THE STATE OF LAKE MICHIGAN IN 2000

Prepared for the Lake Michigan Committee

Great Lakes Fishery Commission

SPECIAL PUBLICATION 05-01

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March 2005

THE STATE OF LAKE MICHIGAN IN 2000

Prepared for the Lake Michigan Committee

Edited by

Mark E. Holey
United States Fish and Wildlife Service (USFWS)
Green Bay Fishery Resources Office
2661 Scott Tower Drive
New Franken, Wisconsin, U.S.A. 54229-9565

Thomas N. Trudeau
Illinois Department of Natural Resources
9511 Harrison St.
Des Plaines, Illinois, U.S.A. 60016

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Executive Summary

This report on the state of Lake Michigan in 2000 initiates the five-year rotational reporting process established by the 1998 revision of *A Joint Strategic Plan for Management of Great Lakes Fisheries*. The Lake Michigan Fish-community Objectives (FCOs), published in 1995, established a goal to *restore and maintain the biological integrity of the fish community so that production of desirable fish is sustainable and ecologically efficient*. A special conference focusing on progress toward achieving the Lake Michigan FCOs was held in March 2000, and this report is a compilation of the papers presented at this special conference.

Progress has been achieved for much of the Lake Michigan fish community and its environment, but major deficiencies remain. The FCOs should be revised to provide more-recognizable end points, and yield expectations for individual species should be revised based on new knowledge and always reflect potential rather than actual yield to allow for more-conservative fishing policies. Progress and deficiencies for individual objectives are as follows:

Establish a diverse salmonine community capable of sustaining an annual harvest of 2.7 to 6.8 million kg, of which 20-25% is lake trout.

The Lake Michigan salmonine community is as diverse as any in the Great Lakes with seven species (lake trout, rainbow trout, brown trout, brook trout, chinook salmon, coho salmon, pink salmon) and one hybrid (splake) currently present. Five species (lake trout, chinook salmon, coho salmon, rainbow trout, brown trout) are major contributors to sport fisheries, and some species also contribute to commercial fisheries. Abundance of all species except pink salmon is enhanced or maintained by stocking, but chinook salmon, coho salmon, pink salmon, and rainbow trout have naturalized and contribute significant numbers of natural recruits to the salmonine community. However, this contribution is not what it could be because eggs and fry of feral salmonines experience early mortality syndrome (EMS) with mortalities ranging from 60-90% for coho salmon since 1993. The cause of this EMS-related mortality is low levels of thiamine in salmonine eggs. The principal forage species, alewife and rainbow smelt, contain relatively high levels of thiaminase, an enzyme known to destroy thiamine. Although harvest of chinook salmon has been less than expected due to increased disease-related mortality and decreased fishing effort, the overall annual salmonine harvest has been within the objective range because harvest of rainbow trout and brown trout has increased. The contribution of lake trout to annual harvest has been at or near the 20-25% range specified in the objective.

Establish self-sustaining lake trout populations.

Failure of lake trout to establish self-sustaining populations has been the major fish-community disappointment considering the time and money invested to achieve this objective. New initiatives are currently under way or being considered to identify bottlenecks or other factors prohibiting lake trout natural reproduction.

Maintain a diversity of planktivore (prey) species at population levels matched to primary production and to predator demand. Expectations are for a lake-wide planktivore biomass of 0.5 to 0.8 billion kg.

Bloater, alewife, and rainbow smelt contribute most of the planktivore biomass. Currently, predation by salmonines is believed to be limiting alewife and rainbow smelt abundance. Bloaters dominate the planktivore biomass, but their biomass has recently declined. Current planktivore biomass is within the FCO range, but it may not be sustained if the decline in bloater biomass continues.

Maintain self-sustaining stocks of yellow perch, walleye, smallmouth bass, pike, catfish, and panfish. Expected annual yields should be 0.9 to 1.8 million kg for yellow perch and 0.1 to 0.2 million kg for walleye.

Excepting walleye, the species referred to in this objective are self-sustaining. Most walleye populations still require stocking to maintain an adequate level of recruitment. Stocking has been discontinued in southern Green Bay because of sufficient natural reproduction, and natural reproduction has been found in northern Green Bay where stocking is done in alternate years. The expected annual yields of walleye and yellow perch have not been achieved. Recruitment of yellow perch has been poor throughout the 1990s. The other listed species contribute small numbers to sport fisheries, but little is known about their populations.

Maintain self-sustaining stocks of lake whitefish, round whitefish, sturgeon, suckers, and burbot. The expected annual yield of lake whitefish should be 1.8 to 2.7 million kg.

These benthivores are self-sustaining and, with the exception of lake sturgeon, have robust or adequate populations. The harvest of lake whitefish in recent years has been within or has exceeded the expected annual yield. Although mean weight-at-age and condition of lake whitefish has decreased, recruitment remains strong. Burbot populations are now very abundant, and this abundance may have a negative influence on lake trout restoration and abundance of other forage fish. Although burbot are forage for predators, especially lake trout, few are harvested. Little is known about the state of round whitefish and sucker populations. Populations of both are found throughout the lake and sustain limited commercial and sport fisheries. Remnant spawning populations of lake sturgeon have been found in eight tributaries with the largest populations in the Menominee, Peshtigo, and Fox Rivers. Restrictions or elimination of fishing requiring run-of-the-river flows and fish-passages at hydroelectric facilities and further study to identify populations and critical habitat are among efforts necessary for restoration of this species.

Suppress the sea lamprey to allow the achievement of other fish-community objectives.

Larval sea lampreys exist in 121 tributaries, and adult numbers in the lake, although generally stable for the last three decades, have increased slightly in recent years. Species formerly impacted by sea lamprey predation such as lake whitefish, burbot, and bloater are now abundant and self-sustaining, and large numbers of lake trout and walleye survive to adulthood in areas where fishing is regulated. Chemical control remains the major weapon to suppress sea lamprey populations. However, improved application technology and methodology, barriers, and sterile-male-release have reduced the amount of chemical necessary for treatments.

Protect and sustain a diverse community of native fishes, including other species not specifically mentioned earlier.

Lake Michigan still contains a diverse community of native fishes despite extirpations, but the remaining diversity is threatened by fishing, loss of habitat, and invasive species. Harvest of cyprinids in the commercial baitfish fishery is monitored infrequently and not reported by species. Shoreline wetlands and littoral areas are threatened by development and pollution. The influx of non-indigenous species has been dramatic in recent years, and, while they have increased community diversity, some pose a threat to native fishes. Alewife and rainbow smelt have been blamed for the decline in yellow perch and for inhibiting restoration of lake herring. The round gobies and white perch compete directly with some indigenous fishes such as sculpins and yellow perch, and alewife and gobies prey on lake trout eggs and fry. Zebra mussels have had a negative influence on native mollusks and blanketed littoral fish habitats. Non-native crustaceans prey on or compete with native crustaceans.

Protect and enhance fish habitat and rehabilitate degraded habitats.

Pursuant to the Joint Strategic Plan, agencies are developing formal environmental objectives for each of the Great Lakes, including Lake Michigan. State and federal environmental agencies have made significant progress toward elimination of environmental stressors in the Lake Michigan basin. The ten Areas of Concern in the basin are in various stages of remediation. As mandated by the Great Lakes Water Quality Agreement of 1978, a Lakewide Management Plan has been developed for Lake Michigan to allow environmental and resource management agencies to collaborate in addressing all biological, chemical, and physical stressors limiting ecosystem sustainability.

Achieve no net loss of the productive capacity of habitat supporting Lake Michigan's fish communities. High priority should be given to the restoration and enhancement of historic riverine spawning and nursery areas for anadromous species.

The productive capacity of fish habitat remains good. Lake Michigan is still an oligotrophic lake, but some nutrients have increased during the past two decades. Dominance in summer phytoplankton communities has shifted from diatoms to cyanophytes and chlorophytes in the late 1960s and 1970s and then to phytoflagellates in the 1980s and 1990s. The species composition of the zooplankton community has been relatively consistent during the past 15 years. Efforts to restore wetland habitat are under way and some major strides have been made in restoration of historical riverine spawning and nursery habitat, including installation of fish-passage facilities and requiring run-of-the-river flow regimes for dams.

Pursue the reduction and elimination of toxic chemicals, where possible, to enhance fish survival rates and allow for the promotion of human consumption of safe fish.

Although fish-consumption advisories still exist for some sizes of some species caught in the sport fishery, levels of PCB, a chemical of major concern, have declined in Lake Michigan fish since the 1970s. A high level of PCBs was once linked to mortality of lake trout eggs and fry, but it is now believed that low thiamine was responsible.

Goal and Objective Setting

Mark E. Holey
United States Fish and Wildlife Service
Green Bay Fishery Resources Office
2661 Scott Tower Drive
New Franken, Wisconsin, U.S.A. 54229-9565

This report is the first state-of-the-lake report for the fish community of Lake Michigan and will describe progress toward achieving its fish-community objectives (FCOs). Goals and objectives for the Lake Michigan fish community (Eshenroder et al. 1995) were established as a result of the Joint Strategic Plan for the Management of Great Lakes Fisheries (Joint Plan) (Great Lakes Fishery Commission 1980, 1997). The Joint Plan charged the Lake Michigan Committee (LMC) to define objectives for the fish community and to develop means for measuring progress toward their accomplishment. The LMC is composed of one fishery manager each from the states of Michigan, Wisconsin, Illinois, and Indiana, and from the Chippewa/Ottawa Resource Authority (formerly the Chippewa-Ottawa Treaty Fishery Management Authority). This process of reporting on progress serves to focus attention on critical fisheries issues and enhances communication and understanding among fishery agencies, environmental agencies, political bodies, and the public.

Achievement of water-quality goals is a prerequisite for achievement of fishery-related goals and objectives, and this principle is an important feature of the goal statement for Lake Michigan (Eshenroder et al. 1995). The Great Lakes Water Quality Agreement (GLWQA) obligates the governments of Canada and the United States to develop and implement Lakewide Management Plans (LaMPs), which address open-water critical pollutants, and Remedial Action Plans (RAPs), which address specific Areas of Concern (AOCs). Effective cooperation between resource and environmental disciplines is essential for any fishery rehabilitation plan to successfully achieve its objectives. Accordingly, chapters on nutrients and plankton are included in this report. A chapter on fish health is also included because fish health issues have played a major role in recent decisions regarding stocking and the overall health of the fish community. An alphabetical list of the common fish names and their corresponding scientific names is given in Table 1.

Table 1. A list of common and scientific fish names used in this publication.

Common name	**Scientific name**
alewife	*Alosa pseudoharengus*
Atlantic salmon	*Salmo salar*
bloater	*Coregonus hoyi*
brook trout	*Salvelinus fontinalis*
brown trout	*Salmo trutta*
burbot	*Lota lota*
catfish(s)	*Ictalurus* spp.
chinook salmon	*Oncorhynchus tshawytscha*
coho salmon	*Oncorhynchus kisutch*
deepwater cisco	*Coregonus johannae*
deepwater sculpin	*Myoxocephalus thompsoni*
emerald shiner	*Notropis atherinoides*
johnny darter	*Etheostoma nigrum*
lake herring	*Coregonus artedi*
lake sturgeon	*Acipenser fulvescens*
lake trout	*Salvelinus namaycush*
lake whitefish	*Coregonus clupeaformis*
mottled sculpin	*Cottus bairdi*
muskellunge	*Esox masquinongy*
ninespine stickleback	*Pungitius pungitius*
northern pike	*Esox lucius*
Pacific salmon	*Oncorhynchus* spp.
panfish (sunfish)	*Lepomis* spp.
pink salmon	*Oncorhynchus gorbuscha*
rainbow smelt	*Osmerus mordax*
rainbow trout	*Oncorhynchus mykiss*
round whitefish	*Prosopium cylindraceum*
rock bass	*Ambloplites rupestris*
round goby	*Neogobius melanostomus*

Table 1, continued

Common name	Scientific name
sculpin(s)	*Cottus* spp.
sea lamprey	*Petromyzon marinus*
slimy sculpin	*Cottus cognatus*
smallmouth bass	*Micropterus dolomieu*
splake (hybrid)	*Salvelinus fontinalis x S. namaycush*
spottail shiner	*Notropis hudsonius*
sucker(s)	*Catostomus* spp.
sunfishes	*Centrarchidae* spp.
trout perch	*Percopsis omiscomayus*
walleye	*Sander vitreus*
white perch	*Morone americana*
yellow perch	*Perca flavescens*

Description of Lake Michigan

Lake Michigan (Fig. 1) is the sixth largest lake in the world (Beeton and Chandler 1963). It is the only Great Lake located within the United States, affording it the title as the largest lake in the continental United States (Beeton et al. 1999). Lake Michigan is the second-largest Great Lake by volume, 4,920 km^3, and third largest by surface area, 57,800 km^2. Its drainage basin, 118,000 km^2, covers 23% of the total Great Lakes basin, and its water volume accounts for 22% of the total water supply (Beeton et al. 1999). Mean depth is 85 m. The southern basin is relatively smooth in contour, sloping to a maximum depth of 170 m. The northern basin has an irregular bottom and maximum depth of 281 m (Wells and McLain 1972). The largest freshwater sand dunes in the world occur along the eastern shore. Green Bay is the largest embayment and measures 190 km by 23 km (Fig. 1). Grand Traverse and Little Traverse Bays, located in the northeastern corner of the lake, are the only other bays of consequence. The Lake Michigan basin ranks second among the Great Lakes in terms of human population.

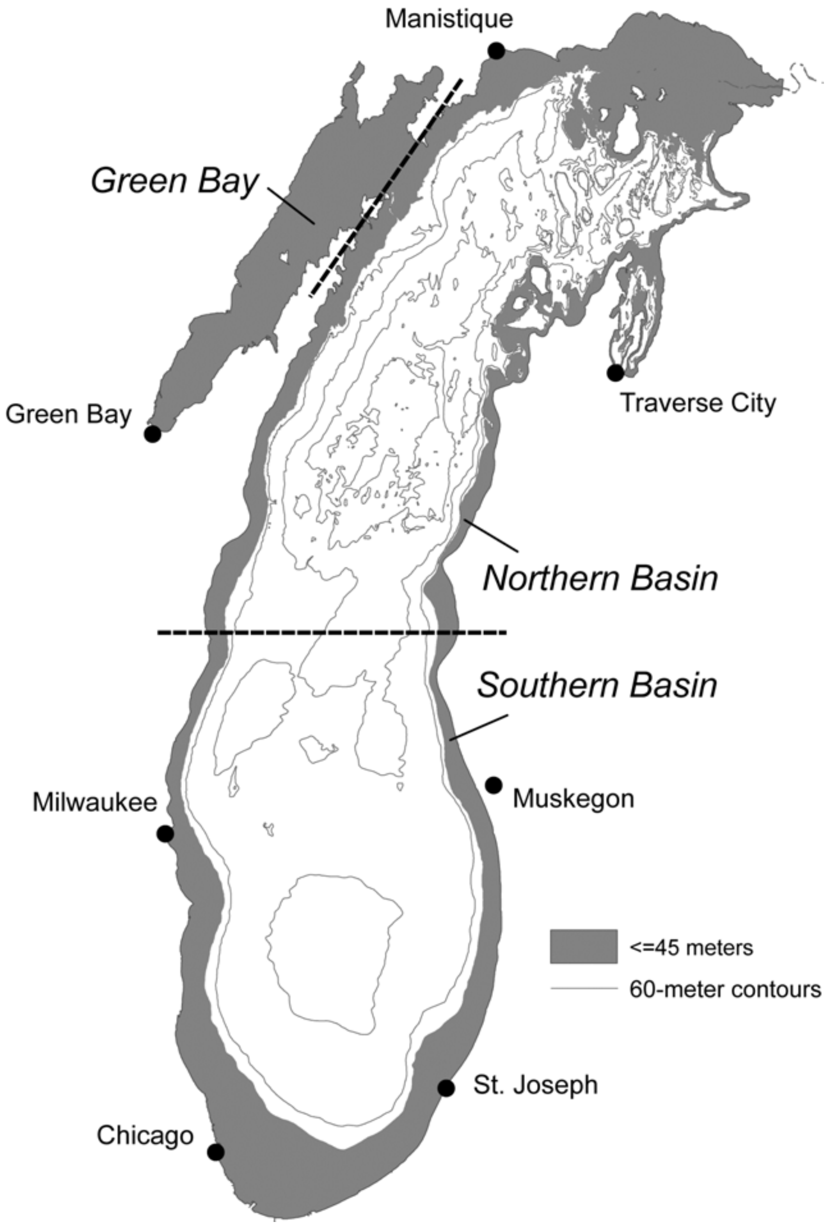

Fig. 1. Lake Michigan depicting inshore (<45 m) waters (shaded), southern and northern basin, and Green Bay.

Beeton et al. (1999) classified Lake Michigan as generally oligotrophic because of its low concentrations of phosphorus, but they reported that the level of total dissolved solids (150 mg/L) is normally associated with eutrophic conditions indicating a possible trend toward mesotrophy. Total alkalinity is 113 ppm; the concentrations of calcium, magnesium, and sodium are 31.5, 10.4, and 3.4 ppm, respectively; the phosphorus concentration is 0.9 ppb; and dissolved oxygen concentrations are near saturation at all depths (Beeton and Chandler 1963).

Goals and Guiding Principles

In recognition of the GLWQA's call for restoration of system integrity and the Joint Plan's focus on sustainable benefits, the LMC's goal statement emphasizes biological integrity, production of desirable fish, and ecological efficiency.

Restore and maintain the biological integrity of the fish community so that production of desirable fish is sustainable and ecologically efficient.

Although the GLWQA divides the ecosystem into three components (chemical, physical, and biological), it implies that integrity is an attribute of the ecosystem as a whole. Fish-community goals, however, address issues related primarily to biological integrity, and achieving them will be limited inevitably by the physical and chemical integrity of the Lake Michigan ecosystem. The term biological integrity was at best abstract and somewhat ambiguous when introduced in water-quality legislation in the 1970s (Karr et al. 1986). Since that time, it has been reworked and defined as, "…the ability of an ecosystem to maintain its structure when confronted with environmental change. Systems that cannot maintain their structure following perturbation are said to have lost their integrity" (Karr and Dudley 1981).

The fluctuations over time in the Lake Michigan fish community can provide examples of the concepts of integrity and ecological efficiency. Before the arrival of European settlers, the fish community was considered to be stable and organized. Lake herring and deepwater ciscoes occupied the offshore zones, and lake whitefish and emerald shiners were important in the inshore areas (Wells and McLain 1972). Burbot and lake trout were the main predators. The low diversity of top predators was compensated for by differentiation of lake trout into specialized shallow-water and deep-water forms enabling them to utilize prey resources throughout the entire water column (Brown et al. 1981; Eshenroder et al. 1995). Attempts to introduce Pacific salmon in the 1900s failed (Parsons 1973) possibly due to the integrity or stability of the fish community at that time. This system remained stable until the invasion of the sea lamprey, which, coupled with extensive fishing pressure, led to the extirpation of the native lake trout populations (Holey et al. 1995). In the 1960s, alewife populations increased substantially in the face of minimal predation pressure to eventually comprise 80% or more of the total fish biomass in the lake; these populations subsequently underwent a massive die-off that fouled beaches and water intakes (Brown 1972). At this point in its history, Lake Michigan had already lost its integrity and was ecologically inefficient.

By the 1980s, control of sea lamprey and the stocking of salmonines restored the piscivore trophic level, which led to increased stability and integrity of the system and made it more acceptable and useful to humans (Eshenroder et al. 1995). Predation by the salmonines reduced alewife populations, and substantial harvests of both sport and commercial species were reported. The early and mid-1980s was a period of optimism for Lake Michigan fishery agencies. Trout and salmon fisheries were flourishing, predation had decreased alewife numbers and the occurrence of die-offs, yellow perch and bloater populations were rebounding, and lake trout reproduction was detected in Grand Traverse Bay. This period of optimism ended in the late 1980s when chinook salmon populations experienced massive die-offs, approaching 50% or more of their abundance, from a bacterial kidney disease (BKD) epizootic triggered by nutritional stress (Holey et al. 1998). Signs of recruitment failure in both yellow perch and bloater were also observed, and, again, the sustainability or integrity of the system was in question.

The LMC established ten guiding principles to provide a decision-making framework to guide managers in achieving FCOs. A fuller exposition of these principles is provided by Eshenroder et al. (1995).

