MICHIGAN DEPARTMENT OF ENVIRONMENTAL QUALITY
WATER RESOURCES DIVISION
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STAFF REPORT

TEMPORAL TRENDS AND SPATIAL DISTRIBUTION OF MERCURY IN FISH FROM MICHIGAN WATERS 1990-2015

I. INTRODUCTION

The Michigan Department of Environmental Quality-Water Resources Division (MDEQ-WRD) has conducted regular monitoring of persistent, bioaccumulative, toxic contaminants in fish since the early 1980s. A trend element was added to the fish contaminant monitoring effort in 1990 to detect changes in contaminant levels over time and to compare concentrations at various sites across the state. Fish tissue contaminant concentrations have been analyzed regularly from a total of 22 locations in the Great Lakes and connecting channels, inland lakes, and river impoundments (Table 1; Figure 1). Samples have been collected from each site every 2 to 5 years and analyzed as whole fish. Selected species of adult fish were targeted for collection and analyses. Species and locations in the Great Lakes and connecting channels were selected to complement and avoid duplication with the United States Environmental Protection Agency's (USEPA) Great Lakes whole fish trend monitoring program. Inland lake and impoundment sites were selected to monitor temporal trends and to allow comparisons between different regions of the state.

In addition to the sampling sites listed in Table 1, the initial plan for fish contaminant trend monitoring included collecting samples from the Lower Scott Flowage of the Menominee River (impoundment of the first dam), the Hodenpyl Reservoir on the Manistee River, and the Manistique River upstream of the Manistique Dam. Sampling at these stations was discontinued after 2 collection efforts due to difficulties collecting samples. Lake trout (*Salvelinus namaycush*) were collected from Grand Sable Lake (Alger County) during 3 sampling efforts but sampling was discontinued after 1995 when it was determined that the presence of splake (lake trout x brook trout hybrids) would make trend evaluations problematic; potential metabolic or other differences between the hybrids and lake trout along with difficulties in identifying pure lake trout would add extra uncertainties to evaluations. Lastly, collection of carp (*Cyprinus carpio*) from the River Raisin upstream of the Monroe Dam was discontinued after 2010 when a dam bypass was constructed, allowing passage to the sampling site by fish migrating to and from Lake Erie.

Ten trend monitoring sites were established in the Great Lakes and connecting channels (Table 1; Figure 1). Carp were monitored at 9 of those locations, walleye were collected from 7 locations, and lake trout were collected from 3 locations since 1990.

From 1990 through 2015, lake trout, walleye (*Sander vitreus*), or largemouth bass (*Micropterus salmoides*) were collected from 7 inland lake trend monitoring sites (Table 1). In that period Lake Gogebic has been sampled 8 times, Higgins, Houghton, and Pontiac Lakes have been sampled 9 times, and Gull, Gun, and South Manistique Lakes have been sampled 11 times.

Carp were collected from 5 river impoundment trend monitoring sites between 1990 and 2014 (Table 1). The River Raisin upstream of the Monroe Dam was sampled 8 times, the

St. Joseph River at Chapin Lake was sampled 9 times, the Grand River upstream of the 6th Street Dam and the Muskegon River at the Croton impoundment were sampled 10 times, and the Kalamazoo River at Lake Allegan was sampled 12 times in that period.

Several state and federal agencies and tribal organizations assisted with the MDEQ-WRD fish contaminant monitoring efforts by collecting samples. These include the Michigan Department of Natural Resources (MDNR), the USEPA, the United States Fish and Wildlife Service, the Grand Traverse Bay Band of Ottawa and Chippewa, the Little Traverse Bay Bands of Odawa Indians, the Chippewa Ottawa Resource Authority, the Keweenaw Bay Indian Community, and the Great Lakes Indian Fish and Wildlife Commission.

Fish contaminant trend samples have been analyzed by the Michigan Department of Health and Human Services Analytical Chemistry Laboratory (MDHHS-ACL) or by other labs under contract with the state laboratory. This report includes the analytical results for samples collected through 2015.

II. SUMMARY

1) Fish have been collected regularly from a total of 22 sites in Michigan waters since 1990 and analyzed for mercury and other contaminants. Up to 3 species were sampled at selected sites.
2) Overall, mercury concentrations have remained stable between 1990 and 2015.
3) Statistically significant trends were measured in 13 of the 31 fish populations sampled; 6 populations showed increasing mercury and 7 showed decreasing mercury over the period.
4) Comparisons within species indicated spatial differences in mercury concentrations both between Great Lakes sites and between inland water bodies, though most differences were not statistically significant.
5) Mercury concentrations declined between 1990 and 2015 in 4 of the 9 sampled Great Lakes carp populations, while 4 of 10 Great Lakes top predators (walleye and lake trout) increased over that time.
6) Changes in food webs and overall ecology in the Great Lakes due to invasive exotic species has likely changed mercury transport in the system and affected growth rates in the predators; both could explain the difference in trends measured for carp and top predators. Invasive species have also disrupted river impoundment and inland lake ecology possibly making the evaluation of temporal trends more difficult.

III. METHODS

A. Fish Collection and Processing

The MDNR-Fisheries Division and the MDEQ-WRD collected the majority of the fish using standard fish sampling techniques determined to be appropriate for individual water bodies. These techniques included electrofishing, trap nets, gill nets, and trawling. Samples were iced in the field and later frozen.

The fish were thawed prior to being processed by the MDEQ-WRD in accordance with the Surface Water Assessment Section Procedure WRD-SWAS-004 (MDEQ, 1990). Total length (nearest 0.1 centimeter), total weight (nearest gram), and sex was determined for each fish. Fish were prepared as whole-body samples. Each sample was individually wrapped in aluminum foil, placed in a plastic bag, labeled, and refrozen.

B. Chemical Analysis

Most of the fish tissue sample analyses for the Fish Contaminant Monitoring Program (FCMP) were conducted by the MDHHS-ACL, although certain analyses were conducted by one of several contract laboratories as needed. Current and past analytical laboratories all have quality assurance programs and use peer-reviewed methods of tissue homogenization, digestion, extraction, and quantification. Table 2 lists the standard contaminants measured in most fish tissue samples. All results are reported to the MDEQ as wet weight concentrations.

Mercury was measured as total mercury by thermal decomposition, amalgamation, and atomic absorption spectrometry. Mercury is a naturally occurring element and exists in the environment in several forms. Methylmercury, a highly toxic and bioaccumulative compound, comprises 70 to 99 percent of the total mercury measured in fish tissue (Kannan et al., 1998; May et al., 1987). The analytical method used for the MDEQ fish tissue samples measures total mercury, but it is generally assumed that most of the mercury measured in fish tissue is methylmercury.

The MDHHS-ACL does not report concentrations below the quantification level (QL), but above the detection level for mercury. Concentrations that are below the QL are coded with a “K” in the FCMP database. In these cases, the “K” coded concentrations represent the MDHHS-ACL QLs.

C. Statistical Analysis

Various factors can have substantial effects on the concentrations of mercury in fish. Often a strong relationship exists between the age of a fish and its mercury burden. Fish length was used as a surrogate measure of age for this analysis.

Multiple linear regression analysis was used to evaluate relationships between the mercury concentrations, sample collection date, and fish length. Since the raw data often do not meet the assumptions needed for valid regression analysis the data were first transformed using the natural log of the concentration. Natural log transformed mercury concentrations (wet weight) were used to fit the data into exponential decay rate models and obtain estimates of annual rates of change. The trend model for each subset of data was developed using an iterative process. The initial multiple linear regression model for mercury concentrations included fish length and collection date as explanatory variables. If fish length was not a statistically significant factor ($p \leq 0.05$) the final regression equation included only sample collection date as an explanatory factor.

Minimum detectable trends were calculated in cases where the regression model failed to detect a significant temporal trend in mercury concentration, that is, when the collection date factor in the trend model had a p value >0.05. The minimum detectable trend is the smallest possible trend that could have been detected with the available data for each species and site. The statistical significance of slope (or trend) in a linear regression model is calculated using a t-test. The minimum detectable trend can be calculated by rearranging the t-test, establishing a desired significance level ($p=0.05$), and obtaining the standard error of the slope from the regression analyses (Exponent, 2003). For example, a minimum detectable trend of +/-1.9 percent per year in Little Bay de Noc carp mercury concentrations (Table 3) indicates that no mercury trend was detected and the data were sufficient to detect a trend with an absolute value greater than 1.9 percent per year. Therefore, the absolute value of the real trend (if any) was 1.9 percent per year or less.

Estimates of mercury concentrations by sampling event for given species/site combinations were made using the General Linear Model (GLM) with fish length as a covariate. Least-squares means (sometimes called predicted marginal means) are computed using the GLM; because the statistics were calculated using natural log transformed concentrations that were then back transformed to a linear scale, the values presented represent a geometric mean of the concentrations adjusted for the covariate (length).

Between site comparisons of mercury concentrations were made using results for the same species to allow for between species differences in physiology, food habits, and growth rates. Fish length was used as a covariate for within species comparisons when it was statistically significant; doing so assumes that fish growth rates and food habits were similar between sites.

Statistical analyses were run using the Minitab software package (Version 17). The Minitab version of the GLM computes both the least-squares means and standard errors, which allows the calculation of confidence intervals on the least-squares means.

IV. RESULTS AND DISCUSSION

A total of 2,840 samples from 19 Great Lakes and connecting channel fish populations (trend-site/species combinations) and 12 inland water populations have been analyzed between 1990 and 2015. Significant temporal trends in total PCB, total DDT, and total chlordane concentrations have been detected in nearly all (94 percent) of those populations, and all the significant trends indicate that levels have declined. Those results will be presented in a separate report. In contrast, there was no detectable change in mercury concentrations in 18 of the 31 fish populations sampled (58 percent) while 6 (19 percent) of the populations showed significant increases and 7 (22 percent) showed significant decreases over time.

Mercury concentrations in a given species varied between sampling sites, though differences were not always statistically significant. In addition, mercury concentrations in different species from the same Great Lake/Connecting Channel sampling site varied as expected; in almost all cases the top predator species (walleye and lake trout) had higher concentrations than carp from the same site.

A. Temporal Trends

Atmospheric transport of anthropogenic mercury has been a source of surface water contamination globally through direct deposition or terrestrial runoff since the beginning of the industrial age in the mid-1800s, but most significantly in the latter half of the 20th century (Schuster et al., 2002; Streets et al., 2011). Globally, estimated anthropogenic mercury emissions have declined since 1990, although recent years have shown a possible increase largely attributed to increased industrialization in Asia (Zhang et al., 2016). In North America, measurements of both atmospheric mercury concentrations and wet deposition of mercury show a steady decline of about 1.5 percent per year since the mid-1990s (Zhang et al., 2016).

While it is likely that mercury inputs to aquatic systems are gradually declining the results of the analysis of temporal trends in fish from Michigan waters do not indicate significant changes in mercury concentrations. Overall, statistically significant trends were detected in less than half of the populations monitored since 1990, meaning that mercury levels in most populations have been relatively stable. Of the 13 measurable trends roughly half were increases and half were decreases over time (Tables 3 and 4; Figures 2 and 3).

Mercury concentrations in carp from the 4 connecting channels sites (St. Marys River, St. Clair River, Lake St. Clair, and Detroit River) have all declined since the MDEQ-WRD fish contaminant trend sampling began in 1990 with an average rate of decline of 2.8 percent per year (Table 3; Figures 2 and 4-7). Significant trends were not detectable in the 5 Great Lakes carp populations, and minimum detectable trends for those populations ranged from ± 1.1 to ± 1.9 percent per year (Table 4; Figures 8-12).

Mercury concentrations in 2 of the 3 Great Lakes lake trout populations and in 2 of the 7 Great Lakes and connecting channels walleye populations have increased over the MDEQ-WRD trend monitoring period (Table 4; Figures 2 and 9-13). No trend was detected in the remaining Great Lakes lake trout or walleye populations monitored (Figures 4-8 and 10). Where trends were detected for the Great Lakes lake trout and walleye, both top predator species, the results indicate increasing mercury concentrations while the concentrations in carp, a bottom feeding omnivore, have declined over the same time period (Figure 2); it should be noted however that each of the significant trend lines represent a different water body (to the degree that is possible with interconnecting waters). The differences observed between the carp and the top predator species could be explained, in part, by food web changes caused by the introduction of exotic species, most notably zebra and quagga mussels (family Dreissenidae) and the round goby (*Neogobius melanostomus*) (Madenjian et al., 2015). Since the food habits of carp differ substantially from walleye and lake trout the ecological changes due to the numerous non-native species invasions over the last few decades probably affected carp differently than the walleye and lake trout.

