

Accumulation of dietary methylmercury by walleye and white crappie in the Tongue River Reservoir, Montana
by Denise Elaine Knight

A thesis submitted in partial fulfillment of the requirements for the degree of MASTER OF SCIENCE in Zoology
Montana State University
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Abstract:
Food habits and consumption rates, mercury concentrations in food organisms, and mercury accumulation rates of walleye and white crappie from the Tongue River Reservoir, Montana, were studied in detail in order to estimate mercury uptake from the diet and to compare these estimates to observed mercury accumulation rates. Analysis of stomach contents showed that walleye are predominantly piscivorous, feeding principally on young-of-the-year crappie. Age 0 crappie were also important food items for white crappie, however zooplankton and aquatic insects were prominent in their diets as well. Diet composition of both species varied with fish size and season, and white crappie diets varied with time of day. Annual food consumption rates were estimated at 1.5 to 2.2% body weight/day for walleye and 1.1 to 3.5% body weight/ day for white crappie. Mercury in forage organisms averaged 0.08 µgHg/g and ranged from 0.02 to 0.40 µgHg/g. Calculated average concentrations of methylmercury in fish diets averaged 0.05 µgMeHg/g for walleye and 0.04 µgMeHg/g for white crappie.

Mercury concentrations in walleye and white crappie increased with increasing fish length, and were similar in walleye and white crappie of the same age. This appears to stem from similarities in their food habits and in the amount of methylmercury consumed. The percentage of accumulated methylmercury derived from food was estimated at 41-62% for walleye and 51-73% for white crappie, however the error associated with these estimates is potentially quite large. Under conditions which can reasonably be assumed to occur, food is shown to be a major source of accumulated methylmercury in Tongue River Reservoir fishes, however, analytical difficulties prevented an accurate, quantitative determination of its importance.

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A thesis submitted in partial fulfillment
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ABSTRACT

Food habits and consumption rates, mercury concentrations in food organisms, and mercury accumulation rates of walleye and white crappie from the Tongue River Reservoir, Montana, were studied in detail in order to estimate mercury uptake from the diet and to compare these estimates to observed mercury accumulation rates. Analysis of stomach contents showed that walleye are predominantly piscivorous, feeding principally on young-of-the-year crappie. Age 0 crappie were also important food items for white crappie, however zooplankton and aquatic insects were prominent in their diets as well. Diet composition of both species varied with fish size and season, and white crappie diets varied with time of day. Annual food consumption rates were estimated at 1.5 to 2.2% body weight/day for walleye and 1.1 to 3.5% body weight/day for white crappie. Mercury in forage organisms averaged 0.08 μgHg/g and ranged from 0.02 to 0.40 μgHg/g. Calculated average concentrations of methylmercury in fish diets averaged 0.05 μgMeHg/g for walleye and 0.04 μgMeHg/g for white crappie.

Mercury concentrations in walleye and white crappie increased with increasing fish length, and were similar in walleye and white crappie of the same age. This appears to stem from similarities in their food habits and in the amount of methylmercury consumed. The percentage of accumulated methylmercury derived from food was estimated at 41-62% for walleye and 51-73% for white crappie, however the error associated with these estimates is potentially quite large. Under conditions which can reasonably be assumed to occur, food is shown to be a major source of accumulated methylmercury in Tongue River Reservoir fishes, however, analytical difficulties prevented an accurate, quantitative determination of its importance.

INTRODUCTION

Mercury is a dangerous environmental contaminant which has been extensively researched because it accumulates in aquatic organisms to concentrations which endanger human consumers. Methylmercury is the form of greatest concern, as it is both the most toxic and the most readily accumulated chemical species (Hannerz 1968; Clarkson 1971). Inorganic mercury is converted to methylmercury by aquatic bacteria under a variety of conditions, making all forms potentially hazardous (Wood et al. 1968; Jensen and Jernelöv 1969). Interestingly, fish can accumulate methylmercury to concentrations that far exceed recommendations for safe human consumption without manifesting adverse effects themselves (McKim et al. 1976).

Laboratory studies demonstrate that fish assimilate methylmercury from water across gill surfaces, and from food via digestive absorption (Hannerz 1968; Lock 1975; Olson et al. 1975); mercury accumulated from both sources is additive (Phillips and Buhler 1978). However, conflicting evidence in the literature concerning the relative importance of these two sources of mercury to fishes in natural waters, leaves unresolved the question of whether or not mercury is magnified through food chains. Methylmercury accumulation from water has not been directly quantified because current analytical techniques are not sensitive enough to detect the low concentrations of methylmercury which occur in most natural waters (Westöö 1975; National Academy of Sciences

1978). The alternative approach, direct quantification of methylmercury accumulated by fish from their food, has proven equally frustrating due to the difficulty of determining methylmercury consumption by fish in natural waters (National Academy of Sciences 1978).

This study was conducted to try to quantify dietary accumulation of methylmercury, under natural conditions, by two species of fish (walleye, Stizostedion vitreum, and white crappie, Pomoxis annularis) occupying different trophic positions in the Tongue River Reservoir and was part of a project to identify and evaluate sources, fates, and cycling of mercury in the Tongue River Reservoir. To estimate mercury uptake from the diet, data were collected on dietary habits, food consumption rates, and mercury concentrations in food organisms.

DESCRIPTION OF STUDY AREA

The Tongue River Reservoir (TRR) is an irrigation and flood control impoundment located in southeastern Montana, approximately 10 km north of the Montana - Wyoming border, near the small town of Decker in Bighorn County (Figure 1). The region is semi-arid and sagebrush communities predominate. The Tongue River originates in the Bighorn Mountains of Wyoming and flows northeast, eventually joining the Yellowstone River near Miles City, Montana. The river receives sewage effluents from Sheridan, Wyoming, upstream from the reservoir. The reservoir itself lies atop the Fort Union coal formation and has two active surface coal mines adjacent to it; a third mine is proposed.

The TRR is a mildly eutrophic, well-mixed, hardwater impoundment (Whalen 1979); selected chemical and physical characteristics of the reservoir are summarized in Table 1. Important sport fishes in the reservoir's warm-water fishery include white crappie, black crappie (Promoxis nigromaculatus) sauger (Stizostedion canadense), northern pike (Esox lucius), and walleye. Aquatic macrophytes (and the macroinvertebrates normally associated with them) are not well established, presumably due to the extreme fluctuations in water level which regularly occur from spring to fall (Whalen 1979). Benthic fauna is also impoverished, however planktonic communities are moderately to highly productive (Leathe, 1980), and probably serve as a base for reservoir food chains.

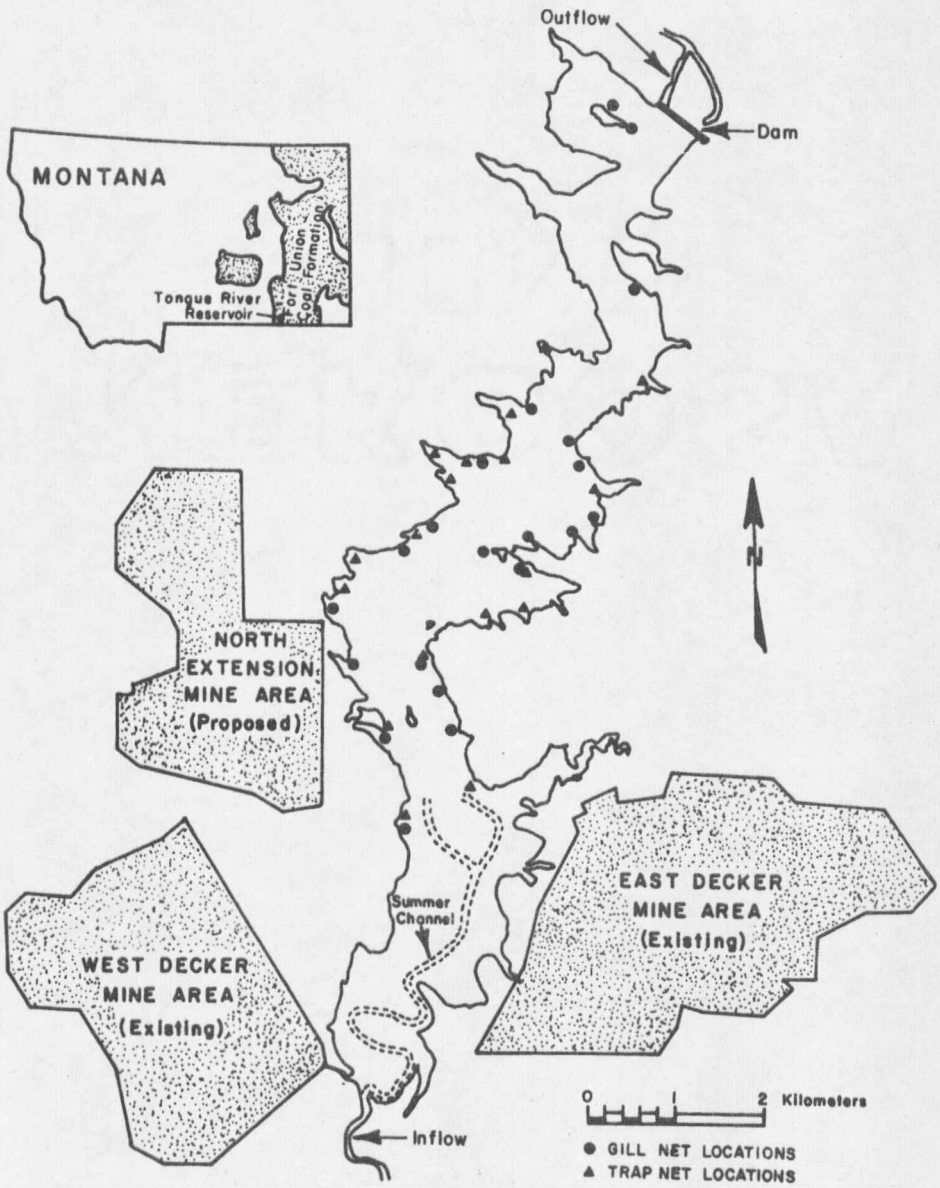


Figure 1. Map of the Tongue River Reservoir showing nearby surface coal mining activity and sampling sites for walleye (using primarily gill nets) and white crappie (using primarily trap net).

Table 1. Some chemical, physical and morphometric characteristics of the Tongue River Reservoir; physical/chemical data collected from November 1975 - November 1976 (Whalen 1979).

Mean depth (m)	5.9
Maximum depth (m)	18.0
Surface area (km^2)	13.0
Volume (m^3)	757×10^5
Depth of outlet (m)	15.2
Temperature (°C)	11.0 (1.2 - 23.9)[a]
Dissolved oxygen (mg/l)	19.3 (0.2 - 19.6)[a]
pH	8.4 (7.5 - 9.0)[a]
Turbidity (JTU)	12.1 (1.3 - 62)[a]
Total alkalinity (me/l)	3.66 (1.56 - 5.62)[a]
Total P (µg/l)	5.1 (1.0 - 260)[a]

[a] Mean and range from three sampling stations.

METHODS

Field Collection

Walleye, white crappie, and their food organisms were collected every other month from ice-off in April through October, 1980. Sampling was confined primarily to the middle third of the reservoir for convenience (Figure 1), as mark-recapture data indicate that both species move freely throughout the reservoir (Riggs 1978; Lenhart pers. comm.).

White crappie were collected at three hour (3-h) intervals using single-lead trap nets. Samples were taken for all times of day, and sets were repeated if the sample size for a given time interval was small. Short sampling intervals allowed observation of daily feeding peaks and provided relatively undigested stomach contents. Walleye were collected using single mesh and "experimental mesh" gill nets which were set in the late afternoon, fished overnight, and worked early the next morning. Identifiable stomach contents were obtained with this schedule, eliminating the need for more frequent sampling. Forage fish were collected using both gill and trap nets while sweep nets and an Ekman dredge were used to collect invertebrates.

An effort was made to capture 30-50 walleye and 60-80 white crappie (six to ten from each time of day) during each of the four sampling periods (April, June, August and October). Fish were selected to cover a wide size range. All fish were sacrificed at collection, weighed to

the nearest ten grams (g), and their total length measured to the nearest millimeter (mm). A muscle sample was taken from the anterior epaxial area and frozen for subsequent individual mercury analysis. The stomach (walleye) or entire gastrointestinal tract (crappie) was removed, preserved in 70% ethanol, and stored for later identification of the contents.

Stomach contents were periodically inspected in the field and predominant food organisms were collected and frozen whole for subsequent mercury analysis and calculation of mercury in diet. For comparison, the frozen stomach and intestinal contents of approximately 80 white crappie (representing all sampling periods except June) were also analyzed for mercury. A few (five to ten) walleye and white crappie were frozen whole to compare mercury concentrations in whole fish to mercury concentrations in muscle.

Mercury Analyses

Mercury analyses were performed by the staff of the Chemistry Station at Montana State University. Total mercury concentrations (μg Hg/g) in fish and invertebrates were determined using a Varian model AA-6 atomic absorption spectrophotometer. Samples were burned in an oxygen combustion chamber and the evolved mercury collected on a hollow gold-plated carbon rod. The tube was then heated in a carbon rod atomizer, thereby releasing the mercury, and the resulting absorption

signal was measured (Siemer and Woodriff 1974). Whole fish were homogenized in a blender with dry ice and an aliquot of the resulting frozen powder was analyzed for total mercury as above. The system was calibrated using freshly mixed standard solutions and tissue samples of known mercury concentration from the U.S. National Bureau of Standards. Blind and known duplicate analyses of samples were also performed. Mean percent deviation was 13.4 (0.03 μgHg/g) for known tissue duplicates, 17.3 (0.01 μgHg/g) for known whole fish duplicates and 31.1 (0.08 μg Hg/g) for blind tissue duplicates. All mercury concentrations are reported on a wet weight basis.

Methylmercury (MeHg) concentration was determined for whole fish as follows: an aliquot of homogenized tissue (prepared as for total mercury) was acidified with hydrochloric acid (forming methylmercuric chloride) and extracted into benzene. Methylmercury was then removed from the benzene by partitioning it into aqueous cysteine; this cysteine layer was acidified and the resulting MeHg salt re-extracted into benzene. MeHg in the final benzene layer was quantified in a gas-liquid chromatograph equipped with an electron capture detector (Watts et al. 1976).

Food Habit Analyses

Volumes of stomach and intestinal (crappie only) contents were measured to the nearest 0.05 cubic centimeter (cc) in the laboratory; white crappie contents were weighed to the nearest 0.01 gram. Fish found in stomachs were identified to species, and their individual lengths and volumes measured when possible. Invertebrates were identified to order or family, depending on state of digestion. Total invertebrate volumes were measured directly for each stomach, however the small volumes of individual orders and families precluded direct measurement. Percent volumes of invertebrate orders and families were therefore estimated visually by distributing the contents evenly over a grid. Percent frequency of occurrence and percent volume were calculated for major diet components by season (sampling period), size (length), and time of day (crappie only). Fish were divided into length categories according to growth rates and length-age class estimates for walleye (Riggs 1978) and white crappie (Elser et al. 1977) from the TRR. Live total lengths of prey fish consumed were estimated from their digested remains, using linear regression equations (Snedecor and Cochran 1967) comparing the total lengths of undigested fish to the lengths of various portions of their bodies (Table 2).

Table 2. Linear regression equations used to estimate live total length (TL) of prey fish eaten from portions of their digested remains. Equations derived from a series of length measurements made on whole fish. $p < 0.001$ for all equations.

Forage species	Regression	r^2
Crappie spp.	TL = 1.30 (standard length) + 1.65	0.99
	TL = 1.67 (trunk & operculum) + 1.39	0.99
	TL = 1.93 (trunk length) + 2.72	0.99
Golden shiner	TL = 1.33 (standard length) - 3.71	0.99
	TL = 1.53 (trunk & operculum) - 2.77	0.99
	TL = 1.69 (trunk length) - 3.21	0.99
Yellow perch	TL = 1.24 (standard length) - 4.68	0.90
	TL = 1.47 (trunk & operculum) + 1.64	0.88
	TL = 1.73 (trunk length) - 3.02	0.89
Combined	TL = 1.19 (standard length) + 6.27	0.94
	TL = 1.41 (trunk & operculum) + 12.83	0.92
	TL = 1.60 (trunk length) + 13.62	0.92

Food Consumption Rates

Walleye. Annual food consumption rates of walleye in the TRR were estimated for each size class from specific growth rates (g/g/day) and metabolic requirements, utilizing the bioenergetics model of Kitchell et al. (1977) as modified by Breck and Kitchell (1978). Metabolic requirements were predicted from average body weights and average reservoir temperatures. Riggs (1978) age and growth data were used to estimate specific growth rates and average body weights. The year was divided into a growing period (May - September) when average monthly reservoir temperatures exceeded 12 C (the physiological threshold for growth of walleye; Kelso 1972), and a non-growing period (October - April) when monthly temperatures were below 12 C. The average temperature for the growing period was 18.2 C over several years, while 4.7 C was average for the non-growing period (Whalen 1979; Leathe 1980; Phillips et al. 1980). Consumption estimates for the two periods were averaged to obtain an annual ration (R). Multiples of the standard metabolic rate of a species, commonly referred to as Winberg I, II and III, were used to estimate resting, average, and maximum metabolic rates (activity levels) of walleye (Winberg 1956; Ware 1975). Possible combinations of these activity levels for growing and non-growing periods gave a range of annual consumption values for use in calculating MeHg uptake from food.

White crappie. Food consumption rates of white crappie were estimated for each sampling period from daily feeding peaks, using the field method described by Nakashima and Leggett (1978); size classes were pooled to improve sample size. For each 3-h sampling interval, the total wet weights of the digestive tract contents (stomach plus intestine) were corrected for the effects of preservation, pooled by sampling period, and expressed as a percentage of the total body weight of the fish. Graphs of these values plotted versus time displayed feeding peaks, which were summed to provide an estimate of 24-h food consumption in that month. Consumption rates for May, July, and September were estimated by extrapolating between calculated values. Maintenance rations based on Kitchell et al.'s (1977) estimates for 100 g yellow perch and mean monthly reservoir temperatures were assumed for November through March. Monthly estimates were averaged to obtain an annual estimate and standard errors were calculated (Snedecor and Cochran 1967), providing a range of consumption values for use in calculating MeHg uptake from food.

Methylmercury in the Diet

Methylmercury concentrations in the diet were calculated for each size class of walleye and white crappie. Total mercury concentrations in food items were measured directly whenever possible. They were converted to methylmercury concentrations by multiplying by the percentage

of total mercury present as MeHg, as reported in the literature (Appendix Tables 13 and 14). Literature values range from 6 to 76% (average 33%) for MeHg present in invertebrates, and from 56 to 100% (average 85%) for MeHg present in fish. Calculations were made using low, mean and high methylmercury percentages due to the wide range of values reported.

Diets were divided into invertebrate and fish components to calculate MeHg concentrations. Invertebrates were subdivided by order; orders comprising 3% or less of the total stomach volume of a size class were combined. Forage fish were subdivided into 10 mm length intervals by species, and mercury concentration of each interval was estimated using species regression equations (Snedecor and Cochran 1967) for mercury concentration versus total fish length (Table 2). The fraction of the diet represented by each component was then multiplied by the appropriate methylmercury concentration and summed, giving the overall concentration of MeHg in the diet (C).

Methylmercury Accumulation

Observed accumulations. Methylmercury accumulation rates were determined by comparing regression equations for total mercury concentration versus fish length from different years. Problems associated with the fit provided by these equations are discussed along with the mercury results for walleye and white crappie, however the equations

provide a valid format for comparison to data previously analyzed in this manner. Average mercury concentrations of each size class were calculated for 1978 and 1980 from estimated lengths of these fish in each year. Multiplying by the average weight gives the average amount of total mercury present in each fish in 1978 and in 1980. The difference in these amounts, divided by two, is the annual total mercury accumulation rate. This value was multiplied by the percentage of total mercury present as MeHg in fish (Appendix Table 14), giving $\Delta M/\Delta t$, the annual rate of MeHg accumulation, with M in µg MeHg. Low mean, and high percentages of MeHg were used to calculate $\Delta M/\Delta t$, giving values designated as $\Delta M/\Delta t$-low, $\Delta M/\Delta t$-mean, and $\Delta M/\Delta t$ high, respectively.

