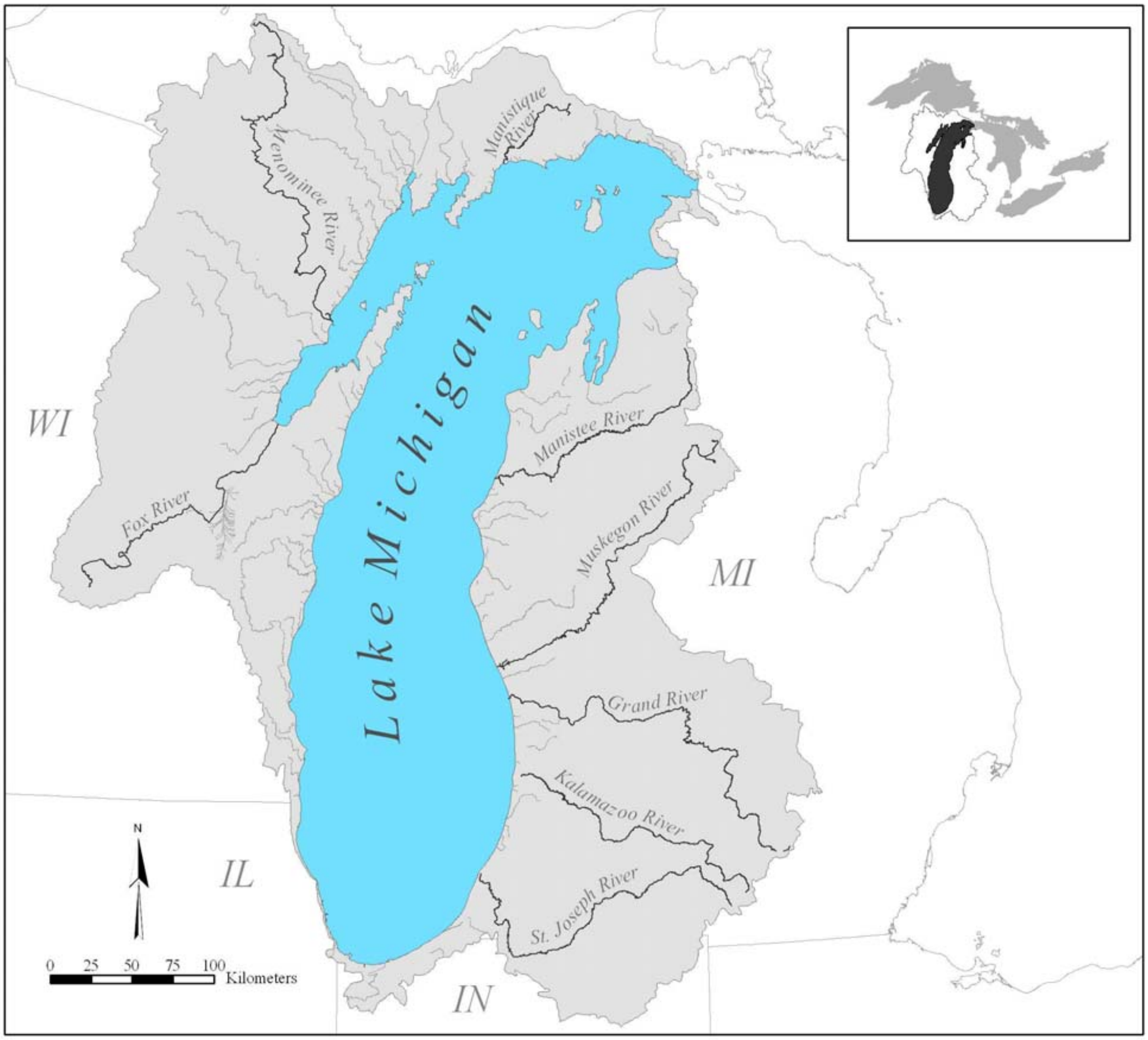
LAKE MICHIGAN ENVIRONMENTAL OBJECTIVES



Edward Rutherford	University of Michigan
Emily Marshall	University of Michigan
David Clapp	Michigan Department of Natural Resources
William Horns	Wisconsin Department of Natural Resources
Tom Gorenflo	Chippewa/Ottawa Resource Authority
Tom Trudeau	Illinois Department of Natural Resources

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Introduction

The Lake Michigan Environmental Objectives (EOs) were developed to serve as a critical component of an ecosystem approach to fisheries management, where the biological, chemical and physical needs of desired fish communities are addressed for effective strategic plan development in support of the Fish Community Objectives (FCOs). The Joint Strategic Plan for Management of Great Lakes Fisheries (SGLFMP), proposed by the Great Lakes Fishery Commission (GLFC 1980), called for the development of FCOs for each of the Great Lakes. In addition, the Lake Committees were asked to identify and clearly articulate environmental issues which may impede achievement of the FCOs. The consideration of an ecosystem approach that recognizes the critical link between fish community structure and its living environment was further emphasized in the Strategic Vision of the Great Lakes Fishery Commission for the First Decade of the New Millennium (GLFC 2001). The following vision statement was formulated on healthy aquatic ecosystems:

> *"The commission shall encourage the rehabilitation and conservation of healthy aquatic ecosystems in the Great Lakes that provide sustainable benefits to society, contain predominantly self-regulating fish communities, and support fisheries with increasing contributions of naturally reproducing fish. Conserving biological diversity through rehabilitation of native fish populations, species, communities, and their habitats has a high priority."*

The Lake Michigan FCOs, completed in 1995, included a broad-scoping habitat objective that dealt primarily with protection, rehabilitation and enhancement of fish habitats. The intent in developing Lake Michigan EOs was to provide guidance to fisheries management agencies as well as non-government organizations regarding specific actions that could create environmental conditions necessary for the achievement of FCOs. In order for the EOs to be practical and relevant, they need to address issues of concern at various spatial scales and timeframes. The level of detail that individual EOs provide reflects a balance between time constraints and providing enough detail that reveals multiple options and therefore flexibility in addressing issues of concern. The Lake Michigan EOs document is a living document; as such it will require periodic reviews and revisions to maintain its relevancy.

For the EOs to be relevant at different scales and practical for fisheries managers they must be consistent with the following properties:

- Address current and emerging ecosystem issues (nutrient inputs and productivity declines, stocking and forage base dynamics, changes in food web structure, etc.)
- Identify critical habitats and their attributes
- Where possible be quantifiable
- Reconcile habitat impairment issues
- Maintain biodiversity

Habitat objectives also have been developed by habitat sub-committees and incorporated to Lake Management Plans (LaMPs) for each lake. However, many managers were discouraged by the lack of immediacy of LaMPs to fisheries, and by the complexity of habitat issues facing Lake Michigan as habitat issues quickly expanded beyond reasonable resolution.

The development of Lake Michigan EOs has benefited from a number of completed or ongoing initiatives that are focused on various aspects of aquatic resource management and research. These initiatives in many cases provided supporting documentation and were compatible with efforts aimed at understanding ecosystem function and change as it relates to fish community structure. These initiatives include:

- The Lake Michigan Mass Balance Project identified sources, sinks and pathways of contaminants into the Lake Michigan ecosystem.
- The EPA's LaMP program for Lake Michigan.
- The Great Lakes GIS project provides data integration and basin wide inventory of aquatic resource information.
- The State of Lake Michigan Symposia.
- SOLEC development and assessment of indicators and identification of management challenges and actions.
- Development of Lake Huron EOs and the Lake Huron GIS.
- The Great Lakes Commission GIS efforts for the Great Lakes Basin.