Fewer than half (5 of 12) of the monitored fish populations from inland waters had statistically significant temporal trends in mercury concentrations between 1990 and 2015 (Table 4; Figure 3). A significant trend in mercury concentrations was detectable in carp from 1 of the 5 river impoundment sampling sites (River Raisin) where levels declined at a rate of 2.6 percent per year (Table 4; Figure 3). Significant trends were not detectable in carp from 4 of the 5 river impoundment sampling sites, where minimum detectable trends ranged from ± 0.9 to ± 2.0 percent per year (Table 4; Figure 14). A significant trend in mercury concentrations was detectable in 4 of 7 inland lake top predator species populations (largemouth bass, walleye, or lake trout); 2 populations (Lake Gogebic walleye and Gull Lake largemouth bass) had declining concentrations and 2 (South Manistique Lake walleye and Higgins Lake lake trout) had increasing concentrations over the monitoring period (Table 4, Figure 15). No significant trend was detected in mercury concentrations in largemouth bass from Houghton, Gun, or Pontiac Lakes.

Exotic species have been introduced to many rivers and inland lakes in Michigan. In particular, zebra mussels are known to have established populations at each of the MDEQ inland lake trend sites except Lake Gogebic and South Manistique Lake, as well as in 1 river impoundment trend site (Lake Allegan/Kalamazoo River) (United States Geological Survey, 2016). As in the Great Lakes, the introduction of zebra mussels to inland waters may have affected the rates of mercury uptake by fish and complicated the evaluation of temporal trends.

Temporal trends in mercury concentrations in fish from Michigan waters have been inconsistent across species and across water bodies. This finding is similar to conclusions from several other studies. Zananski et al. (2011) evaluated data for fish collected from the Great Lakes between 1999 and 2009 and found an increasing trend in walleye from eastern Lake Erie and lake trout from western Lake Superior along with a decreasing trend in lake trout from Lake Ontario, Lake Michigan, and southern Lake Huron. Lake trout from central Lake Superior and northern Lake Huron did not exhibit significant temporal trends in that study. Bhavsar et al. (2010), and Rasmussen et al. (2007) also reported mixed results in Canadian waters of the Great Lakes and in walleye from Wisconsin waters, respectively. Monson (2009) reported a downward trend before the mid-1990s followed by an upward trend in northern pike and walleye from Minnesota inland lakes. A similar finding was reported by Gandhi et al. (2014) for inland lakes in the Province of Ontario. Such trend reversals might explain the low number of detectable trends in the Michigan data set; assuming a linear temporal trend in the statistical model may have masked a more complicated picture. Additional statistical analysis of the Michigan dataset is needed.

The disparity in observed temporal trends for atmospheric mercury deposition versus fish tissue concentrations may largely be due to the significant lag time between deposition and the bioavailability of mercury to aquatic systems. Mercury deposited in terrestrial environments may represent a substantial reservoir and long-term source of contamination that is only slowly released to surface waters (Harris et al., 2007).

B. Spatial and Interspecies Comparisons

Mercury concentrations in whole fish varied by species and by sampling site in the Great Lakes and connecting channels based on a comparison of the most recent results for each site/species combination. In addition, mercury concentrations tended to be higher in inland water fish populations compared to the populations sampled in the Great Lakes and connecting channels.

Great Lakes and Connecting Channels

The length adjusted mean mercury concentration in carp from Little Bay De Noc was nominally higher than in carp from any of the 8 other carp sampling sites, but the difference was statistically significant only for the Detroit and St. Clair Rivers (Table 5; Figure 16).

The length adjusted mean mercury concentration in Great Lakes walleye was nominally highest for samples from the St. Marys River and lowest in Lake Erie (Table 6; Figure 16) although there were no statistically significant differences between the 7 sampling sites where walleye were collected.

The length adjusted mean mercury concentration in lake trout was highest in fish from Thunder Bay (Lake Huron) and it was significantly different from the mean concentration in lake trout from Grand Traverse Bay (Lake Michigan) (Table 7; Figure 16). No other statistically significant differences between lake trout populations were detected.

At Great Lakes sites where both a top predator (lake trout or walleye) and carp were sampled, carp nearly always had the lower mercury concentration. This is consistent with what has been observed with fillet samples from non-trend sites around the state and globally. One exception in the whole fish trend sampling was at Little Bay De Noc where the estimated mean concentration in carp was 0.04 parts per million (ppm) higher than the estimate for walleye.

Inland Lakes and Impoundments

Fish length was not a significant covariate in the GLM for carp from impoundment trend sites. The mean mercury concentrations in carp from Lake Allegan (Kalamazoo River), the Croton Dam Impoundment (Muskegon River), and the Sixth Street Dam Impoundment on the Grand River were similar (Table 8; Figure 17) and the concentrations in all 3 were greater than in carp from Chapin Lake (St. Joseph River). The mean mercury concentration in carp from the River Raisin Monroe Dam impoundment was significantly less than in carp from Lake Allegan but differences with carp from other inland trend sites were not statistically significant.

The length adjusted mean mercury concentration in largemouth bass was highest in fish from Gun and Gull Lakes (Table 9; Figure 18); both had concentrations significantly higher than the bass from Houghton and Pontiac Lakes. Mercury in the Houghton Lake largemouth bass was significantly higher than in the bass from Pontiac Lake. A comparison of mercury concentrations in carp fillets from Houghton and Pontiac Lakes shows a similar difference.

The length adjusted mean mercury concentration in walleye from South Manistique Lake was nominally higher than in walleye from Lake Gogebic, but the difference was not statistically significant (Table 10; Figure 18).

Lake trout were collected from only 1 inland water trend site (Higgins Lake) and spatial trend comparisons with other inland species/lakes would not be useful. The length adjusted mean mercury concentration in lake trout from Higgins Lake was significantly greater than that measured in lake trout from the 3 Great Lakes trend sites (Table 11; Figure 19). Note that the fitted means calculated with the combined inland and Great Lakes lake trout results are slightly different than the means calculated using the Great Lakes data alone (Table 7). Combining all the data sets added information as well as variability to the statistical analysis.

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Table 1. Whole fish trend monitoring locations, target species, and years sampled.

WATER BODY	SPECIES COLLECTED	YEARS SAMPLED
GREAT LAKES AND CONNECTING CHANNELS		
Lake Michigan		
Little Bay de Noc	Carp	1992, 94, 00, 03, 05, 07, 09, 13
	Walleye	1992, 94, 97, 00, 02, 05, 07, 09, 13
Grand Traverse Bay	Carp	1993, 95, 00, 03, 08, 11, 15
	Lake Trout	1990, 92, 95, 98, 01, 04, 06, 09, 12
Lake Huron		
Saginaw Bay	Carp	1990, 92, 94, 98, 01, 03, 05, 09, 12, 15
	Walleye	1990, 91, 92, 94, 98, 03, 05, 07, 09, 12
Thunder Bay	Carp	1992, 94, 95, 99, 01, 04, 06, 08, 10, 12, 15
	Lake Trout	1992, 94, 95, 98, 01, 04, 05, 07, 09, 12
	Walleye	1991, 95, 98, 01, 05, 07, 09, 12
Lake Superior		
Keweenaw Bay	Lake Trout	1991, 93, 96, 99, 01, 04, 07, 10, 13
Lake St. Clair		
L'Anse Creuse Bay	Carp	1990, 92, 94, 98, 02, 05, 07, 09, 11, 14
	Walleye	1990, 92, 94, 98, 02, 05, 07, 09, 11, 14
Lake Erie		
Brest Bay	Carp	1990, 92, 94, 97, 98, 02, 06, 08, 10, 13
	Walleye	1990, 92, 94, 98, 04, 06, 08, 10, 13
St. Marys River		
Munuscong Bay	Carp	1993, 95, 98, 04, 09, 14
	Walleye	1991, 93, 95, 98, 01, 05, 07, 10, 14
St. Clair River		
Algonac	Carp	1992, 94, 02, 05, 07, 09, 12, 15
Detroit River		
Grassy Island	Carp	1990, 92, 94, 96, 98, 01, 04, 07, 09, 11, 14
	Walleye	1990, 94, 96, 98, 01, 04, 05, 11
INLAND WATERS		
RIVERS		
Grand River	Carp	1990, 92, 95, 00, 03, 05, 07, 09, 11, 14
Kalamazoo River	Carp	1990, 92, 94, 97, 99, 01, 03, 05, 07, 09, 11, 15
Muskegon River	Carp	1991, 93, 95, 97, 00, 02, 05, 07, 09, 12
River Raisin	Carp	1991, 94, 97, 00, 04, 06, 08, 10
St. Joseph River	Carp	1991, 93, 97, 00, 02, 05, 07, 09, 12
INLAND LAKES		
Lake Gogebic	Walleye	1992, 94, 97, 00, 02, 05, 09, 15
South Manistique Lake	Walleye	1991, 93, 95, 98, 01, 03, 05, 07, 09, 12, 15
Higgins Lake	Lake Trout	1991, 95, 97, 00, 02, 05, 10, 11, 15
Houghton Lake	Largemouth Bass	1992, 94, 98, 01, 04, 06, 08, 10, 13
Gull Lake	Largemouth Bass	1991, 93, 95, 97, 00, 02, 05, 07, 09, 12, 15
Gun Lake	Largemouth Bass	1990, 92, 94, 97, 00, 02, 05, 07, 09, 12, 15
Pontiac Lake	Largemouth Bass	1992, 94, 97, 99, 03, 06, 08, 10, 14

Table 2. Contaminants quantified in whole fish tissue samples.

Contaminant	Level of Quantification
Hexachlorobenzene	0.001 ppm
gamma-BHC (Lindane)	0.001 ppm
Aldrin	0.001 ppm
Dieldrin	0.001 ppm
4,4'-DDE	0.001 ppm
4,4'-DDD	0.001 ppm
4,4'-DDT	0.001 ppm
2,4'-DDE	0.001 ppm
2,4'-DDD	0.001 ppm
2,4'-DDT	0.001 ppm
Heptachlor Epoxide	0.001 ppm
Mercury	0.010 ppm
Selenium	0.010 ppm
Oxychlordane	0.001 ppm
gamma-Chlordane	0.001 ppm
trans-Nonachlor	0.001 ppm
alpha-Chlordane	0.001 ppm
cis-Nonachlor	0.001 ppm
Octachlorostyrene	0.001 ppm
Hexachlorostyrene	0.001 ppm
Heptachlorostyrene	0.001 ppm
Pentachlorostyrene	0.001 ppm
Heptachlor	0.001 ppm
Terphenyl	0.250 ppm
Apparent Toxaphene	0.050 ppm
Toxaphene $\Sigma 3PC_{26,50,62}$	0.050 ppb
Mirex	0.001 ppm
PBB (FF-1, BP-6)	0.001 ppm
Total PCB (congener method)	0.001 ppm

Table 3. Annual rates of change in mercury concentrations measured in whole fish collected from fixed station trend monitoring sites in the Great Lakes and Connecting Channels.

WATER BODY	SPECIES	SAMPLING PERIOD	ANNUAL RATE OF CHANGE	PROBABILITY
Lake Michigan				
Little Bay de Noc	Carp	1992-2013	± 1.9	--
	Walleye	1992-2013	± 1.3	--
Grand Traverse Bay	Carp	1993-2015	± 1.7	--
	Lake Trout	1990-2012	1.7	0.001
Lake Huron				
Saginaw Bay	Carp	1990-2015	± 1.1	--
	Walleye	1990-2012	2.9	<0.001
Thunder Bay	Carp	1992-2015	± 1.8	--
	Lake Trout	1992-2012	1.7	<0.001
	Walleye	1992-2012	± 1.6	--
Lake Superior				
Keweenaw Bay	Lake Trout	1991-2013	± 1.2	--
Lake Erie				
Brest Bay	Carp	1990-2013	± 1.7	--
	Walleye	1990-2013	1.5	<0.05
Lake St. Clair				
L'Anse Creuse Bay	Carp	1990-2014	-2.4	<0.01
	Walleye	1990-2014	± 1.4	--
St. Clair River				
Algonac	Carp	1992-2015	-2.9	<0.001
Detroit River				
Grassy Island	Carp	1990-2014	-4.1	<0.001
	Walleye	1990-2011	± 1.5	--
St. Marys River				
Munuscong Bay	Carp	1993-2014	-1.7	0.01
	Walleye	1991-2014	± 1.2	--
	Average**		-0.4	
	Median**		-0.1	

± indicates that no significant trend was measured (p>0.05) and the value presented is an estimate of the minimum detectable trend.