1. Recognize the limits on lake productivity
2. Preserve and restore fish habitat
3. Preserve native species
4. Enhance natural reproduction of native and desirable introduced fishes
5. Acknowledge the role of planted fish
6. Recognize naturalized species
7. Adopt the genetic stock concept
8. Recognize that fisheries are an important cultural heritage
9. Prevent the unintentional introduction of exotic species
10. Protect and enhance threatened and endangered species

These principles are essential for achieving a consistent approach for cooperative fishery management in Lake Michigan and are well-accepted, fundamental concepts recognized as having wide application to the Great Lakes.

Fish-Community Objectives for Lake Michigan

An historical perspective of the Lake Michigan fish community was gained largely through harvest records. These records can provide an important measure of the ecological efficiency of the lake's food webs and a measure of progress in achievement of the FCOs. For these reasons, and also because public attention is focused on the harvesting of fish, FCOs will necessarily incorporate some reference to future harvest expectations, including single-species considerations.

In describing FCOs, certain realities must be considered. One is that the number and abundance of species in a fish community are strongly influenced by habitat features (e.g., lake area, depths, and thermal characteristics) that are beyond human control. A second reality is that only a few options exist for altering community structure in a Great Lake. Habitat manipulation is usually limited to remedial action in nearshore environments and tributary streams. Beyond remediation of habitat, managers exert an influence through the regulation of fisheries, stocking, and sea lamprey control. A third reality is that management actions are inexact—their effects cascade through the trophic pyramid to species well beyond those targeted, and those effects can have different time scales for different species. Short-term responses can be deceptive and long-range prediction can prove difficult. FCOs for an entire lake cannot be taken to a high level of exactness—they are reasoned approximations of likelihoods. Management initiatives aimed at achieving objectives will continue to have a large experimental component, and the time frame needed in meeting some objectives will be measured in decades. Last, humans, more than any other organism on earth, have the capacity to alter their environment to their own benefit and desire. Society places a myriad of demands on the Lake Michigan fish community. The Lake Michigan FCOs are designed to produce the fish desired by society within the framework of the capacity of the lake and its biological integrity. Specific objectives will be identified in appropriate chapters.

Nutrients

Glenn Warren
United States Environmental Protection Agency
Great Lakes National Program Office
77 W. Jackson Boulevard
Chicago, Illinois, U.S.A. 60604

Chemical sampling of Lake Michigan, begun in 1983, was done annually at 11 stations in the spring at a time when the lake is homothermal and behaving similar to a modeler's assumption of "mixed reactors." The spring data will be the focus of this report. The main chemicals of interest are total phosphorus, nitrate/nitrite nitrogen, and dissolved silica, which have major effects on algal production (United States Environmental Protection Agency 2003).

Total Phosphorus

The water-quality guideline for concentration of total phosphorus in the open waters of the lake was established at 7 µg/L (International Joint Commission 1980) to maintain the lake in an oligotrophic to mesotrophic state. Total phosphorus concentrations were below the guideline and ranged from a high of 6.4 µg/L in 1983 to a low of 3.8 µg/L in 1992 (Fig. 2). This downward trend in concentration was reversed after 1992. Since 1994, concentrations have ranged from 5.5 µg/L-6.3 µg/L, very similar to levels that occurred prior to 1990. This increase from the low levels of 1992 is significant ($p < 0.05$) for all years after 1994 and indicates that the decreases seen between the late 1970s and 1992 have been reversed. The concentrations of total phosphorus in the northern and southern basins were not significantly different.

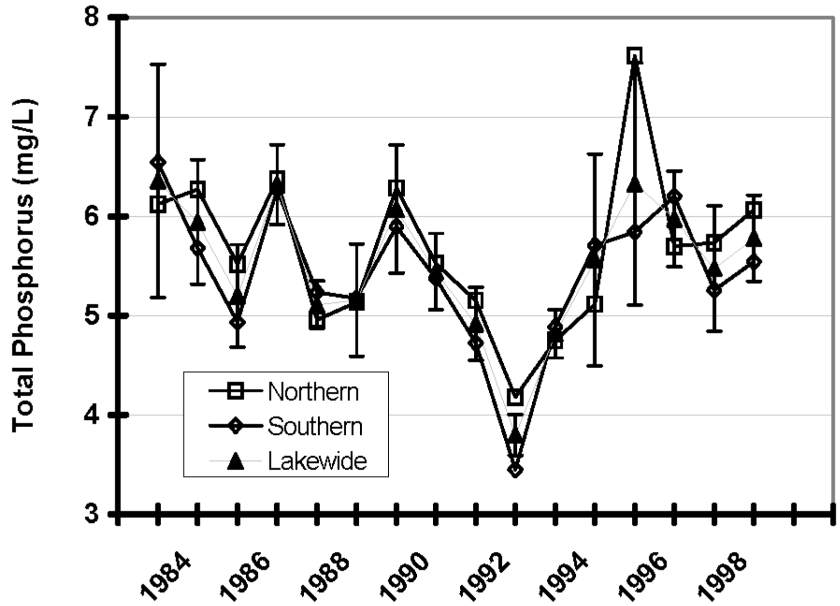

Fig. 2. Total phosphorous concentrations (µg/L) in Lake Michigan (northern, southern, lakewide), 1983-1998. Error bars (±2 standard errors) are included for lakewide data.

The most recent load estimates for total phosphorus are from the Lake Michigan Mass Balance Study and, at approximately 2.5 x 10^6 kg/yr for 1994 and 1995, are close to the average load (3.1 x 10^6 kg/yr) from 1980-1991 based on International Joint Commission (IJC) information (Robertson 1997). The estimates from the study are easily within the error range of IJC estimates. In view of the relatively constant phosphorus load, the introduction of exotic species, particularly the zebra mussel (*Dreissena polymorpha*), might have altered the food web and nutrient distribution sufficiently to account for the rebound in phosphorus concentrations after 1992.

Nitrate/Nitrite-Nitrogen

Nitrogen concentration, particularly nitrate/nitrite nitrogen, has been increasing in Lake Michigan through the monitoring period (Fig. 3). The lakewide average increased from 0.262 mg/L in 1983 to 0.311 mg/L in 1999, with a low of 0.257 mg/L in 1984 and a high of 0.342 mg/L in 1993. Neither basin was consistently higher in nitrate/nitrite nitrogen concentration. Increasing nitrate/nitrite concentrations in the lake, although not of immediate concern from an eutrophication standpoint, indicate continued loading of the nutrient.

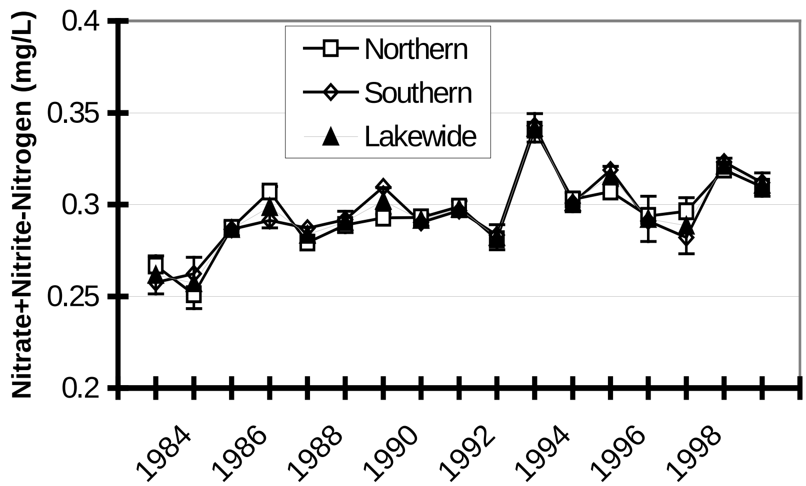

Fig. 3. Nitrogen concentrations (mg/L) in Lake Michigan (northern, southern, lakewide), 1983-1999. Error bars (±2 standard errors) are included for lakewide data.

Dissolved Reactive Silica

Lakewide concentrations of dissolved reactive silica have risen significantly between 1983 and 1999 (Fig. 4). The lakewide average increased from 0.53 mg/L in 1983 to 0.77 mg/L in 1999, with the exception of a low of 0.52 mg/L in 1987. Differences in concentrations between the northern and southern basins were inconsistent. Dissolved reactive silica is a nutrient essential to diatom growth, so a diatom community below historical levels and resorption of diatom frustules in surface sediments along with continuing loads of Si may account for the lakewide increases in Si concentration.

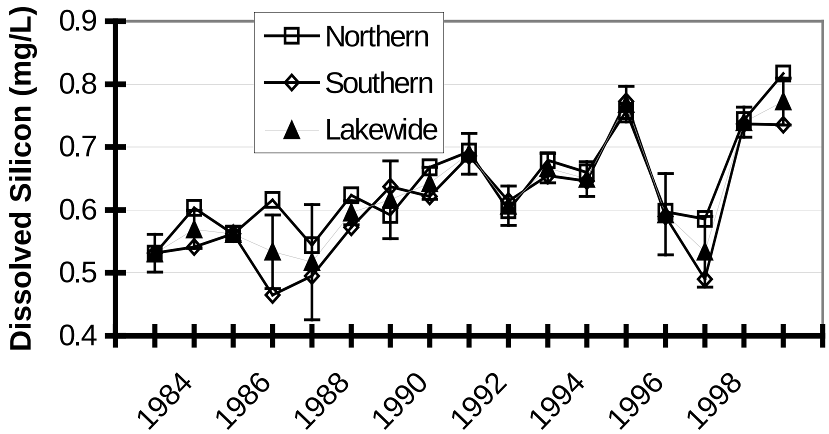

Fig. 4. Concentrations of dissolved reactive silica (mg/L) in Lake Michigan (northern, southern, lakewide), 1983-1999. Error bars (±2 standard errors) are included for lakewide data.

Chloride

Chloride concentration is an indicator of local anthropogenic loads to the lake. Concentrations increased during 1983-1999 and ranged from 8.68 mg/L in 1983 to 10.86 mg/L in 1999 (Fig. 5). This is an increase of 2.18 mg/L in 17 years. There was no consistent difference in chloride concentration between the northern and southern basins of the lake.

A model for conservative, dissolved substances (Sonzogni et al. 1983; W.L. Richardson, U.S. Environmental Protection Agency, Large Lakes Research Station, Grosse Ile, MI, 48138, personal communication) indicates that the chloride level of Lake Michigan will increase for several centuries until equilibrium is reached at approximately 18 mg/L. The rise in chloride is linked to a rise in sodium, which may have implications for the phytoplankton community (Provasoli 1969). The rise in sodium may allow undesirable sodium-requiring cyanobacteria to gain a competitive advantage over other phytoplankton.

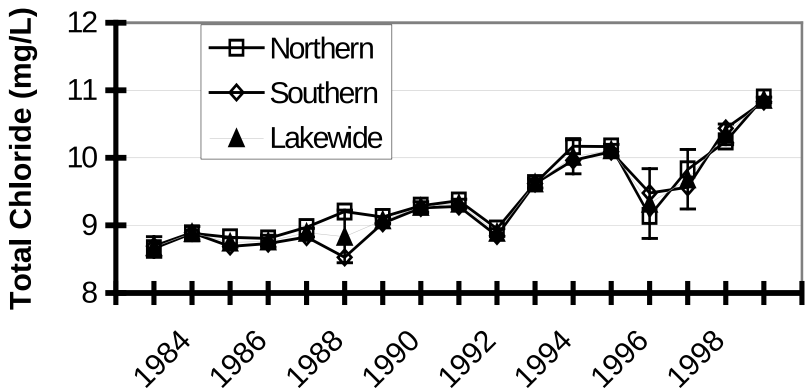

Fig. 5. Chloride concentrations (mg/L) in Lake Michigan (northern, southern, lakewide), 1983-1999. Error bars (±2 standard errors) are included for lakewide data.

Chlorophyll-*a*

Chlorophyll concentration did not trend during 1983-1997. Chlorophyll-*a* lakewide averages ranged from 0.54 µg/L in 1984 to 2.69 µg/L in 1989 and were highly variable from year to year. Lakewide average values were 1.62 µg/L in 1983 and 0.71 µg/L in 1997, the most recent year of available lakewide data. The southern basin of Lake Michigan is consistently higher in chlorophyll-*a* in springtime than is the northern basin. This difference in chlorophyll concentration averaged 0.57 µg/L over the entire spring collection period.

Phytoplankton and Zooplankton

Richard P. Barbiero
Computer Services Corporation
1359 W. Elmdale Ave Suite 2
Chicago, Illinois, U.S.A. 60660

Marc L. Tuchman
United States Environmental Protection Agency
Great Lakes National Program Office
77 W. Jackson Boulevard
Chicago, Illinois, U.S.A. 60604

The Great Lakes National Program Office (GLNPO) of the United States Environmental Protection Agency has primary responsibility for conducting surveillance monitoring of the offshore waters of the Great Lakes. In this report, we provide a brief summary of the results of the planktonic component of GLNPO's spring (March-May) and summer (August-September) biological surveillance sampling at 11 open-water stations on Lake Michigan in 1999, and compare these data both with GLNPO's summer (August) surveys made since 1983 and with other published studies. Information on station locations and methods can be found in Barbiero and Tuchman (2002).

Phytoplankton

The Lake Michigan phytoplankton community in 1999 conformed to the typical progression of a diatom-dominated spring community followed by a more mixed summer community dominated by phytoflagellates. During spring, median phytoplankton biomass was 0.55 gm/m^3, with the filamentous centric diatoms *Aulacoseira islandica* and *A. subarctica* dominating. Median phytoplankton biomass increased to 0.71 gm/m^3 in August. The overwhelming summer dominant was the dinoflagellate *Ceratium hirundinella*, with members of the Chrysophyta and Cyanobacteria increasing in importance compared to spring.

Lake Michigan underwent a dramatic decrease in dissolved silica concentrations from the mid-1950s through 1970 (Schelske 1988), resulting from increased phosphorus loading and a consequent increased deposition of silica to the sediments through increased diatom production (Schelske and Stoermer 1971). These changed nutrient conditions are thought to have promoted a shift in the dominance of the summer community from diatoms to chlorophytes and cyanobacteria during the late 1960s and 1970s (Fahnenstiel and Scavia 1987).

In the 1980s, a further shift towards summer dinoflagellate dominance occurred (Fahnenstiel and Scavia 1987), which our data indicate has continued through the 1990s (Fig. 6). More recently, reductions in phosphorus loadings have reversed the trend of decreasing silica and resulted in increases in summer diatom populations (Barbiero et al. 2002). This trend will likely continue as the silica content of the lake continues to increase, resulting in phytoplankton communities that are closer to the historical condition of year-round diatom dominance.

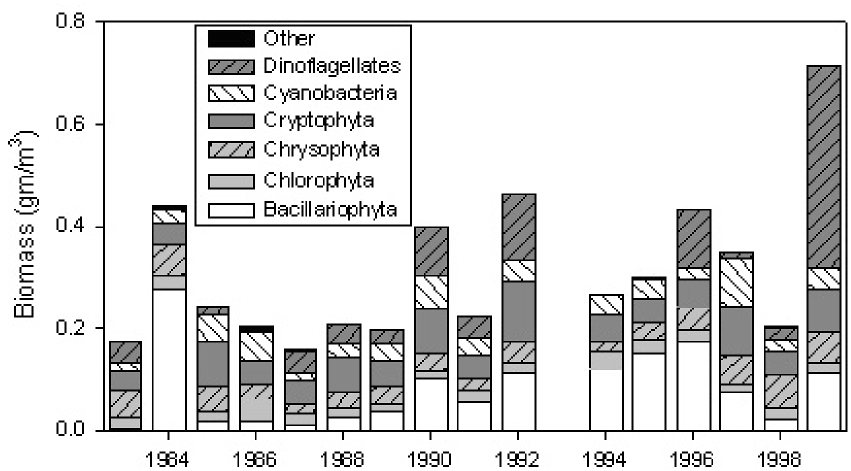

Fig. 6. Phytoplankton biomass by major taxonomic group in Lake Michigan, summer 1983-1999.

Zooplankton

The median lakewide abundance of crustaceans (excluding nauplii) during spring 1999 was 2,690 animals/m^3, with densities in the southern basin greater than those in the northern basin. Only 11 crustacean taxa were found in the lake during spring. The cyclopoid *Diacyclops thomasi* and the calanoids *Limnocalanus macrurus*, *Leptodiaptomus ashlandi*, and *L. minutus*, along with immatures of these genera, accounted for most of the spring zooplankton. Lakewide abundances increased in August to 42,655 animals/m^3, but no clear spatial differences in abundances were noted. *D. thomasi* remained one of the dominant species with the smaller cladoceran *Bosmina longirostris* and the typical summer dominant *Daphnia mendotae* also contributing substantial numbers. Two predatory cladocerans were found, the native *Leptodora kindti* and the exotic *Bythotrephes longimanus*, although abundance of both were less than 5 individuals/m^3.

The crustacean community of Lake Michigan has undergone a number of changes in the past 20 years. Prior to 1987, the cladoceran community included three daphnids: *D. retrocurva*, *D. mendotae* and *D. pulicaria* (Evans and Jude 1986). Since the invasion of *B. longimanus*, *D. retrocurva* and *D. pulicaria* have virtually disappeared from the offshore waters, leaving *D. mendotae* the sole daphnid. A number of less-dominant crustacean species, including *Holopedium gibberum*, *Eubosmina coregoni*, and the cyclopoid copepod *Mesocyclops edax*, have also declined dramatically (Barbiero and Tuchman 2004). Except for *M. edax*, abundance of the numerically dominant copepod community has not changed and continues to be dominated by the same species of diaptomids (*L. ashlandi*, *L. minutus,* and *Skistodiaptomus oregonensis*) and the cyclopoid *D. thomasi* (Barbiero et al., 2005).

In general, cladoceran abundances were higher during 1991-1999 than 1983-1990 (Fig. 7), perhaps indicating reduced predation pressure. Abundances were unusually low in 1998 (Barbiero et al. 2001) compared to the rest of the decade. In 1999, the crustacean community exhibited a marked increase in the smaller cladoceran *B. longirostris* and the cyclopoid copepod *D. thomasi*.

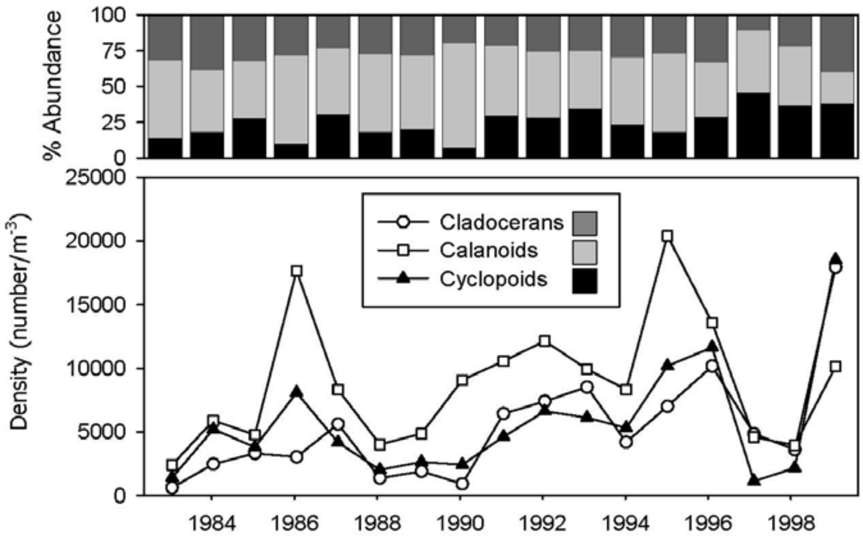

Fig. 7. Total zooplankton density and relative abundance (%) of major taxonomic groups in Lake Michigan during summer, 1983–1999.