The Environmental Objectives for Lake Michigan identify environmental issues and their impacts on fish species and life history stages, summarize current and historic information, and identify priorities and possible future directions required to ensure achievement of FCOs. The area covered by the Lake Michigan EOs includes waters west of the Mackinac Bridge down to the Illinois-Indiana shoreline, including Green Bay. Also included are all watersheds draining into the main basin and Green Bay, and shoreline areas affected by lake hydrology or affecting nutrient loading and sedimentation. The Great Lakes GIS Project can assist in the mapping and identification of critical habitats and issue areas.

Lake Michigan Fish Community Objectives

Salmonine Objective

Establish a diverse salmonine community capable of sustaining an annual harvest of 2.7 to 6.8 million kg (6 to 15 million lbs), of which 20-25% is lake trout.

Establish self-sustaining lake trout populations.

Planktivore Objective

Maintain a diversity of planktivore (prey) species at population levels matched to primary production and to predator demands. Expectations are for a lake wide planktivore biomass of 0.5 to 0.8 billion kg (1.2 to 1.7 billion lbs).

Inshore Fish Objective

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 (2 to 4 million lbs) for yellow perch and 0.1-0.2 million kg (0.2 to 0.4 million lbs) for walleye.

Benthivore Objective

Maintain self-sustaining stocks of lake whitefish, round whitefish, sturgeon, suckers, and burbot. The expected annual yield of lake whitefish should be 1.8-2.7 million kg (4 to 6 million lb).

Sea Lamprey Objective

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

Other Species Objective

Protect and sustain a diverse community of native fishes, including other species not specifically mentioned earlier (for example, cyprinids, gars, bowfin, (Coaster and stream-resident brook trout, and sculpins). These species contribute to the biological integrity of the fish community and should be recognized and protected for their ecological significance and cultural and economic values.

Physical/Chemical Habitat Objectives

Protect and enhance fish habitat and rehabilitate degraded habitats.

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.

Environmental Objective #1-
Protect and restore connectivity and quality tributary spawning and nursery habitats

Relevant Fish Community Objectives

Fish Community Objectives	Importance of Environmental Objective
• Salmonine Objective *Establish a diverse salmonine community capable of sustaining an annual harvest of 2.7 to 6.8 million kg (6 to 15 million lbs), of which 20-25% is lake trout.*	Rainbow trout, brown trout, Coaster brook trout, chinook salmon, coho salmon, and Atlantic salmon are dependent upon access to rivers and streams for spawning and nursery habitats. The most productive watersheds for salmonines are located along the east central shore of Lake Michigan, in coldwater streams with stable flows of low to moderate gradient.
• Planktivore Objective *Maintain a diversity of planktivore (prey) species at population levels matched to primary production and to predator demands. Expectations are for a lake wide planktivore biomass of 0.5 to 0.8 billion kg (1.2 to 1.7 billion lbs).*	Both native cyprinids and non-native forage fishes use river and stream spawning and nursery habitats.
• Inshore Species Objective *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 (2 to 4 million lbs) for yellow perch and 0.1-0.2 million kg (0.2 to 0.4 million lbs) for walleye.*	Naturally producing walleye populations in the Lake Michigan basin are dependent upon access to spawning habitats found in rivers and streams. Pike use off-channel marsh habitats for spawning and rearing, and smallmouth bass use river habitats along with nearshore habitats for spawning and early development.
• Other Species Objective *Protect and sustain a diverse community of native fishes, including other species not specifically mentioned earlier (for example, cyprinids, gars, bowfin, Coaster and stream-resident brook trout, and sculpins). These species contribute to the biological integrity of the fish community and should be recognized and protected for their ecological significance and cultural and economic values.*	Many native fishes such as brook trout and some cyprinids use tributary and creek habitats as spawning and early rearing habitats.

• Benthivore Objective *Maintain self-sustaining stocks of lake whitefish, round whitefish, sturgeon, suckers, and burbot. The expected annual yield of lake whitefish should be 1.8-2.7 million kg (4 to 6 million lb).*	Lake sturgeon depend upon access to spawning habitat in larger rivers that drain into Lake Michigan. Significant rivers with remnant populations include the Millecoquins, Menominee, Peshtigo, Oconto, Muskegon, St. Joseph, Grand, Manistee, Kalamazoo, and Fox Rivers. Suckers are a major component of fish communities in many Lake Michigan tributaries, and spawn and rear in lower reaches of rivers.
• Sea Lamprey Objective *Suppress the sea lamprey to allow the achievement of other fish-community objectives.*	Sea lamprey utilize rivers and streams of all sizes for spawning and nursery habitat where possible. Sea lamprey control barriers need to be selective, allowing passage of other fish species.
• Physical/Chemical Habitat Objective *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.* *Protect and enhance fish habitat and rehabilitate degraded habitats.*	Tributary habitats in the Lake Michigan basin have been significantly degraded in the past two centuries. Dams restrict access to upstream habitats, and alter natural flow and temperature regimes. Land-use changes also have altered flow regimes. Non-point pollution and sedimentation have degraded the remaining available habitats.

Background

Accessible tributary habitats are critical to the production of many Great Lake fishes. However, barriers to fish migration have reduced nearly 30,000 km of available stream habitat to only 5,311 km (Marshall, University of Michigan, unpublished data). With a drainage area of approximately 118,000 km^2, the Lake Michigan basin has a number of large and small river systems that could provide additional suitable habitat to Great Lake spawners. The remaining accessible tributary habitats need to be maintained and protected, and efforts to increase accessibility should be pursued to provide essential tributary habitat to the Lake Michigan fishery.

Lake Michigan has large populations of adfluvial and potamodromous fishes that depend on spawning habitat in its connecting tributaries. Historically, these species included lake trout *Salvelinus namaycush,* lake herring *Coregonus artedii*, lake whitefish *Coregonus clupeaformis,* all salmonines, white sucker *Catostomus commersonii*, longnose sucker *Catostomus catostomus*, redhorse sucker *Moxostoma sp*., lake sturgeon *Acipenser fulvescens*, burbot *Lota lota*, and walleye *Sander vitreus*. The warmer temperatures and increased productivity in streams influence the growth and production of juvenile fish. Stream temperatures warm and trigger spawning earlier than in the lake and permit a longer growing season for fish (Mansfield 1984). The higher stream temperatures also impact rates of metabolism and foraging activity, which may allow greater first-winter survival (Christie and Regier 1973, Hinz and Wiley 1997). Invertebrates benefit from the higher productivity of tributaries that receive allochthonous inputs from large terrestrial areas (Mansfield 1984). An estimated one-third of all Great Lake fishes use tributaries as their principal spawning and nursery habitats (Lane et al. 1996). Therefore, protecting and restoring connectivity to quality tributary spawning and nursery habitats is of great importance.

Issues

Most tributaries in the Lake Michigan basin have been significantly impaired through damming, channelization, sedimentation, dredging, eutrophication, and toxic contamination (U.S. EPA 2002). These impairments have altered the hydrologic regime and compromised the flow stability. As a result, the suitability of these tributaries as spawning and nursery habitats has been compromised.

The most pervasive threats to adfluvial fishes in the Great Lake basin are barriers which prevent migration. Current and future availability of quality stream habitat may be limited by barriers. Nearly every stream draining into the Lake Michigan basin has been dammed, and all of Lake Michigan's large tributaries (mean annual discharge over 1,000 cfs) are impounded. Dams cause several physical and ecological impairments to natural river systems. Dams interrupt the natural physical processes of a river by altering the flow of water, sediment, nutrients, energy and biota (Ligon et al. 1995).