** Average and median concentrations were calculated using only waterbodies and species with significant trends.

Table 4. Annual rates of change in mercury concentrations measured in whole fish collected from fixed station trend monitoring sites in inland water bodies.

WATER BODY	SPECIES	SAMPLING PERIOD	ANNUAL RATE OF CHANGE	PROBABILITY
RIVER IMPOUNDMENTS				
Grand River	Carp	1990-2014	±1.8	--
Kalamazoo River	Carp	1990-2015	±0.9	--
Muskegon River	Carp	1991-2012	±2.0	--
River Raisin	Carp	1991-2010	-2.6	<0.001
St. Joseph River	Carp	1991-2012	±1.2	--
INLAND LAKES				
Lake Gogebic	Walleye	1992-2015	-1.7	0.01
South Manistique Lake	Walleye	1991-2015	1.0	0.05
Higgins Lake	Lake Trout	1991-2015	4.0	<0.001
Houghton Lake	Largemouth Bass	1992-2013	±0.9	--
Gull Lake	Largemouth Bass	1991-2015	-1.8	<0.001
Gun Lake	Largemouth Bass	1990-2015	±1.1	--
Pontiac Lake	Largemouth Bass	1992-2014	±1.2	--
	Average**		-1.3	
	Median**		-2.2	

± indicates that no significant trend was measured (p>0.05) and the value presented is an estimate of the minimum detectable trend.

** Average and median concentrations were calculated using only waterbodies and species with significant trends.

Table 5. Fitted mean total mercury concentrations in whole carp from temporal trend monitoring sites in Michigan waters of the Great Lakes and connecting channels. Means that do not share a letter are significantly different.

Sampling Site (Year)	mg/kg		
Little Bay De Noc (2013)	0.18	A	
Thunder Bay (2015)	0.11	A	B
St. Marys River (2014)	0.10	A	B
Lake St. Clair (2014)	0.10	A	B
Grand Traverse Bay (2015)	0.10	A	B
Saginaw Bay (2015)	0.10	A	B
Lake Erie (2013)	0.09	A	B
St. Clair River (2015)	0.09		B
Detroit River (2014)	0.08		B

Table 6. Fitted mean total mercury concentrations in whole walleye from temporal trend monitoring sites in Michigan waters of the Great Lakes and connecting channels. Means that do not share a letter are significantly different.

Sampling Site (Year)	mg/kg	
St. Marys River (2014)	0.21	A
Lake St. Clair (2014)	0.19	A
Saginaw Bay (2012)	0.18	A
Detroit River (2011)	0.15	A
Thunder Bay (2012)	0.15	A
Little Bay De Noc (2013)	0.14	A
Lake Erie (2013)	0.14	A

Table 7. Fitted mean total mercury concentrations in whole lake trout from temporal trend monitoring sites in Michigan waters of the Great Lakes and connecting channels. Means that do not share a letter are significantly different.

Sampling Site (Year)	mg/kg		
Thunder Bay (2012)	0.14	A	
Keweenaw Bay (2013)	0.12	A	B
Grand Traverse Bay (2012)	0.11		B

Table 8. Fitted mean total mercury concentrations in whole carp from river impoundment temporal trend monitoring sites in Michigan. Means that do not share a letter are significantly different.

Sampling Site (Year)	mg/kg			
Kalamazoo River (2015)	0.19	A		
Muskegon River (2012)	0.15	A	B	
Grand River (2014)	0.14	A	B	
River Raisin (2010)	0.11		B	C
St. Joseph River (2012)	0.09			C

Table 9. Fitted mean total mercury concentrations in whole largemouth bass from inland lake temporal trend monitoring sites in Michigan. Means that do not share a letter are significantly different.

Sampling Site (Year)	mg/kg			
Gun Lake (2015)	0.35	A		
Gull Lake (2015)	0.30	A		
Houghton Lake (2013)	0.19		B	
Pontiac Lake (2014)	0.14			C

Table 10. Fitted mean total mercury concentrations in whole walleye from inland lake temporal trend monitoring sites. Means that do not share a letter are significantly different.

Sampling Site (Year)	mg/kg	
S. Manistique Lake (2015)	0.34	A
Lake Gogebic (2015)	0.28	A

Table 11. Fitted mean total mercury concentrations in whole lake trout from temporal trend monitoring sites in Michigan waters of the Great Lakes and connecting channels compared to whole lake trout from Higgins Lake. Means that do not share a letter are significantly different.

Sampling Site (Year)	mg/kg		
Higgins Lake (2015)	0.23	A	
Thunder Bay (2012)	0.12		B
Keweenaw Bay (2013)	0.11		B
Grand Traverse Bay (2012)	0.10		B

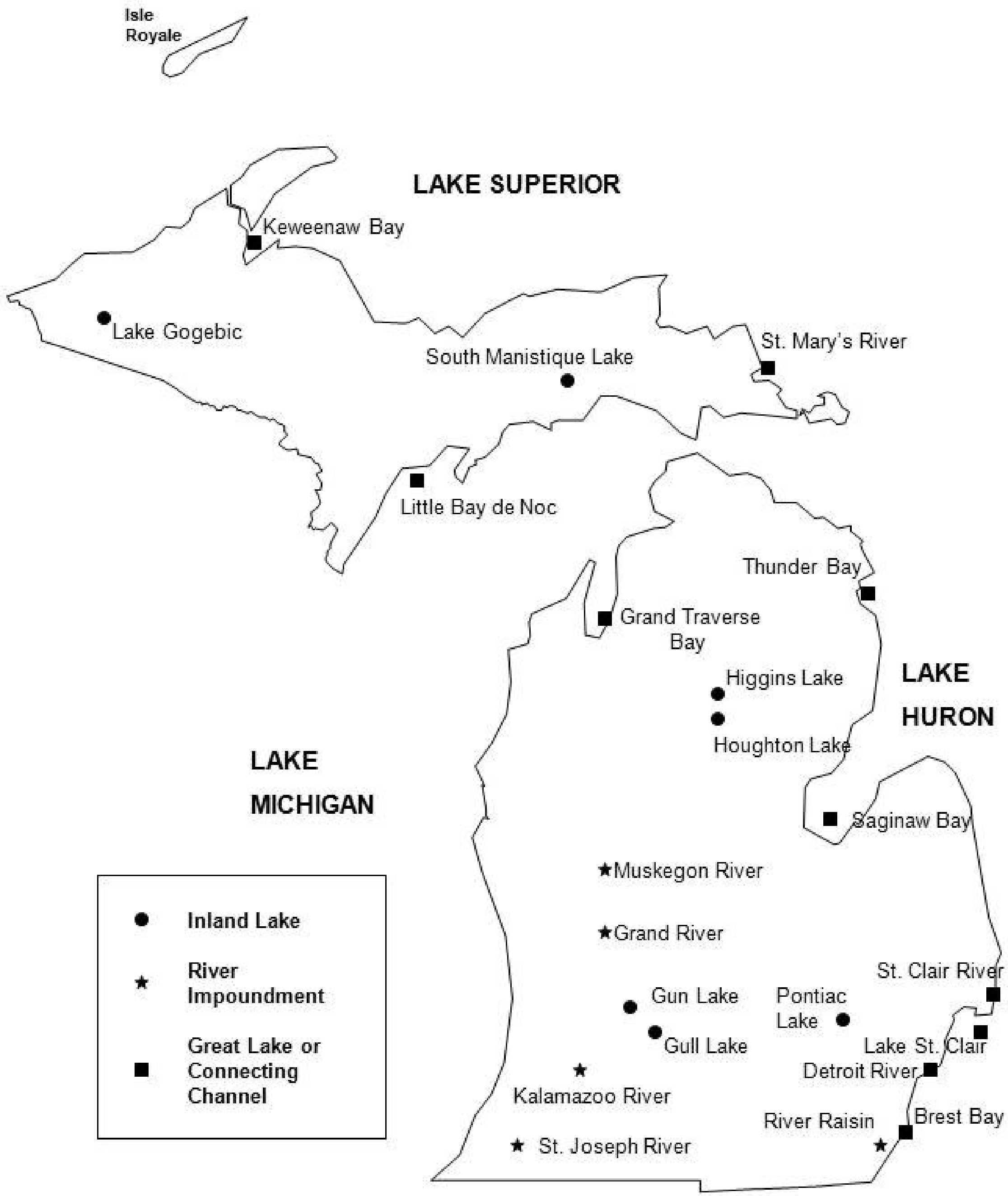


Figure 1. Whole fish temporal trend monitoring sites.

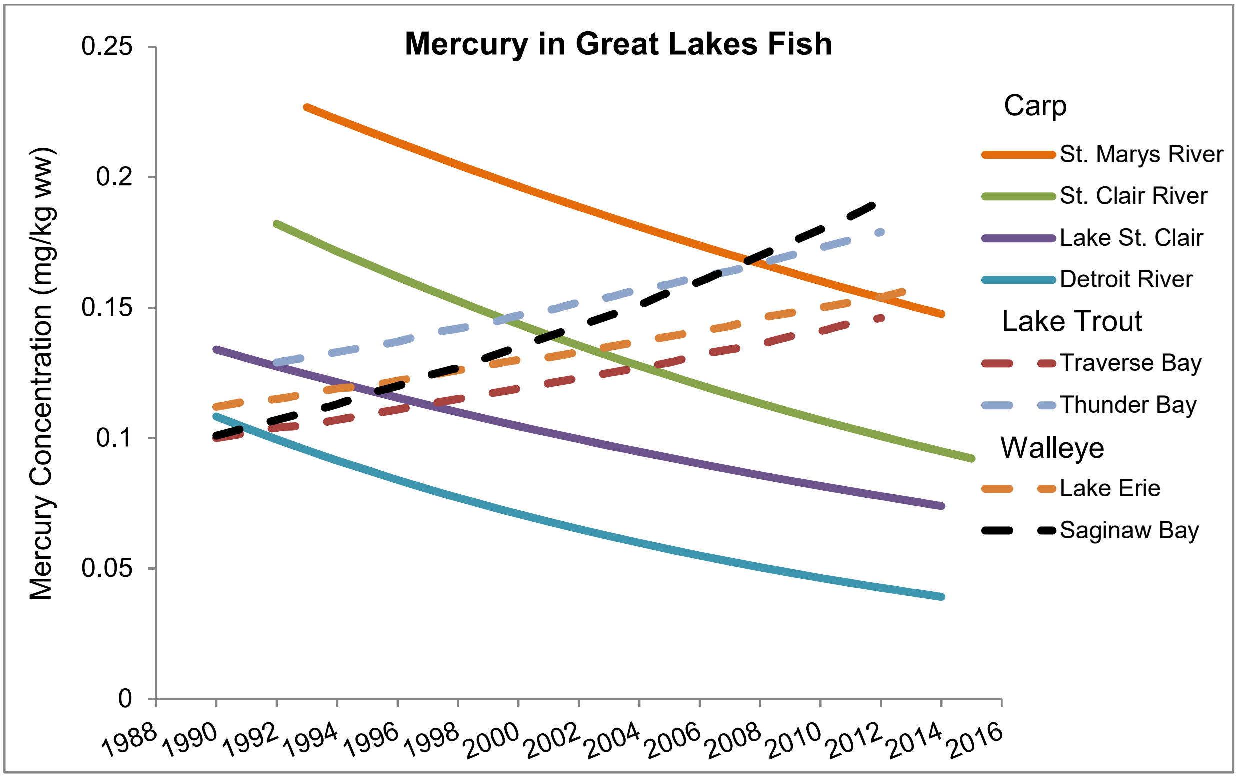


Figure 2. Estimated mercury concentrations versus year for Great Lakes and connecting channel fish populations with statistically significant regression slopes.