Uptake from food. Methylmercury accumulation from food was calculated using the equation:

$$\frac{\Delta F}{\Delta t} = a\ R\ C\ W \qquad (1)$$

where $\Delta F/\Delta t$ is the rate of MeHg uptake from food in µg MeHg per year, `a´ is the assimilation efficiency of MeHg from the diet, R is the ingested ration, C is the concentration of MeHg in the diet and W is the average weight of fish in that size class. This equation is similar to that used by Norstrom et al. (1976) to model the food uptake component of MeHg accumulation by fishes.

Calculations for mean, high and low values of R and C have already been described. For `a´, a wide range of values, 15-88%, was found in

the literature (Appendix Table 15). Both extremes have been used in previous models (Fagerstrom and Asell 1973; Norstrom et al. 1976), therefore both, plus a mean value (33%) were used in these calculations. Five of the 27 possible values for $\Delta F/\Delta t$ were calculated for each size class of walleye and white crappie. Maximum and minimum values provide a possible range for $\Delta F/\Delta t$, while the mean values, from the means of `a´, R, and C, represent middle ground. Since there is evidence to indicate that the lowest assimilation efficiency reported may be the most accurate under natural conditions (Phillips and Gregory 1979), mean and maximum values of $\Delta F/\Delta t$ were also calculated after assuming the minimum value for `a´, and were designated as the low/mean and low/high values for $\Delta F/\Delta t$.

Fraction attributable to food. Methylmercury uptake from food ($\Delta F/\Delta t$) was compared to observed MeHg accumulations ($\Delta M/\Delta t$) in two ways. A rough estimate of the fraction derived from food (FF) was obtained by summing $\Delta F/\Delta t$ over age and dividing by predicted 1980 mercury levels for each size class. This method (1) assumes all accumulated mercury is MeHg and does not correct for elimination.

A more rigorous procedure for estimating the fraction derived from food involves correction of $\Delta M/\Delta t$ for the portion of accumulated MeHg eliminated over the course of the year (method 2). Most investigators (Jarvenpää et al. 1970; Miettinen 1975; Huckabee et al. 1979) have

found MeHg elimination to be an exponential decay or half-life function. Half-life values found in the literature ranged from 0.3 to 7.0 years with an average of 2.25 years (Appendix Table 16). Roughly equivalent annual elimination rates ($\Delta E/\Delta t$) are 10%, 90%, and 30% of the body burden, respectively. Although the reported half-lives are clustered around the mean, many of them must be considered minimal as they represent the durations of tests during which little or no elimination occurred. In addition, the lowest elimination rates (or greatest half-lives) were reported for fish collected from natural (usually contaminated) waters. FF values were therefore calculated using both mean and low elimination rates ($\Delta E/\Delta t$-mean and $\Delta E/\Delta t$-low); high elimination rates were generally reported for trout or small fish and were not used.

The fraction of the total MeHg accumulation derived from food (FF) was then calculated using the equation:

$$FF = \frac{\Delta F/\Delta t}{\Delta M/\Delta t + E\Delta/\Delta t\ (\overline{\Delta M}/\Delta t)} \qquad (2)$$

where $\overline{\Delta M}/\Delta t$ is the mean accumulated MeHg in a fish during a year and all other symbols are as previously described. The correction for elimination assumes that accumulation is a linear function. The fraction of total MeHg accumulation derived from water is assumed to be

(1 - FF). Absolute amounts of MeHg in fish were used in these calculations, rather than concentrations, in order to compensate for the possible effects of growth dilution. This occurs when growth rate (g/g fish) exceeds MeHg accumulation rate (μg MeHg/g fish), resulting in lower tissue concentrations in faster-growing fish even when they are accumulating the same absolute amount of MeHg as their slower-growing counterparts.

RESULTS AND DISCUSSION

Organisms Collected

A total of 163 walleye and 247 white crappie were collected from the TRR in 1980. Walleye ranged from 172 to 790 mm in length and weighed from 50 to 6210 g, while white crappie ranged from 138 to 382 mm in length and weighed from 30 to 789 g (Table 3). Size distributions varied between sampling periods (Appendix Table 17); large walleye predominated in the catch in April, while small walleye were most common in June and August; sizes were fairly evenly distributed in the October catch. Size distribution was more even among white crappie, however large crappie were rarely caught in June and age 1 crappie did not appear in the catch until August.

Table 3. Number and size range of walleye and white crappie collected during each of the four 1980 sampling periods.

Sampling dates	Species	Sample size	Size range	
			length (mm)	weight (g)
4/16-5/9	Walleye	(34)	436-700	820-3600
	White crappie	(78)	163-382	60-780
6/18-7/10	Walleye	(18)	223-675	90-2600
	White crappie	(46)	190-258	90-210
8/7-8/14	Walleye	(59)	172-655	50-2620
	White crappie	(65)	138-288	30-340
9/30-10/8	Walleye	(52)	190-790	80-6210
	White crappie	(57)	154-296	40-385

Mercury in Walleye and White Crappie

Mercury concentrations in axial muscle tissue of walleye and white crappie increased with increasing fish length (Figures 2 and 3), as previously found for these species in the TRR (Phillips 1978; 1979). In other waters, positive relationships of size to mercury concentration have been reported for a variety of species (Bache et al. 1971; Scott and Armstrong 1972; Potter et al. 1975; Richins and Risser 1975; Benson et al. 1976; Koli et al. 1977; Cox et al. 1979; Hildebrand et al. 1980). This relationship has been characterized as exponential by Schell and Barnes (1974 in Huckabee et al. 1979) and Scott (1974), however the data from the TRR suggest a somewhat steeper curve. This may be related to a greater than exponential increase in age with length. Increases in mercury concentration with size and age appear to be universal, but the functions describing these relationships are not well defined.

Mercury residues ranged from 0.02 to 1.22 μgHg/g in walleye and from 0.02 to 0.53 μgHg/g in white crappie. Two of the 163 walleye and none of the 248 white crappie exceeded the current FDA consumption guideline of 1.0 μgHg/g. Numerous investigators have measured total mercury concentrations in freshwater fishes. In presumably uncontaminated waters, mercury concentrations in most fishes range from 0.04 to 0.15 μgHg/g, however, concentrations in predatory fishes, such as pike and walleye are often higher, ranging from 0.4 to 1.0 μgHg/g (Rucker

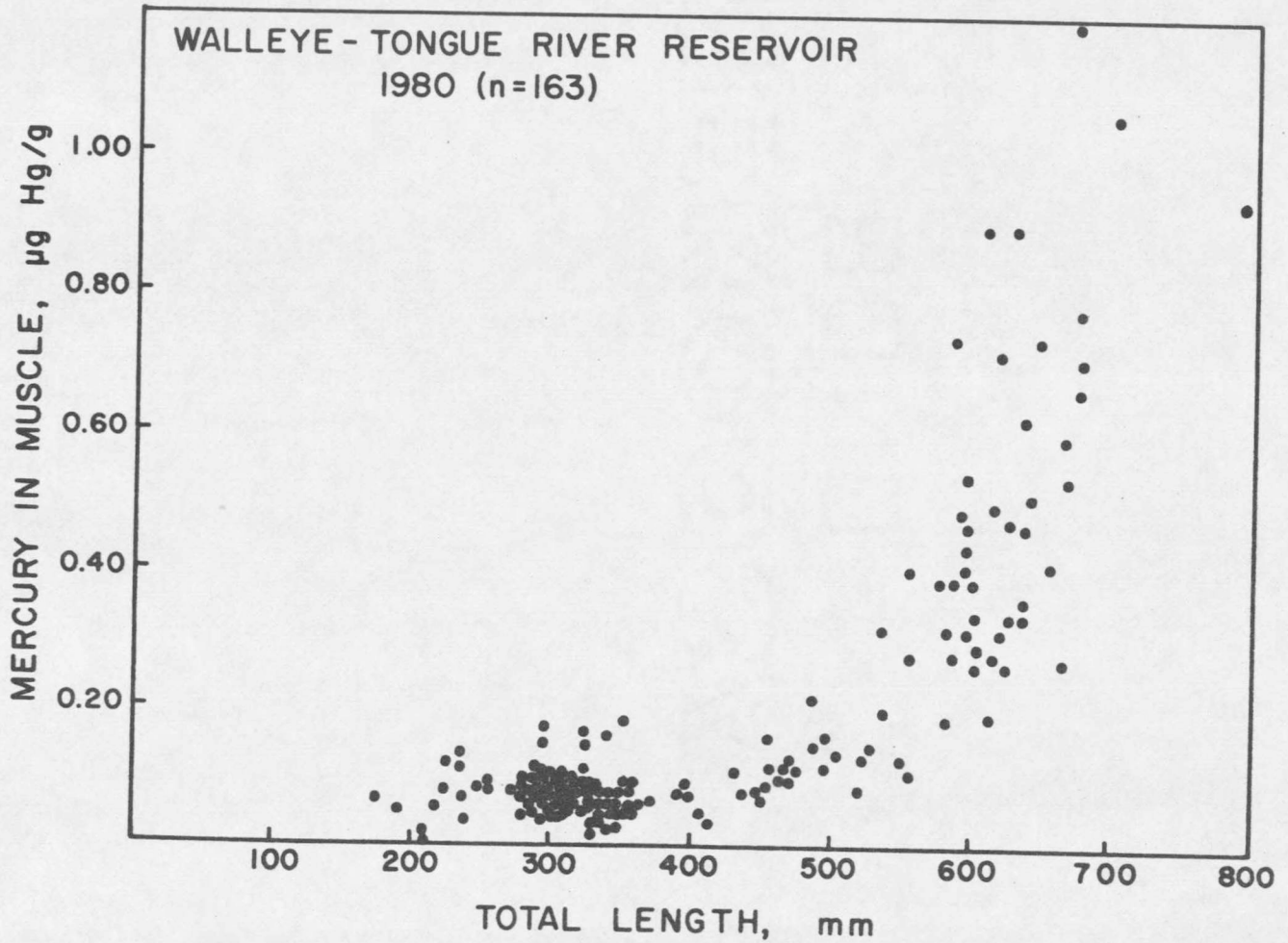


Figure 2. Relationship between concentration of total mercury in axial muscle and total length of walleye collected from the Tongue River Reservoir during 1980. Fish from all four sampling periods are included.

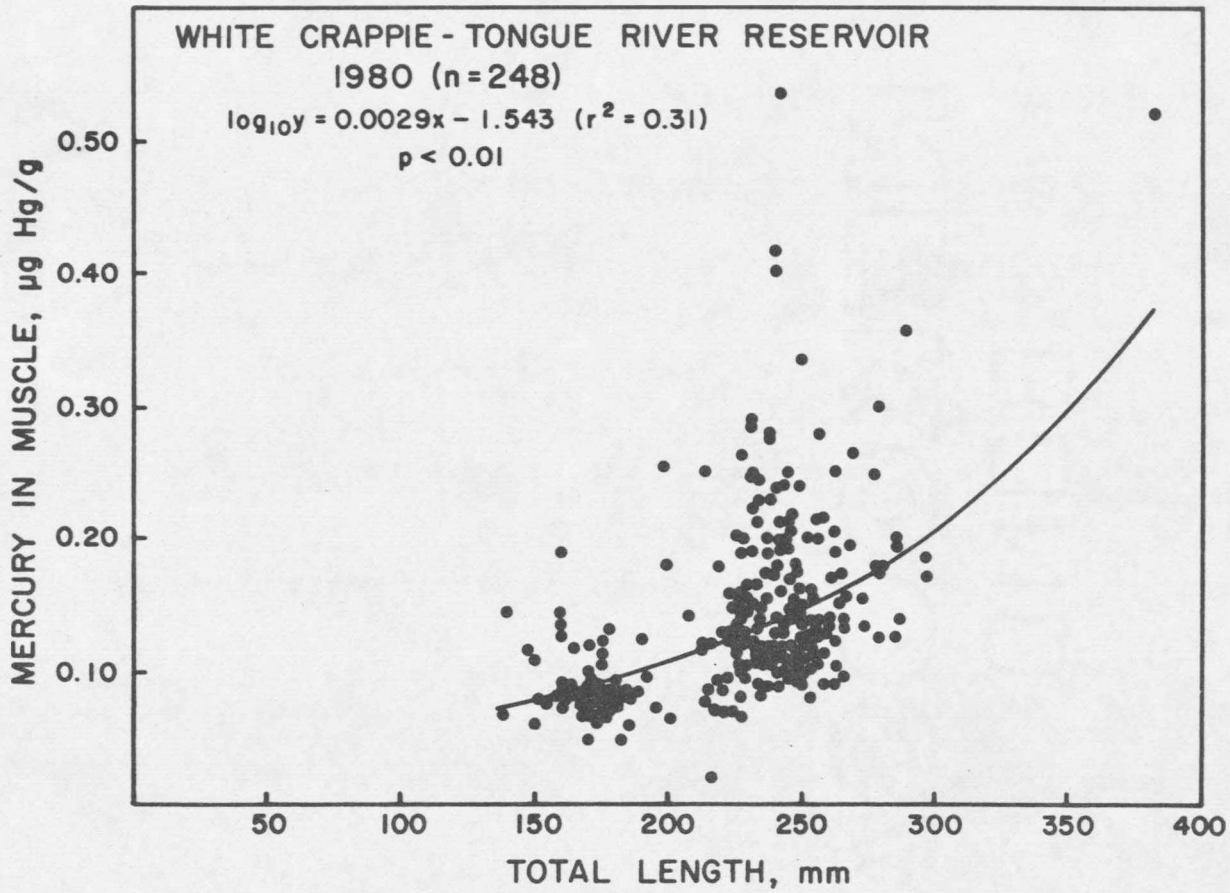


Figure 3. Relationship between concentration of total mercury in axial muscle and total length of white crappie collected from the Tongue River Reservoir during 1980. Fish from all four sampling periods are included.

1968; Johnels and Westermark 1969; Wobesor et al. 1970; Huckabee et al. 1974; Olsson 1976). Fish from contaminated freshwaters commonly exceed 1.0 µgHg/g; in highly contaminated waters, adult predatory fish average 10 µgHg/g and a few exceed 24 µg/g (Johnels and Westermark 1969; Bishop and Neary 1974; Annett et al. 1975; Olsson and Jensen 1975; Sherbin 1979). It should be noted that degrees of contamination are usually both relative and subjective, based on the author's judgment of the situation. Total mercury concentrations in TRR fish fall predominantly within the uncontaminated range, which is consistent with the lack of a known significant anthropogenic source of mercury to the reservoir.

Average mercury concentrations in walleye from other waters range from 0.11 to 7.83 µgHg/g, depending on size and degree of contamination (Wobeser et al. 1970; Henderson and Shanks 1971; Bails 1972; Scott 1974; Walter et al. 1974; Potter et al. 1975); white crappie concentrations range from 0.06 to 1.44 µgHg/g (Buhler et al. 1971; Walter et al. 1974; Meister et al. 1979). Previous studies on the TRR have found concentrations ranging from 0.10 to 1.3 µgHg/g in walleye, and from 0.10 to 0.60 µgHg/g in white crappie (Phillips 1979). These ranges are approximately the same as observed in this study, and fall on the lower end of the observed range for their species.

Walleye and white crappie of the same age have similar mercury concentrations in the TRR, as shown by comparing the mean, standard

error (SE) and range of total mercury concentrations observed for each age class (Figure 4). This similarity is apparently related to the mutual reliance of these species on a common prey organism (see food habits), and is discussed in more detail in conjunction with calculations of MeHg in the diet.

Seasonal regression equations for total mercury concentration versus length were statistically different ($p \leq 0.05$) for both walleye and white crappie (Figures 5 and 6). Problems associated with an exponential description of this relationship have already been discussed, however the seasonal fit is adequate for purposes of comparison. The seasonal pattern is similar for both species: slopes were steepest in April (when the largest fish were caught) and Hg concentrations were highest in June, dropping off in August and October. However, the range of mercury values associated with a given season and fish size usually encompasses all seasonal lines for that species, casting doubt on the biological significance of their statistical differences. Studies focusing on seasonal differences in mercury concentrations and accumulation rates might clarify this point. Granting that differences may occur, speculation as to the possible causes of seasonal variations in mercury concentrations is quite interesting.

A pulse of methylmercury to the system, might explain the high mercury concentrations in April and June. Methylmercury is usually accumulated more rapidly from higher water concentrations (Lock 1975),

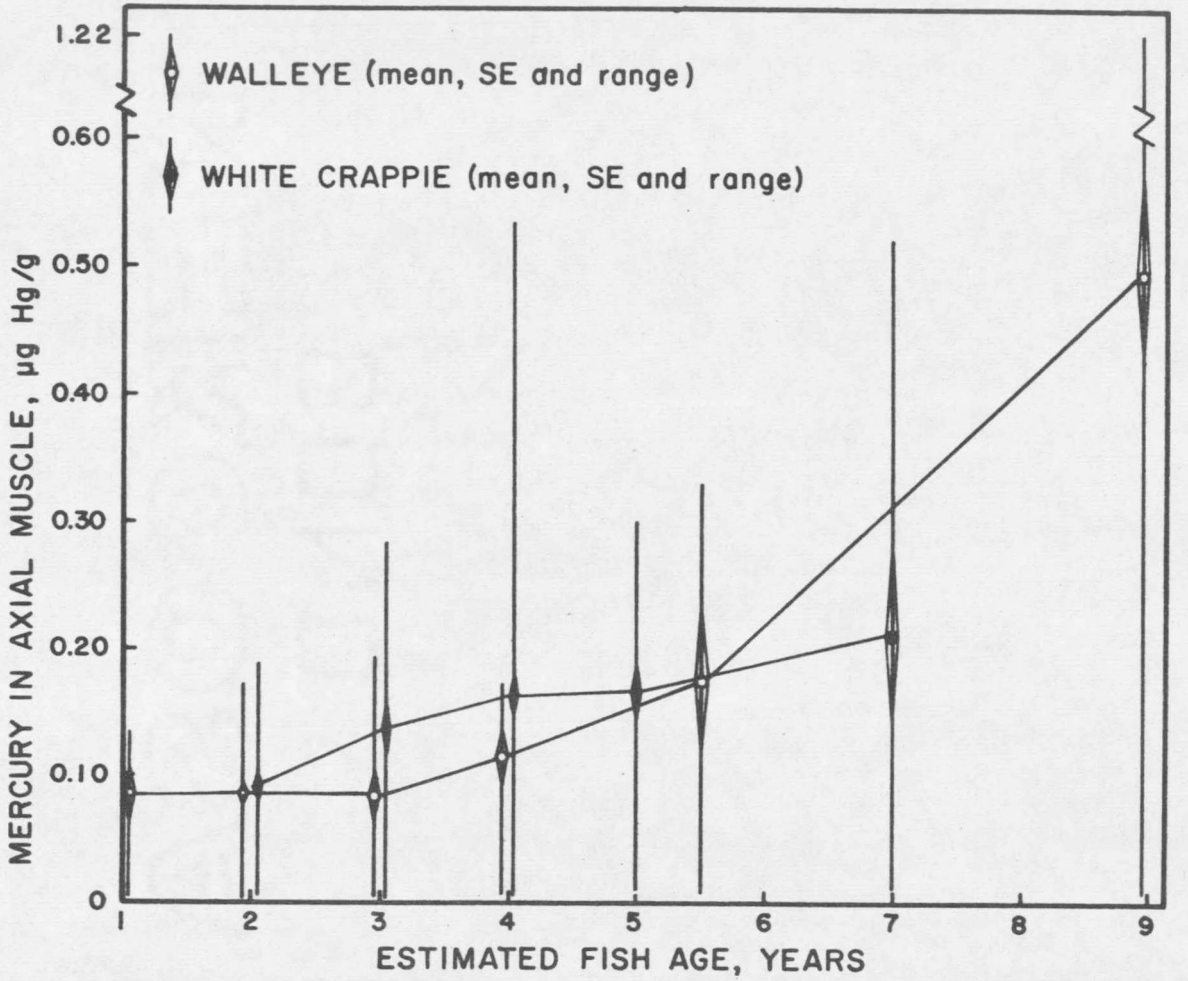


Figure 4. Comparison of predicted total mercury concentrations in walleye and white crappie of similar ages from the Tongue River Reservoir, 1980. See text for derivation of mercury values.

