescens*) and walleye (*Stizostedion vitreum*). A three-fold range in mercury concentrations in the axial muscle of yearling yellow perch was observed among the six lakes (0.035–0.14 ug g^{-1}). Similar trends existed for 40 cm walleye and 60 cm northern pike.

Bodaly et al. (1993) hypothesized that the observed fish mercury trends were due to increased methylmercury supply in the smaller, warmer lakes. The present study used a bioenergetics-based model to test an alternative hypothesis that the effects of water temperature and growth rates on internal fish mercury dynamics could explain a significant portion of the observed

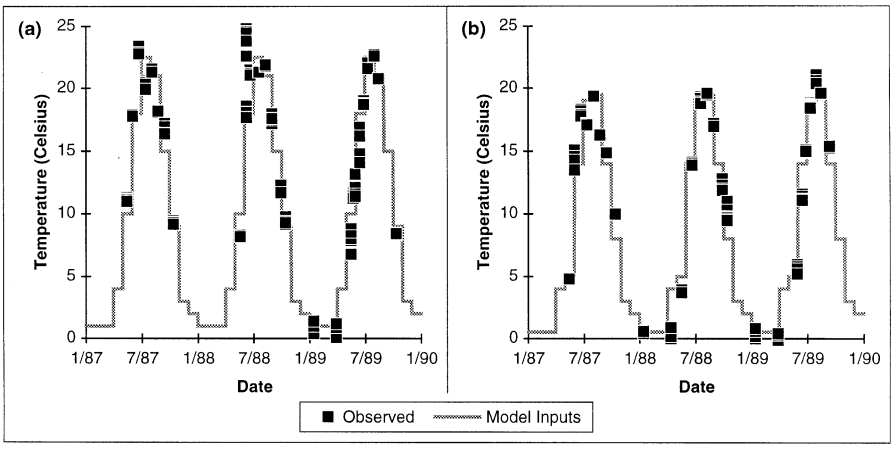

Figure 1. Water temperatures in Orange Lake and Trout Lake (1987-89); (a) Orange Lake, (b) Trout Lake; legend: ■ observed, — model inputs.

trends in these lakes. For this study, the warmest (Orange Lake) and coolest (Trout Lake) of the six lakes studied by Bodaly et al. (1993) were selected for comparison.

Study lakes

Orange Lake was smaller (1.67 km^2), had warmer temperatures, slower growth, and higher fish mercury concentrations than Trout Lake (347 km^2). Mean epilimnetic water temperatures (June–August) for the period 1986–1989 were 20.1 C and 16.9 C for Orange Lake and Trout Lake respectively. Figure 1 shows measured temperatures in the upper 3 metres at stations in the central areas of the two lakes from 1987–1989. Vertically aligned points indicate samples from multiple depths on a given date. pH levels were comparable between the lakes, and both lakes had moderate levels of dissolved organic carbon. Table 1 provides selected characteristics and observed fish mercury concentrations for the two lakes. Water chemistry values in Table 1 are means based on three to four sample periods per year during the NOLSS study. More information describing the lakes is available from Bodaly et al. (1993).

Model description

Models describing mercury uptake and dynamics in fish began to appear in the 1970's (e.g. Fagerstrom & Asell 1973; Fagerstrom et al. 1974; Norstrom et al.

Table 1. Selected characteristics of Orange Lake and Trout Lake, Ontario (Source: Bodaly et al. 1993).

Parameter	Orange Lake	Trout Lake
Lake area (km^2)	1.67	346.9
Mean depth (m)	14.4	13.7
Volume ($m^3 * 10^6$)	24.0	4758.0
Drainage basin area (km^2)	12.7	1065.0
Ratio of drainage basin to lake area	7.6	3.07
Ratio of drainage basin area to lake volume (m^{-1})	0.53	0.24
Ratio of epilimnetic sediment surface to epilimnetic volume	0.04	0.04
Mean epilimnetic water temperature (June 1986–August 1989) (Celsius)	20.13	16.88
Specific Conductance (at 25 C) ($\mu S * cm^{-1}$)	48	62
pH (mean)	7.5	7.69
DOC (mean, $mg * L^{-1}$)	8.8	5.0
Alkalinity (mean, $meq * L^{-1}$)	373	545
Ca (mean, $mg * L^{-1}$)	5.3	8.5
Observed walleye Hg concentration (ug g^{-1} wet muscle, 40 cm fork length)	0.84	0.26
Observed yearling yellow perch Hg concentration (ug g^{-1} wet muscle)	0.12	0.036