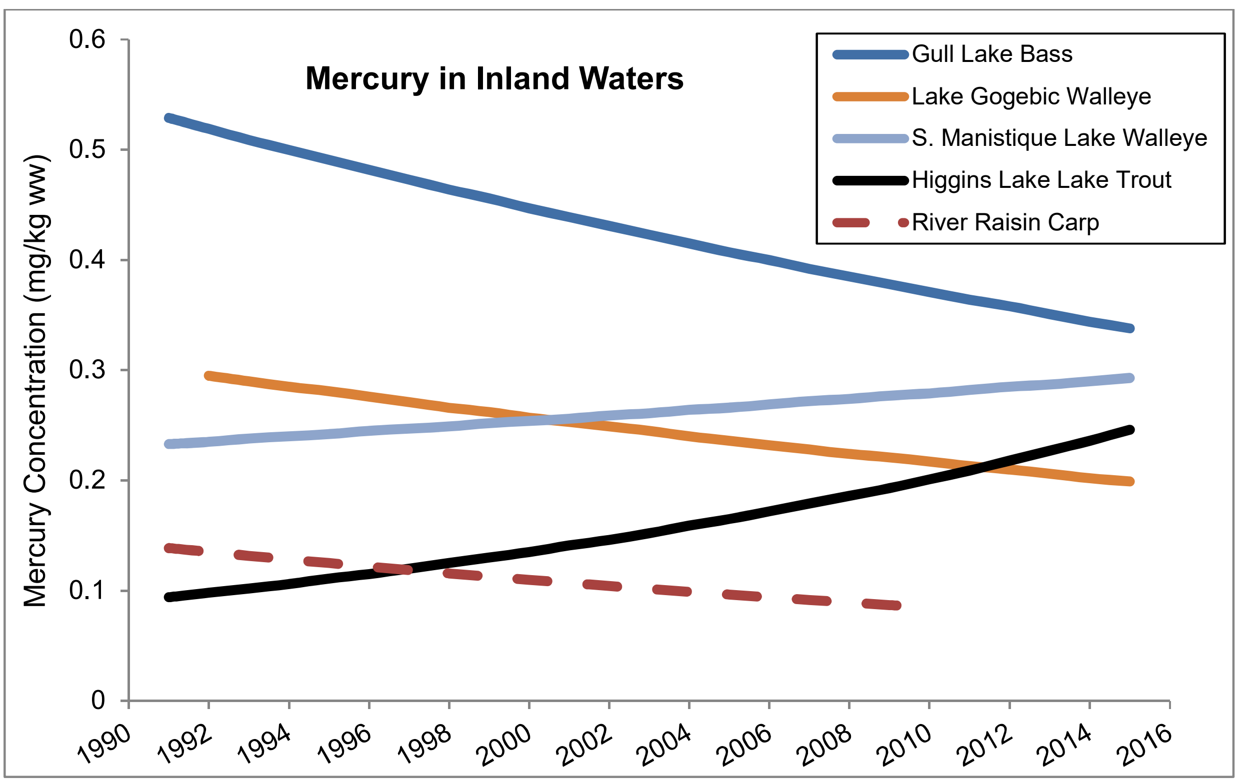
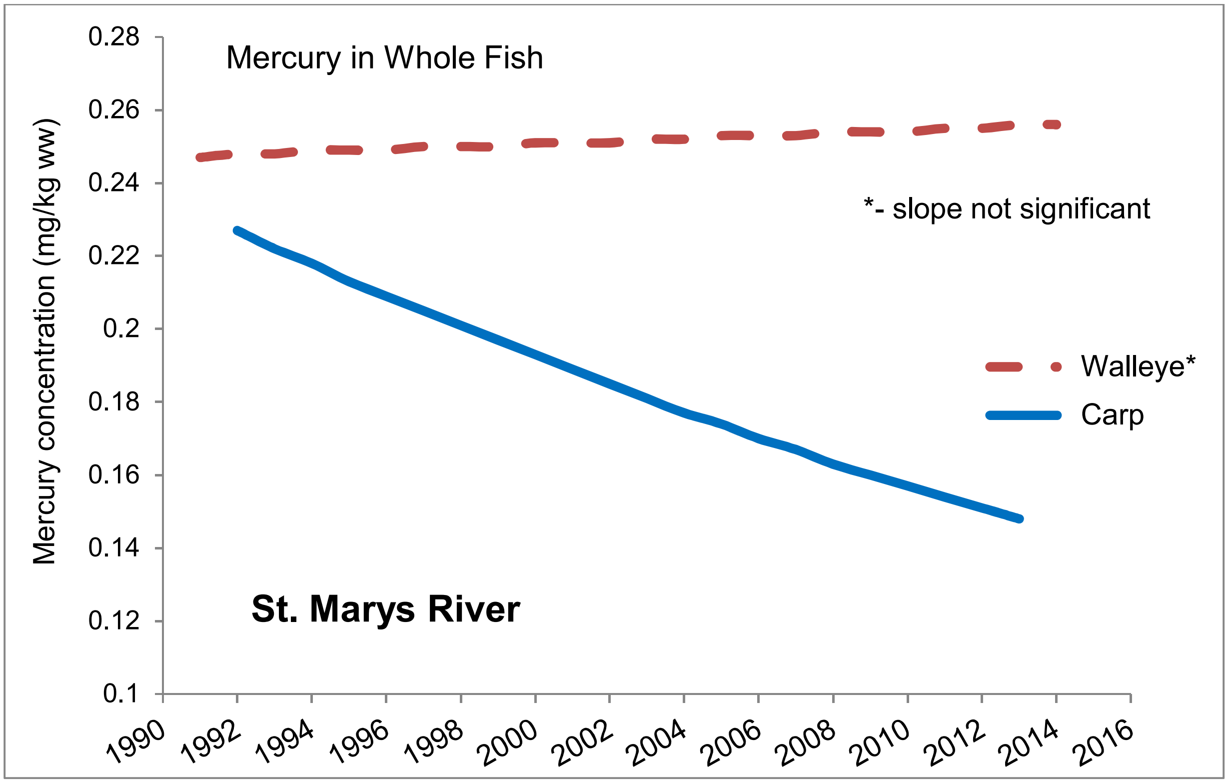


Figure 3. Estimated mercury concentrations versus year for inland water fish populations with statistically significant regression slopes.



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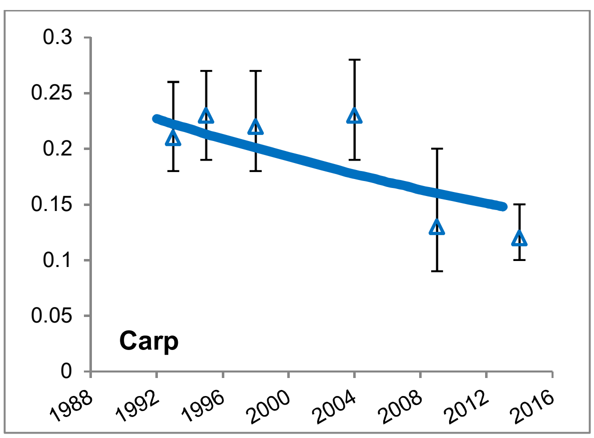

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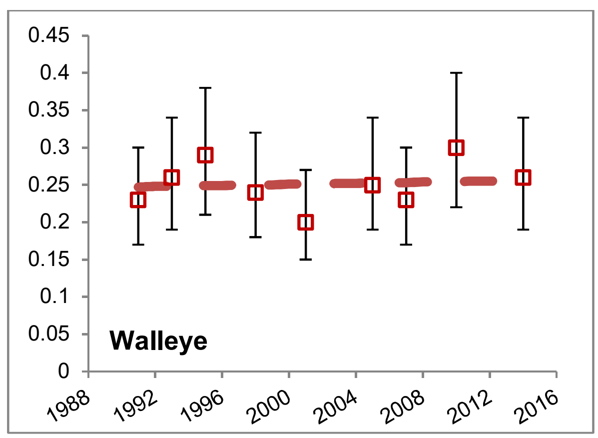


c.

Figure 4. (a) Temporal trend regression lines for total mercury (mg/kg ww) in carp and walleye collected from St. Marys River between 1991 and 2014, and the same lines with the least-squares means for each sample event plotted with 95 percent confidence intervals for (b) carp and (c) walleye.

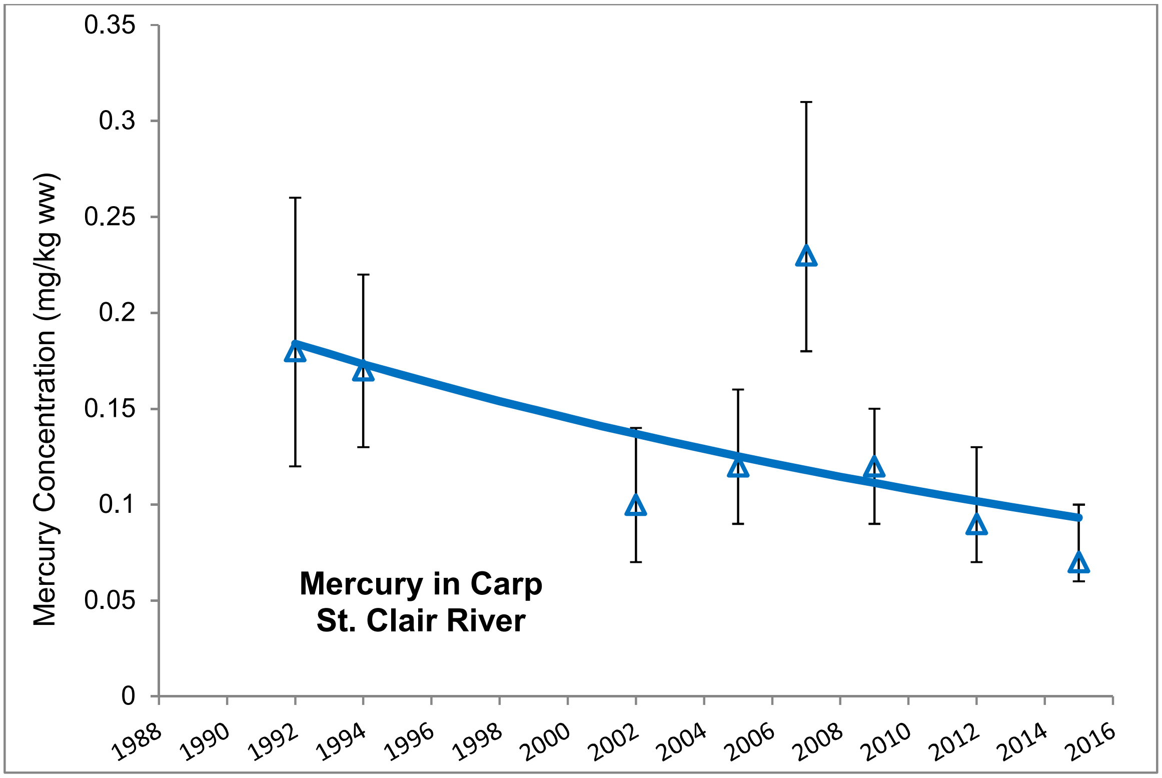
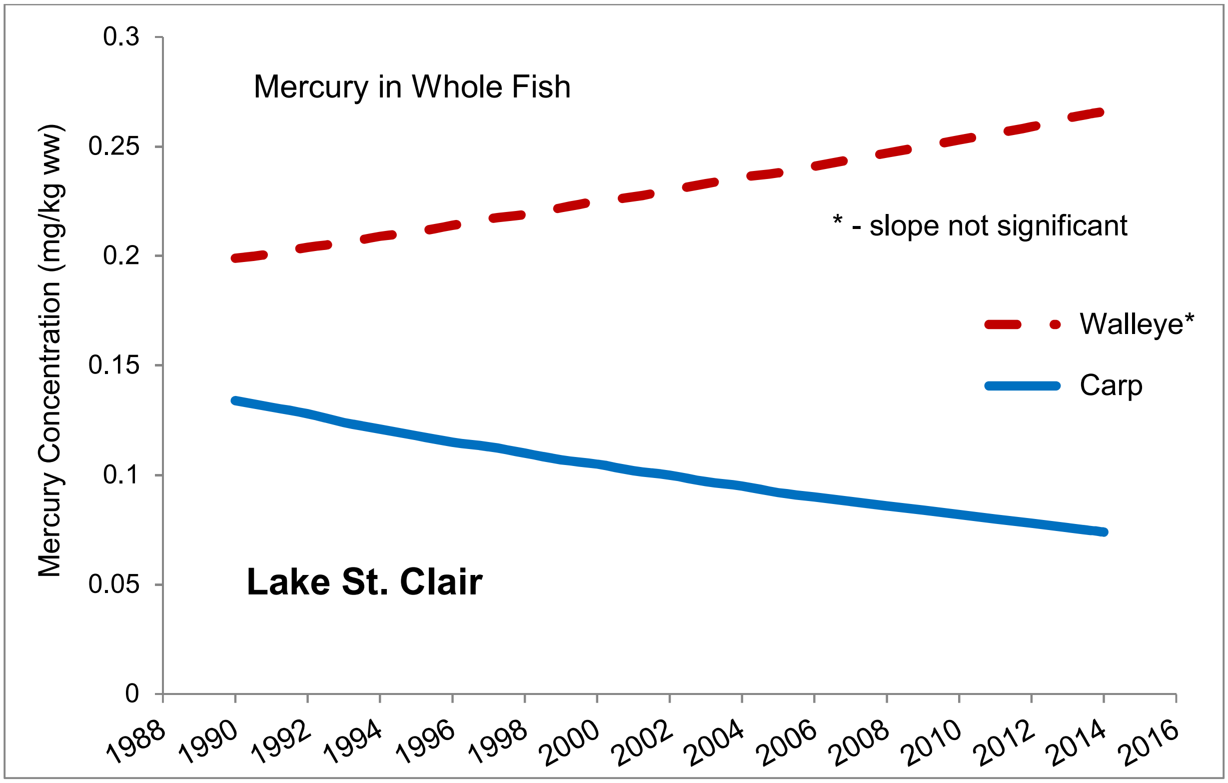


Figure 5. Temporal trend regression line for total mercury (mg/kg) in carp collected from the St. Clair River between 1990 and 2015 with the least-squares means and 95 percent confidence intervals plotted for each sample event.