The influences of dams on ecological processes include temperature changes, prevention of fish migration, and altered flow regimes which all affect the survival and integrity of fish communities (Woldt and Rutherford 2002, Mistak 2001). Increased summer temperatures from dam outflow can limit the production of fishes below the dam (Woldt and Rutherford, 2002, Horne et al. 2004). Additionally, impoundments formed behind dams replace reaches of flowing water and eliminate river habitat with suitable gradient and substrate for spawning (Creque 2002). These impoundments bury high-gradient habitat, limiting the amount of available habitat to some species and completely eliminating spawning habitat for other species such as lake sturgeon. Finally, hydroelectric dams and lake-level control structures can cause substantial alterations to daily flow regime and impose alterations on the river and its fish community (Cushman 1985). Flow stability is important to the suitability of stream habitat for many Great Lake spawners such as walleye, brook trout, brown trout, and Chinook salmon (Casado et al. 1989; Rozich 1998). The fluctuations in flows created by peaking hydropower operations can destabilize banks, create large bedloads, strand organisms, and disrupt habitat, thus reducing aquatic production and diversity (Abbott and Morgan 1975; Anderson and Nehring 1985; Cushman 1985; Camargo and DeJalon 1990).

Other physical alterations that degrade riverine habitats result from various land use activities and changes. Timber harvest, agriculture, urban development and mining are among the most harmful activities. Removal of large woody debris through extensive logging decreases available benthic invertebrate habitat and reduces cover for resident fish (Maser and Sedell 1994). Saw dust waste is a consequence from the timber industry that still creates a problem in some streams. Large amounts of sawdust create high biological oxygen demand forcing fish to leave that habitat because of the absence of benthic prey and low oxygen levels (Saunders 1981). Furthermore, the conversion of old growth forests to agriculture and urbanized land alters flow patterns by decreasing infiltration and in-basin storage which result in increased erosion and non-point pollution (Hay-Chmielewski and Whelan 1997). Encroachment of agriculture and urbanization on riparian buffers around streams can affect stream water quality. Vegetated riparian buffers are important for maintaining stream temperatures and bank stability. The above land uses all create water quality problems from excessive inflows of fine sediment, sand and heavy metals. These inputs create disturbances on critical spawning substrate and sediment transport.

Agricultural and urban land uses also impose greater demands for groundwater withdrawals. Water withdrawals reduce summer base flows and negatively affect river systems (Fulcher et al. 1986). Groundwater discharge to streams provides important habitat for aquatic organisms such as stable, cool water temperatures and small amounts of nutrients, and increased concentrations of dissolved oxygen (Grannemann et. al. 2000). Lake Michigan has more sand and gravel aquifers near the shore than any of the other Great Lakes, thus has the greatest amount of direct groundwater discharge of 2,700 cfs (Grannemann et. al. 2000). Irrigation is the largest consumptive use of water in the Great Lakes watershed, and groundwater sources contribute about half of the water used for irrigation. Irrigation of agricultural fields lowers flow stability, decreases water flows in stream beds, and saturates soils which increase overland flows leading to peak flows in streams. In the urban setting, industrial withdrawals for production, cooling, and bottling as well as domestic withdrawals and diversions for drinking water have the potential to place significant strain on Lake Michigan streams and rivers.

Significant tributary habitats

A Geographic Information System (GIS) is a useful tool for identifying significant tributary habitats. Two GIS layers, the National Hydrography Database (NHD) stream line work and the Lake Michigan Basin dam database, were used to assess the amount of accessible stream available to adfluvial and potamodromous fishes (Table 1). The quantity of available habitat was estimated by calculating the length of the stream network below the first dam on major river systems of Lake Michigan. These estimates include all small tributaries and connecting channels that are open to Lake Michigan. The length upstream of the first dam provides an estimate of how much habitat would become available to Great Lakes spawners with the removal of the first dam.

Table 1. Mean annual discharge from USGS stream gauges, length of accessible stream habitat below the first dam, length of upstream habitat between the first and second dam on the main stem of the river, and total length of inaccessible stream habitat above the first dam of major river systems in the Lake Michigan basin (Emily Marshall, University of Michigan, unpublished data).

River system	Mean annual discharge (cms)	Accessible reach length (km)	Length upstream of 1st dam (km)	Total inaccessible reach length (km)
St. Joseph	111	368.3	11.8	3,190.7
Kalamazoo	64	96.2	41.2	1,029.9
Grand	149	406.9	1.3	2,926.7
Muskegon	79	263.3	166.9	1,485.3
White	13	194.4	80.3	128.0
Pere Marquette	20	447.5	------	44.4
Manistee	59	209.0	237.6	971.2
Manistique	50	2.6	900.1	1,366.9
Whitefish		251.5	70.3	125.0
Escanaba	25	2.2	3.3	642.0
Ford	11	338.3	------	0
Menominee	91	3.5	2.1	1,464.3
Peshtigo	25	18.0	34.9	870.0
Oconto	16	26.4	32.9	697.3
Fox	117	152.9	9.8	263.4
Kewaunee	2	13.7	93.4	93.4
East Twin	2	16.7	3.1	79.4
West Twin	2	9.6	93.5	124.6
Manitowoc	9	89.5	108.0	232.1
Sheboygan	5	15.8	48.2	254.0
Milwaukee	12	18.9	21.0	498.5
Little Calumet	14	86.7	48.1	135.1
Total		3,063.0	2,011.0	16,622.2

Restoring additional spawning habitat to Lake Michigan's adfluvial and potamodromous fishes should be accomplished by identifying specific barrier removals or fish passage provisions that would yield the highest spawning benefits. One way to approach this analysis is to use stream classifications and landscape scale models to help determine stream reaches above dams with suitable habitat, and predict their fish production potential. Habitat characteristics attributed to the stream segments can be used to predict the suitability of potential habitat and estimate numbers of fish below and above dams. It is also important to consider the relative location and accessibility to nursery areas. The ability for newly accessible spawning habitat to increase production will depend on the flow and temperature conditions in the river downstream of the spawning site (Jones et al. 2003).

Creque (2002) developed regression models that predicted the density of adult brown trout, Chinook salmon, steelhead, and white sucker using landscape-scale habitat variables for five river systems in Michigan using the MI VSEC. She found that if fish passage were provided at the Croton dam on the Muskegon River, the reach between the Croton and Hardy dams would produce an additional 3,900 brown trout, 5,650 steelhead, 2,200 white sucker, and 21,500 Chinook salmon (Creque 2002). Permitting access to the Manistee River from Tippy dam to Hodenpyle dam would produce an additional 20,453 brown trout, 29,700 steelhead, 11,500 white sucker, and 109,050 Chinook salmon (Creque 2002). These types of estimates depend on a stream classification model. With the development of extended stream classifications, these dam removal scenarios could be run for additional streams in the Lake Michigan basin.