1976). A bioenergetics approach was used to consider the energy requirements of a fish and the associated methylmercury exposure via the diet and across the gills. More recent applications include studies of methylmercury dynamics in walleye, northern pike, yellow perch, lake trout and finescale dace (Rodgers 1996; Harris et al. 1996; Rodgers 1994; Korhonen et al. 1995; Tetra Tech 1994; Harris & Snodgrass 1993). For this study, bioenergetics equations developed at University of Wisconsin (Hewett & Johnson 1992) were coupled to methylmercury kinetics (see Appendix). Processes included MeHg uptake via food and water, clearance, egestion of unassimilated MeHg, and fish growth rates (Figure 2).

Based on field experiments and previous bioenergetics analyses, fish uptake of methylmercury in locally uncontaminated lakes is primarily from food ($>$90%, Hall et al., in press; Harris & Snodgrass 1993). Food consumption is estimated in the model based on energy requirements for growth, metabolism, and reproduction. When using a size standard for fish mercury concentrations, the model predicts that slower growth results in higher concentrations, although this is not necessarily the case when using an age standard (Harris & Watras 1996). Warmer temperatures can also increase

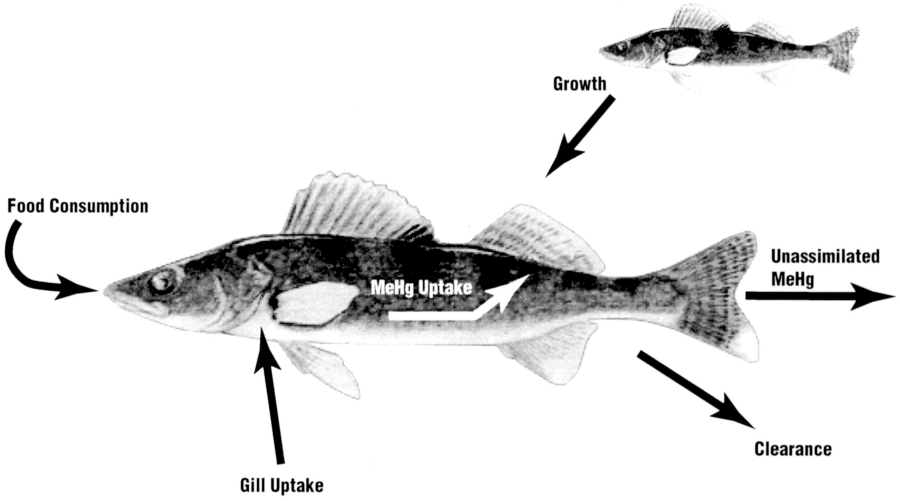

Figure 2. Processes included in bioenergetics analysis.

fish mercury concentrations by increasing the metabolic energy needs and methylmercury uptake to reach a standard size.

Approach

Predicted mercury concentrations in axial muscle were compared to observations for walleye and yellow perch sampled from Orange Lake and Trout Lake. Table 2 provides selected input values used for the simulations. Observed fish growth rates (Fudge et al. 1994) were used. A repeating annual cycle of mean monthly temperatures was fitted to the field data and used as model inputs (Figure 1).

Dietary MeHg concentrations were adjusted until predicted walleye concentrations matched observed values. Predicted dietary concentrations were then compared to observed concentrations in yearling yellow perch, an important component of the walleye diet. A similar approach was used for yellow perch, although data on the dietary MeHg exposure were not available to test the predicted dietary exposure.

Observed concentrations in this study were of total mercury in muscle, while the model is based on a whole-body mass balance for methylmercury. It was assumed that 80–100 percent of the mercury in fish is methylmercury (whole body) at uncontaminated sites. Predicted whole body methylmercury concentrations were adjusted to muscle concentrations using a multiplier of 1.5, a value which encompasses some uncertainty. Measurements of the ratio

Table 2. Selected inputs for simulations.