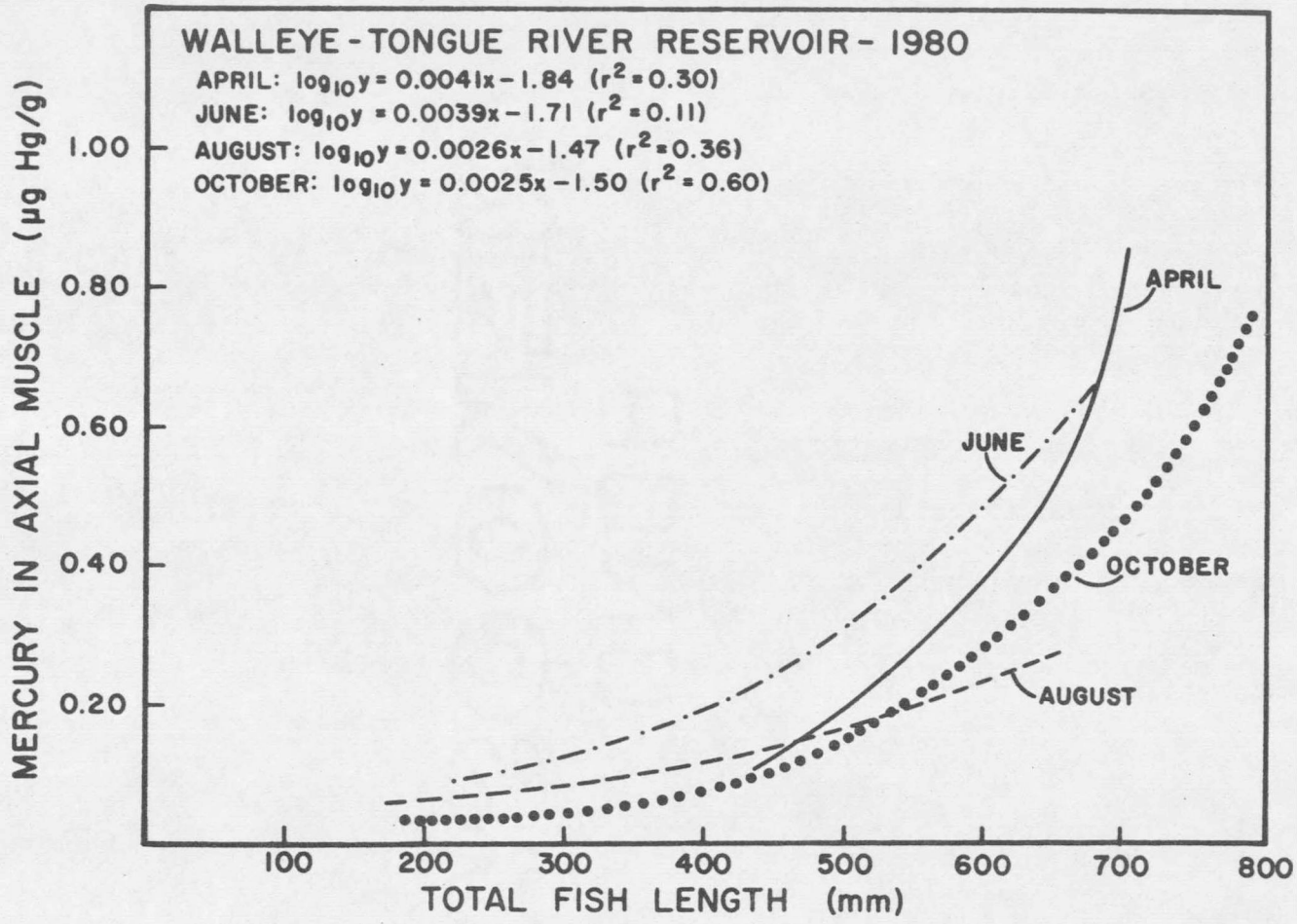


Figure 5. Relationship between concentration of total mercury in axial muscle, date sampled, and total length of walleye from the Tongue River Reservoir, 1980. $p < 0.01$ for all regression equations.

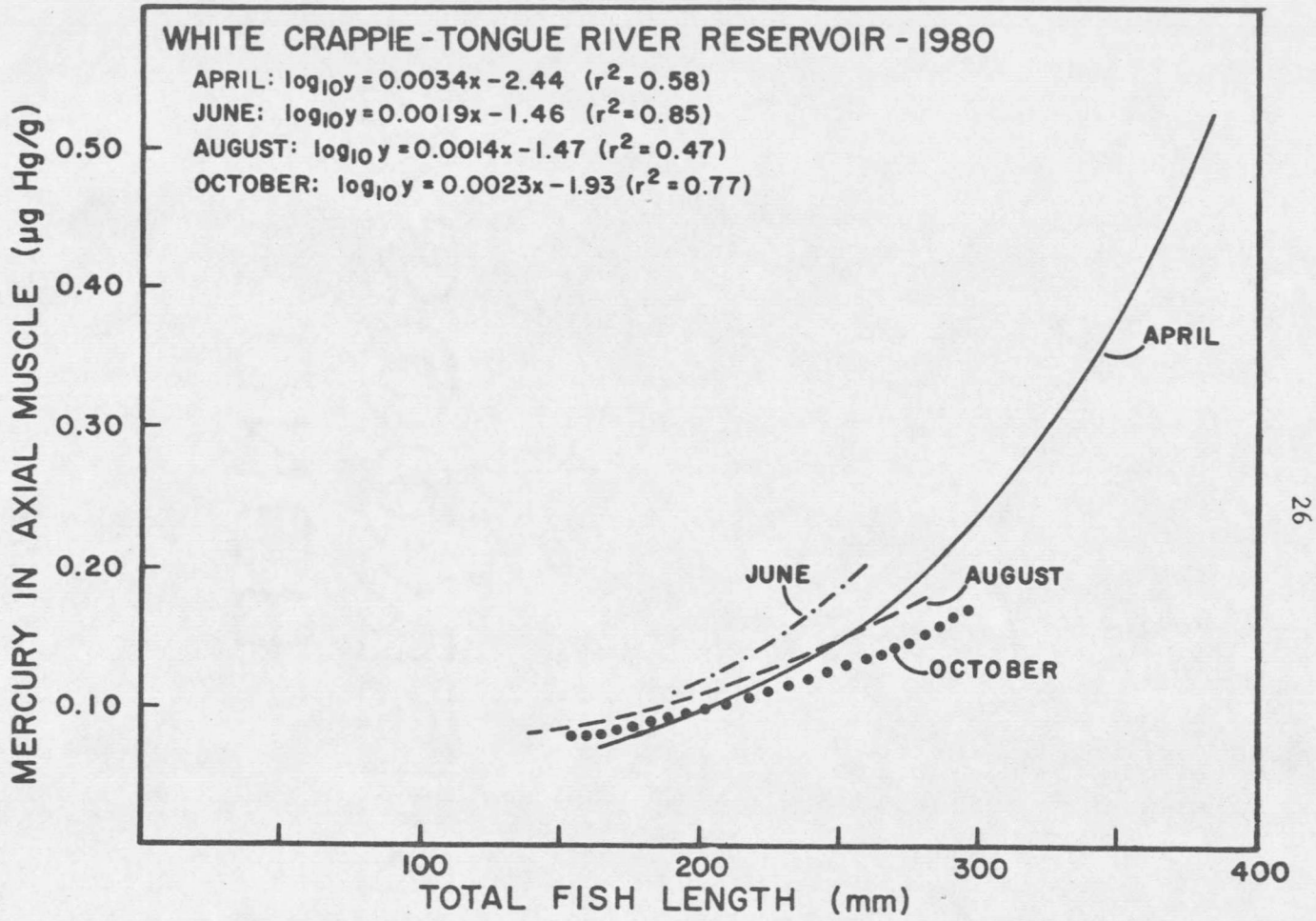


Figure 6. Relationship between concentration of total mercury in axial muscle, date sampled, and total length of white crappie from the Tongue River Reservoir, 1980. $p < 0.01$ for all regression equations except June, where $p = 0.02$.

and is apparently assimilated more efficiently by predators when accumulated by forage organisms under these conditions than when accumulated from low concentrations over long time periods (Phillips and Gregory 1979). This would tend to exaggerate trophic effects on a short term basis. Methylmercury elimination by fish is biphasic, with a rapid initial loss (half-life approximately 20 days) followed by a much slower rate of loss (Miettinen et al. 1970; Huckabee et al. 1979). The slow phase is most important on an annual basis, however the initial fast phase could conceivably account for the losses from June to August.

Data from other portions of this project have led to the hypothesis that elevated concentrations of mercury in TRR fishes in 1979 were a consequence of the previous spring's unusually high flood levels and the associated influx of potentially mercury-bearing particulate matter. The seasonal patterns of mercury concentration for walleye and white crappie in 1980 follow inflow patterns for the reservoir (Whalen 1979; Leathe 1980) and periods of elevated mercury concentrations coincide with high inputs of particulate matter and high water levels. Since much of the mercury in riverways is associated with particulate matter (Ottawa River Project 1979), this could account for the seasonal patterns observed.

Changes in other environmental factors associated with increases in reservoir inflow might also be responsible. Furutani and Rudd

(1980) have shown that methylation of mercury in sediments by aquatic bacteria, and subsequent release of methylmercury to the water column is apparently episodic and related to changes in nutrient supply and microbial activity. The largest peaks of methylating activity coincided with spring runoff.

Eight walleye and 18 white crappie averaged 0.08 and 0.10 μgHg/g, respectively in homogenized whole body tissues. Fish of these lengths (walleye 238-352 mm; white crappie 140-300 mm) had weighted average total mercury concentrations in muscle of 0.09 and 0.12 μgHg/g. Other workers have also shown that mercury concentrations in muscle tissue are representative of whole body values (Miettinen et al. 1970; Lockhart et al. 1972; McKim et al. 1976; Phillips 1978; Ribeyre and Boudou 1980). These results justify the use of mercury concentrations in muscle to estimate whole body mercury concentrations.

MeHg concentrations were generally at or below detection limits due to low total mercury concentrations in the few fish analyzed. Collection of larger fish for MeHg analyses probably would have yielded better results. For the one fish where MeHg concentration clearly exceeded the 0.10 μgMeHg/g detection limit, MeHg comprised 73% of the total mercury present. This is lower than most reported mean values (Appendix Table 14), however variability around the mean can be ± 20% or more, so no conclusions can be drawn. Because of this, literature values for the percentage of MeHg in fish were used in all calculations.

Food Habits

Walleye. Walleye of all size classes in the TRR are predominantly piscivorous; fish constituted 80-100% of the stomach content volumes, and occurred in all but two of the stomachs sampled (Table 4). Invertebrates were found only in the stomachs of walleye under 350 mm in length (ages 0-2). They were important only in the diets of walleye under 250 mm in length (ages 0-1), occurring in 54% of the stomachs and occupying 20% of their volumes. Most other studies have also shown adult walleye to be highly piscivorous (Raney and Lachner 1942; Kelso 1973; Walker and Applegate 1976; Ney 1978; Ryder and Kerr 1978).

Average and maximum size of fish consumed increased with walleye size (Figure 7), however the minimum size of fish eaten changed very little, because all walleye consumed age 0 fish whenever available. The largest differences in length of forage fish consumed by walleye in different size classes occurred in April, when age 0 fish were not available. Parsons (1971) and Forney (1974) also found that walleye selected for young-of-the-year fish when available and that larger walleye ate larger forage fish when young-of-the-year fish were not available. Stomach content volumes and the frequency of empty stomachs (average 16%) also tended to increase with walleye length, suggesting that older walleye feed less frequently, but eat larger meals. Individual stomach content volumes varied greatly, however sample sizes

Table 4. Frequency of occurrence and percent volumes of food items comprising stomach contents of different size and age groups of walleye from the Tongue River Reservoir.

Walleye length[a]	Stomach contents		
	Food items	Frequency (%)	Volume (% ± SE)
170-247 mm age class 1 (11)	Invertebrates	54	22 ± 10.5
	Diptera	45	22 ± 10.6
	Ephemeroptera	9	< 1
	Fishes	82	78 ± 10.5
	Centrarchidae fry[b]	9	13 ± 8.6
	Pomoxis spp.	9	11 ± 6.6
	Unidentifiable	64	54 ± 13.8
248-349 mm age class 2 (58)	Invertebrates	3	< 1
	Combined[c]	3	< 1
	Fishes	100	> 99 ± 0.02
	Perca flavescens	12	10 ± 1.0
	Pomoxis spp.	48	75 ± 1.6
	Unidentifiable	50	15 ± 1.1
350-426 mm age class 3 (10)	Fishes	100	100
	Catostomus commersoni	10	14 ± 8.0
	Pomoxis spp.	60	75 ± 7.1
	Unidentifiable	60	11 ± 4.1
427-477 mm age class 4 (8)	Fishes	100	100
	Pomoxis spp.	38	52 ± 18.7
	Unidentifiable	63	48 ± 18.7
478-535 mm age classes 5-6 (7)	Fishes	100	100
	Catostomus commersoni	14	34 ± 25.6
	Notemigonus crysoleucas	14	6 ± 7.2
	Pomoxis spp.	57	48 ± 13.7
	Unidentifiable	71	12 ± 9.1
536-790 mm age classes 7-11+ (37)	Fishes	100	100
	Cyprinus carpio	3	6 ± 2.1
	Perca flavescens	35	16 ± 3.0
	Pomoxis spp.	38	69 ± 4.4
	Unidentifiable	43	9 ± 1.2

[a] Number of walleye in parentheses; fish with empty stomachs or only unidentifiable contents excluded. Age class estimates based on data of Riggs (1978).

[b] Identifiable to family only; does not include Pomoxis spp. (listed separately).

[c] Diptera and Ephemeroptera, each constituting less than 1% of the stomach content volume of this length interval.

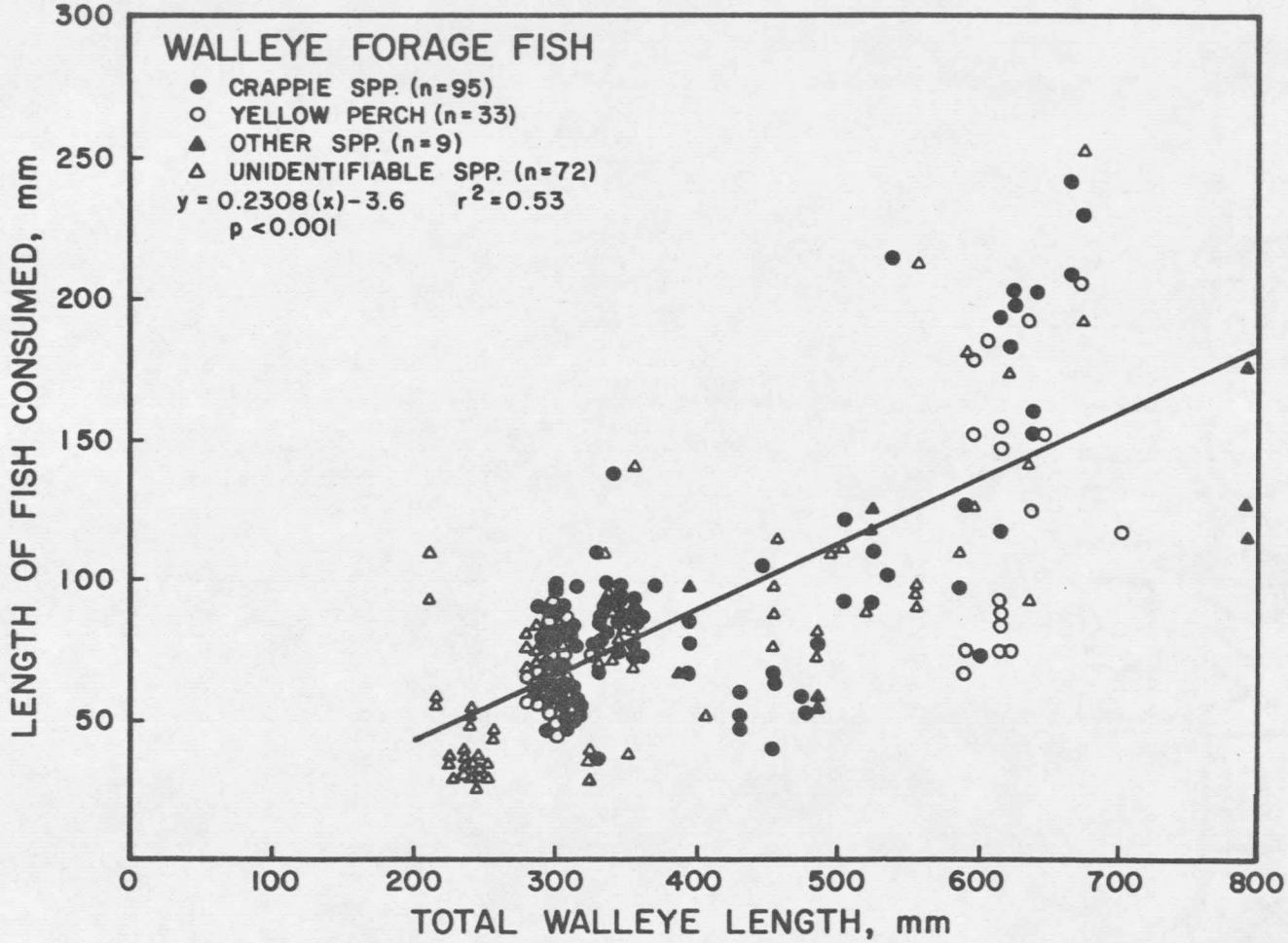


Figure 7. Increase in live lengths (estimated) of fish consumed by walleye with increasing walleye length.

were large enough to compensate, as evidenced by the relatively small standard errors.

Crappie were the principal food item of walleye throughout the year (Figure 8), accounting for 36 to 76% of the volume consumed by walleye at different times of the year (Appendix Table 18), and occurring in 43% of the stomachs overall. Yellow perch (Perca flavescens) were also consumed regularly, but in smaller amounts (9-18% of the volume). Most of the unidentified fish in stomachs appeared to be one of these two species.

Changes in the dietary habits of walleye, with both season and size, appeared to be related to food abundance and food size (Figure 9). In spring, young walleye ate invertebrates (primarily chironomids) and whatever small forage fish were available, while larger walleye consumed larger forage fish. During July, young-of-the-year crappie became available and all sizes of walleye began feeding on them heavily. Young-of-the-year crappie decreased in importance as a forage item in October, perhaps the combined result of a decline in numbers and growth beyond the optimal foraging size for walleye. At that time, walleye diversified their diets, and larger walleye began to feed on larger forage fish once again.

Walleye appear to feed opportunistically on white crappie, the most abundant forage fish species in the TRR (Elser et al. 1977).