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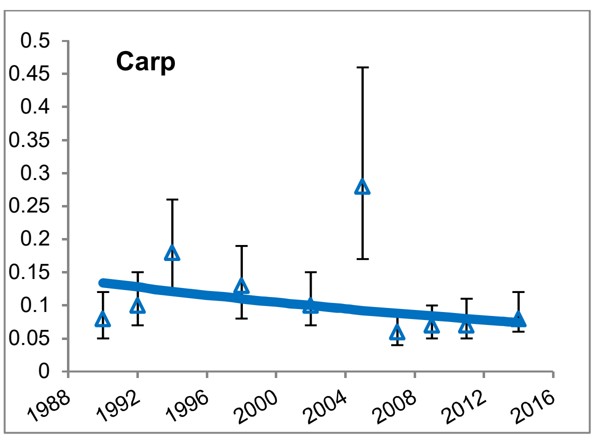

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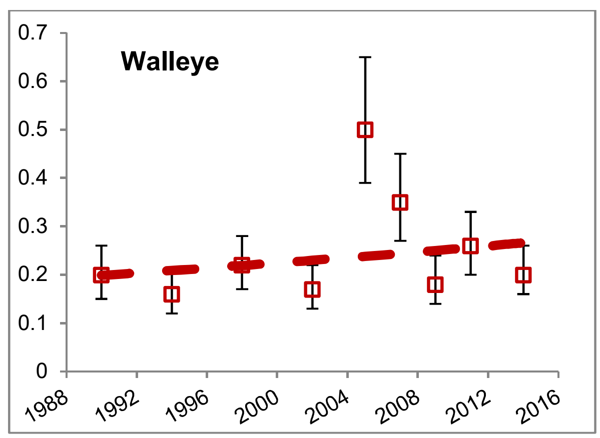


c.

Figure 6. (a) Temporal trend regression lines for total mercury (mg/kg ww) in carp and walleye collected from Lake St. Clair between 1990 and 2014, and the same lines with the least-squares means for each sample event plotted with 95 percent confidence intervals for (b) carp and (c) walleye.

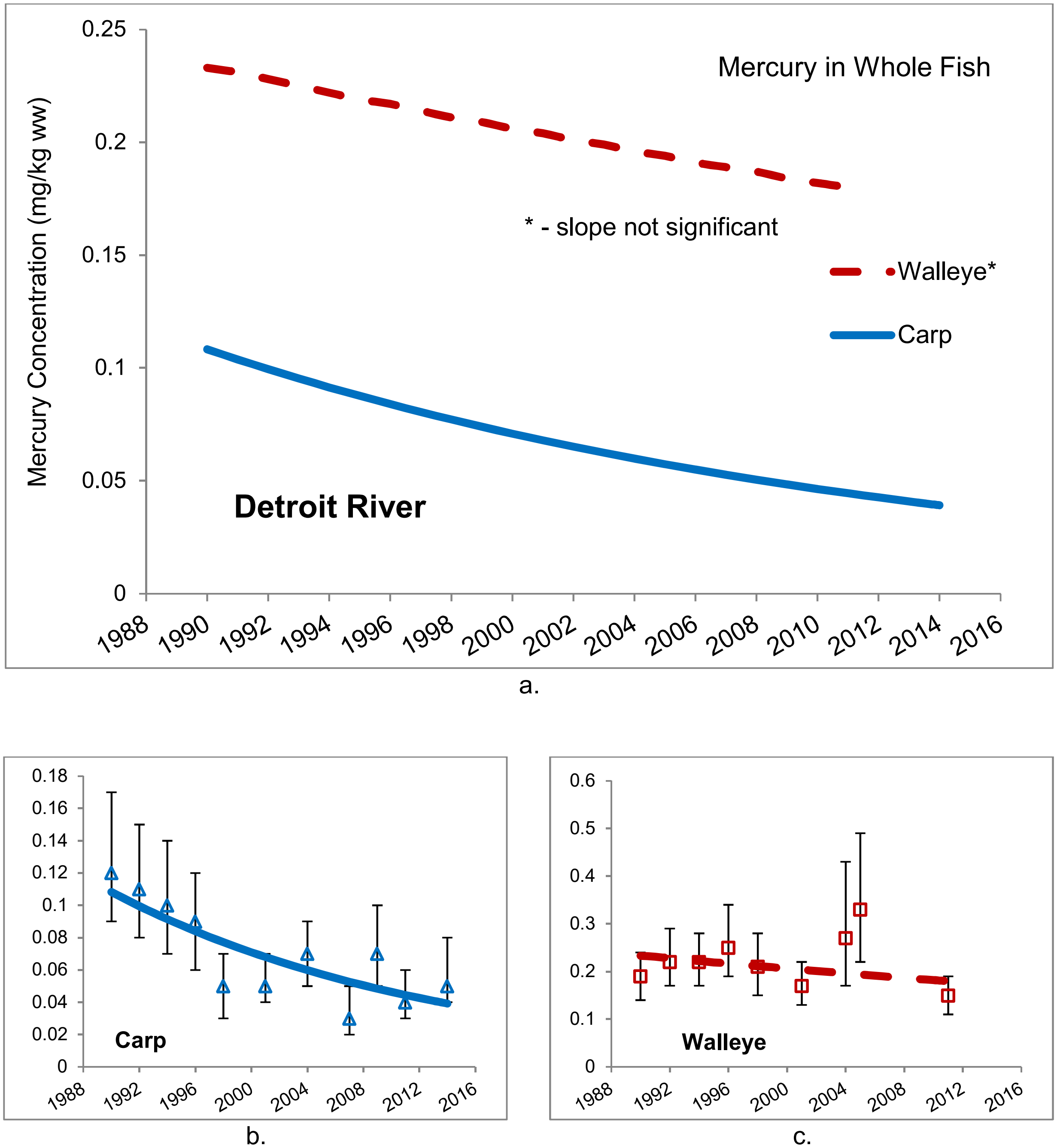


Figure 7. (a) Temporal trend regression lines for total mercury (mg/kg ww) in carp and walleye collected from the Detroit River between 1990 and 2014, and the same lines with the least-squares means for each sample event plotted with 95 percent confidence intervals for (b) carp and (c) walleye.

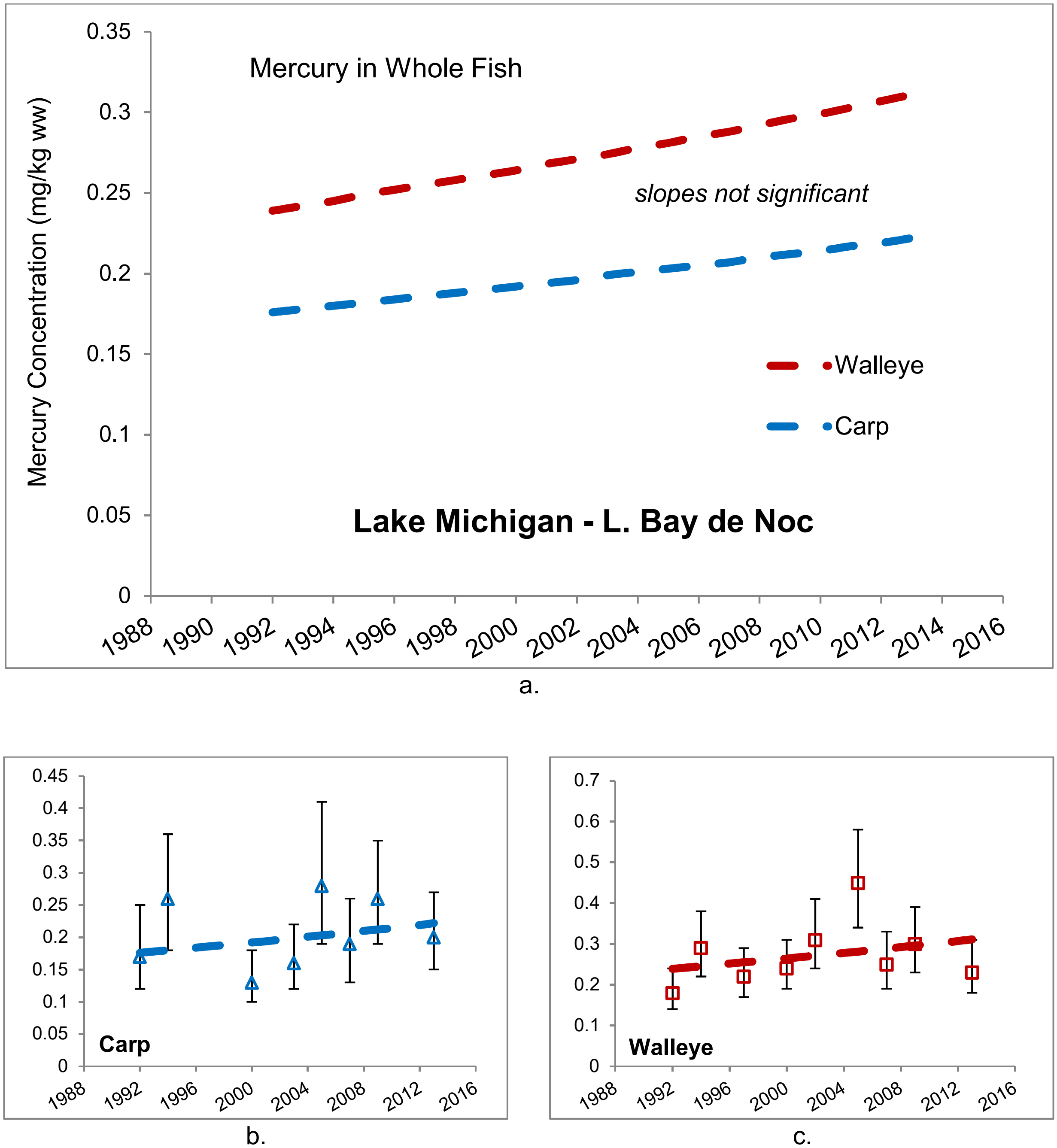


Figure 8. (a) Temporal trend regression lines for total mercury (mg/kg ww) in carp and walleye collected from Little Bay de Noc between 1992 and 2013, and the same lines with the least-squares means for each sample event plotted with 95 percent confidence intervals for (b) carp and (c) walleye.