Planktivores

Guy Fleischer and Charles M. Madenjian
United States Geological Survey
Great Lakes Science Center
1451 Green Road
Ann Arbor, Michigan, U.S.A. 48105

Robert F. Elliott
United States Fish and Wildlife Service
Green Bay Fishery Resources Office
2661 Scott Tower Drive
New Franken, Wisconsin, U.S.A. 54229-9565

Michael L. Toneys
Wisconsin Department of Natural Resources
110 South Neenah Avenue
Sturgeon Bay, Wisconsin, U.S.A. 54235-2718

The segment of Lake Michigan's fish community that we classify as planktivores includes species that, as mature adults, prey extensively on zooplankton. We recognize that juvenile life stages of all fish rely on plankton for sustenance and that invertebrates even contribute to the diet of adult top predators. However, those species that depend on diets of invertebrates, typically crustacean zooplankton, throughout their life history and are the predominate prey for salmonine predators are those fish considered in this section—including both pelagic and benthic species. The dramatic alterations in species composition in Lake Michigan are best illustrated by the changes observed in bloater, rainbow smelt, and alewife. The once prominent endemic planktivores, most notably the various deepwater ciscoes and the emerald shiner, suffered severe declines or extinctions and were replaced with naturalized exotic species such as the alewife and rainbow smelt. By the 1960s, the fish biomass in Lake Michigan was almost entirely dominated by alewife (O'Gorman and Stewart 1999). Since the time of peak alewife abundance, the planktivore fish community has alternated from an assemblage dominated by alewives to one dominated for a time by bloaters, the surviving member of the deepwater cisco complex in Lake Michigan (Fig. 8). More recently, bloaters have peaked and subsequently declined in abundance in an apparent density-dependent response to high abundance (TeWinkel et al. 2002) rather than as a response to interactions with other species.

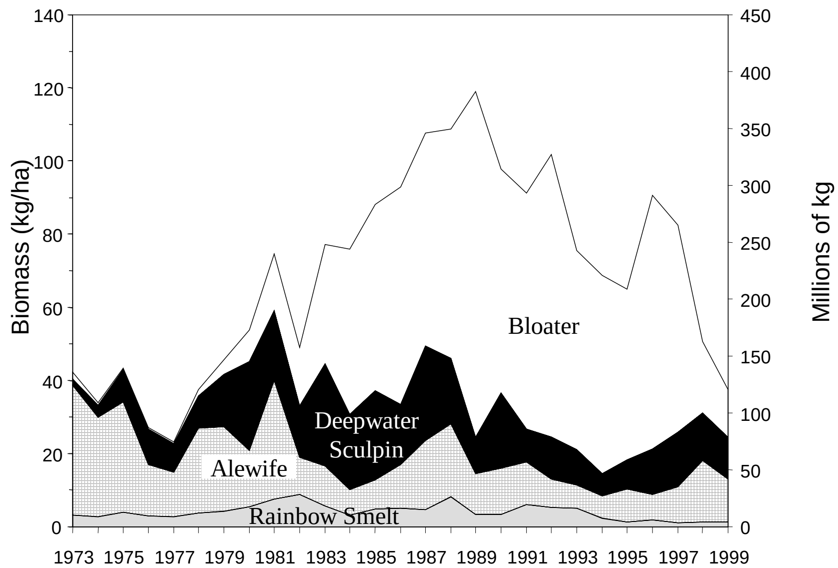

Fig. 8. Biomass of major planktivores (adult) in Lake Michigan, 1973-1999. Estimates based on bottom-trawl surveys performed by the USGS Great Lakes Science Center, Ann Arbor, Michigan.

Planktivore Abundance

Trends in planktivore populations, as indicated from both bottom-trawl catches and acoustic surveys, show that alewife abundance has fluctuated with no consistent trend in recent years. A strong 1995 year class, observed in bottom trawls as adults (Fleischer et al. 1999) and detected in the acoustic surveys as young of the year (YOY) and yearlings (Argyle et al. 1998), now dominates the alewife population. Rainbow smelt have declined in abundance lakewide throughout the 1990s to new low levels. Due to poor recruitment during the 1990s, bloaters have also declined in abundance to the lowest levels since the 1980s (TeWinkel et al. 2002). Deepwater sculpin (not a planktivore but in the planktivore food web) populations have been stable in recent years (Fleischer et al. 1999). Ninespine stickleback catches, which had previously not shown any trends, have dramatically increased in the most recent years.

The lakewide biomass estimates presented here do not include Green Bay or Traverse Bay. Brandt et al. (1991) found that Green Bay contributed 5-14% of the total biomass during 1987. During the 1990s, alewife biomass has ranged from 13,000 to 54,000 metric tons for adults and 8,400 to 148,000 metric tons for YOY (the latter value is the estimate for the 1995 year class). The biomass of the 1995 year class of yearling alewives was 38,000 metric tons. Standing stocks ranged from 3 to 13 kg/ha for adults and from 3 to 35 kg/ha for juveniles (YOY and yearling). In total, alewife standing stocks ranged from 9 to 47 kg/ha. Based on trawl surveys, bloater biomass has declined from 326,000 to 45,500 metric tons during the1990s; acoustic estimates suggest a peak biomass of 475,000 metric tons. These values correspond to standing stocks ranging from 93 to 13 kg/ha, and a peak acoustic estimate of 115 kg/ha. Acoustic-based estimates of rainbow smelt biomass declined from 84,000 to 16,000 metric tons, and standing stock declined from 20 kg/ha to 3 kg/ha. The biomass of deepwater sculpin ranged from 21,500 to 52,000 metric tons, and standing stocks ranged from 6 to 15 kg/ha. Ninespine stickleback biomass varied between 210 and 9,000 metric tons (0.1-2.5 kg/ha standing stock). These values compare favorably with estimates of biomass in other large freshwater systems. In Lake Tanganyika, Moreau et al. (1993) modeled the trophic structure and estimated the standing stock of smaller pelagic fishes at 65 kg/ha. Using the same approach in Lake Ontario, Halfon and Schito (1993) estimated standing stocks of alewives at 81 kg/ha, rainbow smelt at 7 kg/ha, and sculpin at 2 kg/ha. In Lake Superior, planktivore biomass was estimated to be only 8 kg/ha (Kitchell et al. 2000).

For the period (1993-1996) when acoustic estimates were available, total planktivore biomass in the aggregate totaled 300,000-650,000 metric tons in Lake Michigan proper. The biomass was dominated by pelagic species (those that exhibit diel vertical movements). Deepwater sculpin, a demersal species, contributed on average only about 33,000 metric tons. These values represent an overall standing-stock range of 150-65 kg/ha, with an average of 114 kg/ha for pelagic planktivores and 9 kg/ha for deepwater sculpin. By way of comparison, Brown (1972) estimated an alewife standing stock of 191 kg/ha.

Demands on Planktivores as Prey

During the past three decades, the lake trout restoration program and introductions of hatchery-reared trout and Pacific salmon have resulted in successful and highly desired fisheries. Due to this success, attention has been focused on the capacity of the planktivore populations, especially of alewife, to sustain these predators. The dramatic shift in planktivore dominance from alewife to bloater that occurred during the late 1980s did not result in a similar shift to bloaters as the dominant prey for most predators. Several authors have concluded that much of the adult bloater biomass in Lake Michigan is too deep and occupies water too cold to be available as prey for salmon (Crowder and Crawford 1984; Brandt et al.1991; Eck and Brown 1991; Stewart and Ibarra 1991; Elliott 1993). In contrast, alewife prefer temperatures similar to salmon and thus occupy similar habitat (Brandt et al. 1980), making them much more available as prey.

Juvenile bloaters, which typically remain spatially segregated from adult bloaters by inhabiting pelagic waters (Crowder and Magnuson 1982; Crowder and Crawford 1984; Brandt et al. 1991), are presumably more available as prey for salmon than are adult bloaters. In the mid-1980s to early 1990s, when bloater recruitment was high and the bloater population was increasing, juvenile bloaters (<160 mm) were a substantial component in the diet of Lake Michigan salmon and nearshore lake trout, particularly for intermediate-sized fish (Elliott 1993; Rybicki and Clapp 1996). However, since 1992, when bloater recruitment was poor, the abundance of juvenile bloaters has been low (Fleischer et al. 1999), and they contributed very little to the diet of salmon and nearshore lake trout (Madenjian et al. 1998).

Spatial variation in planktivore distribution and abundance in Lake Michigan is commonly observed in predator diets. Adult lake trout that inhabit the deepwater offshore reef habitats of southern waters have a much higher proportion of adult bloaters and sculpins in their diet than do salmon and nearshore lake trout, although alewife still contribute seasonably to the offshore diet (Madenjian et al. 1998; Miller and Holey 1992). Chinook salmon in offshore waters (>40-m depth) have a higher proportion of alewife in their diet than salmon from inshore waters (Rybicki and Clapp 1996). Bloater and yellow perch have typically contributed more to the diet of salmon and trout in eastern and southeastern inshore waters (Elliott 1993; Elliott et al. 1996; Rybicki and Clapp 1996; Madenjian et al. 1998). The gradual but consistent decline in rainbow smelt abundance, as measured in bottom trawls (Fleischer et al. 1999), is consistent with their lower composition in the diets of trout and salmon in the mid-1990s (Rybicki and Clapp 1996; Elliott 1997; Madenjian et al. 1998) relative to earlier periods (Jude et al. 1987; Miller and Holey 1992; Elliott 1993). Rainbow smelt have typically contributed more to predator diets in northern and western waters, and, overall, the diet of lake trout from the northern waters of Lake Michigan has been more diverse and shown less dominance by alewife than elsewhere in the lake (Elliott et al. 1996; Lake Michigan Technical Committee, Great Lakes Fishery Commission, 2100 Commonwealth Blvd., Ann Arbor, Michigan, 48105-1563, unpubl. data).

Diets of Lake Michigan salmonines typically exhibit seasonal trends. YOY alewife are often prevalent in the diets of salmon during late summer and fall, whereas, adult alewife are often the dominant food item during summer (Stewart and Ibarra 1991; Elliott 1993). The extent of seasonal variation in size of prey consumed depends on the year-class strength and distribution of the various life stages of available planktivores.

According to Stewart and Ibarra (1991), annual consumption of alewives by salmonines averaged about 34,000 metric tons between 1978 and 1988. Peak consumption occurred in 1982 and 1987 when, on average, about 40,000 metric tons of alewives were eaten by salmon and trout. The estimates of population sizes of salmon and trout used in the Stewart and Ibarra (1991) modeling exercise may have been substantially biased. Stewart and Ibarra (1991) did not include naturally reproduced chinook salmon and age-4 chinook salmon in their modeling exercise. The SIMPLE (Jones et al. 1993; Lake Michigan Technical Committee, Great Lakes Fishery Commission, 2100 Commonwealth Blvd., Ann Arbor, Michigan, 48105-1563, unpubl. data) and CONNECT (Rutherford 1997) model estimates of total salmonine biomass during 1978-1988, which included estimates of naturally reproduced and age-4 fish, are substantially higher than the estimates of total salmonine biomass by Stewart and Ibarra (1991). According to the CONNECT and SIMPLE models, salmonines were eating between 70,000 and 95,000 metric tons of alewives per year during 1978-1988, which is two to three times higher than estimated by Stewart and Ibarra (1991).

Demands on Planktivores as Commercial Species

A commercial fishery for alewife was established in the Wisconsin waters of Lake Michigan in the 1960s when a trawl fishery was developed to harvest the then extremely abundant alewife that had become a nuisance and health hazard along the lakeshore (Fig. 9). Although alewife was the target species, the trawls caught bloater and rainbow smelt. Bloaters and rainbow smelt not sorted and sold for human consumption were sold, along with alewives, for fishmeal and pet food. In 1986, a quota on alewife was implemented, which was replaced by a targeted rainbow smelt only trawl fishery in 1991. Because of these rule changes and seasonal and area restrictions, the alewife harvest declined from about 7,600 metric tons in 1985 to an average (now incidental) harvest of 12 metric tons after 1990.

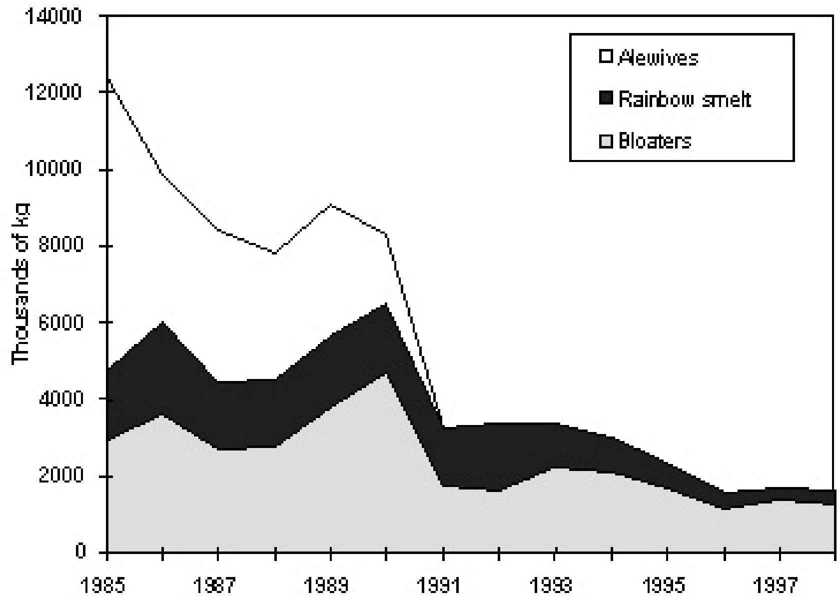

Fig. 9. Commercial catch of alewife, rainbow smelt, and bloater in Lake Michigan, 1985-1998 (Fleischer 1992; Kubisiak 2000).

The commercial harvest of bloater and rainbow smelt has also declined substantially since 1985 due to changes in population abundance and in regulation (Fig. 9). The bloater harvest declined from almost 4,700 metric tons in 1990 to less than 1,300 metric tons in 1998. Very low recruitment since 1991 is at least partly responsible for this decline in harvest, especially in recent years. The commercial harvest of rainbow smelt occurs almost exclusively in Wisconsin waters, and trawls account for most of the harvest. The harvest of rainbow smelt has declined substantially from a high of about 2,400 metric tons in 1986 to less than 350 metric tons in 1998. The decline is attributed to poor recruitment during the 1990s as well as to the implementation of a harvest quota in Wisconsin in 1992.

Planktivore Biomass Expectations

The planktivore objective for Lake Michigan is to maintain a diversity of planktivore (prey) species at population levels matched to primary production and to predator demands with expectations for a lakewide planktivore biomass of 0.5-0.8 billion kg (Eshenroder et al. 1995). Based on our analysis, the planktivore objective for Lake Michigan can be characterized as obtainable but not sustainable. The expected biomass was reached in the 1980s due, for the most part, to proliferation of the bloater but was not sustained as the biomass of bloater and other planktivores declined in the 1990s (Fig. 8). The basis for the expected biomass in the objective was the application of a biomass spectrum model by Sprules et al. (1991), which assumed constant trophic transfer efficiencies and production to biomass relations. Sprules et al. (1991) recognized that these equilibrium models provide only approximations. We note that the measurements of fish biomass used by Sprules et al. (1991) were made during 1987, a year of peak biomass for many key fish species (Fig. 8). Therefore, it should not be surprising that the predictions of prey-fish biomass from this model were provisional and not sustainable. Given our current understanding of longer-term trends as well as current population effects on the various planktivores, we expect the total planktivore biomass, especially for alewife, bloater, and rainbow smelt, to remain at or near current levels in Lake Michigan.

Salmonine Community

Jory L. Jonas
Michigan Department of Natural Resources
Charlevoix Great Lakes Station
96 Grant Street
Charlevoix, Michigan, U.S.A. 49720

David F. Clapp
Michigan Department of Natural Resources
Charlevoix Great Lakes Station
96 Grant Street
Charlevoix, Michigan, U.S.A. 49720

James R. Bence
Michigan State University
Department of Fisheries and Wildlife
East Lansing, Michigan, U.S.A. 48823

Mark E. Holey
United States Fish and Wildlife Service
Green Bay Fishery Resources Office
2661 Scott Tower Drive
New Franken, Wisconsin, U.S.A. 54229-9565

Populations of top predators in the open-water Lake Michigan fish community changed dramatically within the past 100 years (Smith 1968; Wells and McLain 1972). Prior to the 1900s, the community was dominated by a single salmonine, the lake trout, and a member of the cod family, the burbot. Lake trout populations were extirpated, and burbot populations were greatly reduced by the 1950s as a result of overexploitation by the commercial fishery and high rates of predation by sea lamprey. The current predator population is composed of mainly introduced salmonines, including seven species of exotic trout and salmon, and lake trout. Among the introduced salmonines, chinook salmon, rainbow trout, coho salmon, and brown trout are prominent and are considered to be the key species (Fig. 10; Wells and McLain 1972).

Pink salmon, an accidental introduction into Lake Superior in the 1950s, naturalized and spread to other Great Lakes, including Lake Michigan where populations are small. Brook trout and the brook trout-lake trout hybrid (splake) are stocked in small numbers at a few inshore locations in the northern part of the lake and Green Bay.

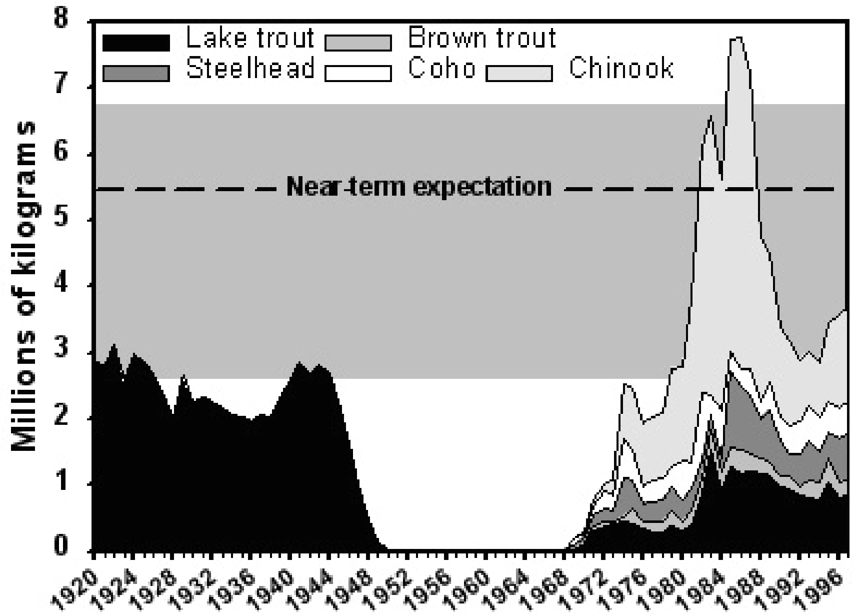

Fig. 10. Harvest of major salmonines from Lake Michigan 1920-1997, target harvest range (shaded area), and near-term yield expectations (dashed line) (Eshenroder et al. 1995).

Salmonines were introduced into the Great Lakes for several reasons. Rainbow trout, brook trout, splake, and brown trout were introduced to provide more-diverse fishing opportunities, whereas chinook and coho salmon were introduced to control the large populations of introduced alewife and diversify fishing opportunities (Tody and Tanner 1966; Keller et al. 1990).

Lake Michigan's salmonine fisheries are currently sustained in large part by stocking. However, as introduced salmonines naturalized, determining the amount of natural reproduction is increasingly important. Because lake trout is the only major salmonine predator that was native to Lake Michigan and knowledge of impediments to their recruitment is incomplete, rehabilitation remains an important and yet unattained goal for managers and researchers.

Salmonine Objectives and Yields

The FCOs for Lake Michigan salmonines (trout and salmon) are: 1) to establish a diverse salmonine community capable of sustaining an annual harvest of 2.7-6.8 million kg, of which 20-25% is lake trout, and 2) to establish self-sustaining lake trout populations (Eshenroder et al. 1995). These objectives recognize the limits of the system and the need to balance a desire for abundant populations of top predators with the possibility that overstocking could lead to a collapse of planktivore populations and instability of predator populations. The decline in chinook salmon fisheries during the late 1980s provided an example of the limits of the Lake Michigan fish community. The objectives of the current management approach include sustaining a diverse predator community that supports sport and commercial fisheries, and that utilizes alewife and rainbow smelt populations sufficiently to minimize the negative influences of these exotic planktivores on native species, especially on the bloater (Eshenroder et al. 1995). Declines in alewife abundance and increases in bloater abundance during the early 1980s emphasized the advantages of a diverse salmonine community that could take advantage of a changing prey-fish community. The lower bound of the desired salmonine yield, 2.7 million kg, was determined from the historical catch of lake trout before the collapse of the native population. The upper bound, 6.8 million kg, was determined from biomass size-spectrum models (Borgmann 1987; Sprules et al. 1991) assuming 100% ecological efficiency. Model estimates indicated that a mix of salmonine species would more efficiently use the pelagic fish community, and thus could support higher yields than were realized from a fish community with only lake trout as the top predator. The LMC agreed to the following species-specific near-term yield expectations (within the 2.7 to 6.8 million-kg range) chinook salmon—3.1 million kg; lake trout—1.1 million kg; coho salmon—0.7 million kg; rainbow trout—0.3 million kg; and brown trout—0.2 million kg; or an overall lakewide yield of 5.5 million kg (Eshenroder et al. 1995; Fig. 11). The LMC recommended that these initial expectations be refined by evaluating the relation between yield (sport, commercial, harvest-weir) and the mix of predators in the system and that a determination be made as to how these different mixtures of species meet a variety of needs identified by society.