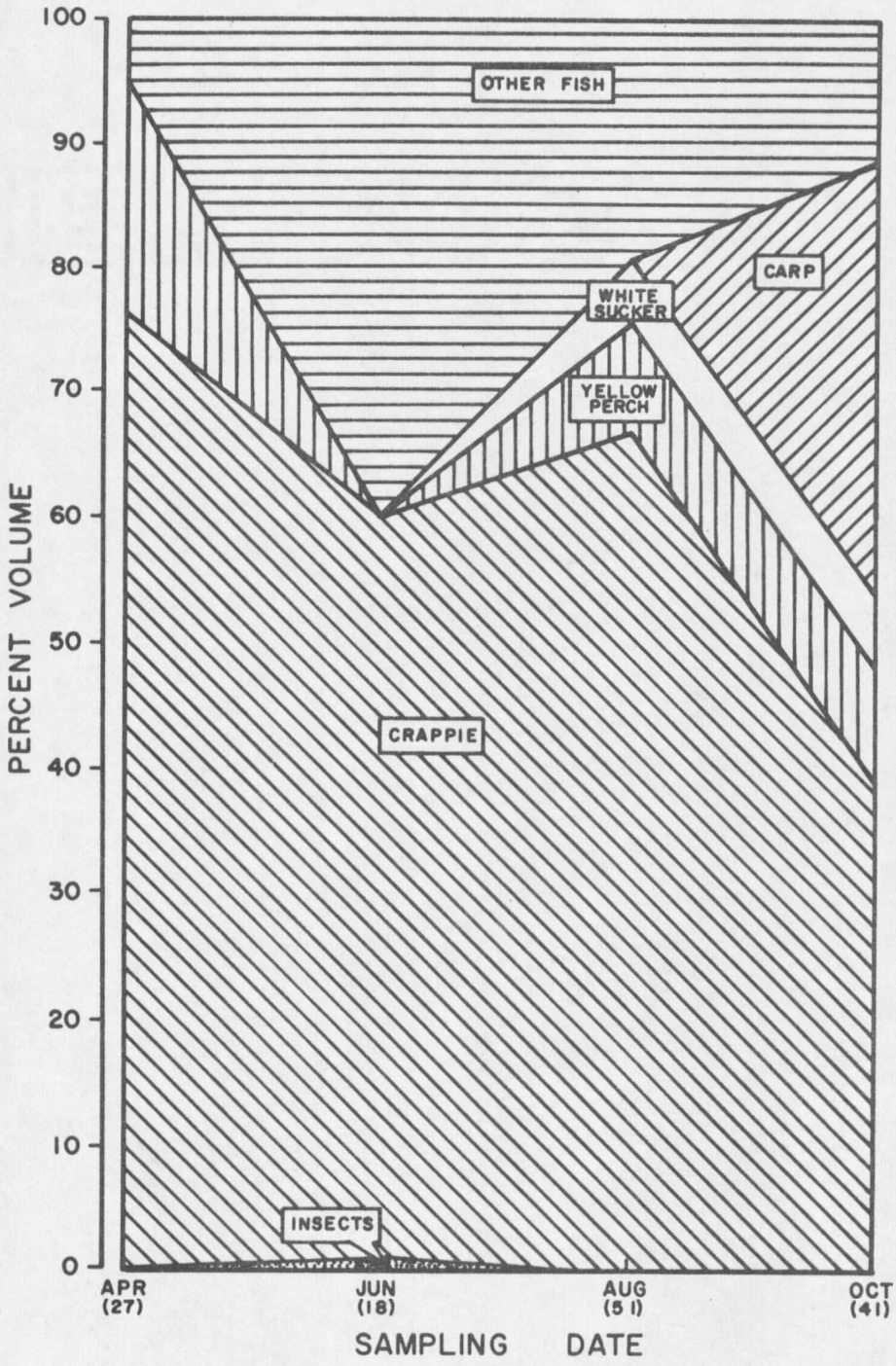


Figure 8. Seasonal change in composition of stomach contents of walleye. Sample size indicated in parentheses below the month.

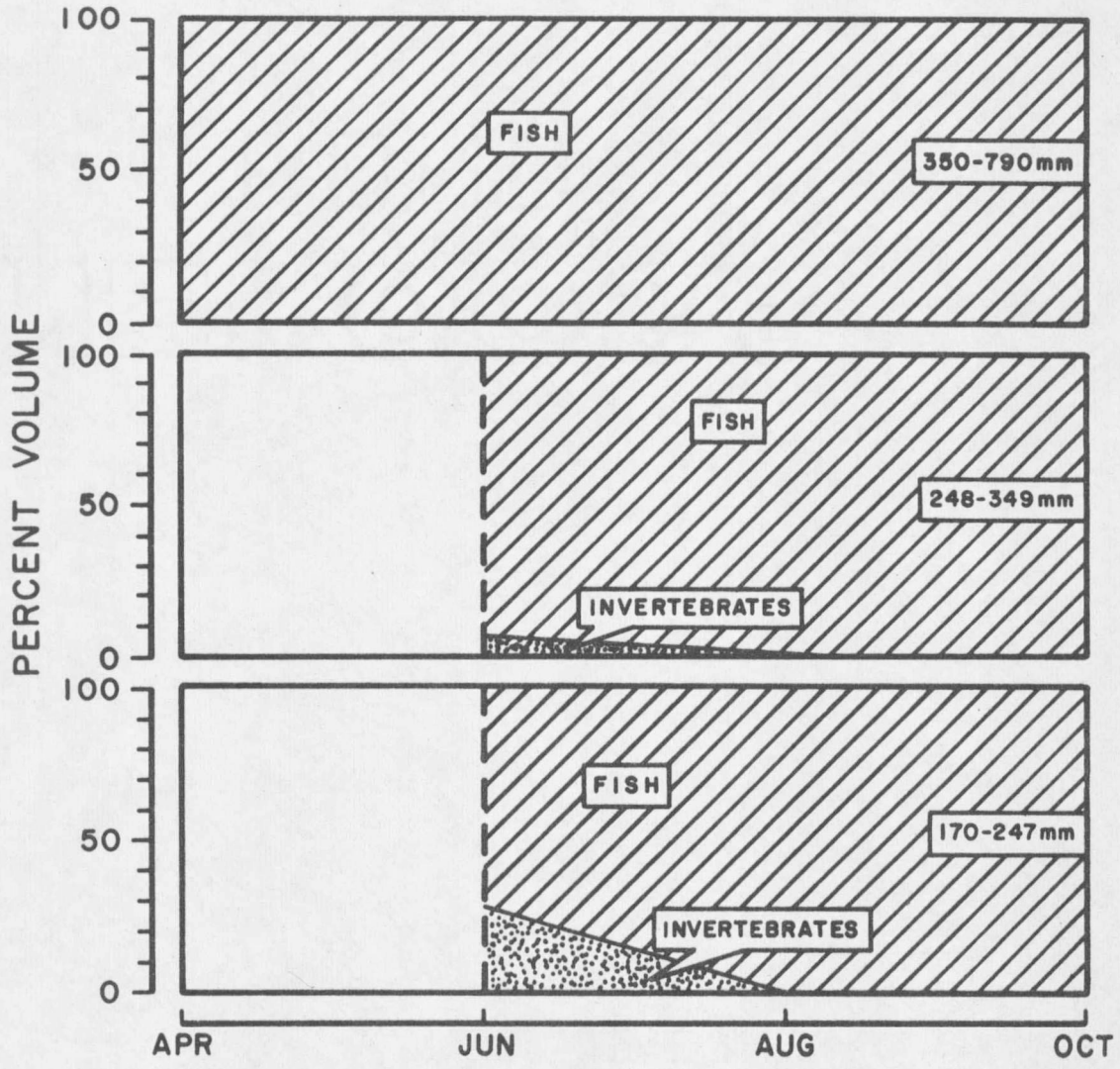


Figure 9. Comparison of the effects of season and body length on major components of the diet of walleye from the Tongue River Reservoir, 1980.

Young-of-the-year crappie size appears to be optimal for walleye foraging; young-of-the-year crappie may also be more vulnerable to predation than older fish since they frequent open waters (Pflieger 1975). Walleye exploited other forage species when crappie were not available. Forney (1974) reported, that for walleye in Oneida Lake, seasonal diet patterns are also related to changes in the availability and size of the predominant forage fish (young-of-the-year perch). The variety of fish species consumed by walleye in different water bodies provides further evidence that walleye are opportunistic feeders (Priegel 1963; Wagner 1972; Swenson 1977).

In waters where yellow perch are the predominant forage species, variations in abundance of year classes of walleye and yellow perch are often synchronous (Forney 1974; 1977; Swenson and Smith 1976; Swenson 1977). High densities of yellow perch appear to decrease the incidence of cannibalism by walleye and thus increase numbers in the walleye year class as well (Chevalier 1973). No cannibalism was observed among TRR walleye, which may be due to the large numbers of age 0 crappie observed. No comparison of year class strengths of walleye and white crappie in the TRR has been made.

White crappie. Fish are also an important food item for white crappie in the TRR, occurring in 46% of the stomachs and occupying 78% of their volume. Crappie longer than 255 mm had the largest percentages (volumes) of fish in their stomachs (Table 5). Cannibalism of

Table 5. Frequency of occurrence and percent volumes of food items comprising stomach contents of different size and age groups of white crappie from the Tongue River Reservoir.

White crappie length (mm)[a]	Stomach contents		
	Food items	Frequency (%)	Volume (% ± SE)
138-196 (age class 2) (46)	Invertebrates	72	23 ± 2.2
	Crustacea[b]	30	10 ± 1.4
	Diptera	70	10 ± 0.9
	Other[c]	32	3 ± 0.4
	Fishes	59	77 ± 2.2
	Perca flavescens	2	5 ± 1.6
	Pomoxis spp.	13	50 ± 3.8
	Unidentifiable	39	22 ± 2.3
197-232 (age class 3) (55)	Invertebrates	85	32 ± 2.3
	Crustacea[b]	64	12 ± 0.9
	Diptera	73	6 ± 1.1
	Other[c]	47	4 ± 0.4
	Fishes	40	68 ± 2.3
	Perca flavescens	4	4 ± 0.8
	Pomoxis spp.	15	46 ± 3.0
	Stizostedion spp.	2	8 ± 2.0
	Unidentifiable	24	10 ± 0.9
233-254 (age class 4) (83)	Invertebrates	88	37 ± 1.6
	Crustacea[b]	63	11 ± 0.6
	Diptera	82	19 ± 0.9
	Hemiptera	30	4 ± 0.3
	Other[c]	28	3 ± 0.2
	Fishes	40	63 ± 1.6
	Notemigonus crysoleucas	1	5 ± 1.1
	Percidae	4	10 ± 1.4
	Pomoxis spp.	8	32 ± 2.0
	Unidentifiable	28	16 ± 1.1
255-271 (age class 5) (23)	Invertebrates	57	4 ± 0.9
	Other[c]	57	4 ± 0.9
	Fishes	57	96 ± 0.9
	Cyprinus carpio	4	11 ± 4.5
	Perca flavescens	4	9 ± 4.1
	Pomoxis spp.	26	60 ± 6.1
	Stizostedion spp.	4	5 ± 2.2
	Unidentifiable	39	11 ± 1.8
272-382 (age classes 6-8) (14)	Invertebrates	50	4 ± 1.6
	Other[c]	50	4 ± 1.6
	Fishes	64	96 ± 1.6
	Cyprinus carpio	7	20 ± 8.2
	Perca flavescens	7	16 ± 9.0
	Pomoxis spp.	36	46 ± 7.3
	Unidentifiable	36	14 ± 5.1

a Number of white crappie in parentheses; fish with empty stomachs or only unidentifiable contents excluded. Age class estimates based on data from Elser et al. (1977).

b Cladocerans and copepods.

c Identified invertebrates constituting 3% or less of the total volume from each length interval, plus Insecta which could not be identified to order.

age 0 white crappie was prevalent among all sizes of crappie sampled. While cannibalism by white crappie has been occasionally reported in the literature (Burris 1956; Marcy 1954), the levels found in this study are unusually high. Cannibalism has also been observed among black crappie (Seaburg and Moyle 1964; Keast 1968).

Invertebrates, chiefly zooplankton (Cladocera) and aquatic insects (Chironomidae larvae and pupae), are also prominent components of the white crappie diet. Invertebrates occurred in 70 to 90% of the stomachs of white crappie under 255 mm in length (ages 0-4), and occupied an average of 31% of their volume (Table 5). Invertebrates continued to occur regularly (50-60%) in the stomachs of crappie longer than 255 mm (age 5+), however, they represented only 4% of the stomach content volume.

Crappie in the TRR generally consumed the same kinds of organisms reported for adult crappie from other waters (Marcy 1954; Hoopes 1960; Neal 1961; Keast 1968; Greene and Murphy 1971; Mathur 1972; Baumann et al. 1973); however, the relative importance assigned to the different prey categories varies considerably. Hoopes (1960) reported that insects (especially mayflies) predominated in the diet of white crappie. Baumann et al. (1973) found zooplankton almost exclusively in the stomachs of their fish, while Mathur and Robbins (1972) found that both zooplankton and insects (primarily chironomids) were important in the diet of young adults. Other studies, including this one have found

fish to be an important component of the crappie diet. Marcy (1954) found mainly zooplankton in the stomachs of smaller crappie, however larger crappie ate fish almost exclusively. Crappie examined by Keast (1968) had consumed large percentages of Diptera, however, fish were important in the diets of larger fish and at certain times of the year. Green and Murphy (1971) and Mathur (1972) found fish to be the most important diet component. These results indicate that crappie are very flexible in their dietary habits.

Average and maximum sizes of fish consumed tended to increase with white crappie length (Figure 10), while minimum size remained relatively constant as all white crappie consumed young-of-the-year fish when available. Stomach content volumes increased markedly with increasing crappie length. As with walleye, great individual variation in stomach content volume was observed, but sample sizes compensated. The frequency of empty stomachs averaged 9% and showed no temporal or length patterns.

The greatest changes in feeding habits of crappie occurred between seasons (Figure 11). Invertebrates dominated the diet in April and June, occurring in 99 and 98% of the stomachs, and occupying 75 and 85% of their volumes respectively (Appendix Table 19). Cladocerans accounted for 25 and 19% and chironomids for 38 and 44 %, of the volumes in April and June. A radical shift to a predominently fish diet occurred by August and continued through October. Fish occurred in 89

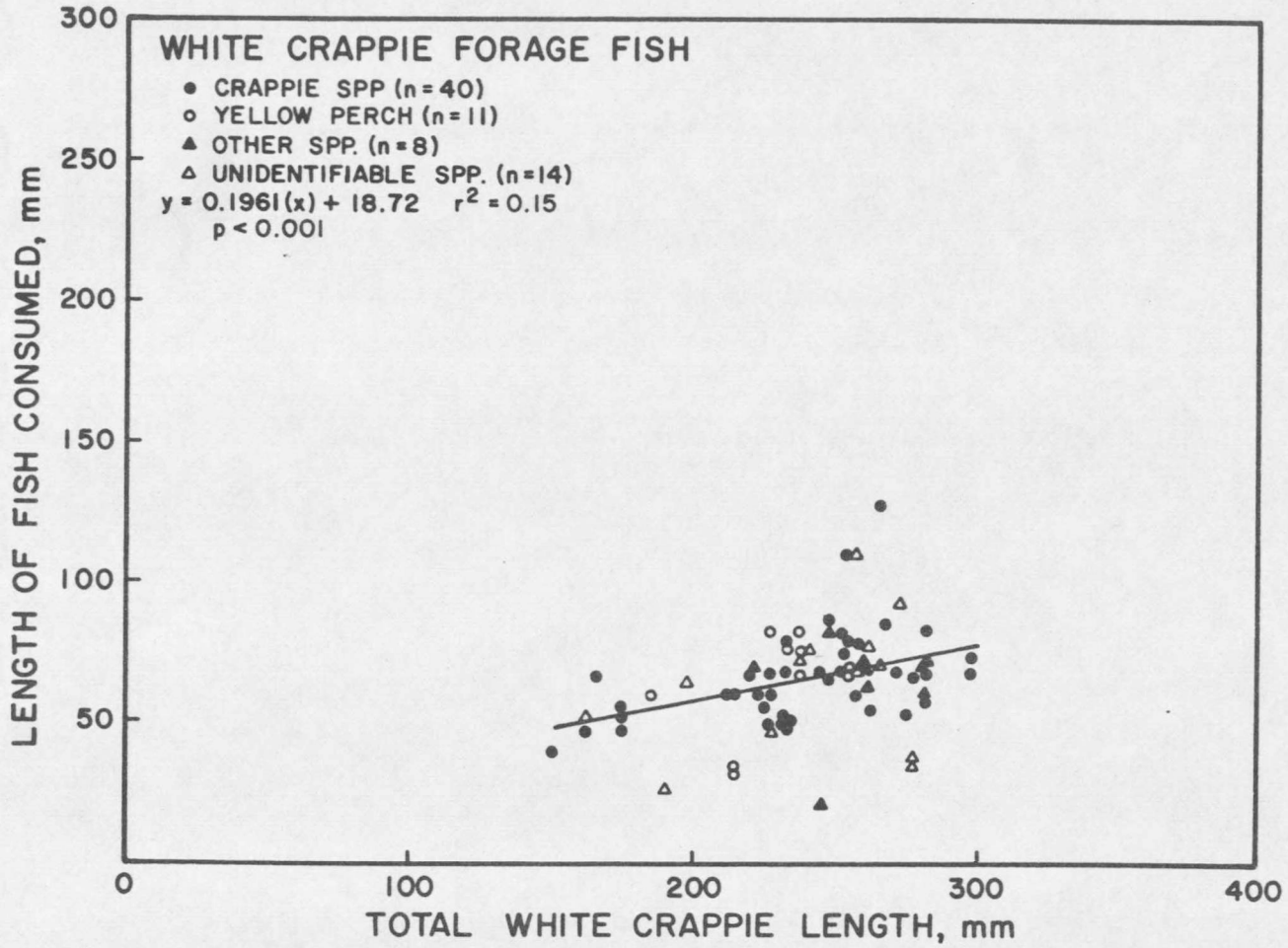


Figure 10. Increase in live total lengths (estimated) of fish consumed by white crappie with increasing crappie length.

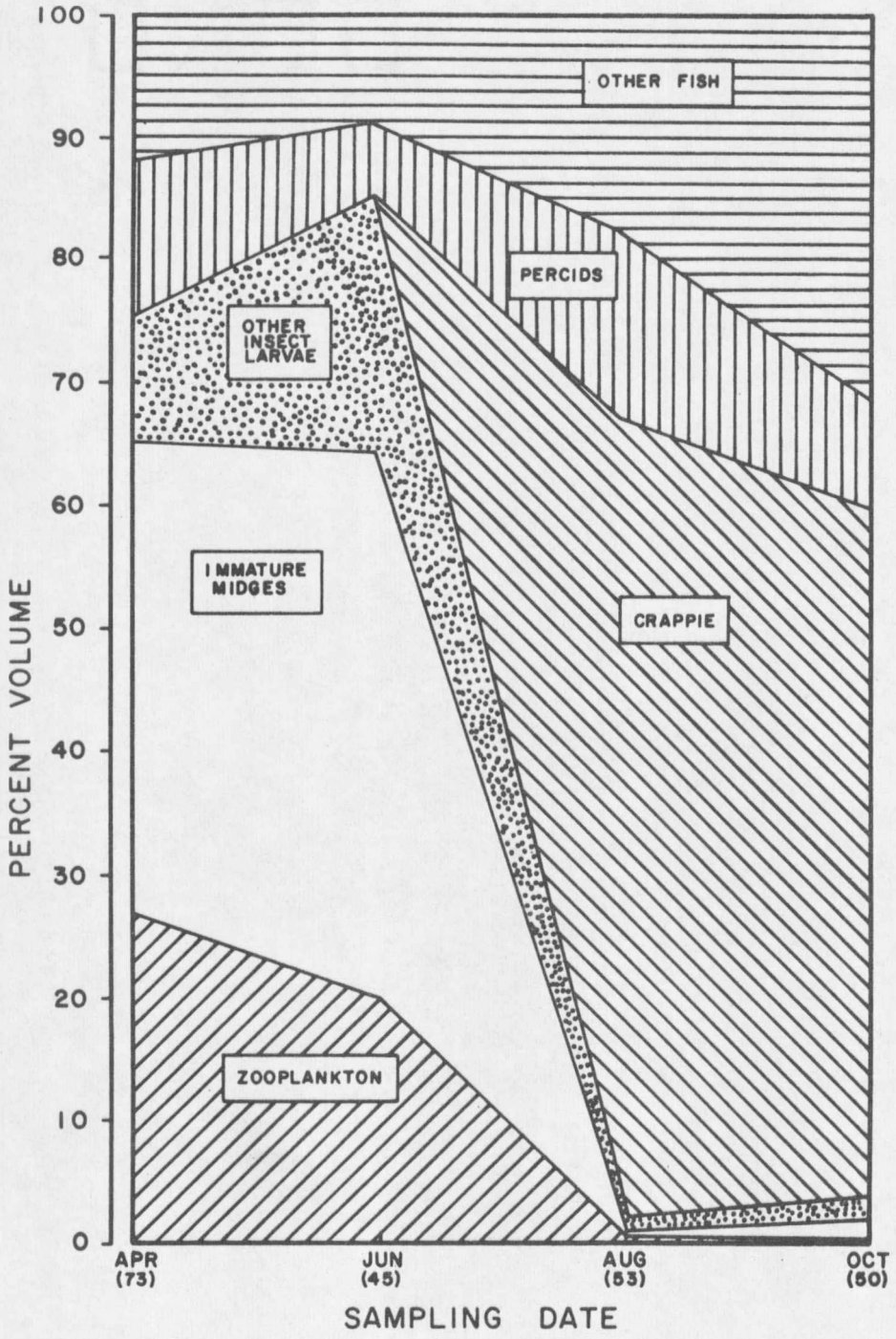


Figure 11. Seasonal change in composition of stomach contents of white crappie. Number of white crappie in parentheses below the month.

and 76% of the stomachs, and occupied 98 and 96% of their volumes in August and October respectively. Young-of-the-year crappie were the predominant prey, accounting for 64 and 56% of the volumes. This seasonal pattern was similar for all sizes (Figure 12), with two exceptions: 1) large crappie (>270 mm) fed mainly on fish throughout the year, and 2) invertebrates increased slightly in importance from August through October, increases being greatest in the smallest crappie. This may be due to the replacement of age 0 crappie as they grow too large for consumption.