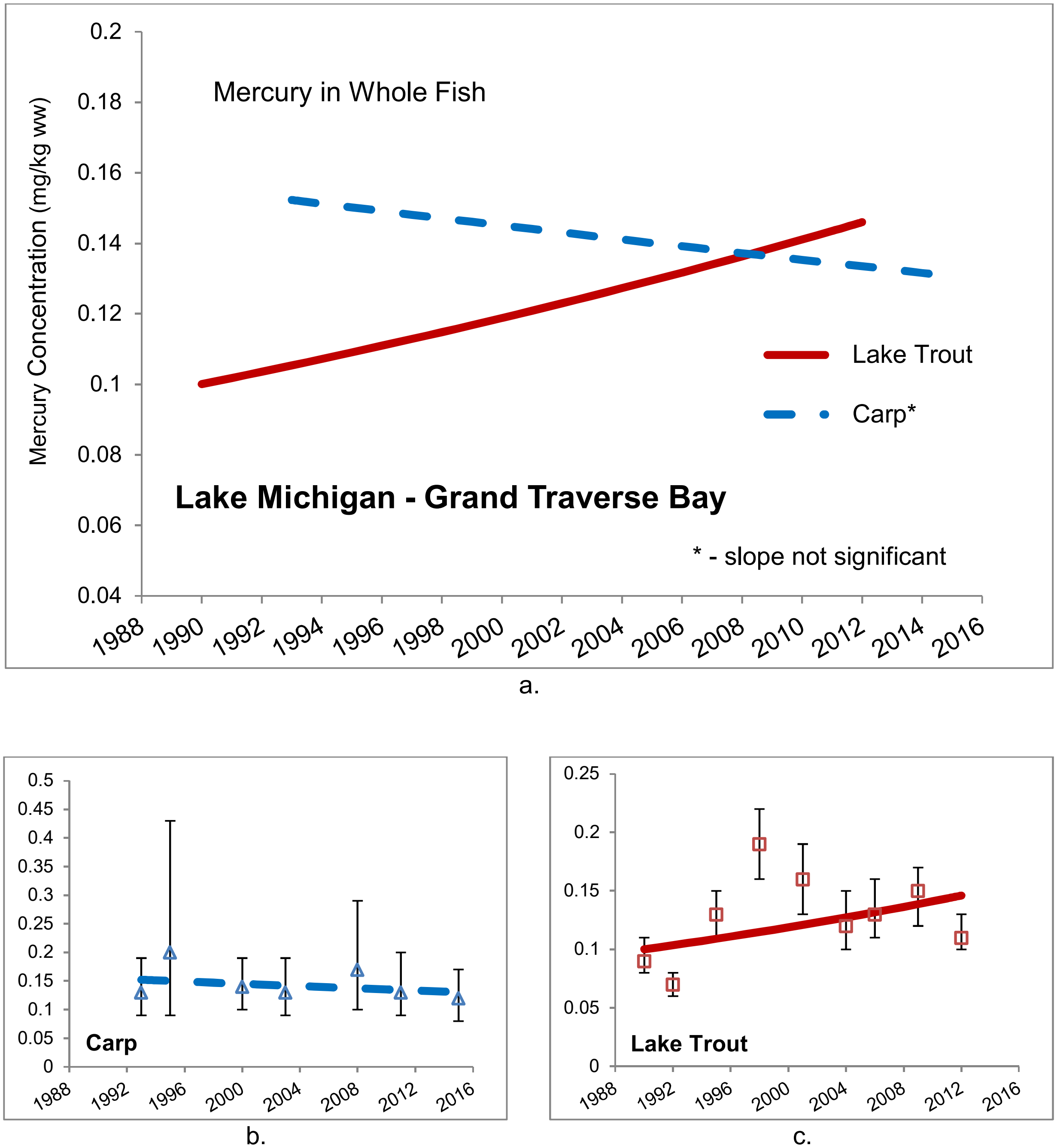
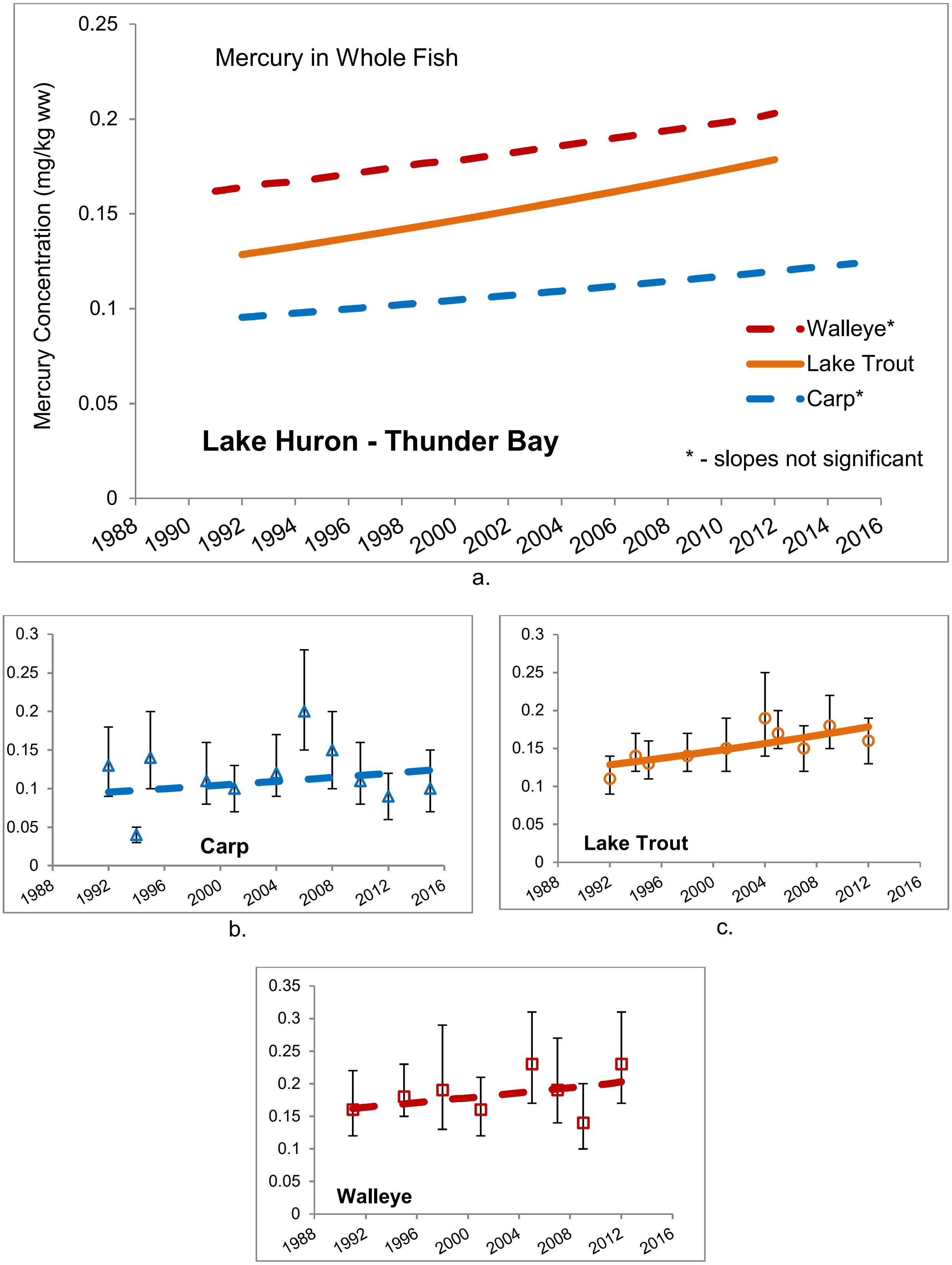


Figure 9. (a) Temporal trend regression lines for total mercury (mg/kg ww) in carp and lake trout collected from Grand Traverse Bay between 1990 and 2015, and the same lines with the least-squares means for each sample event plotted with 95 percent confidence intervals for (b) carp and (c) lake trout.



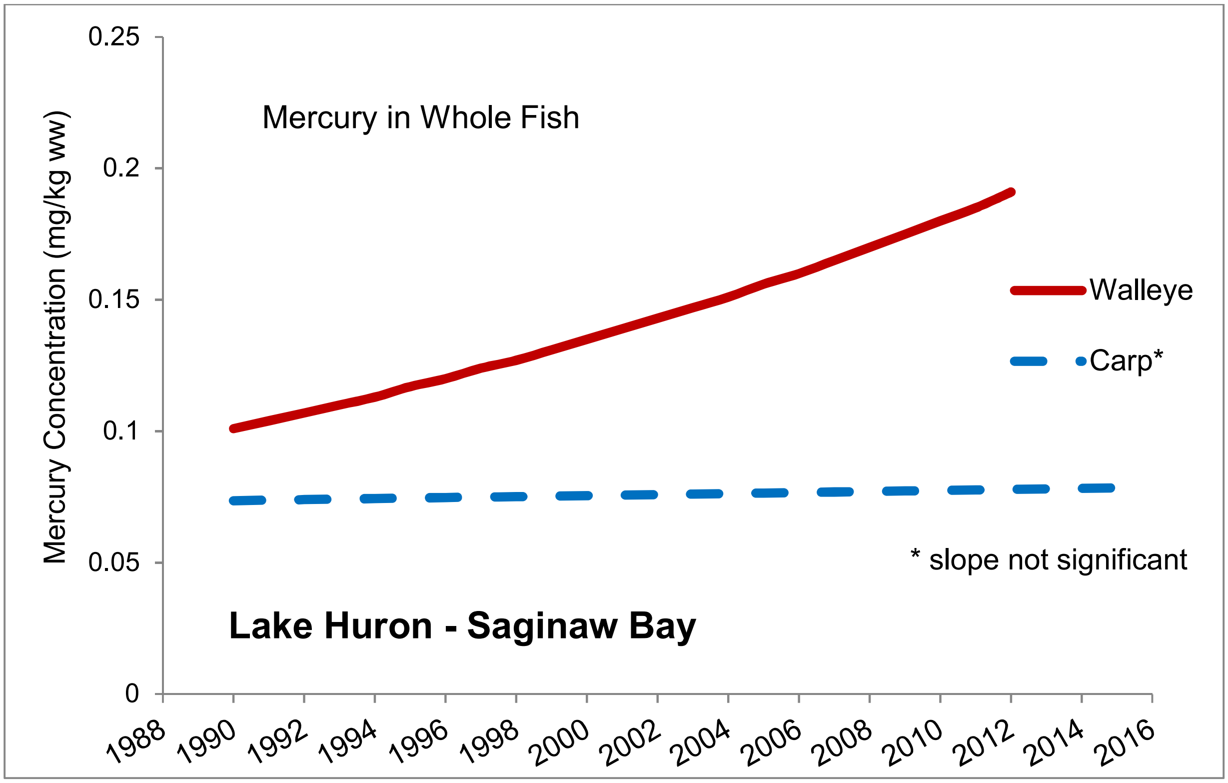
a.

b.

c.

d.

Figure 10. (a) Temporal trend regression lines for total mercury (mg/kg ww) in carp, lake trout, and walleye collected from Thunder Bay between 1991 and 2015, and the same lines with the least-squares means for each sample event plotted with 95 percent confidence intervals for (b) carp, (c) lake trout, and (d) walleye.



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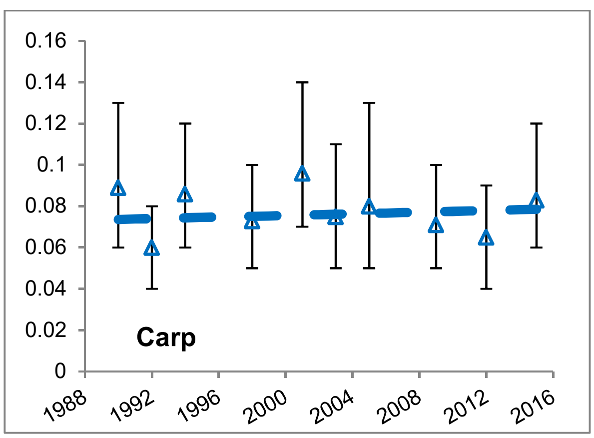

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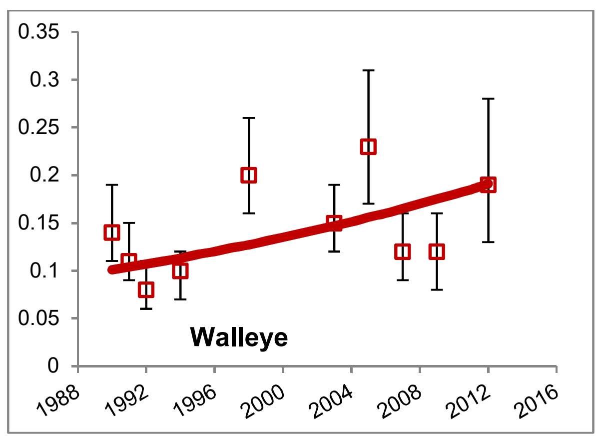
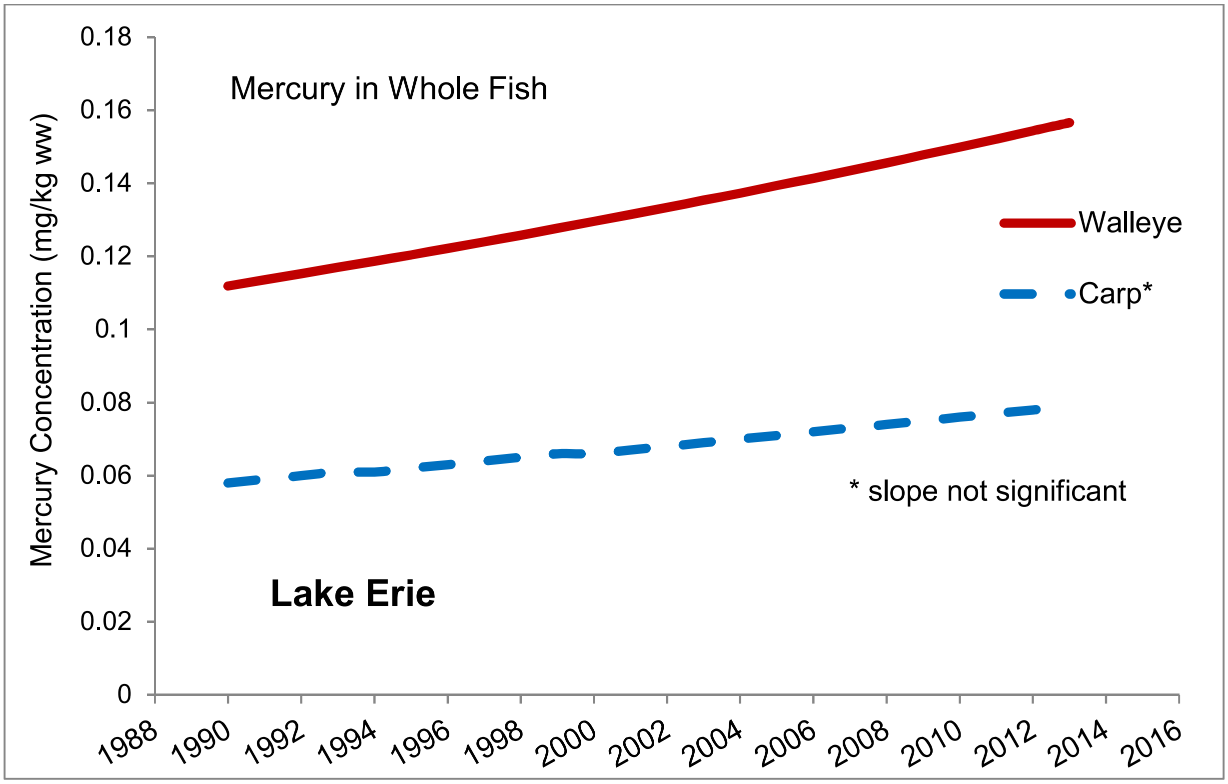


c.