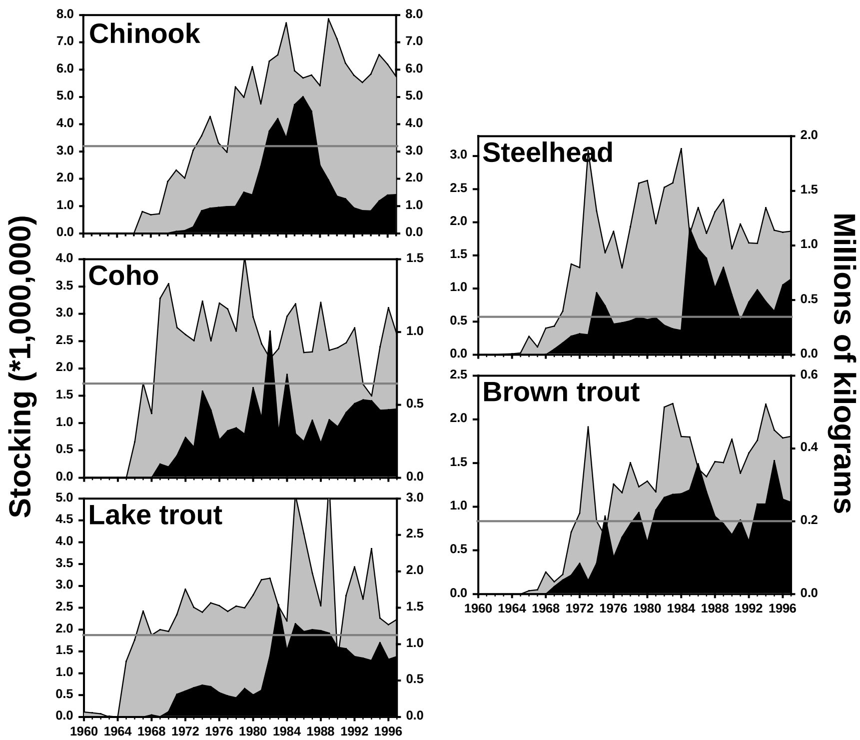

Fig. 11. Estimated yield (kg, dark shaded area) of chinook salmon, rainbow trout, coho salmon, brown trout, and lake trout; number stocked (light shaded area); and near-term yield expectations (line) identified in Eshenroder et al. (1995).

During the 1980s and 1990s, overall yield was within the expected yield range identified in the FCOs, although in recent years it has been substantially below the near-term yield expectation of 5.5 million kg (Fig. 10). Yields exceeded 5.5 million kg during the mid-1980s, but declines in chinook salmon biomass (Fig. 12) and fishing effort (Benjamin and Bence 2003) led to substantial reductions in yield. Although estimated predator biomass increased recently, fishing effort remains much lower than in the mid-1980s (Bence and Smith 1999; Benjamin and Bence 2003).

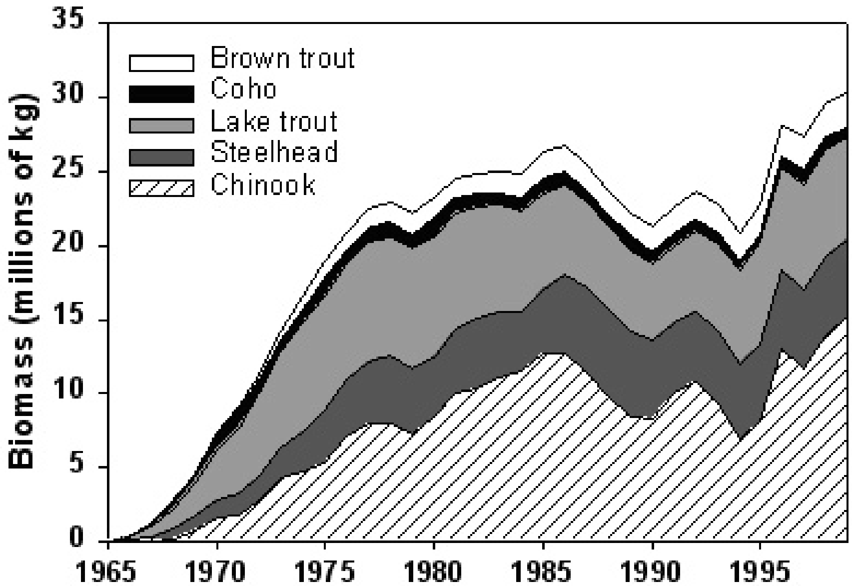

Fig. 12. Estimated biomass of salmonines in Lake Michigan, 1965-1999 (Connect Model; Rutherford 1997).

Chinook Salmon

The annual yield of chinook salmon was less than half of the 3.1 million-kg near-term yield expectation during 1980-1999 except in 1984-1989 (Fig. 11). During the late 1980s and early 1990s, population-model estimates of chinook salmon biomass (based on recreational catch statistics) declined significantly (Rutherford 1997; Fig. 12), probably as a result of density- and forage-mediated increases in disease (Holey et al. 1998). Estimates of biomass for the mid-1990s to late 1990s were at or above former levels. Yield has not increased proportionately with increases in biomass, in part because fishing effort has not increased to levels seen during the 1980s. Management agencies reduced stocking levels of chinook salmon in recent years in an attempt to improve survival by reducing population density.

The relation between the number of chinook salmon stocked and the number harvested changed following the population collapse in the late 1980s. Sport harvest of chinook salmon was positively related to numbers stocked through the late 1980s, but the relation was no longer apparent after 1990 (Fig. 11; Hansen et al. 1990; Hansen et al. 1991; Hansen and Holey 2001). Hence, it now appears that managers cannot increase the yield of chinook salmon simply by increasing the number stocked. Even though the predicted biomass has rebounded to pre-population crash levels or greater, yield remains below the 3.1 million-kg near-term expectation level (Fig. 13) due to reduced fishing effort. Whether or not the chinook salmon harvest can recover to the high levels achieved in the 1980s is now in question. Managers should reexamine the yield expectation for this species.

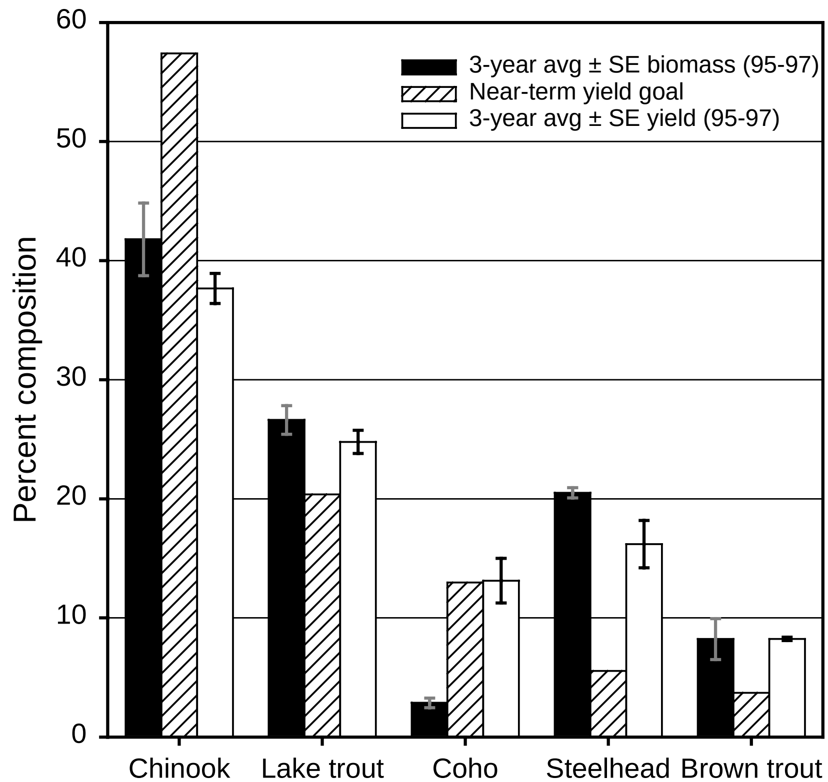

Fig. 13. Species composition of near-term yield targets from the fish-community goals (Eshenroder et al. 1995) compared to 1995-1997 mean actual yield (white bars) and 1995-1997 mean modeled estimate of relative biomass (solid bars).

Coho Salmon

The annual yield of coho salmon increased with increased stocking in the early years of the program, but numbers stocked have not been reflected in recent yield estimates (Fig. 11). Coho salmon were consistently harvested at levels well below the near-term expectation established in the FCOs (Fig. 11). However, the percentage contribution to the harvest was close to the expectation (Fig. 13). Coho salmon make up the lowest portion (3%) of the overall biomass of the five key species in Lake Michigan, but they are expected to produce 13% of the harvest. Coho salmon are short-lived, very fast growing, and recruit quickly to the fishery. Consequently, their biomass estimates at the beginning of the year are often well below their annual harvest. Given the yield history and current stocking rates, the near-term yield expectation for coho salmon is probably not realistic.

Rainbow Trout and Brown Trout

Yield of rainbow and brown trout increased during the late 1960s and 1970s as stocking increased (Fig. 11). The relation between yields and stocking in recent years warrants further analysis. Yields and percentage contribution to total salmonine yield for these two species have remained consistently at or above expectations (Figs. 11, 13), so current near-term expectations are probably realistic.

Lake Trout

Yield of lake trout in most years since rehabilitation efforts began in the 1960s has been below the near-term yield expectation identified in the FCOs (Fig. 11). However, that part of the FCOs that state that lake trout should constitute 20-25% of the total harvest has consistently been met in recent years (Fig. 13).

Natural Reproduction and Self-Sustaining Populations

Naturalized populations of salmonines are believed to play an increasingly important role in Lake Michigan fisheries. The FCOs emphasize the desirability of enhanced natural reproduction and establishment, to the extent possible, of self-sustaining populations. Naturalized populations require less-intensive management, may result in more-stable ecosystem dynamics, may increase fitness of populations through genetic selection, and in general are expected to have better survival and productivity in the wild than hatchery-reared fish (Chilcote et al. 1986; Leider et al. 1990; Berejikian et al. 1996). Regulation of hydropower facilities, habitat improvement, and improvements in the water quality of riverine and Great Lakes environments likely contributed to increased productivity of naturalized fish (Holey 2005). In particular, naturalized chinook salmon now make up a large portion of the chinook salmon population. Based on identification of oxytetracycline (OTC) marks in 1992 and 1993, about 30% of the sport harvest of chinook salmon was made up of naturalized fish (Hesse 1994). Naturalized rainbow trout also make up a large portion of the rainbow trout sport harvest. The proportion of naturalized fish in the entire harvest has yet to be determined, but data from several highly suitable tributaries in Michigan indicate that the contribution of naturalized fish to spawning runs may be as high as 100% (Seelbach and Whelan 1988; Seelbach 1989; Seelbach 1993; Seelbach et al. 1994). In tributaries that are less suitable for rainbow trout reproduction (e.g., St. Joseph and Grand Rivers in Michigan), wild rainbow trout comprise 5-20% of the run (Seelbach et al. 1994). Coho salmon spawn in tributaries of Lake Michigan, but compared to chinook salmon and rainbow trout, much less is known about the contribution of this reproduction to coho salmon populations and fisheries (Becker 1983). Between 1976 and 1979, Carl (1982) found evidence of natural reproduction by coho salmon in 25 of 60 Michigan streams surveyed. Patriarche (1980) reported that 9% of the sport catch in Michigan waters in 1979 was from natural reproduction. Brown trout stocked into Lake Michigan generally do not migrate up streams to spawn, but they may attempt to spawn on structures in the lake. There is little if any information regarding the success of brown trout spawning (Becker 1983). Whether the recruitment of these species has changed considerably since the early 1990s when the FCOs were written is unknown, in large part because lakewide monitoring of natural reproduction has not been consistent. Currently, efforts are being made to increase knowledge of recruitment mechanisms and their influences on estimates of population biomass.

Lake Trout Rehabilitation

Efforts to restore self-sustaining lake trout populations began with the initiation of sea lamprey control, followed by the stocking of lake trout yearlings in 1965 (Holey et al. 1995). Since 1985, a Lakewide Management Plan for Lake Trout Rehabilitation in Lake Michigan (Lake Michigan Lake Trout Technical Committee 1985) has guided restoration efforts. This plan targeted annual stocking at 5.84 million fish, focused stocking efforts in habitats where rehabilitation was judged to have the best chance for success, increased genetic diversity of the stocked fish, and established total mortality limits in areas targeted for rehabilitation

(Krueger et al. 1983; Eshenroder et al. 1984; Lake Michigan Lake Trout Technical Committee 1985; Holey et al. 1995). The plan also defined areas of the lake as refuges or primary, secondary, and deferred rehabilitation zones (Fig. 14). The plan prioritized stocking efforts. Refuges received the highest priority, secondary zones the lowest priority, and deferred zones were not stocked at all. Annual mortality was not to exceed 40% except in deferred zones. Two refuges, mid-lake and northern, were created in 1984-1985 in offshore areas containing high-quality spawning habitat. The refuges were sized to encompass the home range of the fish stocked in them, and sport and commercial harvest was banned to provide maximum protection from fishing (Fig. 14). The rest of Lake Michigan was classified into zones based on the quantity of high-quality spawning habitat, historical lake trout yield from commercial fishing, and total mortality.

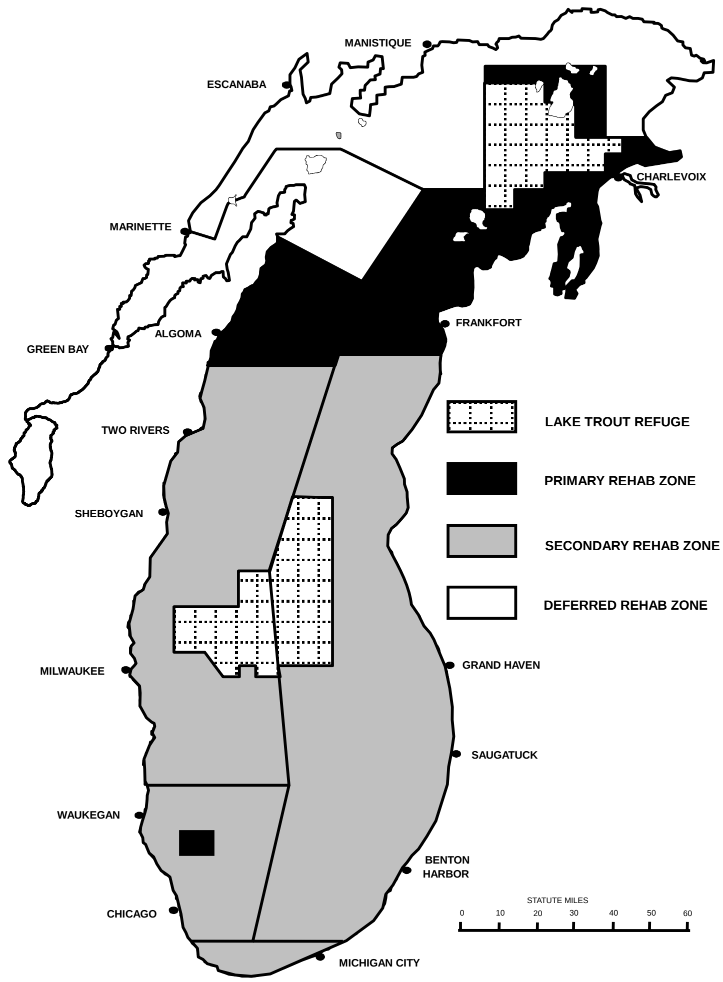

Fig. 14. Lake Michigan lake trout refuge areas, and primary, secondary, and deferred rehabilitation zones.

The number of lake trout stocked annually into Lake Michigan has been consistently about 3 million-fish short of the rehabilitation plan target of 5.84 million fish (Holey et al. 1995). Prior to development of a lake trout rehabilitation plan (1965-1984), 53% of available lake trout were stocked into zones designated as secondary or deferred, and only 9% were stocked into areas now designated as refuges. The majority (90%) of lake trout is currently stocked in either refuges (56%) or primary (34%) zones (Fig. 15). After implementation of the 1985 rehabilitation plan, more than 70% of stocked lake trout were transported by boat and released on offshore spawning reefs compared to only 27% prior to plan implementation (Holey et al. 1995).

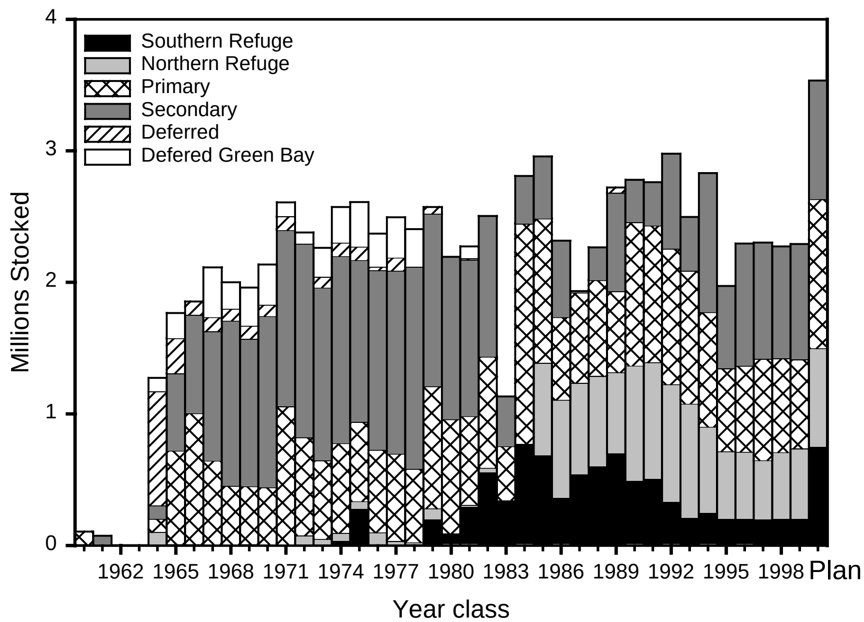

Fig. 15. Numbers of yearling-equivalent (2.44 fall fingerlings stocked = 1 yearling stocked) lake trout, by year class, stocked into Lake Michigan refuges and rehabilitation zones.

Implementation of the 1985 rehabilitation plan increased the number of lake trout strains stocked (Fig. 16) in an attempt to address the concern that genetic diversity may be limiting successful rehabilitation (Krueger et al. 1983; Eshenroder et al. 1984; Lake Michigan Lake Trout Technical Committee 1985; Burnham-Curtis et al. 1995). The Marquette strain, a shallow-water lean strain from Lake Superior, was the predominant strain stocked until 1989. After 1989, as many as six different strains were stocked annually (Holey et al. 1995). A comparison of performance among three strains was scheduled for each refuge (Lake Michigan Lake Trout Technical Committee 1985).