Similar seasonal patterns have been reported for other crappie populations. In Benbrook Lake, Texas, crappie preferred young-of-the-year threadfin shad, but consumed significant amounts of insects during seasons when shad were not available (Green and Murphy 1971). In Conowingo Reservoir, on the lower Susquehanna River, crappie ate mostly fish in the fall while zooplankton and insects were more important in the spring (Mathur 1972). These observations again suggest that crappie are opportunistic feeders, capable of taking advantage of seasonal and geographical abundances of a variety of forage organisms.

White crappie diets in the TRR also varied diurnally (Figure 13); percentages (volumes) of invertebrates were higher during daylight hours, while percentages (volumes) of fish were higher at night. Concurrently, the frequency of occurrence and the absolute volume of fish

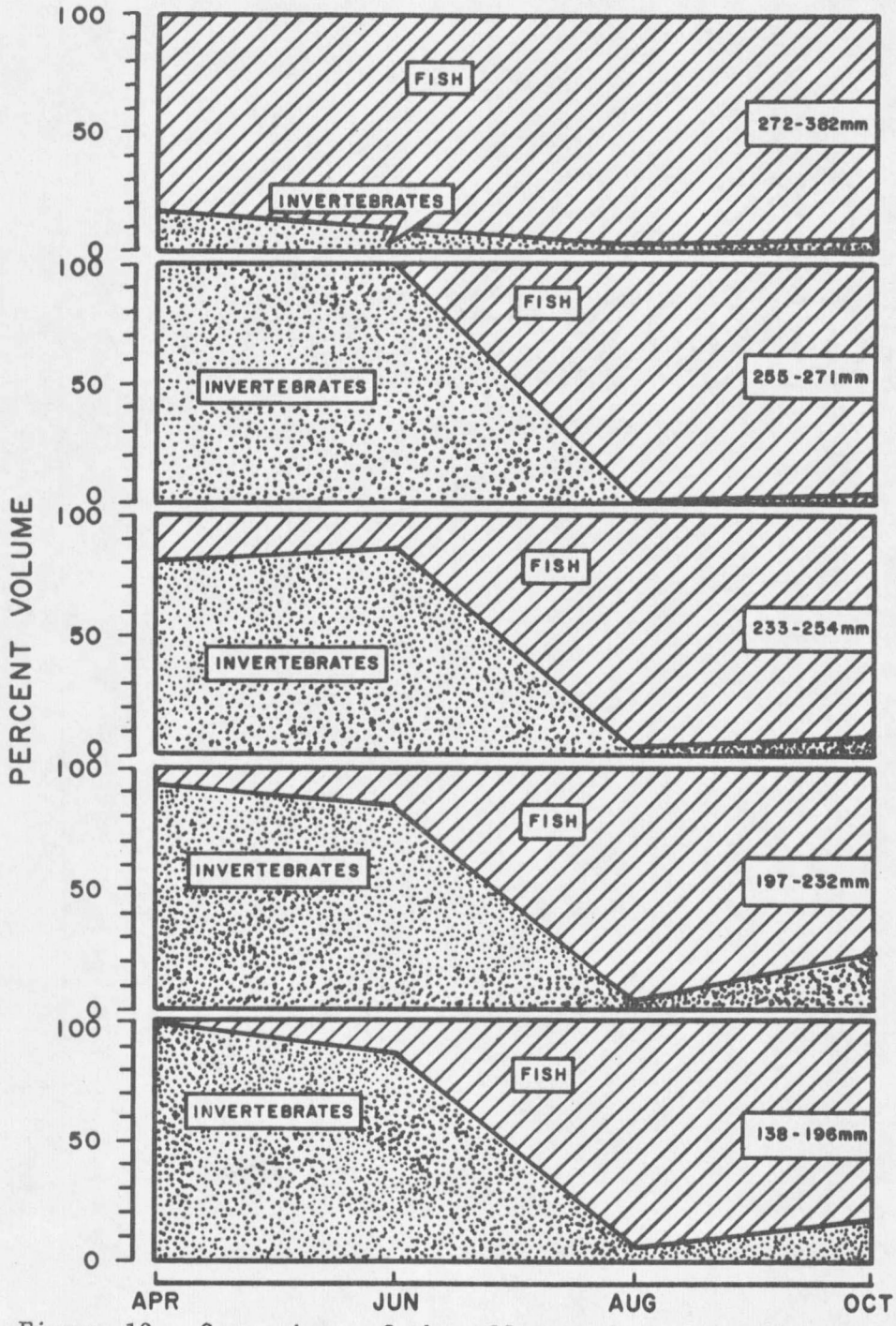


Figure 12. Comparison of the effects of season and length on major diet components of white crappie.

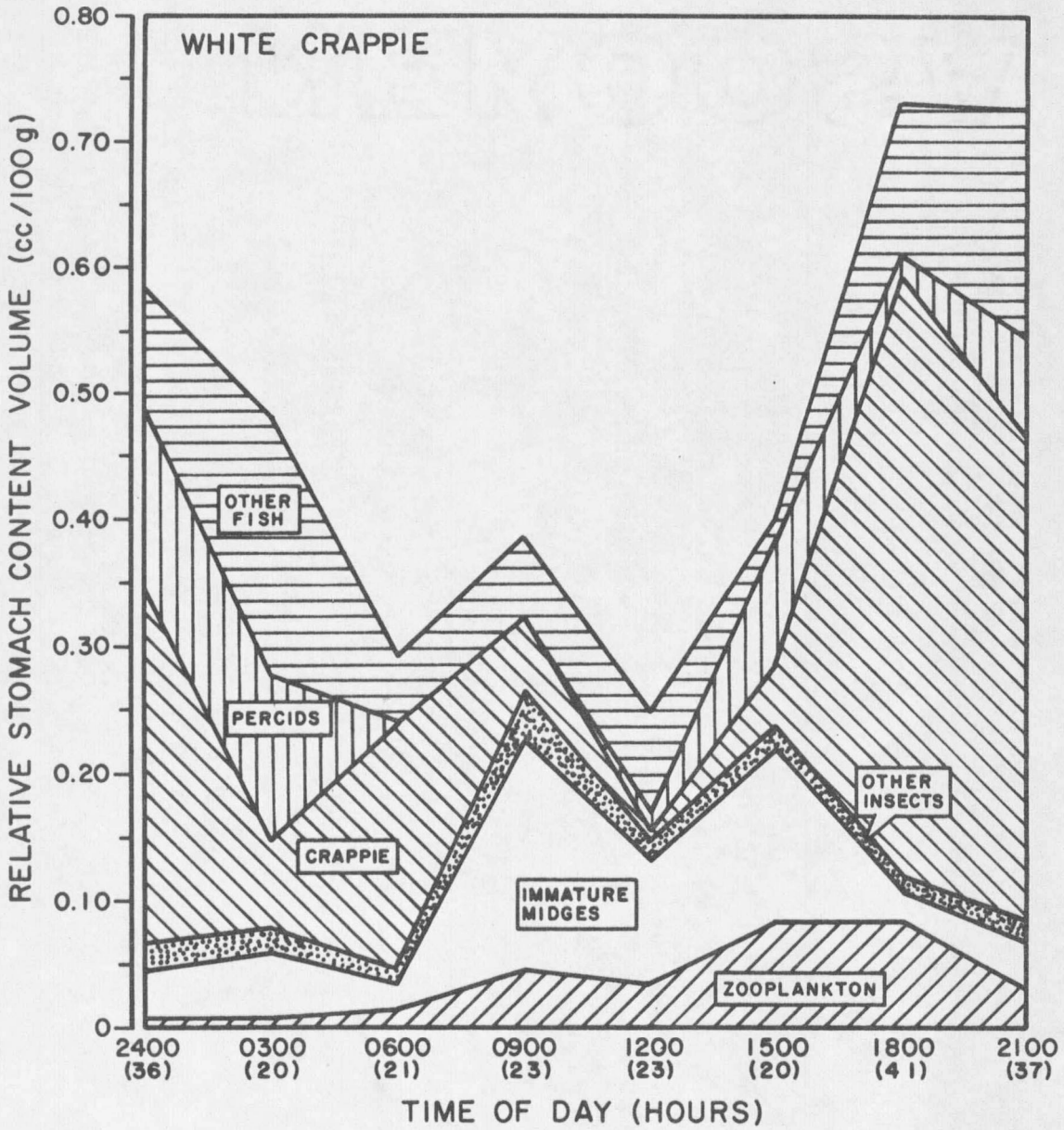


Figure 13. Effects of time of day on diet of white crappie. Number of white crappie in parentheses below the hours.

eaten during daylight hours decreased substantially (Appendix Table 20). Invertebrates increased correspondingly, although not by as much. Higher stomach content volumes from 1800 h through 0300 h produced a slower decline in the volume of invertebrates eaten than indicated by the decreases in percentages.

Daily feeding peaks for crappie in the TRR generally occurred at dawn, around midday, and shortly after dark (Figure 14). Midday peaks coincided with larger percentages of invertebrates in stomachs, while dawn and early evening peaks corresponded to larger percentages of fish. Dawn feeding peaks occurred during seasons when midday peaks were low or non-existent. In general, crappie appear to consume invertebrates during daytime feeding peaks (Keast 1968; Mathur and Robbins 1972; Baumann et al. 1973), and consume fish when feeding at dawn and dusk, or at night (Childers and Shoemaker 1953; Greene and Murphy 1971). Thus, white crappie appear to feed during periods of the day when their primary forage organisms are most easily captured.

The number and relatively low amplitudes of the observed feeding peaks may result from combining fish of differing sizes and diet habits. Similar results were reported by Keast (1968) and Greene and Murphy (1971) who combined fish of varying sizes, although neither comments on the consequences of doing so. Since time of feeding is apparently related to diet composition and size, feeding patterns should be more distinct among fish of similar sizes.

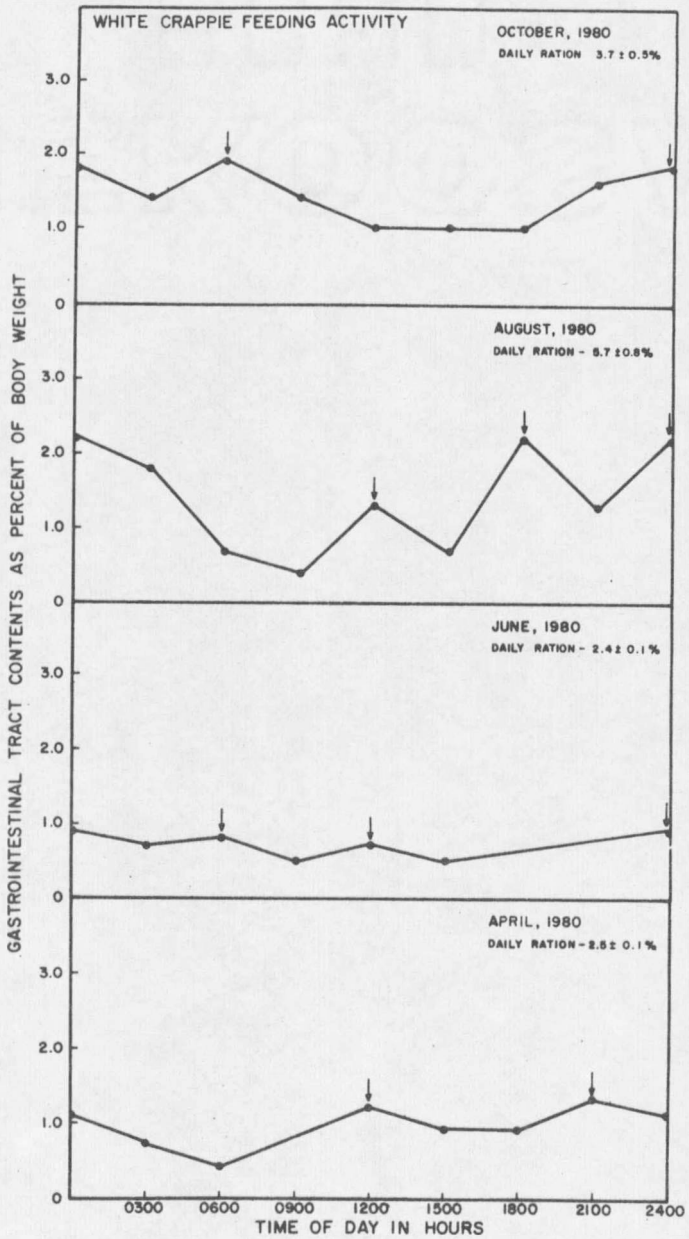


Figure 14. Patterns of white crappie feeding activity from April through October, 1980. Arrows indicate points used to calculate daily ration (estimates expressed as % body weight/day ± 1 standard error).

Overview. Age 0 crappie are obviously an important food source for both walleye and white crappie in the TRR; they are the most abundant forage fish, indicating that both walleye and white crappie feed opportunistically. The major differences in the diets of the two species are: 1) the importance of invertebrates in the diets of white crappie in the spring and 2) the larger size(s) of forage fishes, other than young-of-the-year crappie, consumed by walleye. These divergent alternate foraging patterns in the absence of a common dominant prey appear to be related to differences in the sizes of the two species.

Food Consumption Rates

Walleye. Estimated annual food consumption rates of walleye ranged from 0.9-3.9% body weight/day depending on fish size and combinations of summer and winter activity levels (Appendix Table 21). Daily consumption rate averaged from 1.5-2.2% for all size classes (Table 6). Annual maintenance ration for a 1000 g fish was estimated to average 0.7% (Kitchell et al. 1977), using average monthly Tongue River Reservoir temperatures. Although daily ration is inversely related to body size, the relationship is asymptotic and differences are not pronounced among fishes larger than 100 g (Brett 1971; Kitchell et al. 1977). Since virtually all of the walleye in this study exceeded 100 g in weight and given the uncertainties of estimating food consumption rates, especially indirectly, consumption of methylmercury by

Table 6. Estimates of annual food consumption rates (range and median) for different size classes of walleye from the Tongue River Reservoir. Estimates predicted from body weight, growth rate and reservoir temperatures (Kitchell et al. 1977). Range is based on probable combinations of growing and non-growing period (summer and winter) activity levels (Appendix Table 21).

Walleye length	Daily ration (% body wt./day) range (median)
170-247 mm (age class 1)	2.8 - 3.9 (3.35)
248-349 mm (age class 2)	1.8 - 2.6 (2.20)
350-426 mm (age class 3)	1.4 - 2.1 (1.75)
427-477 mm (age class 4)	1.2 - 1.8 (1.50)
478-535 mm (age classes 5-6)	1.0 - 1.6 (1.30)
536-+ (age classes 7+)	0.9 - 1.4 (1.15)
Average	1.5 - 2.2 (1.85)

walleye was calculated using the average range of annual food consumption rates (1.5 to 2.2% body weight/day) for all size classes.

Other workers have estimated similar rations for walleye. Kelso (1972), in laboratory studies on walleye aged 2 to 7 reported maintenance rations consistently around 0.5% body weight/day. Swenson and Smith (1973) estimated average rations for adult walleye in Lake of the Woods, Minnesota at 2.3% (range 0.5 to 4.1%) from June to September. Swenson (1977) also compared walleye from several other lakes and estimated that they consumed from 2.1 to 2.9% of their body weight daily during the growing season, depending on prey densities. Combining Swenson's (1977) and Kelso's (1972) estimates, for growing and non-growing periods respectively, yields an annual average of 1.3 to 1.7%. Since Kitchell et al.'s (1977) model incorporates these data, it is not surprising that this annual estimate agrees with mine. Both estimates may be low since Swenson and Smith's (1973) assumption that a linear relationship exists between the amount of food evacuated from the stomach and time has since been shown to be incorrect (Elliot and Persson 1978).

White crappie. The field method of Nakashima and Leggett (1978) was used to estimate food consumption rates for white crappie from the TRR by summing feeding peaks. Estimates were 2.5% body weight/day for April and June, increased to 5.7% in August, and decreased to 3.7% by

October (Figure 14). Daily ration estimates exceeded predicted maintenance rations (Kitchell et al. 1977) in all months sampled (Figure 15). Average annual rate of food consumption was estimated at 2.3% (± 1.2% - 1 SE). All calculations of methylmercury consumption utilized this range of consumption values. The estimates made in this study are similar to estimates made for yellow perch using current methodologies (Thorpe 1977; Nakashima and Leggett 1978).

Mathur and Robbins (1972) and Mathur (1972) also reported peak feeding activity from June to October. Moderate feeding occurred in April and May, and low levels of feeding were observed from November to March. Greene and Murphy (1971) estimated that minimum crappie food consumption rates ranged from 1.6 to 2.8% in late summer. These estimates are probably low because no correction was made for gastric evacuation.

Mercury in Forage Species

Invertebrates. Total mercury concentrations (μgHg/g) in invertebrates from the TRR ranged from 0.02 to 0.33 and averaged 0.08 (Table 7). While sample sizes were small, variability among total mercury concentrations was also relatively small (with the notable exception of Notonectidae) lending credibility to the values. Attempts to analyze mercury concentrations in zooplankton were unsuccessful, so literature values were used to calculate MeHg concentrations in fish diets.

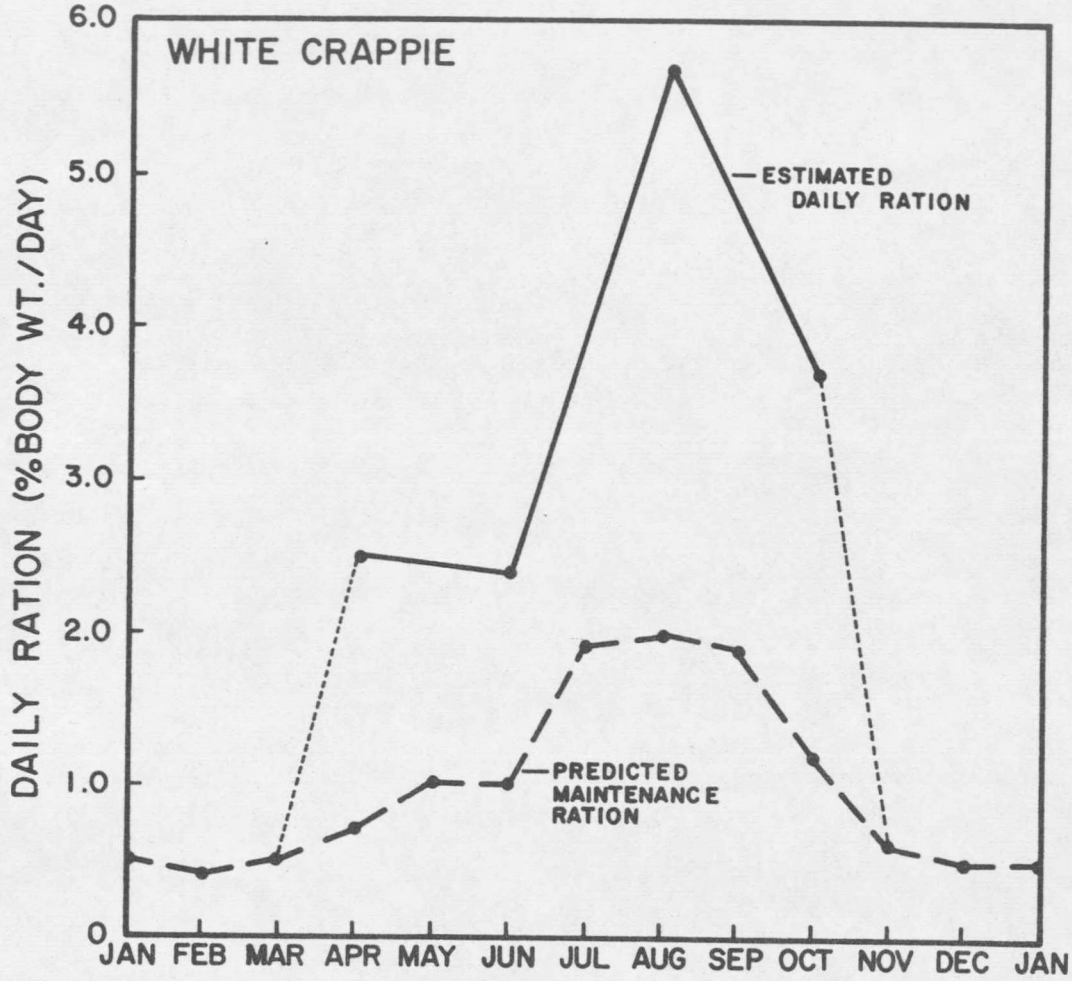


Figure 15. Comparison between daily ration estimates of white crappie and predicted maintenance rations for a 100 gram yellow perch at monthly TRR temperatures (Kitchell et al. 1977).