Rutherford et al. (University of Michigan, unpublished data) used a similar landscape-scale approach to determine the natural reproduction of steelhead from major tributaries entering Lake Michigan. Regression models were developed using map-derived habitat data from the 1:100,000 scale NHD and historic population estimates of steelhead densities. Significant habitat variables in the steelhead models were; mean July temperature, percent outwash and percent coarse substrates. The regression models provided an estimate of age-1 steelhead densities for each stream reach. Smolt numbers were predicted by multiplying age-1 densities by stream segment area and then applying a survival rate. The total smolt estimates for major tributaries to Lake Michigan (in the state of Michigan) were 131,850 steelhead smolts, which is lower than, but similar to Rand et al.'s (1993) estimate of 180,000 smolts. Figure 1 shows the number of predicted smolts below dams for each stream reach in Michigan with the Little Manistee, Manistee and Pere Marquette Rivers having the greatest amount of productive habitat. Removing all dams, the models predict that Michigan tributaries would produce a total of 335,300 smolts. Figure 2 shows the increase in the number of smolts produced from major tributary systems in Michigan with the removal of all dams.

Figure 1. Steelhead smolt estimates for Michigan tributaries (Rutherford et al., University of Michigan, unpublished data).

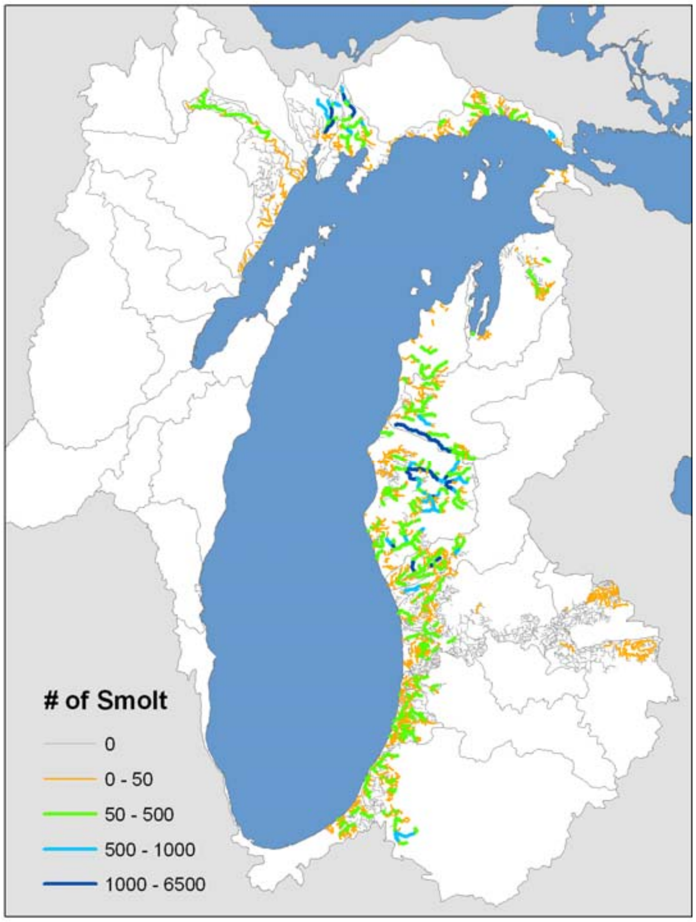
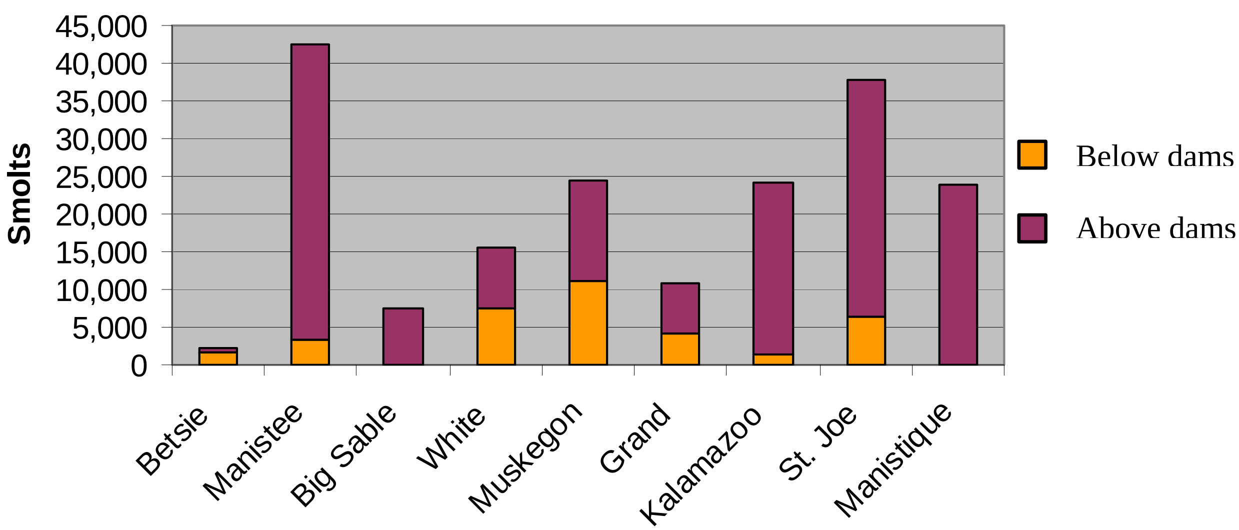


Figure 2. Numbers of predicted steelhead smolts below and above dams (Rutherford et al., University of Michigan, unpublished data).



Summary of Data and Current Initiatives

The resolution and extent of data on tributary habitats are limited on a basin-wide scale. To date, a river classification system exists for the state of Michigan. The Michigan Valley Segments (MI VSEC) are ecological units for streams defined by physical and biological processes. Catchment size, hydrology, water chemistry, water temperature, valley and channel character, and fish assemblages are examples of attributes that describe each valley segment (Seelbach et al 1997). An EPA-STAR project is underway to develop an ecological classification of rivers in Illinois, Wisconsin, and Michigan similar to that of the MI VSEC (Li Wang, Michigan DNR. unpublished data). The goal of this project is to couple landscape-based modeling from large, regional data sets and regional land transformation models with a valley segment ecological classification approach already being employed in several Midwestern states. This river classification will be at a higher resolution and larger extent than the existing MI VSEC.

A spatially-explicit dam database has been compiled for the Lake Michigan basin using dam information from state agencies. There are approximately 1,947 dams in the Lake Michigan basin (Marshall, University of Michigan, unpublished data). From 1918 to 2003, 67 dams have been reported as removed, 58 in Wisconsin and 9 in Michigan. Wisconsin has actively removed a number of small dams and is a national leader in the removal of small dams. Only 17 dams in the Lake Michigan basin have some sort of fish passage structure, all of which are in Michigan.

A relatively limited amount of scientific information exists that relates dam removal to responses of habitat and fish populations within a river system. In Michigan, the Stronach dam removal study began in 1995 and is documenting the effects of dam removal on physical attributes and the fishery of the Pine River (Klomp 2000). As of October 2003, responses of the river have been limited to physical habitat alterations and changes in fish populations have not yet been documented, but annual monitoring will continue to occur (Daniel Hayes, Michigan State University, personal communication, 2003). It is expected that fish populations will increase in abundance as further changes in habitat occur, or until the river reaches a stage of equilibrium (Mistak 2001). In Wisconsin, researchers have shown that the diversity of fishes in the Milwaukee River has increased since the removal of the Chair Factory dam in 2000 (LaMP 2004).

River habitats above dams likely could support increased populations of adfluvial and potamodromous fish in Lake Michigan. Increasing habitat carries the potential for increasing natural reproduction, thus decreasing the dependence on stocking to support the sport fishery. Additionally, benefits of returning a river system to its natural flow conditions through dam removal would be experienced by fish species, aquatic invertebrates, aquatic plant communities, and riparian vegetation.