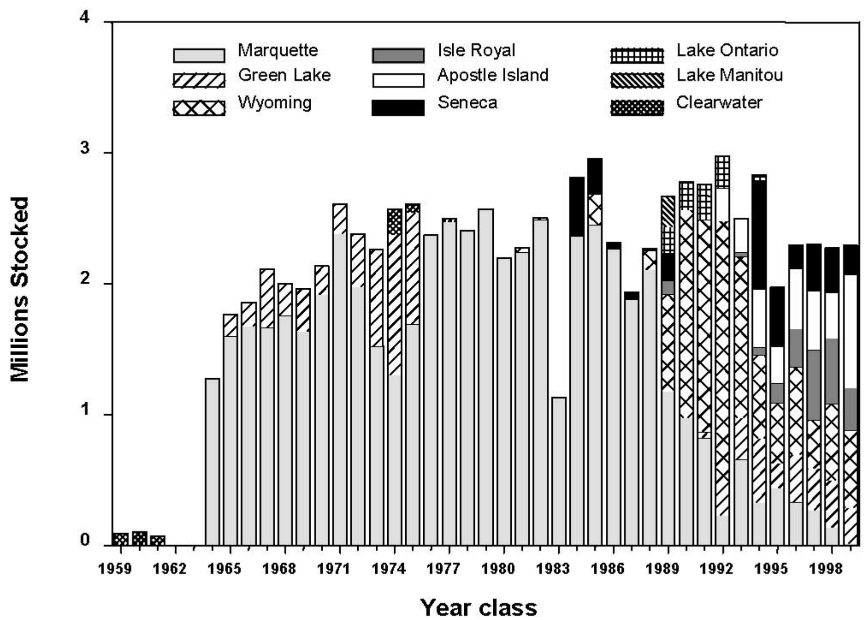

Fig. 16. Numbers of yearling-equivalent (2.44 fall fingerlings stocked = 1 yearling stocked) lake trout stocked into Lake Michigan by year class and strain.

Current abundance levels of lake trout in Lake Michigan are maintained exclusively by stocking. At many sites in southern and western Lake Michigan, the abundance of adult lake trout has increased to levels commensurate with reproducing stocks in Lake Superior (Selgeby et al. 1995), but there has been no evidence of natural recruitment to adult populations in recent years. Densities of lake trout during spawning in the northern refuge have been generally low, and densities along the western shore have been generally greater than along the eastern shore (Holey et al. 1995). The density of lake trout required to achieve recruitment of naturalized fish remains unknown.

In spite of a buildup of adult lake trout populations, evidence of natural reproduction in Lake Michigan has been sparse. During the past 30 years, fertilized eggs have been found at 19 of 25 sites sampled (Peck 1979; Dorr et al. 1981; Jude et al. 1981; Wagner 1981; Goodyear et al. 1982; Horns et al. 1989; Marsden 1994; Edsall et al. 1995), and fry have been captured at four of 15 sites sampled (Peck 1979; Jude et al. 1981; Wagner 1981; Marsden 1994). The abundances of eggs and fry are significantly lower than those observed in other systems with naturalized populations such as Lake Ontario (Fitzsimons 1995; Perkins and Krueger 1995), Perry Sound in Lake Huron, and Lake Champlain (John Fitzsimons, Department of Fisheries and Oceans, P.O. Box 85120, Burlington, Ontario, Canada, L7R 4K3, personal communication). In 1983-1989, Rybicki (1991) attributed 13% of the 1976 year class and 7% of the 1981 year class in Grand Traverse Bay to natural recruitment, as well as 4% of the 1983 year class in Platte Bay. No evidence of natural recruitment to yearling and older lake trout has been reported since the 1980s; however, assessment efforts targeting juvenile lake trout have not occurred consistently or on a lakewide basis.

After 17 years, new information is available regarding lake trout reproductive strategies and factors limiting survival. The LMC recently initiated efforts to update and revise the existing rehabilitation plan.

Recommendations

1. Harvest expectations for salmonines should be reviewed and updated at five-year intervals.
2. The contribution of naturalized fish to salmonine recruitment should be determined.
3. Population models that increase the accuracy of estimates of yield, predator abundance, prey abundance, and consumption should be developed and continually updated to reflect our current understanding of processes influencing Lake Michigan fish communities.
4. Managers, biologists, and researchers should use a metric other than fishery yield to indicate the success or failure of management actions. Population or biomass estimates would better represent fish populations and would not be as strongly linked to the behavior of individuals harvesting fish (i.e., angler effort).
5. The components of mortality experienced by lake trout at a variety of life stages need to be determined. Information on age-specific harvest, sea lamprey marking, and abundance is needed continually to evaluate progress toward rehabilitation.
6. The rehabilitation plan for lake trout needs to be updated. The current plan is 17 years old and a considerable body of new information is available regarding limiting factors (i.e., reproductive bottlenecks). The LMC recently initiated efforts to update and revise the rehabilitation plan, incorporating this new information.

Acknowledgments

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Inshore Fish Community

David F. Clapp
Michigan Department of Natural Resources
Charlevoix Great Lakes Station
96 Grant Street
Charlevoix, Michigan, U.S.A. 49720

Philip J. Schneeberger
Michigan Department of Natural Resources
Marquette Fisheries Research Station
484 Cherry Creek Road
Marquette, Michigan, U.S.A. 49855

Richard P. O'Neal
Michigan Department of Natural Resources
Central Lake Michigan Management Unit
Oceana Field Office
1757 East M-20
Shelby, Michigan, U.S.A. 49455

Terry J. Lychwick
Wisconsin Department of Natural Resources
200 N. Jefferson
Green Bay, Wisconsin, U.S.A. 54301

Brian Belonger
Wisconsin Department of Natural Resources
P.O. Box 127
Peshtigo, Wisconsin, U.S.A. 54157

Steven M. Shroyer
Minnesota Department of Natural Resources
P.O. Box 86
Waterville, Minnesota, U.S.A. 56096

The inshore fish community of Lake Michigan makes up an extremely important part of the lake ecosystem. Inshore (≤45-m depth) waters make up 31% of the lake area, and include tributary estuaries and drowned river mouths (Fig. 1). Coastal wetlands, especially, provide an interface between the lake and terrestrial habitats. Inshore waters are important areas for nutrient exchange (Hayes and Petrusso 1998) and provide nursery habitat for a variety of fish species (Chubb and Liston 1986; Hayes and Petrusso 1998). Inshore fishes include recreationally and commercially important species such as yellow perch, walleye, smallmouth bass, northern pike, muskellunge, catfish, and panfish, as well as nongame species, including spottail shiner, slimy sculpin, mottled sculpin, trout perch, and johnny darter.

The FCO for the inshore fish community of Lake Michigan (Eshenroder et al. 1995) is to maintain self-sustaining stocks of yellow perch, walleye, smallmouth bass, pike, catfish, and panfish. Expected annual yields should be 0.9-1.8 million kg (2-4 million lb) for yellow perch and 0.1-0.2 million kg (0.2-0.4 million lb) for walleye.

Yellow Perch

Commercial harvest records for yellow perch date from the late 1880s, and sport harvest has been estimated since the mid-1980s (Baldwin et al. 1979; Kubisiak 2000). Harvest of yellow perch has shown a somewhat cyclic pattern generally fluctuating to within the target FCO range of 0.9-1.8 million kg every 20-25 years or so (Fig. 17).

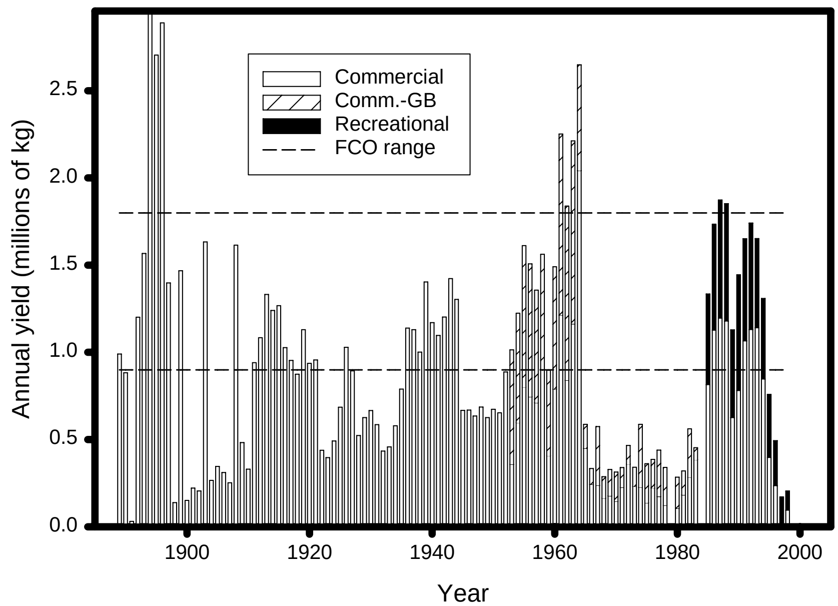

Fig. 17. Annual yield (kg) of yellow perch from Lake Michigan commercial and recreational fisheries, 1889-1998. Commercial catch data from the waters of Green Bay are available for later years (Comm.-GB). Data are from Baldwin et al. (1979) and Kubisiak (2000).

Yield is presently below target levels primarily due to poor year classes in the 1990s and more-stringent fishing regulations. Historically, most of the commercial harvest of yellow perch has come from Green Bay and the southern basin. The longest time series on yellow perch recruitment are by the Wisconsin Department of Natural Resources (WDNR) from southern Green Bay (dating from 1978) and by Ball State University (Indiana) from the southern basin (dating from 1975) (McComish et al. 2000). Both series show a lack of recruitment in the late 1970s, generally moderate to strong year classes in the 1980s, and no strong year classes in the early to mid-1990s (Fig. 18). This fluctuating pattern of recruitment is evident in other areas of the lake in the 1980s and 1990s. There have been some indications of better recruitment since the mid-

1990s. Measurable year classes were observed in Green Bay in 1995 and 1998 and in the southern basin in 1998 (Fig. 18).

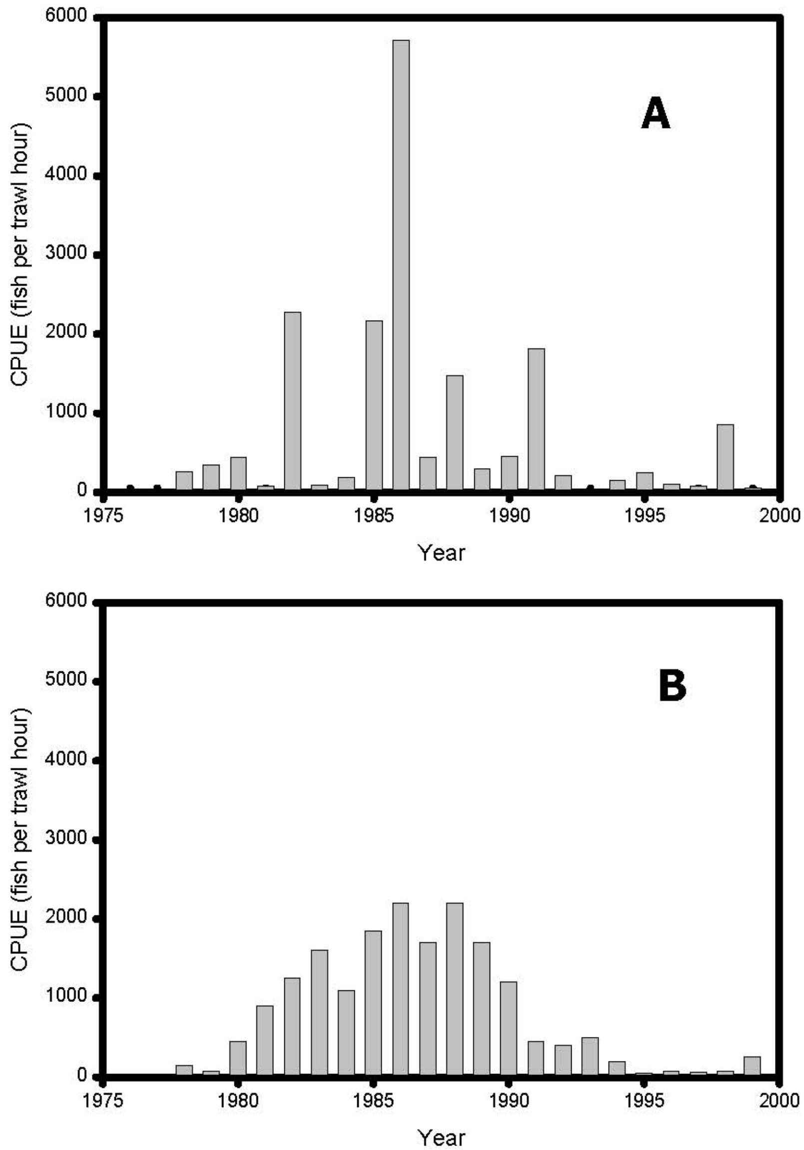

Fig. 18. Trawl catch (number per hour) of young-of-the-year yellow perch in Green Bay (A) and of age-1 yellow perch in southern Lake Michigan (B), 1975-2000.

Despite poor year classes in the early to mid-1990s, yellow perch remain self-sustaining in Lake Michigan. Recruitment has improved in recent years and, in the long term, the target annual yield of 0.9-1.8 million kg is probably achievable. Factors causing poor yellow perch recruitment need to be identified (Makauskas and Clapp 2000). In Southern Green Bay, there is evidence of predation on yellow perch by exotic white perch, the numbers of which have increased dramatically since the late 1980s (BB, unpublished WDNR file data). In the southern basin, target yields may only be achievable if average alewife abundance is low (Shroyer and McComish 2000). Additional information on dynamics of yellow perch populations will come through development of lakewide population models (Allen 2000; Makauskas and Clapp 2000).

Walleye

The walleye was mainly a commercial fish through the 1950s, but harvest in recent years has been primarily in the sport fishery (Fig. 19). With the exception of the 1890s and 1950s, the annual yield of walleye has generally been below the FCO target range of 0.1-0.2 million kg. Most of the commercial harvest since the 1940s has been from Green Bay. Average annual yield for recent years (1985-1998) was 71,740 kg (range = 37,909-108,915 kg). Yield was within the FCO target range in only three years (1994-1996).

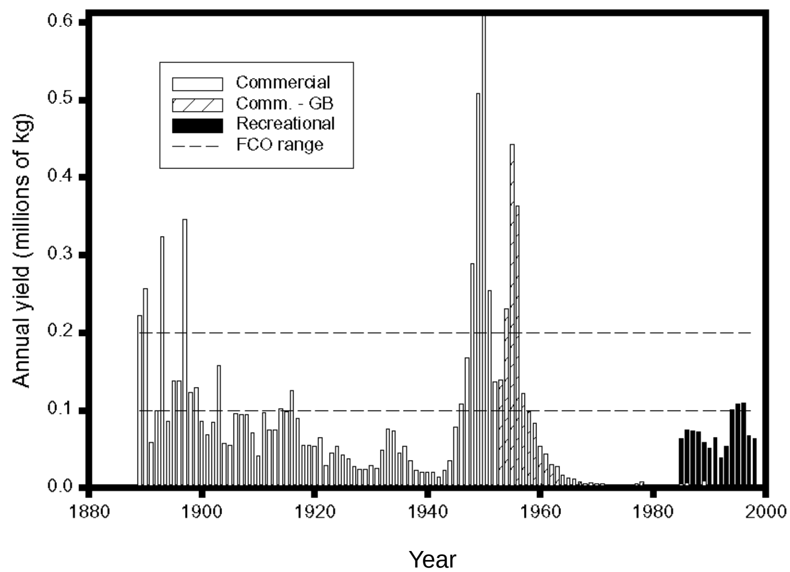

Fig. 19. Annual yield (kg) of walleye from Lake Michigan commercial and recreational fisheries, 1889-1998. Commercial catch data from the waters of Green Bay are available for later years (Comm.-GB). Data are from Baldwin et al. (1979) and Kubisiak (2000).

Walleye utilize tributaries as well as the lake for reproduction. Impoundment of tributaries, declining water quality, high fishing pressure, and abundant exotic species all affected walleye reproduction (Schneider and Leach 1979), such that stocked fish now play a substantial role in walleye recruitment. The Muskegon River is an area of historical importance for walleye in the southern basin (O'Neal 1997). About 600,000 walleye fingerlings have been stocked annually in the Muskegon River system in recent years, and, based on OTC marking, these stocked fish represent the only current source of recruitment to this system (RPO, unpubl. data).

Although walleye recruitment in the southern basin is dependent on stocking, natural recruitment is occurring in Green Bay. Walleye are still stocked (in alternate years) in northern Green Bay (Schneeberger 2000), but walleye are beginning to produce natural year classes in some of the tributary systems (i.e., Cedar River, Menominee River) (Schneeberger

2000). The Fox River system historically contributed large numbers of naturally produced walleye to southern Green Bay (Schneider and Leach 1979). Stocking was recently discontinued in this area of the bay when renewed natural recruitment from the Fox River system became evident (Lychwick 1997).

The FCO goal of achieving and maintaining self-sustaining stocks of walleye was reached only in Green Bay. Walleye populations in the remainder of the lake still depend almost entirely on stocking. Stocking resulted in some rebuilding of adult populations in the Muskegon River system. Adult abundance was less than 10,000 individuals in the 1970s, but recent population estimates put that number at close to 50,000 (Day 1991; RPO, unpubl. data). The expected-yield component of the walleye FCOs needs to be revised. Yields within the expected annual yield range of 0.1-0.2 million kg were achieved in only three relatively short periods during 1889-1998, and the expected range was exceeded in only two periods when most harvest was by commercial fisheries (Fig. 19). Most harvest in recent years has been in the recreational fishery. The average yield for the entire period of record (90,000 ± 20,000 kg for the years 1889-1998) would be a more-realistic target.

Other Commercially and Recreationally Important Species

Little long-term information is available on yield of other inshore fishes such as smallmouth bass, northern pike, muskellunge, catfish, rock bass, and sunfishes. Although these fishes may be locally important, they represent a minor component of fisheries. Smallmouth bass and northern pike combined made up less than 1% of the total Lake Michigan harvest (numbers of fish) by Michigan anglers in 1999 (G. Rakoczy, Michigan Department of Natural Resources, Charlevoix Great Lakes Station, 96 Grant Street, Charlevoix, Michigan, 49720, personal communication). Little is known about their populations, but they persist without stocking and appear to be self-sustaining. Important areas of the lake for smallmouth bass recruitment include the Waugoshance Point/Beaver Island Archipelago area of northern Lake Michigan (Latta 1963), Green Bay, and the Door Peninsula in western Lake Michigan (T. Kroeff, Wisconsin Department of Natural Resources, 110 S. Neenah Ave., Sturgeon Bay, Wisconsin, personal communication). There is also some evidence of recruitment in the nearshore areas of southern Lake Michigan from Hammond, Indiana, to Chicago, Illinois (J.T. Francis, Indiana Department of Natural Resources, Lake Michigan Fisheries Station, 100 W. Water St., Michigan City, IN, 46360, personal communication; R. Hess, Illinois Department of Natural Resources, 9511 Harrison St., Des Plaines, IL, 60016, personal communication). However, long-term estimates of recruitment and year-class strength of smallmouth bass are not available for any area of Lake Michigan. Green Bay is probably the only area with substantial populations of northern pike. Green Bay also produced muskellunge historically, and the WDNR is attempting to rehabilitate this population through stocking (BB, personal communication). Stocked fish have survived to adulthood, but reproduction has not been documented. Long-term estimates of recruitment and year-class strength are not available for either northern pike or muskellunge.

Non-Game and Non-Commercial Species

Although not directly harvested commercially or recreationally (with the exception of some limited baitfish harvest), many other inshore fish species are important to the inshore ecosystem. Long-term data are not available for many of these species, but some important population changes for a few have been documented in recent years often coincident with changes in the abundance of sport and commercial species. For example, abundance of spottail shiners increased dramatically in the 1990s coincident with a decline in yellow perch numbers (Tonello 1997). Emerald shiners, in contrast, were scarce throughout the 1970s and 1980s (Eck and Wells 1987) and have remained so through recent years (DFC, unpubl. data). Other changes in non-game, non-commercial populations can be attributed to human activities in the system. The number and abundance of exotic species increased throughout the Great Lakes in recent years (Mills et al. 1993), and this altercation is particularly apparent in Lake Michigan. For example, the round goby is now a substantial part of the inshore community in certain areas (Charlebois et al. 1997; Clapp et al. 2000; McComish et al. 2000). Exotic species will continue to enter the system (Ricciardi and Rasmussen 1998), and the potential effects of these introductions need to be evaluated.