Notonectidae were rarely seen in stomachs, so this value was not used in subsequent calculations, however, note that the mercury concentrations of the two Hemipteran families differ by an order of magnitude. Differences in their feeding habits may be responsible, as Corixidae are planktivorous while Notonectidae are predaceous on other insects.

Table 7. Total mercury concentrations in invertebrate food items.

	n[a]	Total Hg(µg/g) (mean ± SE)	range
Crustacea[b]	16	0.06 ± 0.03	(0.003 - 0.20)
Diptera			
Chironomidae	2	0.07 ± 0.02	(0.066 - 0.069)
Hemiptera			
Corixidae	9	0.03 ± 0.004	(0.02 - 0.04)
Notonectidae	2	0.27 ± 0.78	(0.21 - 0.33)

a n = number of mercury analyses; specimens pooled when dictated by size

b derived from literature values for zooplankton (Appendix Table 22).

Total mercury concentrations ranging from 0.002 to 23.2 µgHg/g have been observed in freshwater invertebrates (Johnels et al. 1967; Jernelöv and Lann 1971; Armstrong and Hamilton 1973; Cox et al. 1975; Potter et al. 1975; Trudel et al. 1977; Hildebrand et al. 1980). Invertebrates from uncontaminated waters usually contain less than 0.10 µgHg/g, while those from contaminated environments commonly exceed 1.0 µgHg/g (Huckabee et al. 1979). Invertebrates from the TRR fall in the uncontaminated range.

Fishes. Total mercury concentrations were determined in 197 whole forage fish, comprising seven species and ranging from 40 to 300 mm in length. The size range closely parallels that of the reconstructed lengths of forage fish found in the stomachs of walleye and white crappie (21 to 254 mm). Total mercury concentrations (in μgHg/g) in forage fish ranged from 0.02 to 0.40 (crappie, 0.02 - 0.18; shiners, 0.03 - 0.40; perch, 0.03 - 0.23; suckers, 0.03 - 0.07) and increased with fish length (Figure 16). Linear regression equations of length versus mercury concentration were similar for all species except golden shiner. The regression equation for the pooled data of all species was used to estimate mercury concentrations in unidentifiable fish remains. All regressions were significant at the $p = 0.05$ level, however, correlations were somewhat low. Differences in age, sex, species (where combined), and individual behavior probably account for the variability observed (Bache et al. 1971; MacLeod and Pessah 1973; Cross et al. 1973; Prabhu and Hamdy 1977). As with invertebrates, mercury concentrations in forage fish from the TRR generally fall within the ranges observed for these species in uncontaminated waters (Buhler et al. 1971; Gebhards et al. 1971; Potter et al. 1975; Richins and Risser 1975).

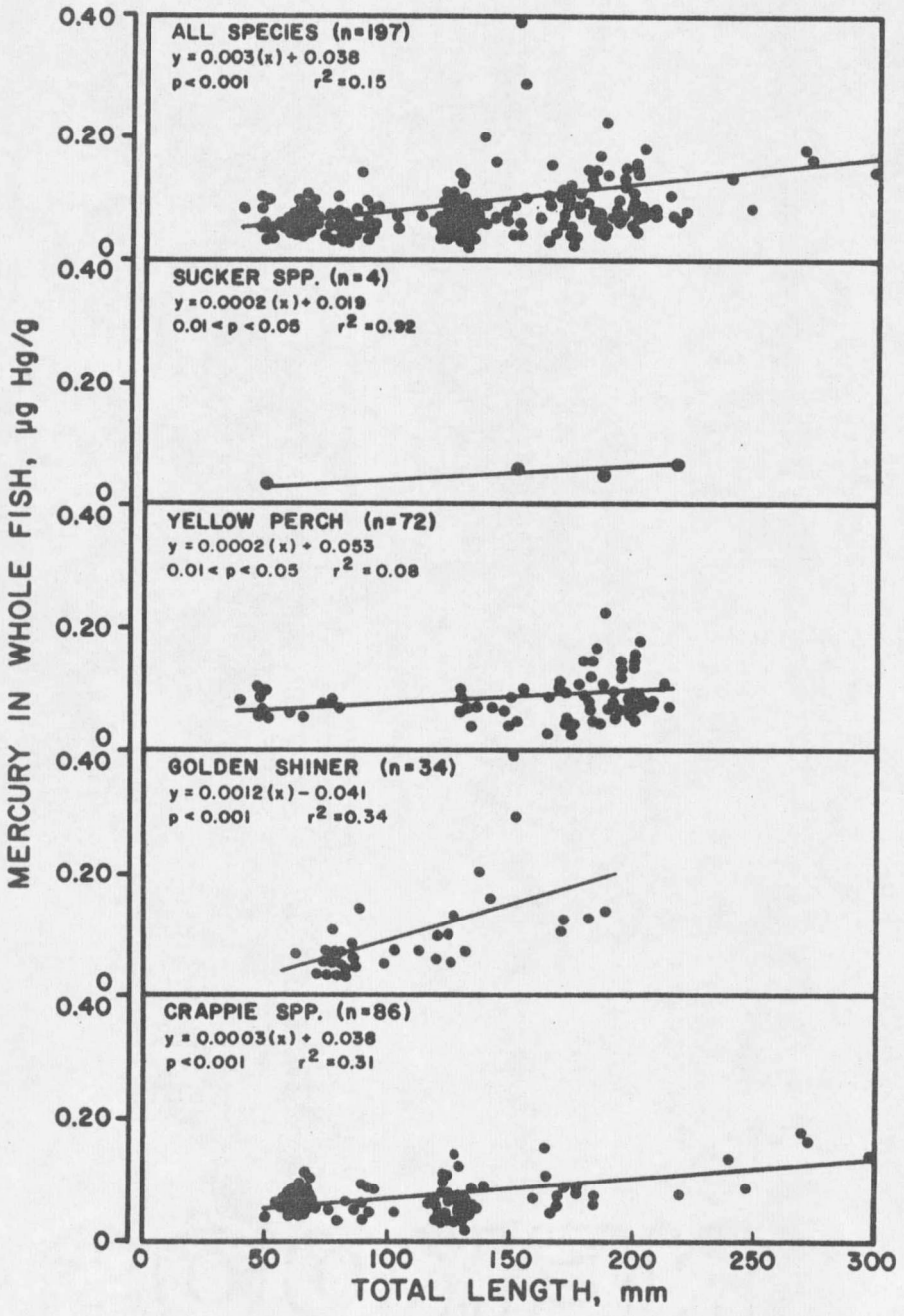


Figure 16. Relationship between concentrations of total mercury in whole fish and length of forage species collected from the TRR in 1980.

Methylmercury in Diet

Calculated concentrations of MeHg in the diet (in μgMeHg/g) ranged from 0.023 to 0.088 for walleye (mean 0.051), and from 0.023 to 0.055 for white crappie (mean 0.042), depending on fish size and the assumed percentages of total mercury present as MeHg in diet components (Table 8). The diet fractions represented by fish and invertebrates vary with fish size, resulting in different overall MeHg percentages in the diets of different size classes.

Data on concentrations of mercury, particularly methylmercury, in the diets of fish are scarce. Jernelöv (1972) measured mercury concentrations in whitefish from the stomachs of northern pike collected from a contaminated lake; pike averaged 5.8 μgHg/g, while whitefish averaged 3.1 μgHg/g. Bottom fauna observed in whitefish stomachs and collected seperately averaged 0.3 μgHg/g. Similarly, mercury concentrations in organisms collected from uncontaminated waters were: pike-1.2 μgHg/g, whitefish-0.6 μgHg/g and bottom fauna-0.05 μgHg/g. Data given below indicate that mercury may be concentrated in food as it moves through the digestive tract, therefore Jernelöv's (1972) values for whitefish (collected from stomachs) may be high. His value for bottom fauna from an uncontaminated water body, if corrected for percentage MeHg is similar to my values for MeHg in diets. Norstrom et al. (1976) found MeHg concentrations averaging 0.033 μgMeHg/g in the primarily invertebrate diets of yellow perch from the Ottawa River. My values for walleye and

Table 8. Calculated concentrations (C) of methylmercury in the diet of walleye and white crappie for different size (and age) classes. Low, mean and high values correspond to varying percentages of MeHg (see methods).

Species length (mm)	Age[a] (years)	MeHg (µg/g) in diet (C) low	mean	high
Walleye				
170-247	1	0.023	0.039	0.052
248-349	2	0.032	0.049	0.058
350-426	3	0.031	0.047	0.056
427-477	4	0.032	0.048	0.057
478-535	5-6	0.032	0.048	0.057
536-790	7-11+	0.049	0.075	0.088
	Av.	0.033	0.051	0.061
White crappie				
138-196	2	0.023	0.038	0.050
197-232	3	0.022	0.038	0.052
233-254	4	0.022	0.039	0.055
255-271	5	0.032	0.049	0.058
272-382	6-8	0.030	0.046	0.055
	Av.	0.026	0.042	0.054

a Age class estimates are the same as for food habits data.

white crappie were slightly higher, probably due to higher mercury concentrations in the fish component of their diets.

Total mercury concentrations in the stomach and intestinal contents of crappie were generally higher than calculated diet concentrations (Table 9); moreover, mercury concentrations in intestinal contents were generally higher than those of stomach contents. This suggests that mercury is not efficiently assimilated during digestion and is therefore concentrated in the digestive tract. Low mercury assimilation efficiencies have been reported for mercury bound in food items under natural conditions (Jernelöv 1968; Phillips and Gregory 1979).

MeHg concentrations were consistently 0.01 μgMeHg/g higher in the diets of walleye aged 4 and under (< 477 mm) than in the diets of similarly aged white crappie (Figure 17). The MeHg content of the diets of both species increases sharply at certain points, probably in response to observed increases in the amount and size of fish consumed (Tables 4 and 5). One such shift occurred between ages 4 and 5 in crappie while a larger shift occurred between ages 6 and 7 in walleye. Increases in dietary MeHg concentrations roughly correspond to increases in the rates of mercury accumulation with age (Figure 4).

Other workers have observed higher mercury concentrations and/or higher percentages of MeHg in higher trophic levels (Armstrong and Hamilton 1973; Huckabee et al. 1974; Potter et al. 1975; Richins and Risser 1975; Kendall 1978; Cox et al. 1979; Meister et al. 1979) and

Table 9. Mercury in stomach and intestinal contents of selected white crappie from the Tongue River Reservoir.

Length (mm) interval	Length (mm) $\bar{X}$	Date	Stomachs n	Stomachs Hg(µg/g) ($\bar{X}$ ± SE)	Stomachs Est. MeHg[a] (µg/g)	Intestines n	Intestines Hg(µg/g) ($\bar{X}$ ± SE)	Intestines Est. MeHg[a] (µg/g)
138-196	166	8/80	3	0.086 (±0.037)	0.063	2	0.053 (±0.045)	0.039
		10/80	4	0.043 (±0.035)	0.031	1	0.161	0.118
		all	7	0.062 (±0.029)	0.045	3	0.079 (±0.137)	0.058
197-232	224	5/80	5	0.051 (±0.024)	0.035	6	0.077 (±0.035)	0.053
		8/80	9	0.090 (±0.013)	0.062	7	0.093 (±0.047)	0.059
		10/80	3	0.071 (±0.057)	0.049	2	0.145 (±0.925)	0.099
		all	17	0.075 (±0.013)	0.051	15	0.094 (±0.029)	0.064
233-254	244	5/80	9	0.040 (±0.019)	0.026	8	0.065 (±0.014)	0.043
		8/80	7	0.089 (±0.050)	0.059	6	0.067 (±0.035)	0.044
		10/80	11	0.098 (±0.047)	0.064	8	0.073 (±0.030)	0.048
		all	27	0.076 (±0.023)	0.050	22	0.068 (±0.012)	0.045
255-271	263	5/80	1	0.074	0.061	1	0.074	0.061
		8/80	2	0.099 (±0.296)	0.082	2	0.059 (±0.099)	0.049
		10/80	11	0.081 (±0.021)	0.067	9	0.106 (±0.061)	0.088
		all	14	0.083 (±0.018)	0.071	12	0.095 (±0.045)	0.079
272+	283	10/80	-	-	-	1	0.033	0.027

a Methylmercury concentration was estimated by dividing the total mercury concentration into fractions attributable to invertebrates and fish (Table 5), multiplying each by the appropriate mean % MeHg (from literature) and summing the resulting values.

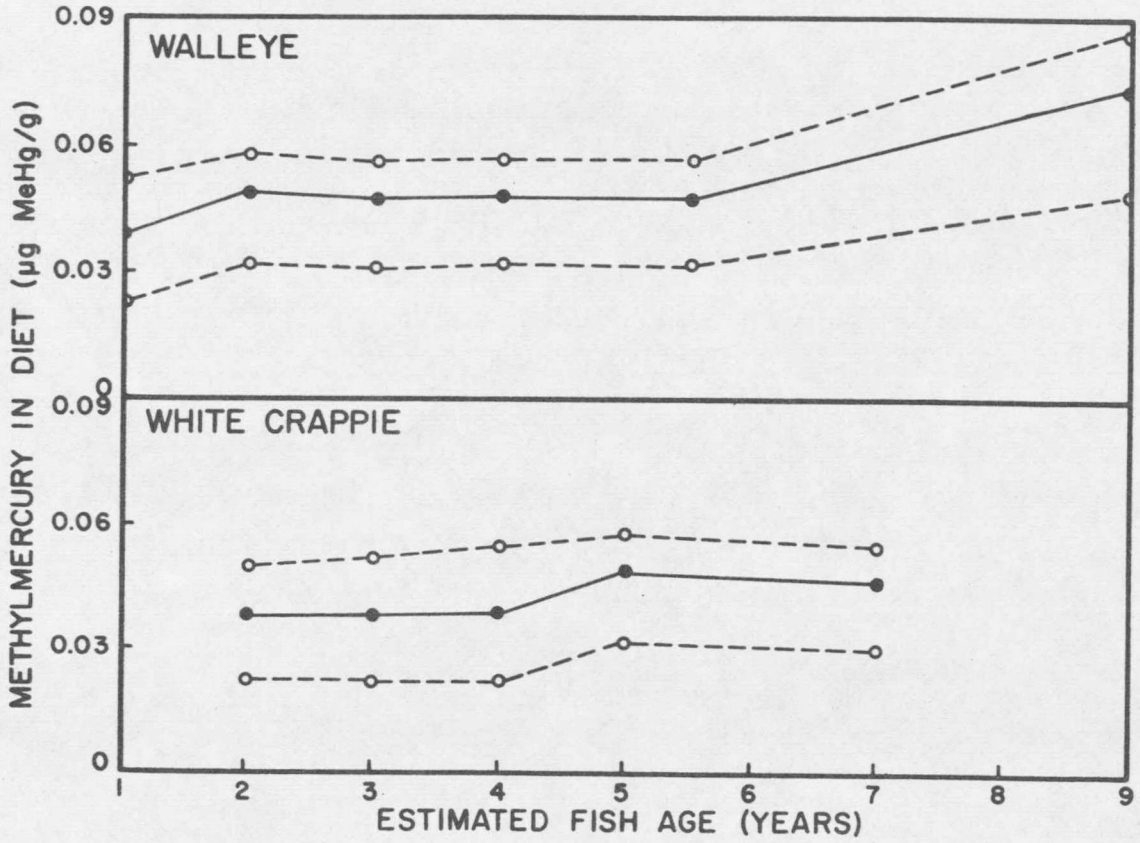


Figure 17. Comparison of calculated concentrations of methylmercury in the diets of walleye and white crappie from the TRR. Low, mean and high values correspond to different MeHg percentages.

have often related these findings to differences in feeding habits, regarding them as evidence of food chain biomagnification. DeFreitas et al. (1977) and Huckabee et al. (1979) offer the following valid criticisms to this line of reasoning: 1) because predators live longer their exposure to mercury is greater, and they attain higher mercury concentrations irregardless of trophic magnification, and 2) most studies fail to account for mercury dilution by growth, which results in lower mercury concentrations in faster-growing species. These authors feel that organisms occupying lower trophic levels usually grow faster than those at higher trophic levels, causing trophic effects to be exaggerated. Neither argument appears to apply to this study; age was accounted for by comparing fish of similar ages, and specific growth rates (g/g/day) were greater for walleye than for white crappie, which would tend to mask rather than exaggerate trophic effects. Such masking might account for the similarity in walleye and white crappie mercury concentrations, however differences in food habits and therefor in the amounts of MeHg consumed, were smaller than expected (white crappie in the TRR were originally thought to be planktivores). These differences were probably not large enough to result in detectably different mercury concentrations. The question of trophic magnification of mercury remains unanswered.

Methylmercury Accumulation by Fish

This study provides estimates of MeHg accumulated from food by walleye and white crappie, based on estimates of food consumption rates and diet concentration of MeHg. These estimates were compared to observed MeHg accumulations, and a theoretical framework was developed for assessing the relative importance of food as a source of MeHg to fish.

Observed accumulations. Total mercury concentrations in walleye and white crappie were less in 1980 than in fish of the same ages in 1978 (Figure 18), however the amount and concentration of mercury in individual cohorts increased from 1978 to 1980 (Table 10). For example, the regression equations for length versus mercury concentration in walleye are $\log_{10}Hg = 0.0018$ (length)-1.447 (Phillips 1978) and $\log_{10}Hg = 0.0022$ (length)-1.759 for 1978 and 1980 respectively. In 1978 age 2 walleye averaged 0.13 µg/g or 33.9 µg total mercury while in 1980, the same fish were age 4 and averaged 0.175 µg/g or 154.7 µg total mercury. Age 2 walleye in 1980 averaged only 0.08 µg/g or 22 µg total mercury. The quantity of mercury in the cohort increased by 120.8 µg or 60.4 µg/year, despite the decline between years in fish of the same age. Correction for the percentage MeHg yields the values in Table 10. Increases between years were smaller than the data from either year alone (ie: the difference between age 4 and age 2 fish from the same year) suggests.