Figure 11. (a) Temporal trend regression lines for total mercury (mg/kg ww) in carp and walleye collected from Saginaw Bay between 1990 and 2015, and the same lines with the least-squares means for each sample event plotted with 95 percent confidence intervals for (b) carp and (c) walleye.



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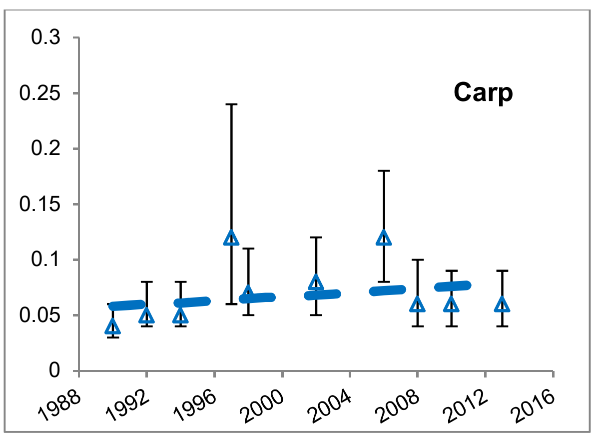

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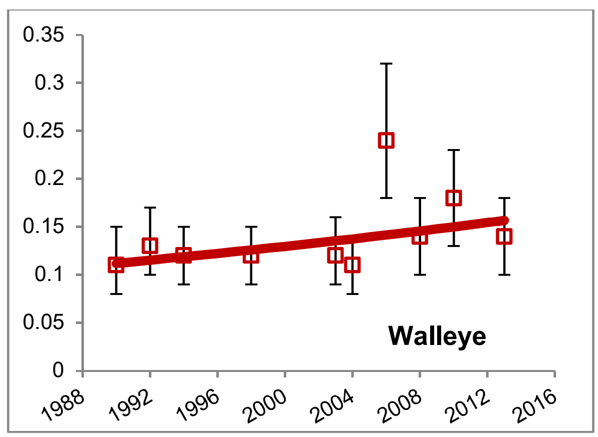

c.

Figure 12. (a) Temporal trend regression lines for total mercury (mg/kg ww) in carp and walleye collected from Lake Erie between 1990 and 2013, and the same lines with the least-squares means for each sample event plotted with 95 percent confidence intervals for (b) carp and (c) walleye.

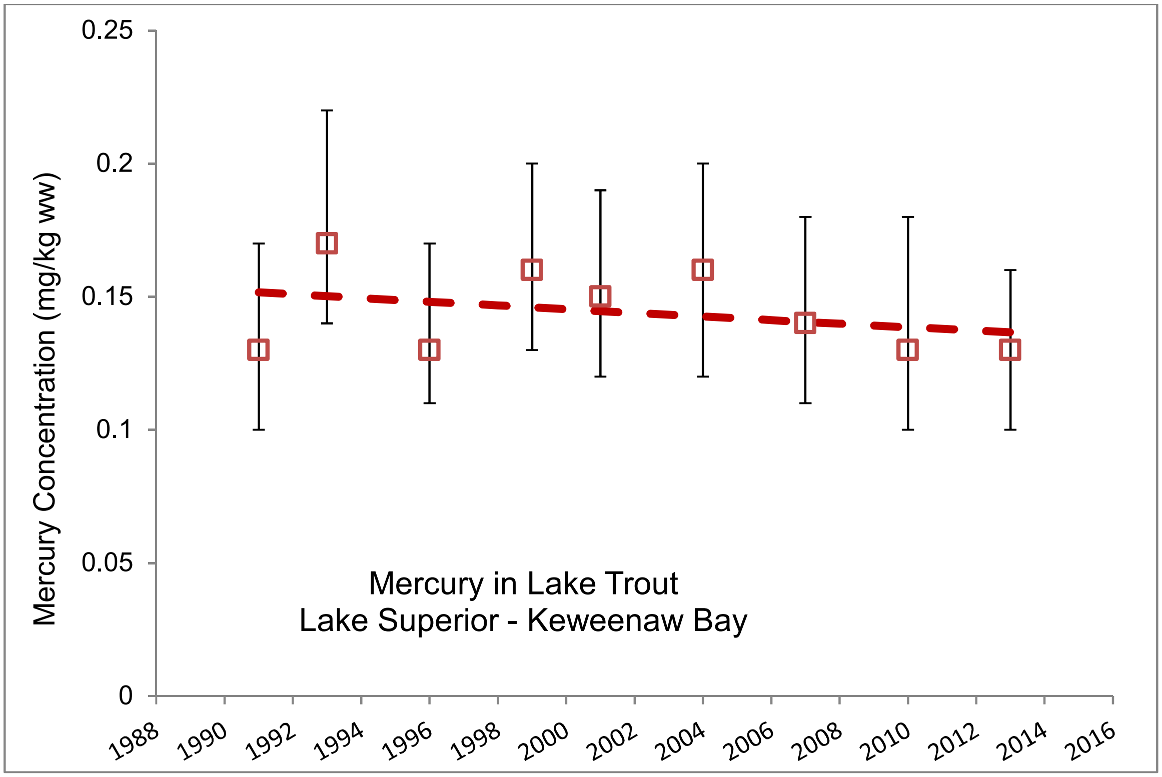

Figure 13. Temporal trend regression line for total mercury (mg/kg ww) in lake trout collected from Keweenaw Bay between 1991 and 2013 with the least-squares means and 95 percent confidence intervals plotted for each sample event.

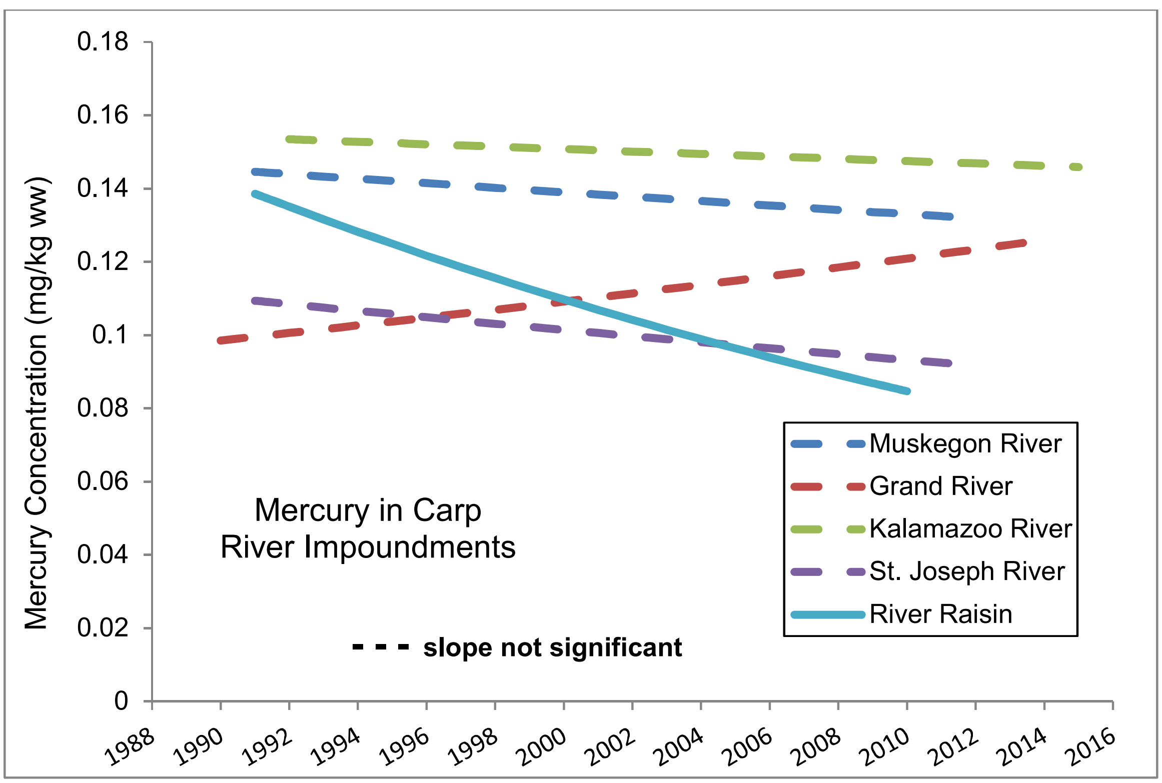

Figure 14. Estimated mercury concentrations versus year in whole in whole carp samples collected from river impoundment trend sites between 1990 and 2015. Dashed lines indicate the slope of the line is not statistically significant.

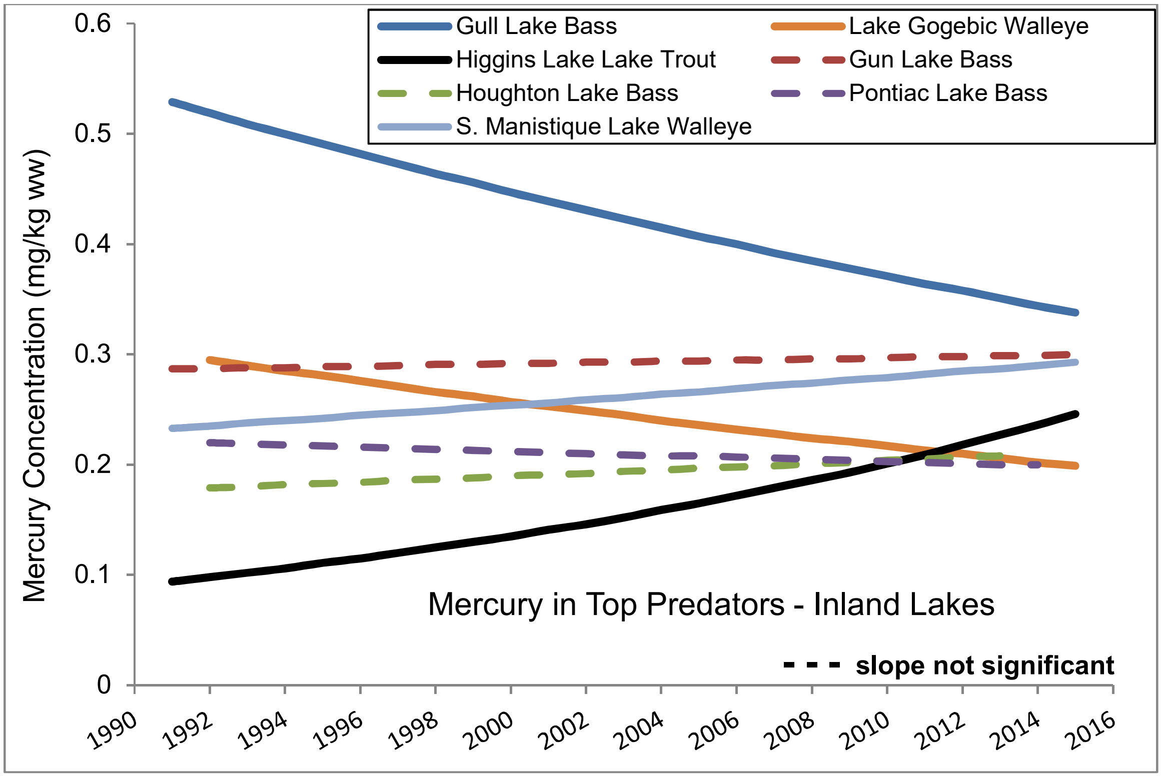

Figure 15. Estimated mercury concentrations versus year in whole fish samples of top predators collected from inland lake trend sites between 1991 and 2015. Dashed lines indicate the slope of the line is not statistically significant.