Parameter	Orange Lake	Trout Lake	Both lakes
Walleye growth	40 cm fork length, 643 g at age 8.9 years	40 cm fork length, 700 g at age 5.8 years	–
Yellow perch growth	5 g at age 1.25 years	6 g at age 1.25 years	–
Water temperatures	–	–	See Figure 1
MeHg uptake efficiency from food	–	–	0.70 (walleye) 0.75 (yellow perch)
MeHg uptake efficiency from water (little effect on results)	–	–	0.36 (walleye and yellow perch)
MeHg clearance rate (halflife in years, depends on temperature, metabolic rate)			Walleye: 0.6–12 years Yellow perch: 0.25–2.5 years up to age 1.25
Caloric density of fish (kcal g^{-1} wet)	–	–	1.1 (walleye and yellow perch)
Caloric density of diet (kcal g^{-1} wet)	–	–	1.1 (walleye) 0.9 (yellow perch)
Assumed MeHg concentration in water (ng L^{-1})	–	–	0.05 to 0.30, base case 0.1
Walleye weight when piscivory begins (g)	–	–	50
Rate of increase in dietary MeHg once walleye become piscivorous (ug Hg g $food^{-1}$ g $fish^{-1}$)			0.00003
Ratio of mercury concentrations in muscle and whole body	–	–	1.5

of total mercury in muscle to whole body for finescale dace (R. Bodaly, unpublished data) ranged from 1.29 to 2.39 (n = 8). Goldstein et al. (1996) reported mean ratios of muscle to whole body total mercury concentrations of 1.72 and 1.64 for carp and catfish respectively from the Red River of the North.

Methylmercury clearance was included but assumed to be a secondary influence, particularly in larger adult fish. There is some question regarding methylmercury clearance rates in fish and the relationship between mercury clearance and metabolism (Norstrom et al. 1976). Rodgers (1994) included a temperature dependence for methylmercury clearance in a study modelling mercury dynamics in yellow perch and lake trout. This was necessary to avoid dramatic decreases in predicted mercury concentrations in small fish in winter. To avoid similar difficulties in this study, clearance was modelled to be proportional to the rate of excretion of nitrogenous wastes. In this manner, clearance was indirectly related to metabolic rate and temperature. Methylmercury clearance half-lives were on the order of months to years in this study, being faster in small fish in warmer waters. It is recognized that there are other possible mechanisms for clearance (e.g. via the gills), and further research is needed on methylmercury clearance and the effects of weight loss on mercury concentrations in fish.

Results

Observed mercury concentrations in the axial muscle of standardized 40 cm fork length walleye were 0.26 ug g^{-1} and 0.84 ug g^{-1} in Trout Lake and Orange Lake respectively. The principal factor explaining higher walleye Hg concentrations in Orange Lake was MeHg in the diet (73% of total difference, Figure 3). Growth rate (19%) and temperature/metabolism (8%) effects were significant but secondary. Predicted dietary MeHg concentrations for walleye at the time piscivory began (50 g fish) were 0.033 ug g^{-1} and 0.086 ug g^{-1} in Trout and Orange Lakes, respectively (whole body concentrations in the diet). This agreed well with observed MeHg concentrations in yearling yellow perch, adjusted to a whole body basis, which were approximately three-fold higher in Orange Lake (Table 3).

Observed mercury concentrations in the axial muscle of yearling yellow perch were 0.036 ug g^{-1} and 0.12 ug g^{-1} in Trout Lake and Orange Lake respectively. Dietary MeHg exposure was also predicted to be the main source of difference in yellow perch Hg concentrations between the two lakes (91%), while growth and temperature/metabolism effects were small (Figure 4).

Data were not available for methylmercury concentrations in water. A range of concentrations was tested (0.05 to 0.3 ng L^{-1}, base case 0.1 ng L^{-1}) to

Table 3. Comparison of predicted Hg in walleye diet and observed Hg in yearling yellow perch.

	Mercury concentrations (ug g^{-1} wet, whole body)	
	Predicted in walleye diet (when piscivory began)	Observed in yearling perch*
Trout lake (coolest)	0.033	0.025
Orange Lake (warmest)	0.086	0.08

* Assumes observed Hg concentration in whole body = 0.67 × observed muscle concentration.

examine the model sensitivity to this parameter. Gill uptake of methylmercury was predicted to be small relative to the food pathway for walleye (<5% of total uptake after piscivory began) and yellow perch (<10%). Predicted walleye and yellow perch mercury concentrations changed less than 5% and 8% respectively in response to changes in the assumed methylmercury concentration in water.