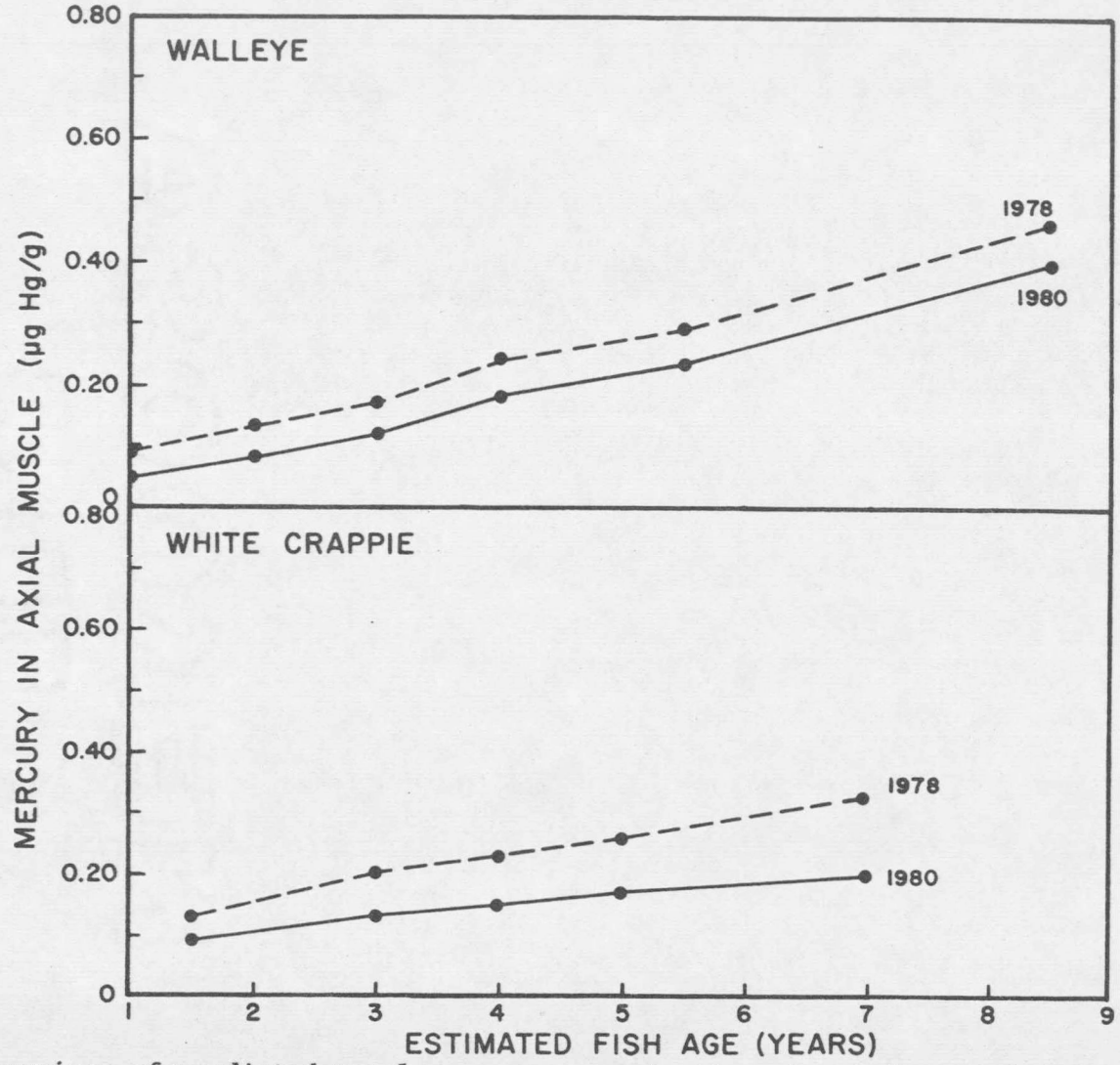


Figure 18. Comparison of predicted total mercury concentrations in similar aged fish in 1978 and 1980. Data for 1978 from Phillips (1978).

Table 10. Observed methylmercury accumulation rate from 1978 to 1980. Low, mean, and high values of $\Delta M/\Delta t$ correspond to varying percentages of MeHg (see methods); see text for example of calculating $\Delta M/\Delta t$.

Species length (mm)	Age[a] (years)	Observed MeHg accumulation $\Delta M/\Delta t$ (µg)		
		low	mean	high
Walleye				
170-247	1	2.76	4.19	4.93
248-349	2	6.17	9.37	11.02
350-426	3	12.82	19.45	22.88
427-477	4	33.82	51.33	60.39
478-535	5-6	42.77	64.92	76.38
536-790	7-11+	193.66	293.95	345.82
White crappie				
138-196	2	1.45	2.20	2.59
197-232	3	4.90	7.44	8.75
233-254	4	5.49	8.34	9.81
255-271	5	2.60	3.95	4.65
272-382	6-8	5.13	7.78	9.15

a Age class estimates are the same as for food habits data

Mercury concentrations in TRR fishes were elevated in 1979 relative to 1978 (Phillips 1979) and 1980, suggesting that the amount of methylmercury available to fish changes from one year to the next, and that differences between years result from fluctuating environmental conditions. Jernelöv et al. (1975) indicate that equilibrium with mercury in the environment is not achieved by top predators until 10 to 15 years after changes in their MeHg exposure regime. Thus, highly dynamic systems such as reservoirs may remain in a state of flux relative to mercury and never attain equilibrium conditions.

The MeHg accumulated by walleye in a year increased rapidly with age while the MeHg accumulated per year by white crappie increased through age 4 but was lower in fishes aged 5-8. Walleye rates of accumulation slowed at about the same age (5-6), but the reason for this is unknown. Walleye accumulated more MeHg at any given age than did white crappie. Accumulation rates appear to be positively related to age.

Uptake from food. Low assimilation coefficients in the range of reported values gave the only values of $\Delta F/\Delta t$ (annual uptake from food) which were less than observed accumulation rates ($\Delta M/\Delta t$), suggesting that 0.15 is the realistic value for `a´ under TRR conditions. Phillips and Gregory (1979) hypothesize that dietary MeHg assimilation is low in natural situations due to the exposure regimes of food items (ie: low concentrations over long time periods) which results in the

binding of MeHg to relatively non-digestible food constituents. They suggest that although high assimilation values are frequently observed in the laboratory (Suzuki and Hatanaka 1975; Sharpe et al. 1977), the conditions of these studies generally favor loose binding of MeHg in the diet or binding to more easily assimilated components. This hypothesis is supported by studies which indicate that MeHg is assimilated into the blood and subsequently redistributed to other, less digestible tissues, especially muscle (Giblin and Massaro 1973; Olson et al. 1973; Laarman et al. 1976; McKim et al. 1976). Consequently, only low assimilation efficiencies are presented or used for subsequent calculations in this study.

The amount of MeHg assimilated from food in a year increased with size (and age) in both walleye and white crappie (Tables 11 and 12), due to increases in both MeHg in diet and absolute ration (g food per year). Uptake values were consistently higher in walleye than in crappie of the same age for the same reasons. Many studies have shown that mercury accumulation rates increase with increasing concentrations in food (Miettinen 1975; Lock 1975; Wobesor 1975; Huckabee et al. 1978). It has been widely hypothesized that the amount of MeHg consumed (and assimilated) increases with increasing size and trophic level, and that such increases account for corresponding differences in mercury concentration under natural conditions, (Richins and Risser 1975; Benson et al. 1976; Koli et al. 1977; Phillips et al. 1980).

Table 11. Calculated annual methylmercury uptake from food by walleye from the TRR using a range of food consumption rates and methylmercury concentrations in the diet.

Walleye length (mm)	Age[a] (years)	Assimilation (a)	MeHg in diet (C) (µg/g food)	Ration (R) (g food/ g fish/yr.)	MeHg uptake from food ($\Delta F/\Delta t$) (µg/yr.)
170-247	1	low (0.15)	low (0.02)	low (5.48)	0.88
		low (0.15)	mean (0.04)	median (6.75)	1.82
		low (0.15)	high (0.05	high (8.03)	2.85
248-349	2	low (0.15)	low (0.03)	low (5.48)	4.73
		low (0.15)	mean (0.05)	median (6.75)	8.85
		low (0.15)	high (0.06)	high (8.03)	12.38
350-426	3	low (0.15)	low (0.03)	low (5.48)	9.42
		low (0.15)	mean (0.05)	median (6.75)	17.63
		low (0.15)	high (0.06)	high (8.03)	24.67
427-477	4	low (0.15)	low (0.03)	low (5.48)	17.65
		low (0.15)	mean (0.05)	median (6.75)	33.04
		low (0.15)	high (0.06)	high (8.03)	46.23
478-535	5-6	low (0.15)	low (0.03)	low (5.48)	28.74
		low (0.15)	mean (0.05)	median (6.75)	53.79
		low (0.15)	high (0.06)	high (8.03)	75.26
536-790	7-11+	low (0.15)	low (0.05)	low (5.48)	72.10
		low (0.15)	mean (0.08)	median (6.75)	134.95
		low (0.15)	high (0.09)	high (8.03)	188.85

a Age class estimates the same as for food habits data

Table 12. Calculated annual methylmercury uptake from food by white crappie from the TRR using a range of food consumption rates and methylmercury concentrations in the diet.

Crappie length (mm)	Age[a] (years)	Assimilation (a)	MeHg in diet (C) (µg/g food)	Ration (R) (g food/ g fish/yr.)	MeHg uptake from food ($\Delta F/\Delta t$) (µg)
138-196	2	low (0.15)	low (0.02)	low (4.02)	0.413
		low (0.15)	mean (0.04)	mean (8.40)	1.440
		low (0.15)	high (0.05)	high (12.78)	2.880
197-232	3	low (0.15)	low (0.02)	low (4.02)	1.389
		low (0.15)	mean (0.04)	mean (8.40)	5.044
		low (0.15)	high (0.05)	high (12.78)	10.531
233-254	4	low (0.15)	low (0.02)	low (4.02)	2.271
		low (0.15)	mean (0.04)	mean (8.40)	8.372
		low (0.15)	high (0.06)	high (12.78)	17.745
255-271	5	low (0.15)	low (0.03)	low (4.02)	4.060
		low (0.15)	mean (0.05)	mean (8.40)	13.038
		low (0.15)	high (0.06)	high (12.78)	23.707
272-382	6-8	low (0.15)	low (0.03)	low (4.02)	5.911
		low (0.15)	mean (0.05)	mean (8.40)	18.988
		low (0.15)	high (0.06)	high (12.78)	34.538

a Age class estimates the same as for food habits data

Such increases in MeHg consumption have not been previously documented. Data presented in this study indicate that MeHg uptake from food does increase with size and trophic level, however the magnitude of these increases was not sufficient to result in increases in mercury concentration. Similar studies of fish with widely varying food habits are needed to test this hypothesis.

Fraction attributable to food. The percentage of accumulated MeHg attributable to food ranged from approximately 10% to greater than 100% in both species (Appendix Tables 23, 24 and 25), depending on the various combinations of $\Delta F/\Delta t$, $\Delta M/\Delta t$ and $\Delta E/\Delta t$ used in the estimation. Only combinations yielding totals less than 100% (one) are given. Age and species trends were essentially the same using either method of calculating FF (the fraction derived from food), however, for comparable parameters, the second, more rigorous method (equation 2; pg. 16) gave higher values. This difference is more pronounced among white crappie than among walleye, because crappie $\Delta M/\Delta t$ values were much smaller than predicted by the 1980 data.

When mean values for all parameters except assimilation were used (ie: $\Delta F/\Delta t$-low/mean; $\Delta M/\Delta t$-mean; $\Delta E/\Delta t$-mean; see methods, pp. 13-15 for explanation of terms), the percentage of accumulated MeHg attributable to food ranged from 27 to 83% in walleye, and from 21 to 91% in white crappie, depending on size and estimation method. For the two largest size classes of crappie, only low values of R (ration) and C

(MeHg in diet) produced fractions less than one with equation 2, so low/low values of $\Delta F/\Delta t$ were used for these two size classes. With crappie, the fraction of MeHg derived from food generally increased with size and age. These data support the hypothesis that the higher mercury concentrations found in older fish result from increased exposure via food as well as from longer exposure times. The walleye data are less conclusive. The fraction derived from food was lowest among both the smallest and the largest size classes. Accumulation rates in older fish rose as fast or faster than rates of uptake from food, causing the fraction derived from food to remain the same or even to decline slightly. Although uptake from water may have also increased with size, an alternate explanation for these observations might be provided by further study of the seasonal and yearly changes in the uptake of MeHg from food.

Average percentages of accumulated MeHg from food (using mean parameters) were 41 and 62% for walleye and 51 and 73% for white crappie for methods 1 and 2 respectively. Unfortunately, the error associated with these estimates is potentially quite large and any extrapolation of the data, especially specific percentages, must be approached cautiously. Nonetheless, the data show, that under conditions which can reasonably be assumed to occur, food is a major source of accumulated MeHg in TRR fishes. The results of this study emphasize the difficulties involved in this kind of estimate, and point out the

need for better definition of many of the parameters not measured in this study. With some notable exceptions (Hannerz 1968; Fagerstrom and Asell 1976), most other studies have also concluded that, under certain (variable) conditions, food can be a significant source of MeHg to aquatic organisms (Colwell et al. 1975; Huckabee et al. 1975; Jernelöv et al. 1975; Lock 1975; Huckabee et al. 1978; Hildebrand et al. 1980; Ribeyre et al. 1981). The question now becomes, how significant? This study, and others have failed to accurately determine the importance of food, primarily due to the analytical difficulties of measuring MeHg in food organisms. As with MeHg in water, levels in food organisms in natural systems often fall below current detection limits. Since many factors affect the rate and efficiency of MeHg uptake by fishes from both food and water, it seems reasonable to suggest that their relative contributions may vary from system to system. Hopefully, further delineation of mercury uptake kinetics and pathways in natural systems will answer the questions raised above and suggest methods of avoiding the human health problems associated with mercury in the environment. The importance of such research is emphasized by the current push for increased reliance on coal-fired power generating plants, which will probably result in higher mercury levels in aquatic environments.

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APPENDIX

Table 13. Total mercury present as methylmercury; mean percentages reported for invertebrates.

Reference	% MeHg
Cox et al. 1975	6[a]
Kendall 1978	13[b]
Jernelov and Lann 1971	15
Cox et al. 1975	18[c]
Ottawa River Project Group 1979	30
Kendall 1978	31[d]
Knauer and Martin 1972	39
Hildebrand et al. 1976	50
Hildebrand et al. 1980	54
Huckabee and Hildebrand 1974 (in Huckabee et al. 1979)	76
Mean (± SE)	33 ± 22

a During input of mercuric ion
b Uncontaminated natural water
c Two weeks after input of mercuric ion ceased
d Contaminated natural water

Table 14. Total mercury present as methylmercury; mean percentages reported for fish.

Reference	% MeHg
Freeman and Horne 1972	56
Cox et al. 1979	58
Doi and Fukuyama 1980	72
Burrows and Krenkel 1973	73
Qadri et al. 1977	73
Johnels et al. 1967	75
Takeda and Ueda 1979	75
Buhler et al. 1971	78
Huckabee et al. 1978	78
Kendall 1978	78
Suzuki and Hatanaka 1975	80
Windom et al. 1976	80
Doi and Ui 1975	81
Bache et al. 1971	82
Solomon and Uthe 1971	83
Ottawa River Project Group 1979	85
Zitko et al. 1971	86
Uthe et al. 1973	88
Bishop and Neary 1974	89
Gillespie 1972	90
Luten et al. 1980	90
Bishop and Neary 1975 (in Sherbin 1979)	92
Hildebrand et al. 1980	92
Kenney 1972	92
Lockhart et al. 1972	92
Noren and Westoo 1967 (in Huckabee et al. 1979)	92
Huckabee et al. 1974	93
Westoo 1973	93
Uthe 1972	94
Laarman et al. 1976	95
McKim et al. 1976	95
Ueda and Takeda 1979	95
Kamps et al. 1972	100
Phillips and Gregory 1979	100
Mean (± SE)	85 ± 11

Table 15. Methylmercury assimilation efficiencies reported for fish (after Phillips and Gregory 1979).

Reference	% MeHg assimilated
Jernelov 1968	15[a]
Phillips and Gregory 1979	19
Miettinen et al. 1970	38[b]
Jernelov 1968	43[c]
Lock 1975	51
Miettinen et al. 1970	55[d]
Suzuki and Hatanaka 1975	67
Phillips and Buhler 1978	68
Sharpe et al. 1977	80
Suzuki and Hatanaka 1974	88
Mean (± SE)	52 ± 25

a Prey fish collected from nature
b MeHg added to food
c Prey fish exposed in laboratory
d Orally administered water solution

Table 16. Methylmercury elimination rates (half-lives) reported for fish.

Reference	Half-life (years)
Stary et al. 1980	0.30
Burrows and Krenkel 1973	0.36
Sharpe et al. 1977	0.44
Giblin and Massaro 1973	0.55[a]
Ruohtula and Miettinen 1975	1.03
Miettinen et al. 1969	1.29
Tillander et al. 1969 (in Huckabee et al. 1979)	1.64
Lockhart et al. 1972	1.90[b]
Miettinen 1975	1.99
Norstrom et al. 1976	2.00
Suckcharoen and Lodenius 1980	2.00
Uthe 1972	2.00
Laarman et al. 1976	2.10[a]
Miettinen 1975	2.44[b]
Huckabee et al. 1975	2.70[a]
Massaro and Giblin 1972	2.70[a]
Miettinen 1975	2.70[b]
McKim et al. 1976	2.80[a]
Armstrong and Scott 1979	7.00
Olsson 1976	7.00
Mean (± SE)	2.25 ± 1.82

a Greater than or equal to this value
b Values for different species in this study

Table 17. Numbers and length distributions of walleye and white crappie collected during the four 1980 sampling periods.

Species	Sampling period	Length (mm)	No. of fish
Walleye	4/16 - 5/9	436-477	2
		478-535	2
		536-700	30
	6/20 - 7/10	223-247	7
		248-349	5
		350-426	1
		427-477	1
		536-675	4
	8/7 - 8/14	172-247	3
		248-349	44
		350-426	5
		427-477	5
		536-655	2
	10/2 - 10/7	190-247	3
		248-349	19
		350-426	8
		427-477	4
		478-535	7
		536-790	11
White crappie	4/29 - 5/8	163-196	8
		197-232	21
		233-254	38
		255-271	7
		272-382	4
	6/18 - 7/2	190-196	3
		197-232	18
		233-254	23
		255-258	2
	8/8 - 8/14	138-196	33
		197-232	14
		233-254	10
		255-271	5
		272-288	3
	9/30 - 10/8	154-196	14
		197-232	4
		233-254	19
		255-271	14
		272-296	7

Table 18. Stomach contents of walleye collected from the Tongue River Reservoir.

Sampling period[a]	Food items (No.)	Frequency % (No.)	Volume % ± SE	Volume (cc)
April 16-May 9 (26)	Invertebrates (0)	—	—	
	Fishes (44)	100 (26)	100	(1582.2)
	Perca flavescens (16)	42 (11)	18 ± 4.5	(278.4)
	Pomoxis spp. (14)	42 (11)	76 ± 4.6	(1207.7)
	Unidentifiable (14)	42 (11)	6 ± 1.0	(96.1)
June 20-July 10 (18)	Invertebrates (308)	44 (8)	1 ± 0.5	(1.4)
	Diptera (306)	39 (7)	1 ± 0.5	(1.4)
	Ephemeroptera (2)	11 (2)	<1	(<0.1)
	Fishes (30)	89 (16)	99 ± 0.5	(143.4)
	Centrarchidae fry (7)	6 (1)	1 ± 0.4	(0.8)
	Pomoxis spp. (2)	11 (2)	58 ± 15.2	(84.0)
	Unidentifiable (21)	72 (13)	40 ± 12.2	(58.6)
August 7-14 (49)	Invertebrates (0)	—	—	
	Fishes (95)	100 (49)	100	(103.4)
	Catostomus commersoni (2)	2 (1)	5 ± 1.3	(5.3)
	Perca flavescens (13)	14 (7)	9 ± 2.0	(8.9)
	Pomoxis spp. (54)	49 (24)	67 ± 2.8	(69.8)
	Unidentifiable (26)	49 (24)	19 ± 0.3	(19.4)
October 2-7 (38)	Invertebrates (0)	—	—	
	Fishes (76)	100 (38)	100	(296.4)
	Catostomus commersoni (2)	3 (1)	6 ± 1.7	(19.0)
	Cyprinus carpio (3)	3 (1)	38 ± 9.2	(112.0)
	Notemigonus crysoleucas (2)	3 (1)	1 ± 0.7	(3.3)
	Perca flavescens (4)	11 (4)	9 ± 2.4	(27.3)
	Pomoxis spp. (29)	50 (19)	36 ± 5.5	(105.9)
	Unidentifiable (36)	66 (25)	10 ± 1.8	(28.9)

a Number of walleye in parentheses; fish with empty stomachs or only unidentifiable contents excluded.

Table 19. Stomach contents of white crappie collected from the Tongue River Reservoir.