Recommendations for Future Management and Research

The following are recommended research and management goals relative to the inshore fish community that should be addressed in the next five years:

1. Develop the ecosystem approach to management of Lake Michigan inshore communities, including the tools necessary to implement this approach. In the near future, geographical information systems descriptions of inshore ecoregions will provide us with more-appropriate and meaningful tools for management of these communities (E. Rutherford, School of Natural Resources and Environment, University of Michigan, 430 E. University, Ann Arbor, Michigan, 48109, personal communication). Development of these tools necessitates shared data collection and analysis efforts that are coordinated throughout the basin (Sherman and Duda 1999).
2. Collect population and harvest data for smallmouth bass, northern pike, muskellunge, catfishes, and panfish (centrarchid sunfishes).
3. Investigate important species interactions, including interactions across ecoregions, ecosystems, and trophic levels. Interactions among inshore species have not received enough attention. These include interactions among native and exotic fishes, interactions between fish and exotic lower-trophic-level organisms (i.e., zebra mussels) (Evans 1986), and even interactions with terrestrial and avian systems. In recent years, double-crested cormorant (*Phalacrocorax auritus*) populations have increased around the Great Lakes where they prey on inshore fish populations (Diana et al. 1997).
4. Protect and, where necessary, rehabilitate habitat, especially walleye spawning habitat, wetlands, and drowned river-mouth lakes. Habitat is critically important to the inshore fish community (Hayes and Petrusso 1998). Dam removals or operational changes significantly improved habitat for some species in certain tributaries; for example, walleye in the Milwaukee and Muskegon Rivers (P. Hirethota, Wisconsin Department of Natural Resources, 600 E. Greenfield Ave., Milwaukee, Wisconsin, 53404, personal communication;

O'Neal 1997). On the other hand, wetlands along the shore of Green Bay, critical to northern pike reproduction, are being lost to development. Important work is currently under way to quantify and restore wetland and drowned river-mouth resources of Lake Michigan (T. Simon, United States Fish and Wildlife Service, Bloomington Field Office, 620 S. Walker St., Bloomington, IN, 47403-2121, personal communication).

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Benthivores

Philip J. Schneeberger
Michigan Department of Natural Resources
Marquette Fisheries Station
484 Cherry Creek Road
Marquette, Michigan, U.S.A. 49855

Robert F. Elliott
United States Fish and Wildlife Service
Green Bay Fishery Resources Office
2661 Scott Tower Drive
New Franken, Wisconsin, U.S.A. 54229-9565

Jory L. Jonas and Stephanie Hart
Michigan Department of Natural Resources
Charlevoix Great Lakes Station
96 Grant Street
Charlevoix, Michigan, U.S.A. 49720

Benthivorous fish species are commonly known as bottom feeders because they target food items that are associated primarily with aquatic substrates. This chapter will cover four benthivorous species in Lake Michigan: lake whitefish, round whitefish, lake sturgeon, and burbot. The lake whitefish is the most important commercial fish in Lake Michigan in terms of numbers caught and monetary value. During 1990-1999, Lake Michigan provided an average 61% by weight and 63% by value of the total lake whitefish commercial yield in the Great Lakes (National Marine Fisheries, http://www.st.nmfs.gov/pls/webpls webst1.MF_GL_SPECIES_HELP .SPECIES#by_lake). Round whitefish have been exploited by commercial fisheries for more than a century, although annual yield is relatively low. Management agencies have become increasingly interested in lake sturgeon in recent years, as illustrated by the scope of the work and associated rehabilitation plans developed for this species. Burbot abundance increased substantially following successful sea lamprey control efforts. The burbot's role in the contemporary Lake Michigan fish community needs to be better understood.

Lake Whitefish

The historical lake whitefish harvest fluctuated dramatically over the last century, but relatively high and increasing harvests have been sustained since 1971 (Fig. 20). The average annual harvest during 1879-1970 was .983 x 10^9 kg, and the average during 1971-1998 was 2.314 x 10^9 kg. Prior to 1970, harvests above the 1879-1970 average occurred about every 15-40 years. These harvest peaks were short-lived and were attributed to single, strong year classes moving through the fishery. After 1970, average yields increased each decade or so in a stepwise fashion: 1.536 x 10^9 kg during 1971-1980, 2.562 x 10^9 kg during 1981-1990, and 3.418 x 10^9 kg during 1991-1998. The FCO specified a target harvest range for lake whitefish of 1.8-2.7 x 10^9 kg (Fig. 20). Although the lower bound of the targeted range is nearly twice as large as the 1879-1970 average, harvests have been within or exceeded the targeted range since 1979.

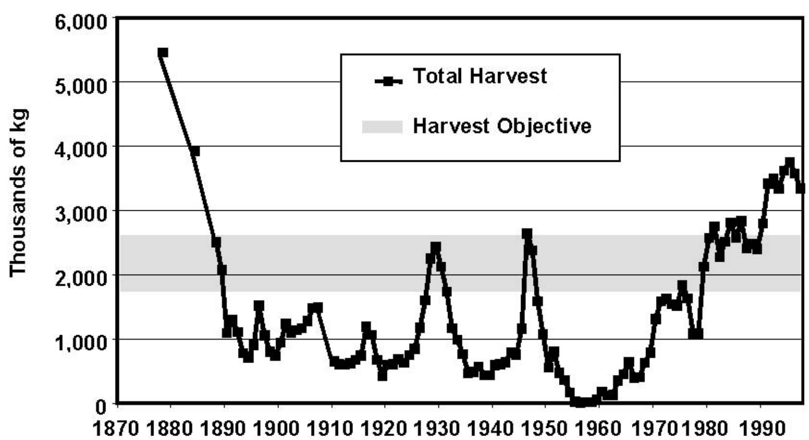

Fig. 20. Commercial harvest of lake whitefish from Lake Michigan, 1879-1998, compared with the FCO targeted harvest range (shaded). Data from Baldwin et al. (1979).

Lake whitefish commercial fisheries are monitored at 13 locations around Lake Michigan by personnel from the Michigan Department of Natural Resources (MDNR), Wisconsin Department of Natural Resources (WDNR), and the Chippewa/Ottawa Resource Authority. Although mixing certainly occurs, lake whitefish at these 13 locations are considered to be distinct stocks for management purposes. Proportions of the total harvest taken by Michigan (~45%), Wisconsin (~22%), and Native American (~33%) fishermen remained relatively stable over the last 18 years. An examination of harvest by gear type between 1981 and 1998 showed that trapnets accounted for the largest portion (58%) of the lakewide harvest, followed by gillnets (35%), trawls (6%), and pound nets (<1%). Increasing trends in the catch per effort (CPE) for all four gear types reflected an increase in whitefish abundance throughout the lake over this period.

Historically, several factors influenced lake whitefish abundance in Lake Michigan. Overfishing and pollution from sawmills were thought to be reasons for whitefish declines in the late 1800s (Wells and McLain 1972). The dramatic decline in abundance during the late 1950s was associated with sea lamprey predation and a substantial increase in rainbow smelt (Wells and McLain 1972). Sea lamprey control measures helped lake whitefish populations rebound during the 1960s.

High lake whitefish abundance over the last three decades contributed to decreasing lake whitefish size-at-age and condition. During 1992-1998, length-at-age decreased 4-7% and weight-at-age decreased 36-47%. Consequently, lake whitefish condition factors decreased dramatically after 1992 in several northern management units where this statistic was calculated annually (Fig. 21). Sustained high levels of lake whitefish abundance likely resulted in increased intraspecific competition for food. Exacerbating this situation are changes in food-web dynamics due to proliferation of zebra mussels, which became abundant in northern waters during the same time that lake whitefish growth and condition declined most precipitously. Of interest, zebra mussels are blamed for poor body condition and decreased abundance of lake whitefish in Lake Ontario (Hoyle et al. 1999).

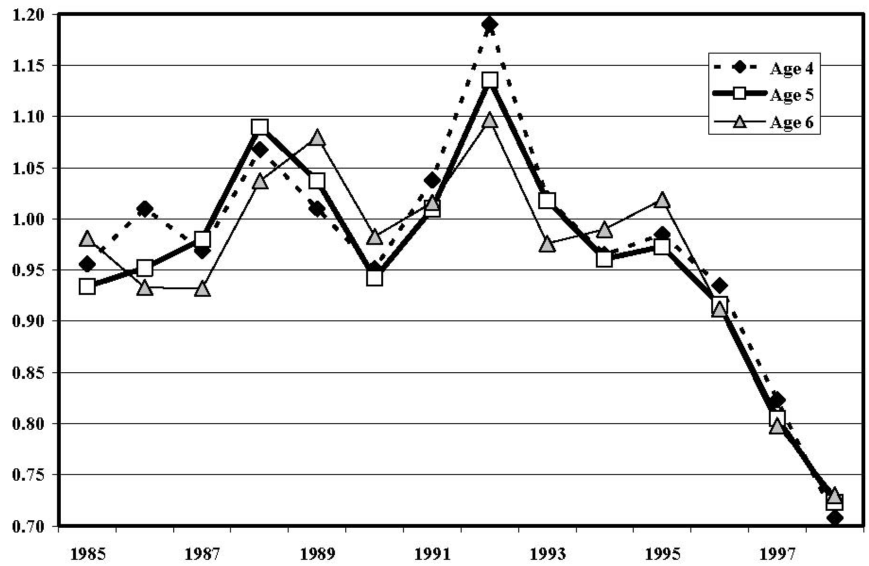

Fig. 21. Coefficients of condition (K) for lake whitefish age groups that contribute most fish to the commercial fishery in northern Lake Michigan, 1985-98.

Declines in lake whitefish growth and condition could lead to decreased fecundity and decreased egg quality, and could potentially affect year-class strength and stock stability in future years. Thus far, however, reproduction and survival have been sufficient to sustain productive fisheries even in northern management zones where total annual mortalities are very high (0.70-0.83). These high mortalities are partly offset by ice cover and spring warming conditions, which are generally favorable for overwinter survival of eggs and early growth and survival of fry (Taylor et al. 1987; Brown et al. 1993).

In general, effects of parasites and diseases on lake whitefish populations have not been quantified. Lake whitefish can be infected by *Renibacterium salmoninarum* (Rs), a bacterium that had been previously documented only in salmonines (Jonas et al. 2002). Rs can lead to BKD and cause mortality in chinook salmon, but such a progression has not been observed in lake whitefish. This observation implies that contemporary stocks retain some level of resistance to the bacterium.

Contaminants are a concern with regard to consumption of lake whitefish by humans (R. Day, Michigan Department of Environmental Quality, P.O. Box 30473, Lansing, Michigan, 48909, personal communication). Tests conducted in 1998 indicated that 18 of 30 lake whitefish collected from three Lake Michigan locations had dioxin toxic-equivalent concentrations that exceeded the Michigan Department of Community Health trigger level (10 ppt) for sport-caught fish. However, test concentrations did not exceed the Michigan Department of Agriculture trigger level (25 ppt) for commercially caught fish. As a result, a consumption advisory was issued for sport-caught lake whitefish but not for commercially caught fish. This mixed message resulted in some confusion and misunderstanding by the public in Michigan.

Recommendations

1. Determine lake whitefish bioenergetics through modeling of laboratory- and field-based data, evaluate age-specific diet and growth on a seasonal basis, and measure seasonal and age-specific caloric density of lake whitefish and their major food resources.
2. Conduct long-term monitoring of the incidence of Rs to establish trends and to determine effects on lake whitefish.
3. Identify factors affecting reproductive success, develop a reliable pre-recruit index, and collect fishery-independent data.

Round Whitefish

Commercial harvest of round whitefish has averaged 58,000 kg per year during 1883-1998 with a peak of 235,000 kg in 1899 (Fig. 22). Harvest has averaged 65,000 kg annually since 1970. Round whitefish were harvested principally by state-licensed fishermen prior to 1980 and by Native American fishermen since then. A small but growing group of recreational anglers target round whitefish, but the catch is so small that it neither affects stocks nor relates well to trends in stock abundance. Little is known about the ecology of round whitefish or the size and age structures of round whitefish populations in Lake Michigan, but they appear to be self-sustaining.

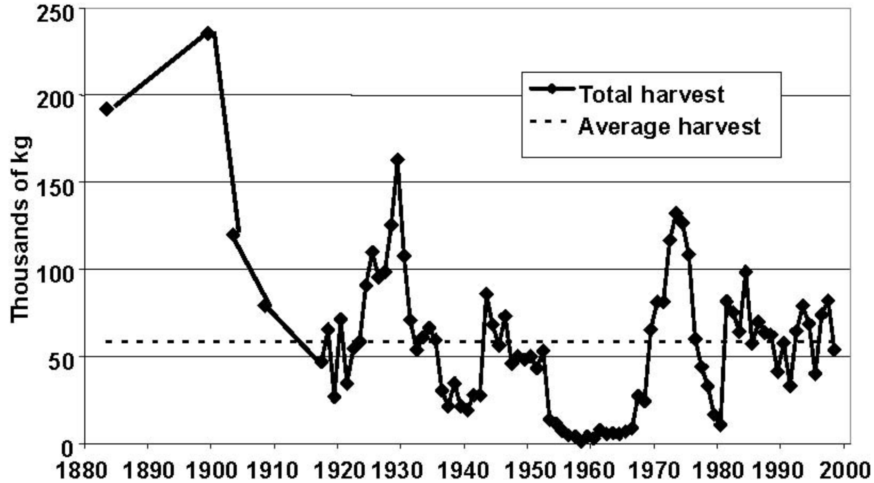

Fig. 22. Commercial harvest of round whitefish from Lake Michigan, 1883-1998. Data from Baldwin et al. (1979).

Lake Sturgeon

The lake sturgeon was abundant historically in Lake Michigan with populations spawning in many of the major tributaries and on some shoal areas. Lake sturgeon were a dominant component of the nearshore, benthivore fish community in the mid-1800s, with a population estimated at 11 million fish lakewide and at least 1 million adult fish (Hay-Chmielewski and Whelan 1997). Currently, the most optimistic estimate of the lakewide abundance is well below 1% of historical numbers.

The decline of lake sturgeon populations was rapid and commensurate with habitat destruction, degraded water quality, and intensive fishing associated with settlement and development of the region. In a span of less than 50 years, beginning in the mid-1800s, it transitioned from a nuisance species of high abundance, to a highly desired commercial species, to a depleted species of little consequence. The lake sturgeon is now considered rare, endangered, threatened, or of watch or special-concern status by the various fisheries-management agencies, and its harvest from the lake and tributary waters is banned or highly limited.

Remnant spawning populations of lake sturgeon currently persist in at least eight tributaries, although their actual abundance and reproductive success is unknown in several of these (Table 2). Lake sturgeon have been observed during spawning in other tributaries and shoal areas, but it is not known if spawning occurred. Lake sturgeon are routinely captured in commercial fishing gear in Green Bay and occasionally captured elsewhere in the lake.

Table 2. Current presence and reproductive status of lake sturgeon in Lake Michigan and tributary waters.

Location	Adult Status	Run Size	Reproduction	Data Source
Fox River	Spawning known Numbers increasing	30 (1999) 50-75 (2000)	Eggs hatch Juveniles unknown[1]	Rob Elliott, USFWS Terry Lychwick, WDNR
Oconto River	Spawning known	Not quantified (<50)	Juveniles known	Greg Kornely, WDNR John Weisser, USFWS
Peshtigo River	Spawning known	100-200 (1998-2000)	Fry produced Juveniles known	Rob Elliott, USFWS Greg Kornely, WDNR

[1]Status below the first dam. Successful reproduction is known for spawning populations located farther upstream that may contribute recruitment to these downstream populations.

Table 2 continued

Location	Adult Status	Run Size	Reproduction	Data Source
Menominee River	Spawning known	>200	Fry produced Juveniles presumed[1]	Tom Thuemler, WDNR Greg Kornely, WDNR
Escanaba River	Occasionally observed	Not quantified (few if any)	No data	Ed Baker, MDNR Nancy Auer, MTU
Manistique River	Regularly observed	Not quantified (<25)	No data	Ed Baker, MDNR Nancy Auer, MTU
Millecoquins River	Occasionally observed	<10 (1998-99)	No data	Ed Baker, MDNR
Manistee River	Spawning known	<50 (1998-2000)	Not documented but presumed successful	Doug Peterson, CMU Ed Baker, MDNR
Muskegon River	Regularly observed	Not quantified (<25)	No data	Gary Whelan, MDNR Ed Baker, MDNR
Grand River	Occasionally observed	Not quantified (small numbers)	No data	Gary Whelan, MDNR Ed Baker, MDNR
Kalamazoo River	Occasionally observed	Not quantified (small numbers)	No data	Jay Wesley, MDNR Ed Baker, MDNR

Table 2 continued

Location	Adult Status	Run Size	Reproduction	Data Source
St. Joseph River	Occasionally observed	Not quantified (small numbers)	1 juvenile observed	Jay Wesley, MDNR Ed Baker, MDNR
Wolf Lake, Ill.	Occasionally observed	None known	No data	Rich Hess, ILDNR
Ludington Shoal	Occasionally observed	<10 (1990-99)	No data	Rob Elliott, USFWS Ed Baker, MDNR

Estimates of adult lake sturgeon abundance in tributaries supporting regular spring spawning runs range from just a few fish to several hundred. At least three tributaries have runs of 25 or more adults and two have runs of 100 or more (Table 2). The largest aggregation of lake sturgeon occurs in the Menominee River, tributary to Green Bay. Abundance during summer in the lower Menominee River was estimated to be 457-1329 fish in 1991 (Thuemler 1997). Visual estimates indicate that over 100 adults have been returning to the Peshtigo River each spring, and 30-75 adults have been returning to the Fox River in recent years. Sex ratios on the spawning grounds in the Fox River have been about 1:5, female to male (RFE, unpubl. data). The length range of spawning adults in the Menominee and Peshtigo rivers was 102-165 cm (G. Kornely, Wisconsin Department of Natural Resource, 101 N. Ogden Rd., Peshtigo, Wisconsin, 54157, unpubl. data), and average lengths of males and females in the Fox River in 2000 was 150 cm and 164 cm, respectively (RFE, unpubl. data).

There are several indications that lake sturgeon are increasing in abundance in Lake Michigan. Sightings and incidental catches of fish in tributaries throughout the lake are increasing, although this could be due in part to increased interest and reporting. In rivers having established spawning runs, numbers observed increased in recent years. In some cases, this increase has been in conjunction with improved flow regimes in rivers where run-of-the-river flows at hydropower facilities have been instituted. In the Manistee River, several strong year classes have been produced in the last 12 years following establishment of run-of-the-river flows (D.L. Peterson, University of Georgia, Warnell School of Forestry Resources, Athens, GA, 30602-2152, personal communication). In the Fox River, the abundance of spawning fish increased from just a few fish (Cochran 1995) to 50-75 (RFE, unpubl. data). However, based on recaptures of tagged fish, much of this increase in the Fox River may be fish emigrating from the Lake Winnebago-Wolf River system. In the fall hook-and-line recreational fishery on the Menominee River, the number of anglers, the harvest, the harvest rates, and the average size of fish harvested from the lower-most section of the river all increased slowly over the past 16 years (T. Thuemler and G. Kornely, Wisconsin Department of Natural Resources, 101 N. Ogden Rd., Peshtigo, Wisconsin, 54157, unpubl. data).

Information from tagged fish indicates that across-lake and interbasin movement of lake sturgeon occurs. Lake sturgeon tagged in the Menominee River have been recaptured as far as 100 km away and in northern Lake Huron. A lake sturgeon tagged in southern Lake Huron has been recovered near Baileys Harbor. Tagged lake sturgeon from the Lake Winnebago system, in addition to contributing to the population in the lower Fox River, have been recaptured as far away as southern Lake Michigan, southern Lake Huron, and Lake Erie. However, several years of telemetry and the majority of tag returns indicate that most fish remain within Lake Michigan and in the general vicinity of the river where they spawn (BB, personal communication; RFE, unpubl. data).

Conclusions

Although the FCO goal for lake sturgeon (maintain self-sustaining populations) is being met, lake sturgeon abundance remains at just a small fraction of historical levels, and the species is no longer the dominant benthivore. Significant impediments to rehabilitation still exist, and some impediments such as dams and sedimentation will continue to have long-term effects. However, improvements in habitat and protection from harvest are likely reasons for the observed signs of slow recovery of some populations. Increased interest, attention, and funding should be beneficial to the recovery of this species and will involve a long-term commitment on the part of all of the Lake Michigan management agencies.

Recommendations

Several rehabilitation plans for lake sturgeon have been developed recently, and they include the Lake Sturgeon Rehabilitation Strategy for the State of Michigan (Hay-Chmielewski and Whelan 1997), Wisconsin's Lake Sturgeon Management Plan (Wisconsin Department of Natural Resources 2000), and the Draft Lake Sturgeon Plan for the Green Bay Basin. These plans identify major impediments to lake sturgeon rehabilitation and lay a framework for future management efforts and research needs. A recent Great Lakes lake sturgeon workshop, sponsored by the Great Lakes Fisheries Trust, identified the research needs for the Great Lakes with emphasis on Lake Michigan. Primary research needs for lake sturgeon identified in each of these plans and at the workshop include status assessments that provide inventories of populations, identification of habitat requirements and habitat availability for various life-history stages, the design of effective passage around artificial barriers (dams), and appropriate artificial-propagation strategies.