Impacted Species

Salmonines constitute an important part of the fish community in Lake Michigan. These species include Chinook salmon, coho salmon, rainbow trout, steelhead, brown trout, and brook trout. From the 1920s to the 1950s, the native fish populations in Lake Michigan were declining as a result of influences of exotic species such as rainbow smelt *Osmerus mordax*, sea lamprey *Petromyzon marinus* and alewife *Alosa pseudoharengus*; deterioration of spawning habitats; and increased commercial fishing pressure (Smith 1968 and 1972; Wells and McClain 1973). In response to the increasing alewife population, non-native salmon and trout were introduced to Lake Michigan beginning in 1966 (Stewart et al. 1981). Since the 1960's, the stocking program has proved to be very successful in controlling the alewife populations and creating a valuable sport fishery. Chinook salmon, coho salmon, and steelhead still rely upon annual stocking to support economically important river, lake, and pier fisheries. However, the extent of annual natural production of Chinook salmon and steelhead smolts in Lake Michigan is roughly 50 and 17%, respectively of numbers of stocked hatchery smolts (Rutherford 1997). Natural recruitment of coho salmon is lower at approximately 10% of numbers stocked, or 200,000 smolts (Rutherford 1997).

Walleyes historically were abundant in Green Bay and southeastern Lake Michigan. Although the walleye fishery of Lake Michigan was greatly reduced in the 1800's as a result of overfishing and destruction of spawning habitat, small naturally reproducing populations still occur in selected tributaries in these areas. The Manistee River still has a naturally reproducing population, while the Muskegon River is heavily dependent upon stocking (O'Neal 1998; Rozich 1998). In addition, the Whitefish River receives the largest spawning run in Little Bay de Noc and there are historic populations in tributaries that flow into Green Bay.

Lake sturgeon populations are estimated to be only 1% of their former abundance in the Great Lakes (Tody 1974). This decline resulted because lake sturgeon were once killed as a nuisance species, then their populations were over fished, barriers were constructed limiting their migration, and the remaining habitat was highly degraded. Today, the largest obstacle for rehabilitating the lake sturgeon population is blockage by dams to upstream spawning habitat (Hay-Chmielewski and Whelan 1997). Eleven out of thirty measured Michigan tributaries to Lake Michigan historically had high habitat suitability for maintaining a self-sustaining Lake sturgeon population (Hay-Chmielewski and Whelan 1997). However, all of these streams have large barriers that currently prevent access to the majority of highly suitable habitat. Remnant adfluvial populations still exist below the first dam to the lake in the Menominee, Peshtigo, Oconto, Muskegon, Kalamazoo, and Fox Rivers, and presumably still exist in the Millecoquins, Manistique, Grand, and St. Joseph Rivers.

Typical lake resident fish species have been shown to utilize the lower reaches of tributaries for reproduction. Fish may take advantage of the earlier occurrence of suitable spawning temperatures in streams than in Lake Michigan and produce two cohorts, a stream cohort and a lake cohort. Yellow perch *Perca flavescens* were documented spawning in the Kalamazoo River at a time when spawning had not yet begun in the lake (Dorr 1982). Subsequent studies in Southern Lake Michigan have collected two cohorts of yellow perch in Lake Michigan, one that spawned inland earlier in the season and another that spawned in the lake (Wells 1973, Perrone et al 1983). Alewife spawned in rivers and drowned-river mouth lakes and their larvae were found in drowned-river mouth lakes 2-3 weeks before peak hatches in Lake Michigan (Mansfield 1984; Höök 2005). Spottail shiners also began spawning one month earlier in streams than in Lake

Michigan, and densities of larvae remained higher in streams than in the Lake Michigan beach zone (Mansfield 1984).

Creeks also are valuable habitats in tributary ecosystems. Tributary creek habitats provide important refugia for fish in rivers that may provide spawning but not nursery habitats. For example, small tributaries are not subjected to thermal fluctuations from upstream dams on the mainstem of rivers. Newcomb (1998) found that over 50% of the age-0 and age-1 steelhead parr sampled in the Betsie River were located in the tributaries which comprise only 11% of the total channel area. On the nearby Manistee River, Woldt and Rutherford (2002) estimated the fall densities of young-of-the-year steelhead to be approximately 4 times greater in Pine and Bear Creeks, two creek tributaries than in the main stem of the Manistee River. Godby et al (2007) found similar results for the Muskegon River watershed. These studies provide examples for steelhead, but creek habitats also are utilized by other adfluvial fishes including Chinook salmon and white sucker.

Alterations of river morphology, flow regime, and loss of habitat affect all life cycles of fish. Limiting access of fish to optimal habitat during each life stage results in poor overall growth. The impacts of dams at the lower end of large rivers are significant on the Lake Michigan fishery. Fish passage and dam removal options should be considered, as blockage to suitable spawning habitat is one of the largest obstacles to rehabilitating natural reproduction.

There are negative consequences of dam removal to consider. Removals of lower dams increase the available spawning habitat to desirable adfluvial fishes but also to undesirable exotic species such as sea lamprey, alewives, and round gobies. Many dams act as physical barriers to sea lamprey spawning and nursery habitat in Great Lakes tributaries. As sea lamprey control is the most expensive management program in the Great Lakes, it is important to consider the additional costs to sea lamprey control of removing a critical barrier. Dam removal may also result in Pacific salmonids competing for habitat with native fish and resident populations of trout, and importing contaminants and diseases from the lake. Furthermore, removing dams and returning rivers to their natural flow regime would eliminate recreational opportunities provided by large reservoirs, such as the warm water fisheries popular with many anglers. Although dam removals could have damaging effects on fisheries and local economies, management decisions could be taken to help mitigate these problems and more broadly benefit native fish communities.

Information and Research Needs

Information and research needs as they relate to the environmental objective to protect and enhance spawning and nursery habitat in tributaries.

- Assess the benefits and effects of dam removal on fish habitat and populations; quantify the ecological benefits and detriments of dam removal.

- Identify habitat restoration initiatives by evaluating where the greatest ecological and socioeconomic benefits are likely to accrue.

- Complete river classification for the entire basin, to determine the suitability of river habitat blocked by dams.

- Estimate effects of opening upstream habitat on sea lamprey production.

- Quantify numbers and species of adfluvial fishes using Lake Michigan tributaries.

- Quantify the amount and relative quality of spawning habitat for adfluvial and potamodromous fishes below and above dams. This has only been done below dams for sea lamprey, and only for steelhead in the Pere Marquette River (Workman 2002).

- Quantify the value of habitat for survival and growth of adfluvial and potamodromous fishes. Some information exists on the effects of tributary flow and temperature on survival of eggs, and growth and production of young salmonids (Chinook salmon: Carl 1982; steelhead: Horne et al. 2004), and on walleye (Jones et al. 2003), but not for most other fishes including lake sturgeon and suckers.