Discussion

These modelling results indicate that higher MeHg exposure in the diet is the primary source of difference in mercury concentrations in walleye and yellow perch between Orange Lake and Trout Lake. Yellow perch are a significant component of the walleye diet. The agreement between predicted dietary MeHg concentrations for walleye at the time piscivory began and observed MeHg concentrations in yearling yellow perch (Table 3) supports model results and the predicted importance of dietary exposure. Predicted temperature/metabolic and growth effects were secondary.

Differences in mercury concentrations could also arise if fish activity levels (e.g. foraging) were different between the lakes. Increased activity would lead to higher metabolic demands, food consumption and fish mercury concentrations. However, we have no evidence to suggest that fish activity levels should be notably higher in the smaller, warmer lakes. Furthermore, the predicted dietary, growth and temperature differences were sufficient to explain the range in fish mercury concentrations between the two lakes, without a need to invoke differences in activity.

The mean concentrations of DOC were 8.8 and 5.0 mg L^{-1} in Orange and Trout Lakes respectively. Since DOC has been reported to correlate positively with methylmercury concentrations in water in some systems (Watras et al. 1995), higher levels of water column methylmercury might occur in Orange Lake than Trout Lake. The simulations indicate however that the

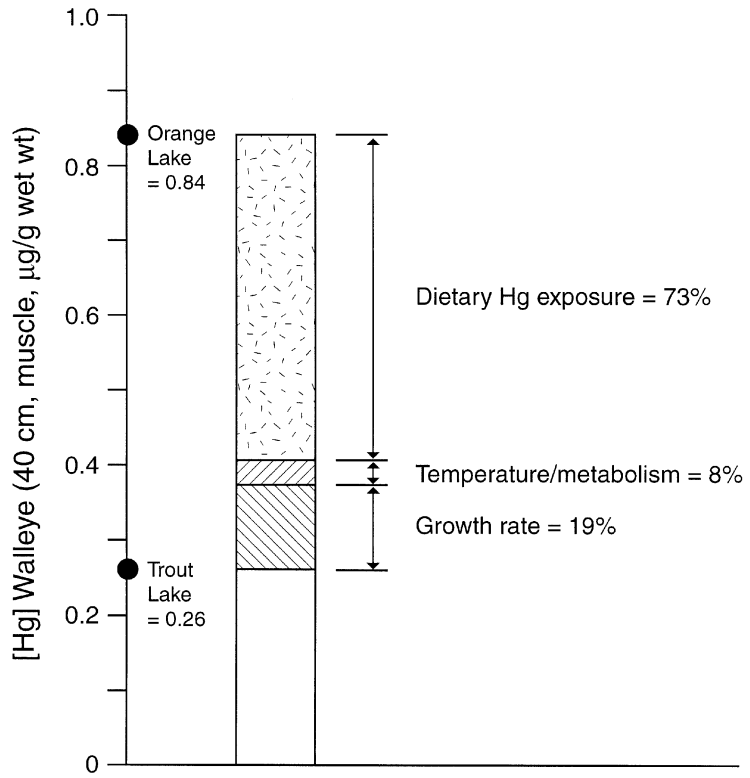

Figure 3. Factors explaining differences in walleye (40 cm fork length) Hg concentrations between Trout Lake and Orange Lake. ● observed

fish mercury concentrations were not sensitive to differences in direct waterborne methylmercury exposure across the gills for dissolved methylmercury concentrations ranging from 0.05 to 0.3 ng L^{-1}.

Temperature effects on fish metabolism and methylmercury

Temperature effects on internal fish mercury dynamics occur as warmer temperatures increase metabolic rates and the associated food (and methylmercury) consumption to reach a given size. Temperatures in the two lakes were below the optimal temperature for walleye respiration (27 Celsius, Hewett & Johnson 1992). Increased temperature was therefore predicted to result in increased respiration demands. However the predicted temperature effects on metabolism can explain less than 10 percent of the observed threefold range of mercury concentrations observed in 40 cm walleye and yearling yellow perch between Trout and Orange Lakes. Although temperature effects on metabolism and internal fish mercury dynamics may be small in these two