Several actions and initiatives are under way that will enhance lake sturgeon rehabilitation:

- Increased requirements for run-of-the-river flows at hydropower facilities
- Development of fish passage technologies that will safely pass lake sturgeon both upstream and downstream around dams and hydroelectric facilities
- Genetic analysis of remnant stocks in Lake Michigan and the Great Lakes
- Continuation of a new protocol to maximize protection of lake sturgeon during lampricide applications in rivers with known populations
- Development and refinement of culture and propagation techniques for lake sturgeon

- New harvest restrictions in Michigan and Wisconsin banning harvest throughout the lake and its tributaries, except in the Menominee River where limited harvest is allowed during an alternate-year, fall hook-and-line recreational fishery
- Ongoing population, spawning, and tagging assessments to gather basic biological information on distribution, status, and behavior

Burbot

Although abundant in the Great Lakes, burbot is not often recreationally or commercially harvested. In the sport fishery, most burbot are captured incidentally by ice anglers, and they rank low in angler preference (Quinn 2000). Large-scale commercial fisheries have not been established, perhaps because burbot are best eaten fresh; the meat becomes tough when frozen and has a rubbery texture when thawed (Becker 1983). Burbot is a freshwater member of the cod family, and many people who have tasted fresh burbot appreciate it for its lobster-like taste (Paragamian 2000). In northern Europe, burbot roe is a delicacy, and its liver is prized because of its high vitamin A and D content (Scott and Crossman 1973).

Burbot populations in Lake Michigan experienced dramatic changes in the last 50 years. Predation by sea lamprey drastically reduced burbot populations during the 1940s and 1950s. Swink and Fredericks (2000) found that mortality of small burbot due to attacks by sea lamprey was greater than that observed for small lake trout, and that larger burbot experienced mortalities similar to those of larger lake trout. However, sea lamprey control programs initiated in the 1960s resulted in the steady recovery of burbot populations. The FCO for burbot in Lake Michigan is to maintain self-sustaining stocks, and this is being achieved lakewide. However, the recent increase in burbot abundance raised concerns regarding the negative influence this may have on the fish community (e.g., increased predation on lake trout and alewife) (Eshenroder et al. 1995).

Burbot densities in Lake Michigan are high relative to other systems in the world and are increasing. The highest published densities for burbot (139 individuals per ha) are from Julian’s Reef in the southern basin in 1990 (Edsall et al. 1993; McPhail and Paragamian 2000). The bycatch of burbot in commercial fisheries in Green Bay almost quintupled during 1980-1985 (Rudstam et al. 1995). Trawl surveys conducted lakewide during 1973-1999 by the United States Geological Survey, Great Lakes Science Center, indicate that the CPE of burbot has been increasing since 1983, and that the highest burbot abundance was in 1998 (Fig. 23). A similar trend of increasing abundance was seen in bottom gillnet surveys conducted during 1984-1997 by the MDNR in the northern, eastern, and Grand Traverse Bay regions of Lake Michigan (JLJ, unpubl. data).

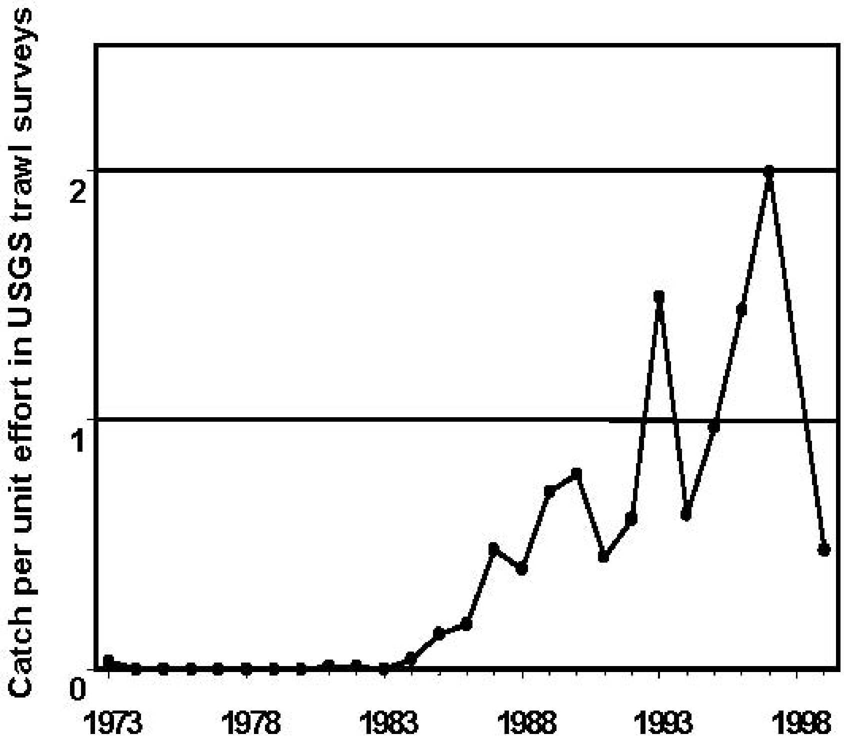

Fig. 23. CPE of burbot in Lake Michigan trawl surveys conducted by the United States Geological Survey, Great Lakes Science Center, 1973-1999.

The age structure and longevity of burbot indicates a population recovery. The majority of burbot collected during 1996 and 1997 in bottom gillnet surveys were between the ages of 9 and 16 and ranged up to age 22 (JLJ, unpubl. data).

Knowledge of burbot foraging dynamics is important for evaluating their interactions in the fish community. Diet studies were conducted in western waters in 1986-1988 by the WDNR and University of Wisconsin-Stevens Point (Fratt et al. 1997) and in eastern waters in 1996-1997 by the MDNR and Central Michigan University (Hart 2001). Burbot diets were similar in both regions, except that bloater, rainbow smelt, and yellow perch were more-prevalent food items in western Lake Michigan (Fig. 24). Alewives were important in the diet of burbot from both areas, particularly during the summer months. The burbot is an important predator in the Lake Michigan ecosystem and should be considered with other predators such as lake trout and chinook salmon.

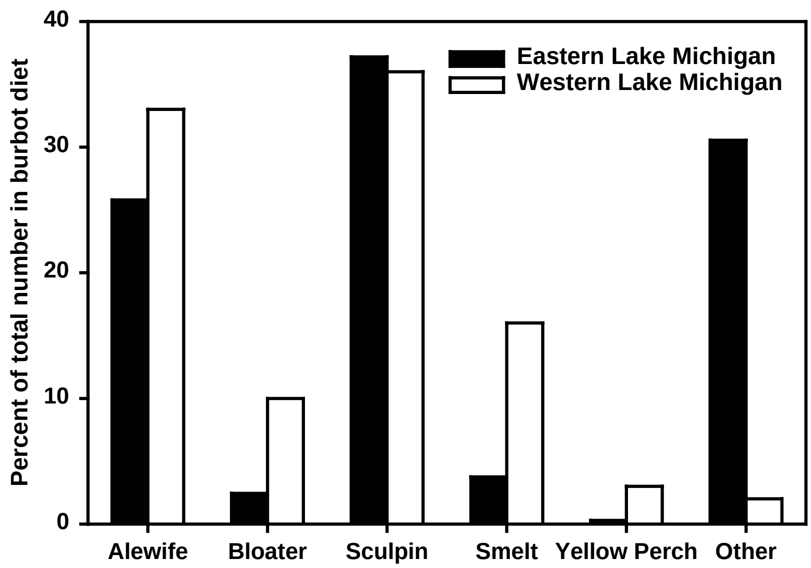

Fig. 24. Diet of burbot collected in western Lake Michigan in 1986-1988 (Fratt et al. 1997) and in eastern Lake Michigan in 1996-97 (Hart 2001).

Recommendations

1. Determine burbot consumption and its effect on the forage community and on other predators, especially lake trout.
2. Incorporate knowledge of burbot populations in lakewide modeling and management efforts.

Acknowledgments

The authors acknowledge Chuck Madenjian and Guy Fleischer (United States Geological Survey, Great Lakes Science Center) who contributed data to this report.

Sea Lamprey

Dennis S. Lavis
United States Fish and Wildlife Service
Ludington Biological Station
229 South Jebavy Drive
Ludington, Michigan, U.S.A. 49431

Control of sea lampreys made possible the socioeconomic and biological revitalization of Lake Michigan and is important to maintenance of the fish community (Fetterolf 1980; Eshenroder 1987; Holey et al. 1995). Accordingly, the sea lamprey objective is to "suppress the sea lamprey to allow the achievement of other fish-community goals" (Eshenroder et al. 1995). Treatment of tributaries with the lampricide 3-trifluoromethyl-4-nitrophenol (TFM) caused adult sea lamprey numbers to decline 80-90% by 1966. Treatment with lampricide continues to be the primary control mechanism. The introduction of integrated pest-management concepts into the sea lamprey control program (Sawyer 1980) provided the impetus to integrate alternative control methods with traditional lampricide control to further reduce populations. The Integrated Management of Sea Lamprey initiative uses all control methodologies to define the optimal sea lamprey control program to meet objectives for sea lamprey abundance. Currently, the level of sea lamprey control effort applied throughout the Great Lakes, including Lake Michigan, is based on a resource-limited, benefit/cost analysis.

The first known sea lamprey in Lake Michigan was taken in 1936 from a commercially netted lake trout near Milwaukee, Wisconsin. Sea lamprey numbers increased greatly over the next 15 years, and, by 1950, lake trout had been virtually eliminated from the lake. Sea lampreys were believed to be a major factor in the dramatic decline of lake trout, and an inventory of tributaries was initiated in the 1940s to document the extent of sea lamprey spawning. Spawning runs were confirmed in 79 streams, and initial control attempts were targeted on these populations. A mechanical weir was installed in a west-shore tributary (Hibbards Creek) in 1947 to block spawning runs, but the device was ineffective because of frequent breakdowns caused by floods. Tests in 1952 demonstrated that electric weirs were effective in blocking spawning runs, and they were installed in 65 tributaries by 1958. However, their efficiency was limited due to a variety of mechanical, physical, and biological problems. With the exception of six streams, electrical barriers were operated for only a few years; only three remained operational after 1960 to measure annual changes in the number of spawning migrants, and all were dismantled by 1966.

Chemical treatment of tributaries with TFM began in 1960, and most sea lamprey producing streams had been treated once by 1966. The resultant destruction of larval populations is reflected in the 80-90% decline in the number of adults captured at index electric weirs by 1966.

Larval Populations and Production Areas

Sea lampreys have been found in 121 of the 511 tributaries of Lake Michigan. Estimates of larval populations in individual streams and production of juvenile (metamorphosed) sea lampreys are used to compare streams. Streams are selected for treatment based on their treatment cost versus their estimated production of parasitic-phase sea lampreys. Most larvae occur in 36 tributaries, and those larvae that survive treatment in these streams are responsible for the majority of sea lampreys in the lake; treatments are 95-98% effective. Larvae escape treatment due to the presence of oxbows, backwaters, and groundwater influx where minimum lethal concentrations of lampricide are difficult to maintain. Some sea lampreys are produced from streams that are too small for cost-effective treatment with lampricide. Minor production also occurs from a few (<5) small lentic areas.

Adult Populations

From 1977 to the present, traps fished in 12-14 index tributaries have been used to measure abundance of spawning-phase sea lampreys; however, since 1986, the number of spawning-phase sea lampreys in the Manistique River has been estimated using a stratified, random mark-and-recapture technique. Prior to 1996, the traps were used only as a measure of relative abundance, but since then, total abundance of spawning-phase sea lampreys entering tributaries has been estimated. The estimate is based on the efficiency of traps in the index tributaries and is expanded to other major sea lamprey producing tributaries based on average stream discharge. The whole-lake estimate has ranged from

57,615 (1996) to 92,430 (1998). There appears to be a tread of increasing population levels since estimates were initiated in 1996 (Fig. 25).

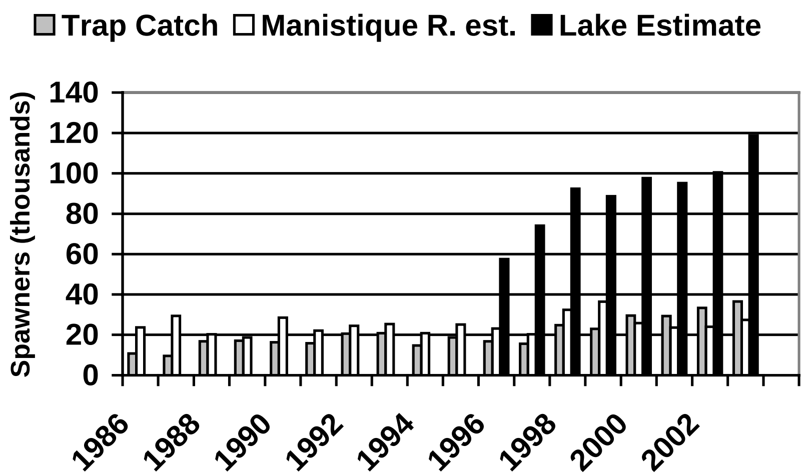

Fig. 25. Number of spawning-phase sea lampreys captured annually in assessment traps in 12-14 Lake Michigan tributaries and the estimated population of spawning-phase sea lampreys in the Manistique River and in Lake Michigan, 1986-2003.

Sea Lamprey Marking on Lake Trout

Sea lamprey wounding rates on lake trout have been low in Lake Michigan and between those in Lakes Huron (higher) and Superior (lower). The incidence of wounds on lake trout in four sections of Lake Michigan (northern Michigan, northern Wisconsin, southern Michigan/Indiana, southern Wisconsin/Illinois) has been summarized since 1971 with wounds classified and reported by type and stage (wound = Type A, Stages I-III) since 1984 (King and Edsall 1979; King 1980; Ebener 2000). In general, wounding rates in the northern jurisdictions of the lake increased since 1996, whereas rates in the southern jurisdictions remained virtually unchanged over the past 23-25 years.

Sea lamprey induced mortality can be computed from a statistical relation between the number of Type AI wounds per fish and the probability of a lake trout surviving a single sea lamprey attack (Swink and Hanson 1986; Swink 1990). The lakewide, sea lamprey induced mortality averaged less than 7% most years during 1984-1998 but increased steadily in the 1990s, especially among large lake trout in northern portions of the lake (Fig. 26).

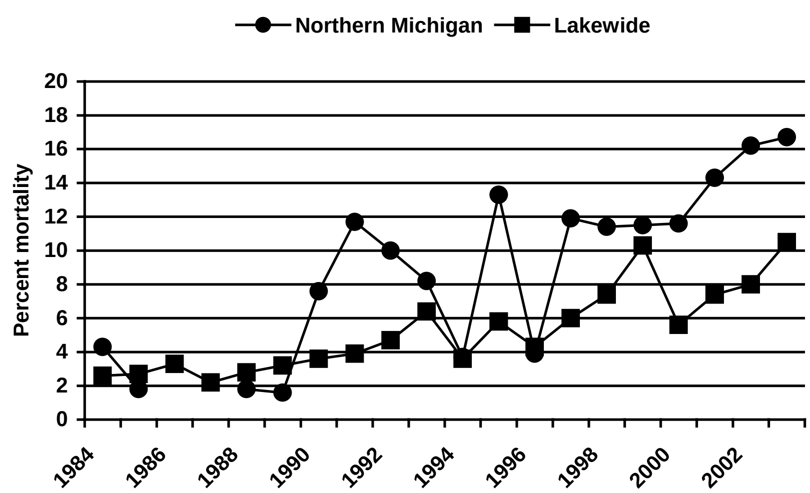

Fig. 26. Annual sea lamprey induced mortality (%) across all sizes of lake trout lakewide and in northern Lake Michigan, 1984-2003.

Control Strategies

Lampricide Treatments

During 1960-1999, 730 lampricide applications were conducted on 115 Lake Michigan tributaries. About 20% of these streams were treated only once, but some were treated up to 17 times. The average number treated annually has been reduced from 21 per year during 1970-1979 to 12 per year during 1990-1999. The reduction is due in part to sea lampreys not reestablishing in some streams following an initial lampricide treatment and to changes in the criteria used in the stream selection process. Prior to 1995, streams were selected for treatment on the basis of relative abundance of larval sea lamprey. From 1995 to present, estimates of the production of juveniles (metamorphosed larvae) allowed for selection of streams based on the cost to treat a stream and its estimated production to the lake (Gavin Christie, Great Lakes Fishery Commission, 2100 Commonwealth Blvd, Suite 100, Ann Arbor, MI, 48105, personal communication). Although the number of streams treated declined during 1970-1999, the kilometers of streams treated remained stable because the streams currently treated are among the largest and most dendritic.

The procedures used to prepare for a stream treatment and to apply TFM are little changed but use improved instrumentation and techniques. Toxicity regressions based on the pH and total alkalinity of stream water (T. Bills, United States Geological Survey, Upper Midwest Environmental Sciences Center, 2630 Fanta Reed Road, LaCrosse, WI, 54603, personal communication), flow-through toxicity testing systems (Garton 1980; Bills and Johnson 1992), and other additional procedural improvements resulted in significant savings in the amount of TFM applied annually. Compared on the basis of TFM (kg) applied per cubic meter of stream discharge, rates of application decreased from an average 310 kg/m^3 during 1960-1969 to 191.9 kg/m^3 during 1990-1999—a reduction of about 38%.

Sea Lamprey Barriers

The Great Lakes Fishery Commission (GLFC) expressed a strong commitment to reduction in TFM use through the implementation of alternative sea lamprey control strategies, including the use of barriers to block sea lamprey migration. U.S. and Canadian Sea Lamprey Barrier Coordinators were appointed in 1993 and charged with preparing a Great Lakes basin-wide sea lamprey barrier strategy and implementation plan, which was completed in 1994 and revised in 1996 and 1999. Currently, there are 12 streams with barriers specifically constructed or modified to block sea lampreys, and barrier installation is being considered for 27 others.

Sterile-Male-Release Technique (SMRT)

The release of sterilized male sea lampreys in Great Lakes tributaries is still experimental and has not seen wide-scale application to date. The technique has not been applied to any Lake Michigan tributary. However, spawning-phase sea lampreys are captured in Lake Michigan streams and used in the SMRT program elsewhere in the Great Lakes, primarily in the St. Marys River.

Fish Health

Greg Wright
Intertribal Fisheries Assessment Program
Chippewa Ottawa Resources Authority
186 East Three Mile Road
Sault Ste. Marie, Michigan, U.S.A. 49783

Dale C. Honeyfield
United States Geological Survey
Research and Development Laboratory
RR#4 Box 63
Wellsboro, Pennsylvania, U.S.A. 16901

Scott B. Brown
Environment Canada
Canadian Centre for Inland Waters
876 Lakeshore Road, Box 5050
Burlington, Ontario, Canada L7R 4A6

Fish managers have become increasingly concerned about fish health during the 1980s and 1990s. This increased focus on fish health was primarily due to the well-publicized chinook salmon die-off (epizootic) that occurred in Lake Michigan during the late 1980s. Holey et al. (1998) reported a 50% or more reduction in chinook salmon abundance due to spring die-offs caused primarily by BKD. Although the exact reasons for the spring epizootics of the late 1980s are still being debated, this mortality led to a reduction in fishing effort of more than 50% by 1995 and substantial economic loss.

Another fish-health concern, early mortality syndrome (EMS), created significant egg-hatchability problems for Lake Michigan coho salmon (Honeyfield et al. 1998b). Survival of coho salmon eggs to the first-feeding-fry stage has been poor in state fish-culture facilities since the early 1990s (Trudeau 1995). By 1995, mortality of coho salmon eggs was so high that there was not enough hatchery space to incubate the eggs required to meet production goals.