Status of Environmental Objective #1-
Protecting and restoring connectivity and quality tributary spawning and nursery habitats

Species	Impediment to achievement	Problems/issues to be addressed
Trout and Salmon Walleye Lake sturgeon	Yes	Dams prevent migration to spawning, nursery and feeding habitats, alter flow stability, and change temperature regimes. Impoundments eliminate higher gradient habitat. Sedimentation, decreased water flows and an increase in peak flows from land-use changes, dredging, channelization, and water withdrawals
Phytoplankton Benthos	Yes	Nutrient inputs and increased sedimentation
Forage fish	Potentially	
Lake trout Lake whitefish Yellow perch	Unlikely	

Yes	Data exists documenting an impediment to achievement of the FCO
Potentially	Available data are inconclusive, but suggest a potential impediment
Inconclusive	Available data suggest neither an impediment or no impediment
Unlikely	Available data are inconclusive, but suggest that there is no impediment
No	Available data document no impediment

Environmental Objective #2-

Protect and restore connectivity and quality coastal wetland spawning and nursery habitats

Relevant Fish Community Objectives

Fish Community Objectives	Importance of Environmental Objective
• Planktivore Objective *Maintain a diversity of planktivore (prey) species at population levels matched to primary production and to predator demands. Expectations are for a lake wide planktivore biomass of 0.5 to 0.8 billion kg (1.2 to 1.7 billion lbs).*	Prey species (alewife) can be found in wetland areas during some time in their life cycle. Coastal wetlands provide prey species with spawning, nursery, and feeding areas.
• Inshore Species Objective *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 (2 to 4 million lbs) for yellow perch and 0.1-0.2 million kg (0.2 to 0.4 million lbs) for walleye.*	Yellow perch, walleye, and basses inhabit littoral areas of Lake Michigan and use the vegetated areas of coastal wetlands for spawning. Wetlands provide shelter and cover for juveniles. Pike are obligate wetland species and require access to wetlands for spawning.
• Other Species Objective *Protect and sustain a diverse community of native fishes, including other species not specifically mentioned earlier (for example, cyprinids, gars, bowfin, Coaster and stream-resident brook trout, and sculpins). These species contribute to the biological integrity of the fish community and should be recognized and protected for their ecological significance and cultural and economic values.*	Coastal wetlands have the highest species diversity in the Great Lakes. Wetlands are potential refuge areas for threatened species including sauger, lake herring, and northern madtom.
• Benthivore Objective *Maintain self-sustaining stocks of lake whitefish, round whitefish, sturgeon, suckers, and burbot. The expected annual yield of lake whitefish should be 1.8-2.7 million kg (4 to 6 million lb).*	Coastal wetlands may serve as migratory pathways to connecting riverine spawning habitats for lake sturgeon. Wetlands also decrease sediment and contaminant loading into the Great Lakes river systems.
• Physical/Chemical Habitat Objective *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.* *Protect and enhance fish habitat and rehabilitate degraded habitats.*	Coastal wetlands provide spawning and nursery habitat, feeding areas and offer cover to many important fish species. Preserving quality wetland habitats as well as maintaining connections between the open water and wetlands will maximize the availability of breeding habitat, shelter for young fish, and food for Great Lakes fish.

Background

The shores of Lake Michigan are the most diverse and unique in all Laurentian Great Lakes. The shoreline encompasses a total of 2,633 km, which include reaches of lake plains, high clay bluffs, low erodible banks, rocky cliffs, dune fields, glacial drift bluffs, and sand ridge shores (Maynard and Wilcox 1997). Each of these shoreline types has geomorphic features that promote the formation of coastal wetlands, which are equally diverse. With approximately 417 wetlands covering an area of 49,000 hectares, the Lake Michigan basin contains the greatest number and area of coastal wetlands in the Great Lakes system (Herdendorf et al. 1981). These areas provide spawning and nursery habitat, as well as feeding areas to many important fish species. Coastal wetlands play a vital role in the ecology of Lake Michigan.

Coastal wetlands are unique because they provide an area with assorted structural habitats and high primary productivity that supports fish production (Jude and Pappas 1992). Whillans (1987) projected that over 90 percent of the 200 fish species in the Great Lakes are directly dependent upon coastal wetlands for some part of their life cycle. Jude and Pappas (1992) reported that 47 fish species of the Great Lakes were closely associated with coastal wetlands, and use these wetlands either on a permanent or temporary basis. Although these estimates vary, wetlands undoubtedly constitute a important habitat for numerous important fish species, including northern pike *Esox lucius*, muskellunge *Esox masquinongy*, largemouth bass *Micropterus salmoides*, smallmouth bass *Micropterus dolomieui*, bluegill *Lepomis macrochirus*, yellow perch *Perca flavescens*, white crappie *Pomoxis annularis*, black crappie *Pomoxis nigromaculatus*, channel catfish *Ictalurus punctatus*, black bullhead *Ameiurus melas*, brown bullhead *Ameiurus natalis*, carp *Cyprinus carpio* and bowfin *Amia calva* (Raphael and Jaworski 1979; Jude and Pappas 1992).

The major coastal wetland complexes are concentrated along Green Bay, Little and Big Bay de Noc and embayments along the Northern and Eastern shores (Table 2, Fig. 3). The wetland types in the Lake Michigan basin are primarily embayments, barrier beach, and riverine. Riverine wetlands are characterized by a permanent channel that meanders through a lateral flood plain

With approximately 40% of the Great Lakes coastal wetlands residing in the Lake Michigan basin, managing the integrity and availability of coastal wetlands has important implications for sustaining the Great Lakes fishery. It is essential to maintain connections between the open water and coastal wetlands to maximize the availability of breeding habitat, shelter for young fish, and an abundance of food for Great Lakes fishes.

Issues

Wetlands across the basin are continually deteriorating as a result of numerous anthropogenic effects. Shoreline development, dredging, draining, land filling, road building, conversion to agriculture, loadings of nutrients, sediment, and contaminants, introduction of non-native species, and diking have all altered the distribution and health of coastal wetland ecosystems (Mitsch and Gosselink 1993). Additionally, natural stressors, e.g., water level changes, sediment supply, ice and storm damage and biological stressors, e.g., exotic herbivores, also act as limiting agents on coastal wetlands (Maynard and Wilcox 1997). While the extent to which these stressors act upon the coastal wetlands in Lake Michigan is not well understood, it is evident that the size of coastal wetlands has decreased and many have completely vanished.

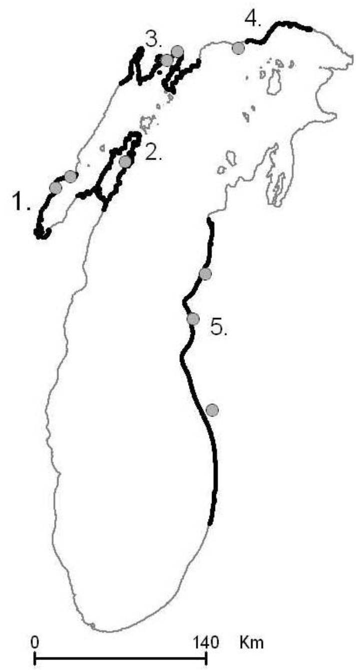
In the Lake Michigan basin, the Green Bay area has suffered severe losses and degradation of its wetlands. In the southern end of the bay and along the western shore, coastal wetlands have been reduced by 60-75% (Bosley 1978); however, they remain some of the most extensive wetland complexes in the Great Lakes (Herdendorf et al. 1981). In the southern end of the lake, many of the interdunal wetlands have been impacted by industrialization. The drowned river mouth wetlands in this area have been affected by road crossings, increased sediment deposition, and colonization by invasive plant species (Maynard and Wilcox 1997). Many of the wetlands remain intact in the northern part of the lake where population density and development pressures are lowest,. Around the Calumet area, efforts have been taken both by public and private agencies to restore and reconnect some of these wetlands to the lake water table. Fragmentation is a threat to the coastal wetlands along the eastern shore, which are under pressure from development.