Sampling period[a]	Food items[b]	Weight (g)[c]	Frequency % (No.)	Volume % ± SE	Volume (cc)
April 29 - May 8 (73)	Invertebrates	33.29	99 (72)	75 ± 2.8	(32.41)
	Cladocera	11.15	89 (65)	25 ± 1.3	(10.68)
	Copepoda	1.25	59 (43)	3 ± 0.2	(1.29)
	Coleoptera	0.002	1 (1)	<1	(0.002)
	Diptera	17.01	99 (72)	39 ± 1.8	(16.74)
	Ceratopogonidae	0.16	19 (14)	<1	(0.15)
	Chironomidae	16.85	99 (72)	38 ± 1.7	(16.59)
	Ephemeroptera	0.59	27 (20)	1 ± 0.3	(0.60)
	Baetidae	0.12	11 (8)	<1	(0.11)
	Caenidae	0.19	5 (4)	<1	(0.19)
	Hemiptera	3.16	44 (32)	7 ± 0.0	(3.06)
	Corixidae	3.16	44 (32)	7 ± 0.0	(3.06)
	Plecoptera	0.002	1 (1)	<1	(0.002)
	Perlodidae	0.002	1 (1)	<1	(0.002)
	Unidentifiable	0.13	4 (3)	<1	(0.13)
	Fishes	10.93 (9)	10 (7)	25 ± 2.8	(10.75)
	Notemigonus crysoleucas	3.97 (1)	1 (1)	9 ± 2.0	(3.96)
	Perca flavescens	5.92 (3)	1 (1)	13 ± 2.6	(5.70)
	Unidentifiable	1.04 (5)	7 (5)	3 ± 0.4	(1.09)
June 18 - July 2 (45)	Invertebrates	10.03	98 (44)	85 ± 1.5	(9.97)
	Cladocera	2.18	69 (31)	19 ± 0.1	(2.22)
	Copepoda	0.16	24 (11)	1 ± 0.5	(0.14)
	Hydracarina	0.01	4 (2)	<1	(0.01)
	Coleoptera	0.51	27 (12)	4 ± 0.4	(0.53)
	Dytiscidae	0.39	20 (9)	3 ± 0.4	(0.39)
	Gyrinidae	0.08	7 (3)	1 ± 1.2	(0.09)
	Hydrophilidae	0.01	2 (1)	<1	(0.02)
	Diptera	5.15	87 (39)	44 ± 1.4	(5.16)
	Ceratopogonidae	0.02	2 (1)	<1	(0.02)
	Chironomidae	5.13	87 (39)	44 ± 1.4	(5.14)
	Ephemeroptera	0.93	24 (11)	8 ± 0.7	(0.89)
	Baetidae	0.17	2 (1)	<1	(0.04)
	Caenidae	0.65	18 (8)	6 ± 0.7	(0.75)
	Hemiptera	0.93	38 (17)	8 ± 0.6	(0.88)
	Corixidae	0.93	38 (17)	8 ± 0.6	(0.88)
	Trichoptera	0.10	4 (2)	1 ± 0.1	(0.09)
	Hydropsychidae	0.05	2 (1)	1 ± 0.5	(0.05)
	Unidentifiable	0.06	4 (2)	<1	(0.05)
	Fishes	1.81	22 (10)	15 ± 1.5	(1.73)
	Percidae	0.79 (3)	4 (2)	6 ± 1.1	(0.66)
	Perca flavescens	0.59 (2)	2 (1)	4 ± 1.1	(0.48)
	Unidentifiable	1.02 (8)	18 (8)	9 ± 2.5	(1.07)

a Number of white crappie in parentheses; fish with empty stomachs or only unidentifiable contents excluded.

b Some items identified to order only; therefore total of families may be less than total for the order.

c Number of fish in parentheses; weight not corrected for effects of preservation.

Table 19. (cont.)

Sampling period[a]	Food items[b]	Weight (g)[c]	Frequency % (No.)	Volume % ± SE	Volume (cc)
August 8 - 14 (53)	Invertebrates	1.51	47 (25)	2 ± 0.2	(1.44)
	Cladocera	0.31	15 (8)	<1	(0.26)
	Copepoda	0.08	8 (4)	<1	(0.08)
	Diptera	1.11	36 (19)	1 ± 0.1	(1.09)
	Chironomidae	1.11	36 (19)	1 ± 0.1	(1.09)
	Ephemeroptera	0.01	2 (1)	<1	(0.01)
	Caenidae	0.01	2 (1)	<1	(0.01)
	Fishes	77.91	89 (47)	98 ± 0.2	(79.39)
	Cyprinus carpio	6.50 (3)	2 (1)	8 ± 2.1	(6.84)
	Pomoxis spp.	50.61 (32)	40 (21)	65 ± 2.1	(52.0)
	Stizostedion spp.	5.51 (2)	4 (2)	7 ± 2.5	(5.60)
	Perca flavescens	7.04 (4)	6 (3)	8 ± 1.6	(6.70)
	Unidentifiable	8.25 (28)	53 (28)	10 ± 0.8	(8.25)
Sept. 30 - Oct. 8 (50)	Invertebrates	3.35	66 (33)	4 ± 0.3	(3.08)
	Cladocera	0.06	8 (4)	<1	(0.06)
	Copepoda	0.04	4 (2)	<1	(0.04)
	Coleoptera	0.03	2 (1)	<1	(0.03)
	Diptera	1.78	50 (25)	2 ± 0.2	(1.62)
	Chironomidae	1.78	50 (25)	2 ± 0.2	(1.62)
	Ephemeroptera	0.44	24 (12)	<1	(0.41)
	Baetidae	0.01	2 (1)	<1	(0.01)
	Caenidae	0.13	10 (5)	<1	(0.12)
	Hemiptera	0.46	10 (5)	<1	(0.42)
	Corixidae	0.40	8 (4)	<1	(0.37)
	Notonectidae	0.06	2 (1)	<1	(0.05)
	Trichoptera	0.06	4 (2)	<1	(0.05)
	Leptoceridae	0.01	2 (1)	<1	(0.01)
	Unidentifiable	0.48	4 (2)	<1	(0.45)
	Fishes	76.36	76 (38)	96 ± 0.3	(74.17)
	Cyprinus carpio	5.40 (1)	2 (1)	7 ± 2.0	(5.10)
	Pomoxis spp.	44.19 (12)	22 (11)	56 ± 3.0	(43.39)
	Perca flavescens	7.67 (2)	4 (2)	9 ± 1.7	(7.34)
	Unidentifiable	19.10 (28)	56 (28)	24 ± 1.9	(18.34)

a Number of white crappie in parentheses; fish with empty stomachs or only unidentifiable contents excluded.

b Some items identified to order only; therefore total of families may be less than total for the order.

c Number of fish in parentheses; weight not corrected for effects of preservation.

Table 20. Composition of stomach contents, expressed as frequency of occurrence and percent volume, relative to time of day captured, for white crappie from the Tongue River Reservoir, 1980.

Time interval[a]	Stomach contents		
	Food items	Frequency (%)	Volume (% ± SE)
2400-0300 (36)	Invertebrates	79	11 ± 1.4
	Diptera	69	6 ± 0.7
	Other[b]	53	5 ± 0.6
	Fishes	62	89 ± 1.4
	Perca flavescens	8	18 ± 3.5
	Pomoxis spp.	22	48 ± 3.4
	Stizostedion spp.	3	6 ± 1.8
	Unidentifiable	36	17 ± 2.1
0300-0600 (20)	Invertebrates	75	16 ± 3.4
	Diptera	70	11 ± 2.3
	Other[b]	45	5 ± 1.4
	Fishes	70	84 ± 3.4
	Cyprinus carpio	5	31 ± 11.1
	Perca flavescens	10	26 ± 9.4
	Pomoxis spp.	10	15 ± 5.1
	Unidentifiable	45	12 ± 3.4
0600-0900 (21)	Invertebrates	87	16 ± 5.2
	Crustacea	57	8 ± 2.5
	Diptera	71	4 ± 1.8
	Other[b]	33	4 ± 1.4
	Fishes	39	84 ± 5.2
	Pomoxis spp.	5	65 ± 11.1
	Unidentifiable	38	19 ± 6.8
0900-1200 (24)	Invertebrates	92	69 ± 6.0
	Crustacea	71	12 ± 1.8
	Diptera	83	47 ± 5.1
	Hemiptera	25	5 ± 1.5
	Other[b]	38	5 ± 1.2
	Fishes	21	31 ± 6.0
	Pomoxis spp.	4	14 ± 5.5
	Unidentifiable	17	17 ± 4.7

a Number of white crappie in parentheses; fish with empty stomachs or only unidentifiable contents excluded.

b Includes identified invertebrates constituting 3% or less of the total volume for a given time interval, plus Insecta, which could not be identified further.

Table 20. (continued).

Time interval[a]	Stomach contents		
	Food items	Frequency (%)	Volume (% ± SE)
1200-1500 (23)	Invertebrates	87	59 ± 5.9
	Crustacea	65	13 ± 2.0
	Diptera	83	40 ± 4.7
	Hemiptera	26	4 ± 1.0
	Other[b]	26	2 ± 0.7
	Fishes	26	41 ± 5.9
	Perca flavescens	4	9 ± 3.5
	Unidentifiable	22	32 ± 5.8
1500-1800 (20)	Invertebrates	90	60 ± 8.8
	Crustacea	70	21 ± 3.7
	Diptera	90	35 ± 5.6
	Other[b]	55	4 ± 1.1
	Fishes	30	40 ± 8.8
	Pomoxis spp.	5	12 ± 5.1
	Stizostedion spp.	5	25 ± 9.4
	Unidentifiable	20	3 ± 0.8
1800-2100 (41)	Invertebrates	61	16 ± 1.7
	Crustacea	49	11 ± 1.3
	Other[b]	54	5 ± 0.5
	Fishes	54	84 ± 1.7
	Notemigonus crysoleucas	2	8 ± 2.4
	Perca flavescens	2	2 ± 0.7
	Pomoxis spp.	24	65 ± 3.2
	Unidentifiable	37	9 ± 0.9
2100-2400 (37)	Invertebrates	73	12 ± 1.6
	Crustacea	41	5 ± 0.7
	Diptera	62	4 ± 0.6
	Other[b]	50	3 ± 0.4
	Fishes	54	88 ± 1.6
	Cyprinus carpio	3	13 ± 3.5
	Perca flavescens	3	11 ± 3.4
	Pomoxis spp.	22	52 ± 3.7
	Unidentifiable	32	12 ± 2.1

a Number of white crappie in parentheses; fish with empty stomaches or only unidentifiable contents excluded.

b Includes identified invertebrates constituting 3% or less of the total volume for a given time interval, plus Insecta which could not be identified further.

Table 21. Estimates of annual food consumption rates for Tongue River Reservoir walleye based on possible combinations of growing period and non-growing period activity levels. Estimates based on the bioenergetics model of Kitchell et al. (1977).

Walleye length (mm)	Activity level[a] winter	summer	Proportion of maximum ration consumed (P)[b]	Daily ration (% body wt./day)
170 - 247	1	2	0.681	2.8
(age class 1)	1	3	0.823	3.7
	2	2	0.987	2.9
	2	3	1.130	3.9
248 - 349	1	2	0.684	1.8
(age class 2)	1	3	0.840	2.5
	2	2	1.032	1.9
	2	3	1.188	2.1
350 - 426	1	2	0.670	1.4
(age class 3)	1	3	0.832	2.0
	2	2	1.051	1.5
	2	3	1.213	2.1
427 - 477	1	2	0.657	1.2
(age class 4)	1	3	0.822	1.7
	2	2	1.055	1.3
	2	3	1.220	1.8
478 - 535	1	2	0.648	1.0
(age classes 5-6)	1	3	0.815	1.5
	2	2	1.062	1.1
	2	3	1.229	1.6
536 +	1	2	0.646	0.9
(age classes 7-11)	1	3	0.817	1.3
	2	2	1.088	1.3
	2	3	1.259	1.4
Average	1	2	0.664	1.5
	1	3	0.825	2.1
	2	2	1.046	1.6
	2	3	1.207	2.2

a Activity levels are: (1) standard metabolic rate as described by Winberg (1956); (2) twice the standard metabolic rate as an estimate of the average metabolic rate of adult fish under natural conditions; (3) three-fold the standard metabolic rate as an estimate of the maximum metabolic rate of adult fish under natural conditions.

b Both maximum consumption rates and activity levels are estimates, therefore P sometimes exceeds 1.0. The calculations in this table provide an estimated range of values and should not be considered absolute.

Table 22. Mercury concentrations reported for zooplankton.

Reference	Total Mercury (μgHg/g)
Sherbin 1979[a]	0.003
Sherbin 1979[a]	0.010
Knauer and Martin 1972	0.011
Trudel et al. 1977	0.019
Cocoros and Cahn 1973	0.024
Sherbin 1979[a]	0.025
Williams and Weiss 1973	0.025
Armstrong and Hamilton 1973	0.035
Sherbin 1979[a]	0.040
Sherbin 1979[a]	0.050
Flegal 1977	0.060
Sherbin 1979[a]	0.065
Sherbin 1979[a]	0.090
Johnels et al. 1967	0.140
Sherbin 1979[a]	0.158
Copeland, 1972	0.200
Mean (± SE)	0.060 ± 0.058

a Summary reference for Canadian fresh waters

Table 23. Fraction of 1980 methylmercury levels in walleye and white crappie accounted for by summing $\Delta F/\Delta t$, where $\Delta F/\Delta t$ is µg MeHg per year derived from food.

Walleye length (mm)	1980 mercury levels (µg)	$\Delta F/\Delta t$[a] low/low Σ	low/low FF[b]	low/mean Σ	low/mean FF[b]	low/high Σ	low/high FF[b]
170-247	4.93	0.88	.18	1.82	.37	2.85	.58
248-349	22.04	5.61	.25	10.67	.48	15.23	.69
350-426	54.05	15.03	.28	28.30	.52	39.90	.74
427-477	154.70	32.68	.21	61.34	.40	86.13	.56
478-535	283.30	61.42	.22	115.13	.41	161.39	.57
536-790	926.10	133.52	.14	250.08	.27	350.24	.38
		av.	.21	av.	.41	av.	.59

Crappie length (mm)	1980 mercury levels (µg)	$\Delta F/\Delta t$[a] low/low Σ	low/low FF[b]	low/mean Σ	low/mean FF[b]	low/high Σ	low/high FF[b]
138-196	5.19	0.41	.08	1.44	.28	2.88	.55
197-232	19.48	1.80	.09	6.48	.33	13.41	.69
233-254	27.12	4.07	.15	14.86	.55	31.16	>1.00
255-271	29.30	8.13	.21	27.89	.71	54.87	>1.00
272-382	67.06	14.04	.21	46.88	.70	89.41	>1.00
		av.	.15	av.	.51	av.	>1.00

a levels of $\Delta F/\Delta t$ correspond to: levels of `a´ C and R used to calculate this number. (See methods).

b fraction of 1980 mercury level accounted for by the corresponding Σ $\Delta F/\Delta t$.

Table 24. Estimated fractions of methylmercury accumulated by walleye from food. Only fractions less than one are given.

Walleye length (mm)	$\Delta F/\Delta t$[a]	$\Delta M/\Delta t$[b]	$\Delta E/\Delta t$[c]	FF[d]
170 - 247	low/low	low	low	0.305
	low/low	low	mean	0.283
	low/low	mean	low	0.201
	low/low	mean	mean	0.186
	low/low	high	low	0.171
	low/low	high	mean	0.158
	low/mean	low	low	0.629
	low/mean	low	mean	0.592
	low/mean	mean	low	0.415[f]
	low/mean	mean	mean	0.383[f]
	low/mean	high	low	0.352
	low/mean	high	mean	0.326
	low/high	low	low	0.987
	low/high	low	mean	0.913
	low/high	mean	low	0.650
	low/high	mean	mean	0.601
	low/high	high	low	0.553
	low/high	high	mean	0.511
248 - 349	low/low	low	low	0.731
	low/low	low	mean	0.676
	low/low	mean	low	0.482
	low/low	mean	mean	0.446
	low/low	high	low	0.409
	low/low	high	mean	0.379
	low/mean	mean	low	0.902[f]
	low/mean	mean	mean	0.834[f]
	low/mean	high	low	0.766
	low/mean	high	mean	0.709
	low/high	high	mean	0.992
350 - 426	low/low	low	low	0.702
	low/low	low	mean	0.649
	low/low	mean	low	0.462
	low/low	mean	mean	0.428
	low/low	high	low	0.393
	low/low	high	mean	0.364
	low/mean	mean	low	0.865[f]
	low/mean	mean	mean	0.801[f]
	low/mean	high	low	0.736
	low/mean	high	mean	0.680
	low/high	high	mean	0.952

a Levels as in Tables 11 and 12.
b Levels as in Table 10.
c Levels described in text.
d Fraction derived using equation (2)
f Estimates for most likely combination of parameters.

Table 24. (continued)

Walleye length (mm)	$\Delta F/\Delta t$[a]	$\Delta M/\Delta t$[b]	$\Delta E/\Delta t$[c]	FF[d]
427 - 477	low/low	low	low	0.498
	low/low	low	mean	0.461
	low/low	mean	low	0.328
	low/low	mean	mean	0.304
	low/low	high	low	0.279
	low/low	high	mean	0.258
	low/mean	low	low	0.933
	low/mean	low	mean	0.863
	low/mean	mean	low	0.615[f]
	low/mean	mean	mean	0.568[f]
	low/mean	high	low	0.522
	low/mean	high	mean	0.483
	low/high	mean	low	0.860
	low/high	mean	mean	0.795
	low/high	high	low	0.731
	low/high	high	mean	0.676
478-535	low/low	low	low	0.641
	low/low	low	mean	0.593
	low/low	mean	low	0.423
	low/low	mean	mean	0.391
	low/low	high	low	0.359
	low/low	high	mean	0.332
	low/mean	mean	low	0.791[f]
	low/mean	mean	mean	0.732[f]
	low/mean	high	low	0.672
	low/mean	high	mean	0.622
	low/high	high	low	0.941
	low/high	high	mean	0.870
536-790	low/low	low	low	0.355
	low/low	low	mean	0.329
	low/low	mean	low	0.234
	low/low	mean	mean	0.217
	low/low	high	low	0.199
	low/low	high	mean	0.184
	low/mean	low	low	0.665
	low/mean	low	mean	0.615
	low/mean	mean	low	0.438[f]
	low/mean	mean	mean	0.405[f]
	low/mean	high	low	0.373
	low/mean	high	mean	0.345
	low/high	low	low	0.931
	low/high	low	mean	0.861
	low/high	mean	low	0.613
	low/high	mean	mean	0.567
	low/high	high	low	0.521
	low/high	high	mean	0.482

a Levels as in Tables 11 and 12.
b Levels as in Table 10.
c Levels described in text.
d Fraction derived using equation (2)
f Estimates for most likely combination of parameters.

Table 25. Estimated fractions of methylmercury accumulated by white crappie from food. Only fractions less than one are given.

Crappie length (mm)	$\Delta F/\Delta t$[a]	$\Delta M/\Delta t$[b]	$\Delta E/\Delta t$[c]	FF[d]
138-196	low/low	low	low	0.272
	low/low	low	mean	0.251
	low/low	mean	low	0.179
	low/low	mean	mean	0.166
	low/low	high	low	0.152
	low/low	high	mean	0.141
	low/mean	low	low	0.947
	low/mean	low	mean	0.876
	low/mean	mean	low	0.624[f]
	low/mean	mean	mean	0.577[f]
	low/mean	high	low	0.530
	low/mean	high	mean	0.490
	low/high	high	mean	0.981
197-232	low/low	low	low	0.271
	low/low	low	mean	0.250
	low/low	mean	low	0.178
	low/low	mean	mean	0.165
	low/low	high	low	0.152
	low/low	high	mean	0.140
	low/mean	low	low	0.982
	low/mean	low	mean	0.909
	low/mean	mean	low	0.647[f]
	low/mean	mean	mean	0.599[f]
	low/mean	high	low	0.550
	low/mean	high	mean	0.509
233-254	low/low	low	low	0.395
	low/low	low	mean	0.365
	low/low	mean	low	0.260
	low/low	mean	mean	0.241
	low/low	high	low	0.221
	low/low	high	mean	0.204
	low/mean	mean	low	0.959[f]
	low/mean	mean	mean	0.887[f]
	low/mean	high	low	0.815
	low/mean	high	mean	0.754
255-271	low/low	mean	low	0.981[f]
	low/low	mean	mean	0.907[f]
	low/low	high	low	0.834
	low/low	high	mean	0.771
272-382	low/low	mean	low	0.725
	low/low	mean	mean	0.671
	low/low	high	low	0.616
	low/low	high	mean	0.570

a Levels as in Tables 11 and 12.
b Levels as in Table 10.
c Levels described in text.
d Fraction derived using equation (2)
f Estimates for most likely combination of parameters.

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