Bacterial Kidney Disease (BKD)

BKD is caused by the bacterium Rs and is a slowly progressive, systemic infection that occurs primarily in salmonids (Lasee 1995). BKD can be found all over the world affecting both cultured and wild-ranging fish (Sanders and Fryer 1980). The pathogen can be transmitted from fish to fish (Mitchum and Sherman 1981) or from adults to eggs (Bullock et al. 1978; Bullock 1980). Outbreaks of BKD are thought to be stress related (Piper et al. 1982; Lasee 1995). No adult chinook salmon in a monitored spawning run in a Wisconsin tributary tested positive for the Rs bacteria prior to 1986; however, by 1988, over 66% of the fish returning to spawn tested positive, and many fish were showing overt clinical signs of disease (Fig. 27). Rates decreased after 1988 and averaged just above 3% since 1993 with very few fish showing overt clinical signs. The slow, progressive nature of this infection is disarming, which makes it difficult to determine when the pathogen will initiate a virulent disease. Understanding the relation between the pathogen and disease should be the primary focus for fish-health experts working in the Great Lakes.

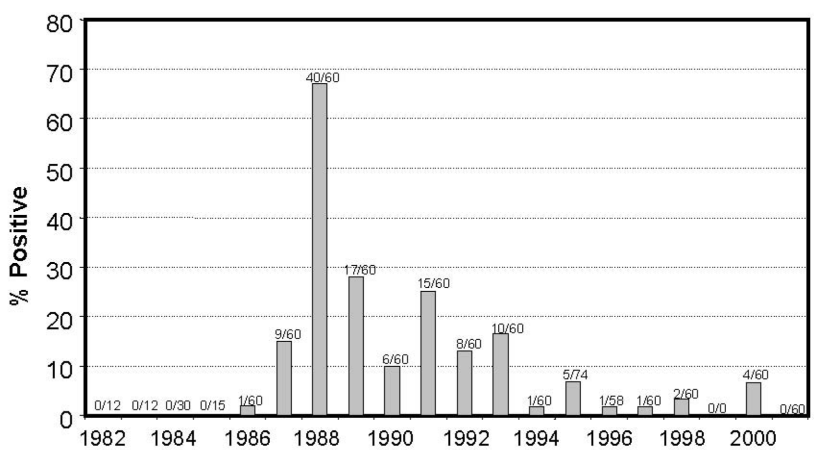

Fig. 27. Prevalence of *Renibacterium salmoninarium* in chinook salmon (number testing positive/number tested using Direct Fluorescent Antibody Technique) returning to the Strawberry Creek, Wisconsin, spawning weir in northwestern Lake Michigan, 1982-2001. Data from Holey et al. (1998) and S. Marcquenski, Wisconsin Department of Natural Resources, 101 S. Webster St. Madison, Wisconsin, 53703, personal communication.

Early Mortality Syndrome (EMS)

EMS is a non-infectious disease that results in variable mortality of the offspring of feral coho salmon, chinook salmon, lake trout, Atlantic salmon, rainbow trout, and brown trout from the Great Lakes (Marcquenski and Brown 1997; McDonald et al. 1998). Mortality may begin as early as the late eyed-egg stage and continue through the period of first feeding (Marcquenski and Brown 1997) and is variable among progeny from different female parents. The many clinical signs include loss of equilibrium, swimming in a spiral pattern, lethargy, hyper-excitability, and hemorrhage (Fisher et al. 1995; Marcquenski and Brown 1997; McDonald et al. 1998). Coho salmon mortality due to EMS ranged from 5-60% prior to 1993, and ranged from 60-90% since then (Honeyfield et al. 1998b). EMS affects coho salmon more than other salmon and trout species.

EMS symptoms in fry from feral Lake Michigan lake trout were correlated with thiamine levels of less than 1 nmol/g. The overall mortality of these fry ranged from a low of 15.6% to a high of 33.4% and averaged 21.8% during 1996-1999 (Carol C. Edsall, U.S. Geological Survey, 1451 Green Rd., Ann Arbor, Michigan, 48105, personal communication). Fitzsimons (1995) discovered that injecting sac fry with thiamine or bathing fry in a thiamine solution increased survival. Injecting fry with other B-vitamins (nicotinic acid, riboflavin, folic acid, or pyridoxine hydrochloride) did not improve survival.

Recent research shows that thiamine in alewife, the primary forage species for salmonines, is adequate to meet its thiamine requirements (Fitzsimons et al. 1998; Tillitt et al. 2002). However, alewife also contain relatively high levels of thiaminase, an enzyme known to destroy thiamine (Deutsch and Hasler 1943; Evans 1975; Greig and Gnaedinger 1971; Ji and Adelman 1998). Thiamine concentrations in alewife from Lake Michigan differed with respect to location in the lake and season (range 4-13 nmol/g) (Tillitt et al. 2002). Alewife collected in the southern part of the lake contained about half the thiamine as those from northern areas. Rainbow smelt contained low thiamine concentrations (1-2 nmol/g) that marginally exceeded levels recommended for salmonid growth. Zajicek et al. (2004) reported that the amount of thiamine-degrading activity in alewife and rainbow smelt was up to a hundred times the activity observed in the (native) bloater (alewife, 6.6 nmol/g; rainbow smelt, 2.6 nmol/g; bloater, 0.02 nmol/g). Honeyfield et al. (1999) reported isolating from alewife viscera two microbial strains of thiaminase-positive bacteria, *Bacillus thiamineolyticus* and an un-named *Bacillus* species, which suggest that these bacteria are a possible source of thiaminase.

Stress

Lake Michigan fish can be separated into two groups regarding their exposure to stress and to their subsequent health status. The first group is native species that had thousands of years to make adaptations necessary for persisting in Lake Michigan. The second group is exotic species that have not benefited from a lengthy natural selection process in the lake, and, consequently, may experience prolonged stress. If the stress is too severe or lasts too long, stress-mediated diseases may progress to detectable, harmful levels. This situation is what has occurred in Lake Michigan, where both the key predator (chinook salmon) and prey (alewife) are exotic and experience periodic stress-related die-offs.

For some exotic species, the winter water temperature of Lake Michigan appears to be very stressful. The stress that results from the temperature regime can be illustrated by comparing the different strategies used by native and exotic species to budget energy reserves. In general, dietary fats or lipids comprise the fish's primary energy supply or reserves (National Research Council 1993). Certain fatty acids are essential for health, growth, and normal appearance (Castell et al. 1972). Recent evidence suggests that exotic fish in Lake Michigan such as alewife and coho salmon undergo pronounced seasonal and inter-annual changes in lipid content, in contrast to native species such as lake trout and bloater (Madenjian et al. 2000). Madenjian et al. (2000) reported large declines in total lipid levels in Lake Michigan coho salmon between fall and spring during their second winter. Spring lipid levels averaged 1.9% wet body weight, not far above the minimum levels reported for survival for other species (Adams 2000). Alewife, the primary prey for both coho and chinook salmon, also undergo pronounced seasonal changes in lipid content in Lake Michigan (Flath and Diana 1985; Madenjian et al. 2000), in contrast to the native bloater. Chinook salmon may respond similarly to coho salmon, experiencing declines in lipid levels over winter. These declines in lipids indicate fish trying to reestablish a normal metabolism or overcome stress. Many diseases develop and spread because the fish can no longer manage stress. Lake Michigan will be stressful for those exotic species that evolved in warmer environments. Therefore, as long as exotic species are the primary forage and predator species, managing Lake Michigan fisheries will continue to be challenging.

Physical and Chemical Habitat Remediation

Mark E. Holey
United States Fish and Wildlife Service
Green Bay Fishery Resources Office
2661 Scott Tower Drive
New Franken, Wisconsin, U.S.A. 54229-9565

This chapter of the state-of-the-lake report presents recent information and sources of information on the remediation of the physical and chemical habitat of Lake Michigan. The material presented is a brief summary of some of the remediation activities beneficial to the fisheries and to achieving fish-community objectives.

Environmental Objectives and the Great Lakes Water Quality Agreement

A specific objective of the GLWQA of 1978 (amended in 1987) states that the federal governments of Canada and the United States shall work in cooperation with state and provincial governments to identify and work toward the elimination of AOCs, critical pollutants, and the zones affected by point-source pollution (IJC 1988). An Area of Concern is a geographic area where failure to meet the objectives of the GLWQA has "caused or is likely to cause impairment of the beneficial use or of the area's ability to support aquatic life" (International Joint Commission 1988). Beneficial use is defined as impaired if a change in the integrity of the Great Lakes system is sufficient to cause any of the following restrictions on fish and wildlife consumption: tainting of fish and wildlife flavor; degradation of fish and wildlife populations; fish tumors and other deformities; bird or animal deformities or reproduction problems; degradation of benthos; restrictions on dredging activities; eutrophication or undesirable algae; restrictions on drinking water consumption or taste and odor problems; beach closings; degradation of aesthetics; added costs to agriculture or industry; degradation of phytoplankton and zooplankton populations; and loss of fish and wildlife habitat.

Ten AOCs are within the Lake Michigan drainage (Table 3). Only in the Grand Calumet River in Indiana is the habitat so degraded that all 14 beneficial uses have been identified as impaired (Lake Michigan Technical Coordinating Committee 2000). Most of the remediation activities completed in Lake Michigan AOCs have been the removal of contaminated sediments, primarily those with PCBs. Extensive sediment removal projects have been completed on the lower Fox River, Sheboygan River, Waukegan Harbor, Grand Calumet River, Kalamazoo River, and Manistique River. A total of 453,600 kg of PCBs was removed from Waukegan Harbor, and sediments containing PCB concentrations in excess of 300 ppm were removed from the Sheboygan and lower Fox River. In addition, RAPs resulted in the removal of the first barrier to the lake on the Milwaukee River (North Avenue Dam) and in the stocking of Great Lakes muskellunge in Green Bay (BB, personal communication 1997). A more-detailed description of completed remediation activities for each AOC can be found at http://www.epa.gov/glnpo/aoc/.

Table 3. Lake Michigan Areas of Concern and the number of beneficial-use impairments per site (http://www.epa.gov/glnpo/aoc/).*

Area of Concern	Location	Impairments per site
Wisconsin	Lower Green Bay and Fox River	10
	Sheboygan River	8
	Milwaukee Estuary	11
Illinois	Waukegan Harbor	5
Indiana	Grand Calumet River	14
Michigan	Kalamazoo River	8
	White Lake	8
	Muskegan Lake	5
	Manistique River	5
	Menominee River	7

Designation of AOCs and the development of RAPs is the process that the GLWQA created to identify impaired beneficial uses and how to remediate the impairment. The Superfund and the Natural Resources Damage Assessment (NRDA) provisions of the Comprehensive Environmental Response, Compensation and Liabilities Act of 1980 are two tools available to water-quality and fishery agencies to achieve goals identified for a given AOC. The Superfund addresses primarily human health issues and resulted in the removal of contaminated sediments. The NRDA provisions address fish and wildlife injuries and can result in additional removal of a contaminated source or the implementation of restoration activities that can benefit a fish community.

To further the achievement of environmental objectives, the GLWQA required the governments to develop LaMPs to reduce the loadings of critical pollutants (International Joint Commission 1988). The Lake Michigan LaMP (www.epa.gov/glnpo/lakemich/) was expanded to embrace an ecosystem approach, which now addresses all biological, chemical, and physical stressors that limit the sustainability of the Lake Michigan ecosystem (Lake Michigan Technical Coordinating Committee 2000). To address the complexity of environmental stressors in Lake Michigan, the LaMP provides a structure for environmental and resource management agencies to collaborate and focus their efforts on the most important problems. The Lake Michigan LaMP identifies environmental goals and objectives, key ecosystem-health indicators, the current status of the Lake Michigan ecosystem and use impairments, and a summary of proposed actions to achieve the objectives (Lake Michigan Technical Coordinating Committee 2000).

Achieving the FCOs for Lake Michigan will require a healthy aquatic environment, which, in turn, will require the successful implementation of the GLWQA. Input by fishery agencies into the development of the tools to achieve environmental objectives will be critical. The ecosystem approach can then be used effectively to achieve the fish-community goals for Lake Michigan.

Decline of PCB Concentrations in Salmonines

Concentrations of PCBs declined substantially in Lake Michigan salmonines since the 1970s when the production of PCBs was banned (Devault et al. 1996; Lamon et al. 1998). Mean PCB concentrations in brown trout, rainbow trout, lake trout, coho salmon, and chinook salmon have been below the U.S. Food and Drug Administration’s tolerance level of 2 ppm since the mid-1990s (Lamon et al. 1998). Using a dynamic linear modeling approach, Lamon et al. (1998) predicted a continued steady decline in PCB concentrations for brown trout, rainbow trout, coho salmon, and chinook salmon, and possible constant levels for lake trout.

PCBs no longer directly affect the ability of lake trout and, likely, other salmonines to produce viable eggs. When both PCB and thiamine concentrations were measured from the same lake trout eggs collected from Lake Michigan from 1996-1998, only thiamine concentrations were correlated with swim-up mortality (Stratus Consulting Inc. 1999). Fitzsimons (1995) also concluded that early mortality was not solely related to the contaminants measured in eggs or larvae. Lake trout embryos from Lake Michigan still have elevated mortalities associated with low egg-thiamine concentrations, and the mechanism or pathway for the lowered thiamine concentrations remains unknown (Honeyfield et al. 1998a; Stratus Consulting Inc. 1999).

Flow Management through Hydropower Dams

The water-flow regime through dams can significantly affect fishery habitat below dams (Hayes 1999). Flow regimes during peaking operations often result in large daily fluctuations in water flow below dams that dewater stream channels and negatively affect fish populations. Flow management that requires a run-of-the-river (i.e., flows below a dam have the same flow pattern as above the dam) operation often results in more-favorable habitat below the dam.

The benefit of run-of-the-river flow management for salmon spawning and nursery habitat is illustrated by the number of chinook salmon smolts produced in two Michigan tributaries. Run-of-the-river flow management was implemented in the early 1990s at the Tippy Dam on the Manistee River and the Croaten Dam on the Muskegon River. Estimated production of chinook salmon smolts increased from 100,000 in the Manistee River and 350,000 in the Muskegon River in the late 1970s (Carl 1982) to 400,000 and 1.0-1.2 million, respectively, under the new flow management (Ed Rutherford, School of Natural Resources and Environment, University of Michigan, 430 E. University, Ann Arbor, Michigan, 48109, personal communication), a fourfold increase. The production of smolts from Lake Michigan tributaries will likely continue to increase as more dams come under run-of-the-river flow management.

Open Forum

Mark E. Holey
United States Fish and Wildlife Service
Green Bay Fishery Resources Office
2661 Scott Tower Drive
New Franken, Wisconsin, U.S.A. 54229-9565

Thomas N. Trudeau
Illinois Department of Natural Resources
9511 Harrison St.
Des Plaines, Illinois, U.S.A. 60016

The Lake Michigan Committee scheduled time for questions and comments at an open forum following the oral presentation of this State-of-the-Lake Report at its March 2000 meeting in Ann Arbor, Michigan. The presenters of oral reports and the members of the committee served as a panel to which Gavin Christie of the Great Lakes Fishery Commission directed questions and comments from an audience consisting mostly of persons from resource agencies and universities and representatives of sport- and commercial-fishing groups. This exchange was recorded, and an abbreviated summary of the highlights is provided here in a question and answer format.

"Should the alewife be considered a pest species in Lake Michigan?"

Describing the alewife as a pest implies that it has attributes that do not enhance the Lake Michigan fish community. Native fishes do tend to fare better during periods of low alewife abundance than during high alewife abundance. A hypothesized mechanism for a negative association between native species and alewife is predation, especially on early life stages of yellow perch, lake trout, and bloater. With the discovery of EMS, we now know that a diet predominately of alewife will reduce the hatching success of eggs from all of the species of trout and salmon in Lake Michigan. Moreover, alewives eat larger zooplankters than do native forage fishes, and this trait reduces grazing efficiency on algae, causing increases in phytoplankton standing crops and decreases in water quality. If alewives come to be considered a pest that should be removed from the lake, the alternatives to alewives need to be considered, because alewives occupy an important niche in the lake's food web. The native species that previously filled this niche were lake herring and deepwater ciscoes.

"If alewives are evil, and the primary control is chinook salmon, are chinook salmon good?"

Few doubt that the chinook salmon played a major role in restoring a more-healthy balance between predators and prey fishes, and this outcome led to increased integrity of the lake's fish community. The pronounced naturalization of chinook salmon is very positive in terms of system health, but the sustainability of chinook salmon remains a concern, especially in view of the spectacular die-off of the species in the late 1980s. Chinook salmon apparently suffers increased mortality during periods of low alewife abundance. Although the chinook salmon, among all of the species of trout and salmon in the lake, is the most efficient predator of alewife, it also appears to be less capable of switching to an alternative prey species when alewives are scarce. This dilemma poses a tough management question for the LMC: what population levels of alewife and chinook salmon should managers seek to achieve? Answering this question will require considerable input from the public, especially from those who fish the lake, regarding their views on a desired fish community.

"Has the relative importance of the species sought by sport fishermen changed?"

Based on the state-of-the-lake presentations to the LMC, more anglers pursued yellow perch than chinook salmon, suggesting a shift in the socioeconomic values of these two species. The economic value of the offshore trout and salmon fishery, however, still exceeds the value of the yellow perch fishery, which operates inshore, even though yellow perch anglers outnumber those fishing for trout and salmon, and the catch in numbers of yellow perch exceeds that of salmon and trout. Nevertheless, the trend since the 1970s has been a shift away from trout and salmon with more emphasis on other fishes.

"Should we be reintroducing non-sport fish, especially a species like lake herring, into the lake?"

The cultural practices for rearing lake herring and other coregonines have not been developed to the level of reliability achieved with trout and salmon. Although lake herring was the native species that occupied the niche now filled by the alewife, the cost to replace a whole trophic level, especially a lower trophic level, in a reasonable amount of time may be prohibitive.

"Is there a plan to restore lake trout in Lake Michigan?"

The current rehabilitation plan for lake trout in Lake Michigan was created in 1985 and is need of revision. The LMC and the Lake Michigan Technical Committee are engaged now in the revision of this plan right now.

"What is impeding rehabilitation of lake trout, and what can be done about it?"

Pulse stocking is being advocated as one way to increase the population of lake trout in a given area with the idea that low spawning populations are a major impediment to rehabilitation. Pulse stocking involves putting all, or almost all, of the available planting stock, say for 1-2 years, in only one area of the lake. Pulse stocking may be the only way to reach historical natural-recruitment levels, which may have been as high as 10 million yearlings—currently only 2.1 million yearlings are planted each year. Pulse stocking was not used as a rehabilitation strategy in Lake Superior, but Lake Superior had fewer stressors on its fish community than Lake Michigan has now. The quantity and quality of habitat is higher than Lake Superior, and residual populations of lean, humper, and siscowet lake trout persisted there. The Lake Superior ecosystem as a whole has been less disrupted than has the Lake Michigan ecosystem. In Lake Superior, the density of adult lake trout of hatchery origin was actually higher during the late 1960s and early 1970s, when natural reproduction surged upwards, than in the decades just before the native populations collapsed. Even in less-disrupted Lake Superior, overcoming a reproductive bottleneck required a very-high spawning biomass of mostly hatchery-reared lake trout. In Lake Michigan, lake trout also need to be abundant enough to overcome added impediments like EMS. The situation in Lake Michigan will probably not turn around until a larger population of lake trout that can respond to more-favorable environmental conditions is established. If such conditions do occur and lake trout do respond, lake trout will likely take over and drive the system as has occurred in Lake Superior.

"Why is so much attention focused on stocking more fish and not on identifying and addressing the bottlenecks that may be limiting natural reproduction?"

Other potential bottlenecks cannot be addressed until the low-population-level bottleneck is overcome first, because large-scale reproduction cannot be achieved with the paltry number of adult fish now surviving to a reproductive age. Bottlenecks or gaps in assessment data, not only for lake trout but also for yellow perch, lake sturgeon and other species, do need to be identified.

"Would the economics of the hatchery-based fishery in Lake Michigan weaken the political will to focus on sustainability and the flexibility needed to remain committed to achieving lake trout rehabilitation?"

Economic pressures to maintain a particular fishery can be so great that fish managers have little leeway to attempt other strategies.

"Is the information available on phosphorus levels and inputs adequate?"

Both the IJC and the GLFC recommended continuation of the phosphorus-loading trend data, especially for Lake Erie, and the same recommendation could be made for Lake Michigan. In Lake Ontario, trend data for phosphorus and lower trophic levels were crucial in enabling biologists to understand how increasing pressure at the top of the food web and the diminishing productivity at the bottom were creating an unsustainable food web.

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