Purple loosestrife *Lythrum salicaria*, Common Reed *Phragmites australis*, zebra mussels *Dreissena polymorpha* and round gobies *Neogobius melanostomus* are examples of non-native species that continue to spread throughout the Great Lakes basin, disrupting the integrity and function of coastal wetland ecosystems. Purple loosestrife and common reed displaces native wetland vegetation and results in the eventual alteration of a wetland's structure and function (Thompson et. al. 1987). As the native plant community is suppressed, natural foods and cover are eliminated for aquatic and waterfowl species (Rawinski and Malecki 1984). Purple loosestrife and common reed are aggressive species that can overrun wetlands and quickly choke out open water habitat. Zebra mussels have virtually eliminated native unionids from open water, but wetlands may provide habitat areas to ensure the survival of native unionids. A study in a coastal marsh in Lake Erie found native clams coexisting with zebra mussels (Bowers and DeSzalay 2003). Bowers and DeSzalay (2003) showed that the warmer temperatures and soft substrates associated with coastal wetland protect the native clams from fatal infestation by zebra mussels. Furthermore, the round goby is another threat to the health of wetland ecosystems, potentially dispersing native fish and competing for food in these ecosystems (Jude 1997).

It is difficult to predict the future status of coastal wetlands in the Lake Michigan basin. There are a number of stressors that will have a significant negative impact if left unchecked. Development pressures are causing fragmentation of coastal wetlands. This is one of the greatest threats, because it can lead to a significant degradation in the productive capacity of the lake. Furthermore, the compounding effects of climate change may lead to lower lake levels; which would reduce the accessibility of fish to the emergent vegetation of coastal marshes.

Significant Coastal Wetland Areas

Figure 3. Major coastal wetland areas along the shore of Lake Michigan 1. Green Bay. 2. Door Peninsula. 3. Bay de Noc 4. North shore 5. Eastern shore. Distribution of wetland complexes over 2,000 hectares represented by grey circles



Wetlands in Green Bay and Lake Michigan’s eastern and southern shores are threatened by development pressures from urbanization. The coastal wetlands of Green Bay are characterized by low sandy banks with low beach ridges and embayment fringe wetlands. The lower bay has intense development along the shore, high contaminant loads, hyper-eutrophic nutrients, and high turbidity. Green Bay wetlands are important spawning habitat for yellow perch and northern pike. The embayment south of Little Tail Point has the greatest abundance of young-of-the-year yellow perch in southern Green Bay. The eastern shore of Lake Michigan is composed of extensive barred, drowned-river mouth estuaries such as the Betsie, Manistee, Pere Marquette, Pentwater and Muskegon Rivers.

The North shore is comprised of fringing wetlands and ridge and swale complexes. The Northern shore of the lake is irregular and more rugged than the other shores. Coastal wetlands in the northern area of the lake are being encroached upon by second-home development. Palustrine complexes of the Door Peninsula are forested wetlands with interspersed pockets of scrub-shrub, emergent, and aquatic bed wetlands. These wetlands are one of the most sensitive areas on the Lake Michigan shoreline because of the concentration of rare species and natural communities. Bay de Noc is dominated by palustrine forested, emergent, and aquatic bed wetlands. Little Bay de Noc supports an important walleye sport fishery and commercial fishery for lake whitefish. Additionally, Bay de Noc is an area of high biodiversity. Sixty seven species have been recorded in Little Bay de Noc which is the area of highest species diversity in the lake (Bailey et. al. 2004).

Table 2. Areas of significant coastal wetland complexes (Hogman 1998).

Region	Wetland Complex	Area (acres)
Green Bay	Oconto Marsh	9,370
	Peshtigo River Wetland	5,040
Door Peninsula	Baileys Harbor-Ephraim Swamp	5,050
	North Bay Complex	2,150
	Rocky Point	1,390
Bay de Noc	Big Bay de Noc	9,555
	Sturgeon River	6,697
Northern Lake Michigan	Seul Choix Point Complex	5,835
	Point Aux Chenes Complex	3,038
Eastern Lake Michigan	Manistee River	9,156
	Pere Marquette River	6,256
	Muskegon River	6,052
	White River	3,902
	Betsie River	380
	Arcadia Lake	360
	Pentwater River	272
	Little Manistee River	243
	Pigeon River	90
Southern Lake Michigan	Lake Calumet Complex	1,057
	Indiana Dunes	404

Summary of Data and Current Initiatives

Inventories exist of the distribution and characteristics of coastal wetlands surrounding Lake Michigan. The Great Lakes Wetlands Consortium has coordinated efforts to create a classified inventory of all coastal wetlands in the Great Lakes basin through the Great Lakes Wetlands Inventory. Built upon the best coastal wetland data currently available and incorporating a standard classification process, the inventory provides a standard reference for the Great Lakes wetland community. The mapping of the U.S. coastal wetlands was done using geographic information systems (GIS) by the U.S. Geological Survey, Water Resources Discipline (USGS WRD) in Columbus, Ohio. The Michigan Natural Features Inventory (MNFI) identified and classified all coastal wetland complexes. The coastal wetland inventory is available for all four states that surround Lake Michigan (http://www.glc.org/wetlands/inventory.html).

Reference conditions for fish, plants, and invertebrate assemblages in Lake Michigan wetlands are now available. The Great Lakes Wetlands Consortium funded research to develop IBIs for different wetlands taxa (http://www.glc.org/wetlands/investigations.html). Three research teams compiled data from six pilot studies, supplemented this with additional data from their own previous work and conducted various analyses to determine which metrics could be combined into an effective IBI. The IBIs were then assessed for overall effectiveness in aligning with disturbance gradients based on land use and physical measures. . A number of the indicators the Consortium investigated require the regular collection of remote imagery and interpretation using satellite imagery or radar to delineate change in wetland area and vegetation along with changes in surrounding land use and habitat. Additionally, an U.S. EPA STAR grant project has develop environmental indicators of condition, integrity, and sustainability of coastal areas in the Great Lakes Basin, and identified relationships between environmental stressors and ecosystem response (Danz et al. 2005, Uzarski et al.2005, Johnston et al. in press).

Geographic Information Systems (GIS) are being used to create databases and analyze spatial distributions of wetlands as well as other habitat types in the Lake Michigan basin. The Great Lake GIS is a comprehensive GIS database with fisheries based spatially explicit data for each lake in the Great Lakes basin (www.glgis.glfc.org). The Great Lakes Coastal Aquatic Gap Analysis is a GIS based project out of USGS Great Lakes Science Center. The goal of this project is to identify gaps in the conservation of nearshore aquatic species by using existing data and GIS to map habitats, species distribution, and land ownership of the Great Lakes region. This project will be focusing on coastal habitats and nearshore fish assemblages to provide information to better study and manage these ecosystems.

Finally, otolith stable isotope microchemistry can provide information on the degree of wetland or tributary dependence by fishes. Brazner et al. (2004) evaluated the utility of elemental fingerprinting for quantifying yellow perch movement between coastal wetlands and offshore waters in western Lake Superior. Their results suggest that this technique can distinguish between juvenile yellow perch that were reared in different wetland nursery habitats from those spawned in open lake habitats. The implications for this research are that contributions of different coastal wetland habitat areas may be quantified in terms of their relative contributions to the recruitment of lake populations (Brazner et al. 2004).