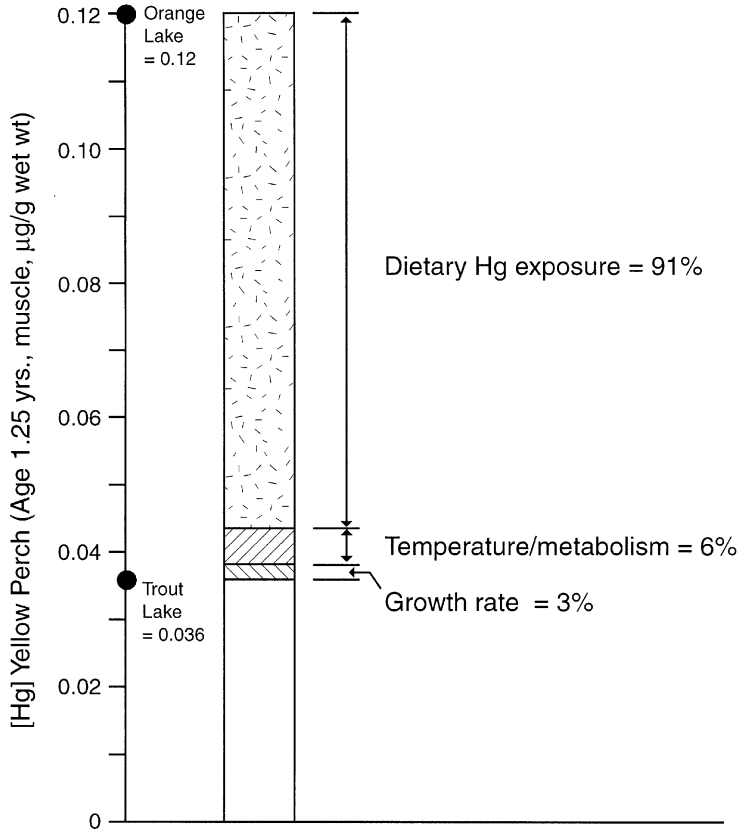

Figure 4. Factors explaining differences in yearling yellow perch Hg concentrations between Trout Lake and Orange Lake. ● observed

lakes, temperature may still exert important effects on processes outside the fish, for example affecting methylation rates.

Growth rate effects on fish methylmercury dynamics

Growth rates can affect fish mercury concentrations (Rodgers 1996; Harris & Watras 1996). Faster growth results in less time required to reach a given size (e.g. 40 cm). Less time is spent metabolizing and eating food for metabolic needs. This results in a lower cumulative mercury exposure and concentration in a faster growing fish, when using a size standard for mercury. Walleye in Orange Lake took approximately 50% longer to reach 40 cm than Trout Lake (see Table 2). Growth associated effects on mercury concentrations in walleye were significant (19 percent of the predicted difference between the two lakes,

Figure 3), but were inadequate to explain the majority of the observed range for standardized 40 cm walleye in Trout and Orange Lakes.

Conclusions

Dietary methylmercury exposure is likely the primary factor explaining the three-fold difference in walleye mercury concentrations observed between Trout Lake and Orange Lake. These model results are consistent with the hypothesis of Bodaly et al. (1993) that the observed trend was due to temperature related effects on gross and net methylation rates in the lakes. It is also possible that variations in other factors could lead to different dietary mercury exposure for yellow perch, and subsequently walleye via the diet, between the two lakes. These factors include MeHg supply from the watershed, other factors affecting in-situ methylation or losses (e.g. photodegradation), MeHg pathways in the lakes, fish activity levels, and bioavailable fractions of MeHg concentrations for uptake at the base of the food chain.

Although the predicted effects of water temperature (approximately 3–4 °C range) and growth on internal fish mercury dynamics were secondary in these two lakes, the effects of greater temperature ranges (eg. on a continental scale) and growth rates need evaluation.

Acknowledgements

We wish to thank Robert Fudge for the important unpublished data and ideas he contributed to this paper.

Appendix: Model equations

The model can be divided into two main sections: (i) a bioenergetics component which simulates the energy and biomass fluxes for a fish; and (ii) a mercury dynamics component which couples mercury to the bioenergetics fluxes.