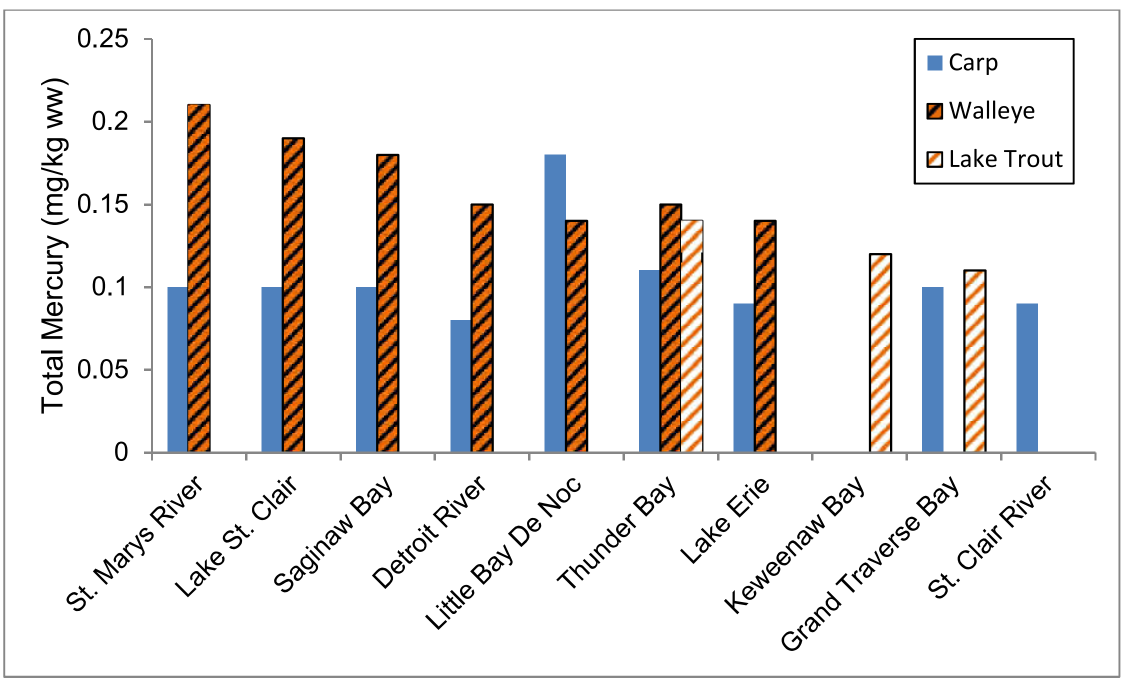

Figure 16. Length adjusted mean mercury concentrations based on the most recent samples of whole carp, walleye, and lake trout from temporal trend monitoring sites in Michigan waters of the Great Lakes and connecting channels.

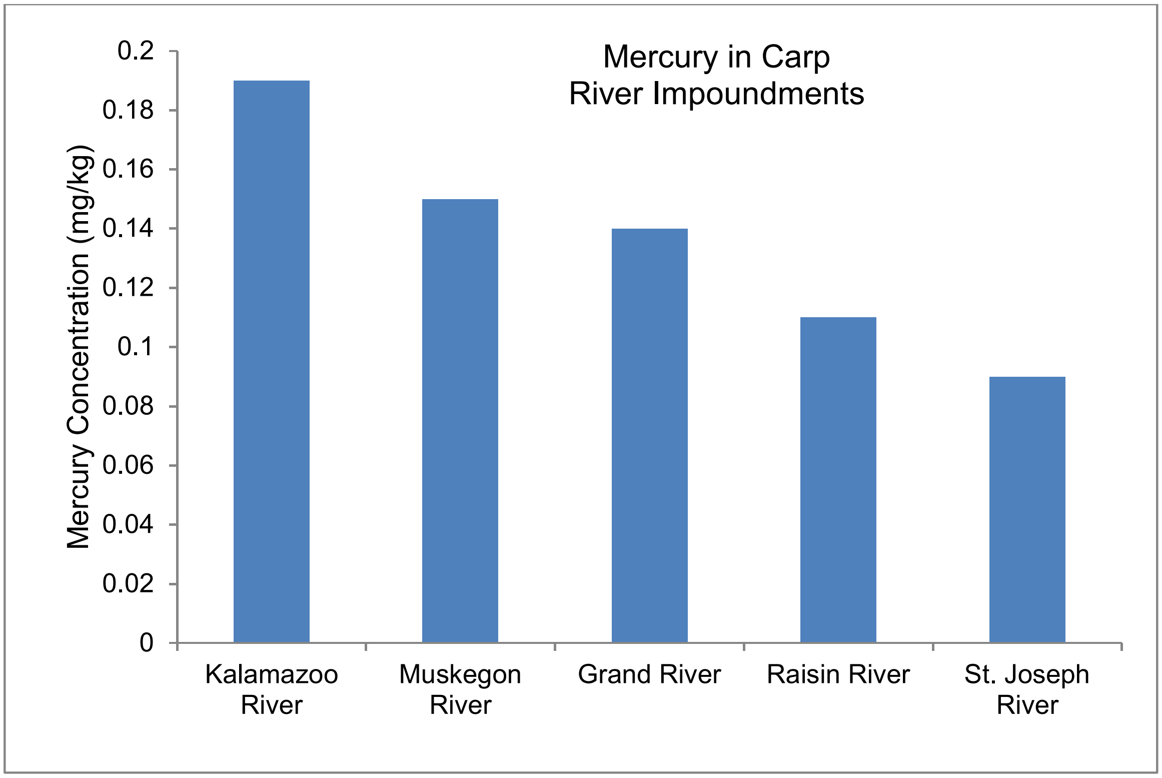

Figure 17. Mean mercury concentrations based on the most recent samples of whole carp from river impoundment temporal trend monitoring sites in Michigan.

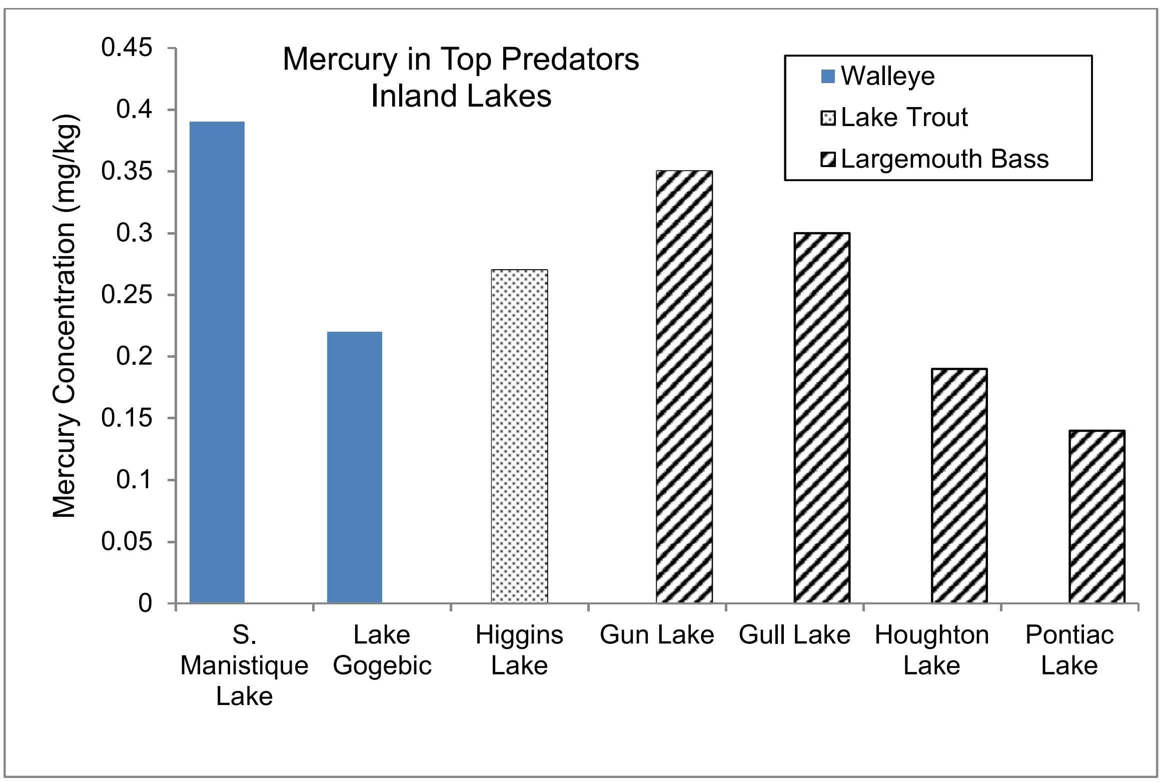

Figure 18. Length adjusted mean mercury concentrations based on the most recent samples of whole walleye, lake trout, and largemouth bass from inland lake temporal trend monitoring sites in Michigan.

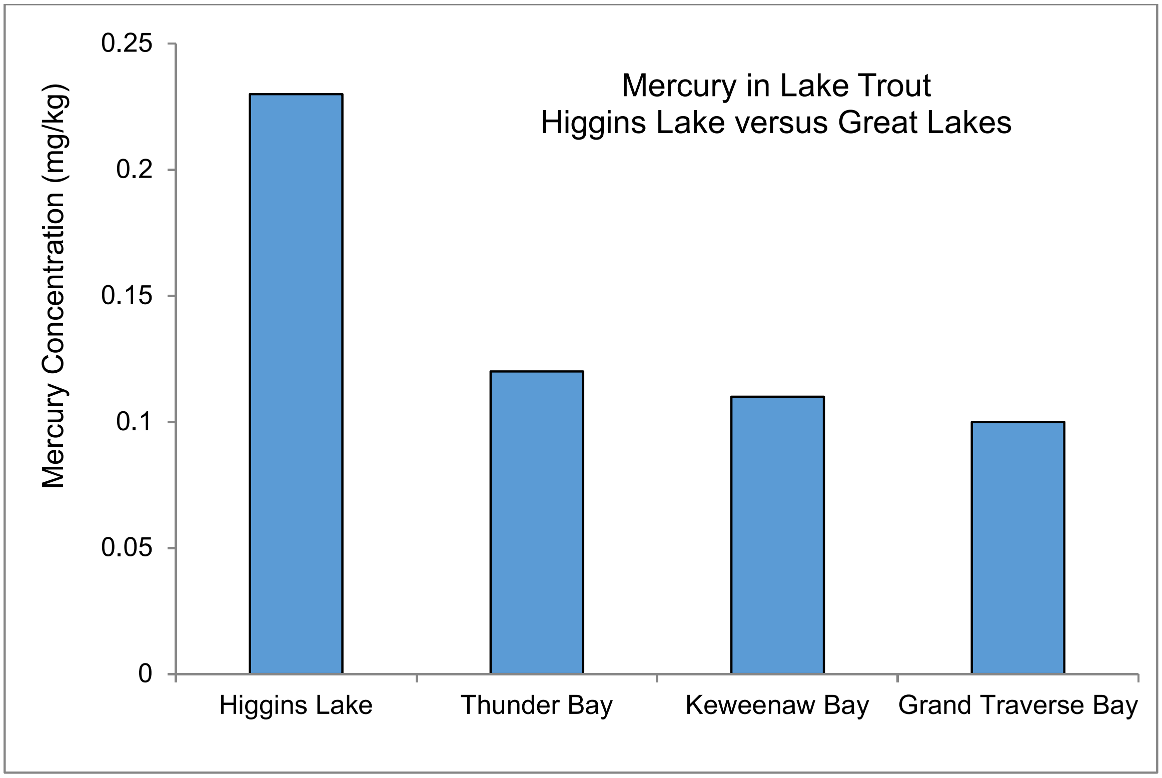

Figure 19. Length adjusted mean mercury concentrations based on the most recent samples of whole lake trout from inland lake and Great Lake temporal trend monitoring sites in Michigan.