1) *Bioenergetics equations*

The bioenergetics equations are based on an energy balance for a fish:

$$C = (R + S) + (U + F) + (dW) \qquad \text{(Hewett \& Johnson 1992)}$$

where:

C = consumption,
R = respiration,
S = specific dynamic action,
U = excretion,
F = egestion, and
dW = growth
(all units: kcal g^{-1} wet fish d^{-1}).

Respiration (R) plus specific dynamic action (S) represent total metabolic rate. Egestion (F) plus excretion (U) represent waste losses. For this study, growth was an independant variable, provided as an input. Respiration, consumption, egestion and excretion were all dependant, modeled variables. Once the energy flows were established using the bioenergetics equations, the mass fluxes (e.g. grams of food eaten) were estimated by adjusting the energy fluxes by the caloric content of the mass (either food or fish). Further information on consumption, respiration, egestion and excretion equations is available in Hewett & Johnson (1992).

2) *Methylmercury dynamics*

Methylmercury fluxes were determined on the basis of the bioenergetic mass fluxes and methylmercury concentrations in the fish, food and water. The expresion for methylmercury fluxes is represented by:

$$\Delta\text{MeHg Burden} = \text{MeHgFlux}_{\text{food}} + \text{MeHgFlux}_{\text{gills}} - \text{MeHgFlux}_{\text{excrete}}$$

where: (all terms in ug MeHg fish^{-1} day^{-1})

ΔMeHg Burden = Change in methylmercury burden in fish
$\text{MeHgFlux}_{\text{food}}$ = Methylmercury flux into fish via food
$\text{MeHgFlux}_{\text{gills}}$ = Methylmercury flux into fish via gills
$\text{MeHgFlux}_{\text{excrete}}$ = Methylmercury flux out of fish via excretion

Concentrations are determined by combining the methylmercury fluxes with growth information.

Methylmercury uptake via consumption

$$\text{MeHgFlux}_{\text{food}} = \text{Eatenfood} * \text{MeHg}_{\text{food}} * \text{E}_{\text{pf}}$$

where:

EatenFood = Food consumed (g wet food fish^{-1} day^{-1})
= $\text{C} * \text{W} * \text{Caldensfood}^{-1}$
W = Fish weight (g)
Caldensfood = Caloric density of food (kcal g^{-1} wet food)
$\text{MeHg}_{\text{food}}$ = Methylmercury concentration in food (ug MeHg g^{-1} wet food)
E_{pf} = Efficiency of uptake of methylmercury in food (dimensionless)

Literature values for E_{pf} are typically in the range of 0.65 to 0.8 (Wiener & Spry 1996; Rodgers 1994; Rodgers & Beamish 1982; Norstrom et al. 1976). It was assumed that walleye ate a diet of constant methylmercury concentration until piscivory began. When consuming other fish, the methylmercury concentration in the walleye diet was assumed to increase as

the fish size increased, reflecting larger prey fish expected to have higher methylmercury concentrations. The following relationship was used:

$$MeHg_{food} = MeHg_{food(pre-piscivory)} + DietSlope * W$$

where:

$MeHg_{food(pre-piscivory)}$	=	MeHg concentration in walleye diet until piscivory begins (ug g^{-1} wet)
DietSlope	=	Rate of increase in dietary MeHg concentration, as a function of walleye weight (ug g^{-1} wet food g^{-1} wet fish).

Methylmercury uptake via gills

$$MeHgFlux_{gills} = E_{pw} * MeHg_{water} * (R + S) * W * (E_{ox} * C_{ox} * Q_{ox})^{-1}$$

where:

E_{pw}	=	Efficiency of uptake of methylmercury from water (dimensionless)
$MeHg_{water}$	=	Methylmercury concentration in water (ug MeHg m^{-3})
E_{ox}	=	Efficiency of uptake of oxygen from water (dimensionless)
C_{ox}	=	Oxygen concentration in water (g O_2 m^{-3})
Q_{ox}	=	Caloric value of oxygen (kcal g^{-1} O_2)

Methylmercury excretion

$$MeHgFlux_{excrete} = MeHg_{fish} * Excretion * X$$

where

$MeHg_{fish}$	=	Methylmercury concentration in fish tissue (ug MeHg g^{-1} wet fish)
Excretion	=	Excretion rate (g nitrogenous wastes $fish^{-1}$ day^{-1})
X	=	Ratio of MeHg concentrations in excreted waste and fish tissue (dimensionless)

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