Impacted Species

Different fish species use wetlands at various life stages for a range of purposes including spawning and nursery, sheltered habitat for forage fish, and food for larger fish species. Chubb and Liston (1986) found high densities of fish larvae in Pentwater Marsh, a drowned river mouth estuary on the eastern shore of Lake Michigan. They estimated that each hectare of shallow-water wetland in Pentwater Marsh contributes roughly 56,000-317,000 minnows, 86,000-283,000 sunfish, 1,900-5,700 northern pike, and 1,400-2,600 yellow perch larvae each year. The extensive use of coastal wetlands by smaller fish provides food for larger predatory species. Larger fish such as northern pike, pickerel

Esox spp., basses (*Micropterus, Morone*) and warmouth *Lepomis gulosus* are temporary residents of wetlands (Jude and Pappas 1992) and use these areas because of the concentrated forage.

Available data are limited on the linkages between fish assemblages and coastal wetland habitat (Jude and Pappas 1992, Brazner and Beals 1997). Uzarski et. al (2003) showed that vegetation type was the most important variable structuring fish community composition in coastal wetlands. Fish communities can change with increasing nutrients, adjacent agriculture, decreasing fetch and pelagic mixing (Uzarski et. al 2005).

Information and Research Needs

- Establish the link between fish production/diversity and coastal wetland health/function.
- Complete the coastal wetland inventory for Lake Michigan.
- Monitor the impact of low water levels and exotic species on coastal wetland form and function.
- Establish a program for monitoring and assessing coastal wetlands and associated fish community structure over time in key or index wetland sites.
- Develop education material that highlights the cyclical nature of Great Lakes coastal wetlands and the need to protect these areas from incremental development.
- Understand how variations in water level and temperature affect survival of wetland spawners. This information exists for northern pike (Farrell et al. 1996, Farrell and Werner 1999), but it is lacking for most other wetland-dependent species.

Status of Environmental Objective # 2-
Protect and restore connectivity and quality coastal wetland spawning and nursery habitats

Species	Impediment to achievement	Problems/issues to be addressed
Walleye Yellow perch Basses Northern pike Bullheads Channel catfish Forage fish Benthos Phytoplankton	Yes	Shoreline development and wetland filling Diking Nutrient and sediment loadings Contaminants Water level changes Exotic plant and fish species Comprehensive wetland inventory and database needed

Trout and Salmon	Inconclusive	
Lake trout Lake whitefish	Unlikely	

Yes	Data exists documenting an impediment to achievement of the FCO
Potentially	Available data are inconclusive, but suggest a potential impediment
Inconclusive	Available data suggest neither an impediment or no impediment
Unlikely	Available data are inconclusive, but suggest that there is no impediment
No	Available data document no impediment

Environmental Objective # 3-
Protect and restore reef spawning habitats

Relevant Fish Community Objectives

Fish Community Objectives	Importance of Environmental Objective
• Salmonine Objective *Establish a diverse salmonine community capable of sustaining an annual harvest of 2.7 to 6.8 million kg (6 to 15 million lbs), of which 20-25% is lake trout.*	Lake trout utilize both nearshore and offshore spawning reefs found throughout Lake Michigan. Historically, the mid-lake reef complex has been thought to be the most productive spawning area in the lake (Holey et al 1995). Boulder Reef, Richard's Reef, and Gull Island Shoal receive all lake trout stocked in the Northern refuge area. Sheboygan, Northeast, East, and Milwaukee reefs are where stocking in the Southern Refuge has been directed.
• Inshore Species Objective *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 (2 to 4 million lbs) for yellow perch and 0.1-0.2 million kg (0.2 to 0.4 million lbs) for walleye.*	Reef spawning populations of walleye were once found in Green Bay and Little and Big Bays de Noc. Nearshore reef habitats are critical for yellow perch spawning in southern Lake Michigan (Robillard and Marsden 2004)
• Benthivore Objective *Maintain self-sustaining stocks of lake whitefish, round whitefish, sturgeon, suckers, and burbot. The expected annual yield of lake whitefish should be 1.8-2.7 million kg (4 to 6 million lb)*	Lake whitefish spawn throughout Lake Michigan. Spawning reefs are located along the northwestern, northeastern and eastern shores with concentrations in Grand Traverse Bay, Beaver Island, Millecoquins Point and the Door County peninsula. Round whitefish spawning reefs are found in the northern half of the lake around the Manitou Islands, Grand

	Traverse Bay, Ludington, and the Door County peninsula.
• Physical/Chemical Habitat Objective *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.* *Protect and enhance fish habitat and rehabilitate degraded habitats.*	Nearshore spawning reef habitats are important to the reproductive success of lake trout, lake whitefish, yellow perch and walleye populations and offshore spawning reef habitats for lake trout in Lake Michigan. High quality reef habitats are required for natural reproduction of lake trout (Marsden et. al. 1995)

Background

Lake Michigan has a number of offshore reefs which are mainly concentrated in the Northeastern and central regions (Figure 4). The widespread availability of deepwater reef habitats structured the historical fish community, which was predominantly deepwater species such as lake trout, whitefish, and ciscoes. However, with the extinction of native lake trout populations, today these reefs are not being utilized for spawning as much as they could be. The nearshore reefs in Lake Michigan (Figure 4) are located along the northern, western and eastern shores as well as in Green Bay, and have been subjected to degradation by sedimentation and the invasion of exotic species. These reefs historically supported reproduction of lake trout, lake whitefish, yellow perch, walleye, and smallmouth bass. Man-made structures such as breakwalls, piers, industrial water intake and discharge structures, and artificial reefs also are utilized as spawning reefs (Fitzsimons 1995).

The geology of spawning substrates in Lake Michigan has been shaped through a history of glaciations. The spawning reefs in Lake Michigan are concentrated where Silurian rocks outcrop on the north and northwest shores, and where middle Devonian rocks outcrop in the Northeast and Mid-Lake areas (Dawson et. al. 1997). The inshore reefs were deposited during a single geologic epoch and therefore have glacial uniformity. A cluster of offshore reefs, on the other hand, occurs at a major nonconformity between the upper Silurian and middle Devonian rock, resulting in slumping and irregular fracturing of the lakebed (Barnes et. al. 2003). This nonconformity may be responsible for the concentration of reefs in this area. In addition to the Paleozoic outcrops, Sommers (1968) has shown glacial outwash, glacial till, and modern lake sediments also are present as offshore deposits in Lake Michigan reef areas.

Fish utilize both the inshore (<30m) and offshore (>30m) reefs as spawning habitat in Lake Michigan. The nearshore reefs are primarily used by lake trout, lake whitefish, yellow perch and walleye (Goodyear et. al. 1982). The deep, offshore reefs are used by lake trout, ciscoes, and sculpins (Goodyear et. al. 1982) (Figure 5). Lake trout are the only species to successfully spawn in both the nearshore and the offshore reefs. Protecting and restoring reef habitats in Lake Michigan will guarantee the availability of spawning habitats for lake trout, lake whitefish, walleye, and other species. Additionally, the presence of high quality reef habitat may play an important role for developing naturally reproducing lake trout stocks in Lake Michigan**.**

Issues

Spawning habitats on offshore reefs have not experienced physical degradation since historic times, while nearshore reefs are threatened by a variety of factors. Lake Michigan offshore reefs are concentrated on stable substrates in deep waters; therefore direct losses are negligible (Holey et. al. 1995). However, reefs in the nearshore area are susceptible to factors that may contribute to alteration, quality and quantity of habitat, including groundwater intrusion, lake level changes, navigation and channelization, as well as sedimentation through shoreline development and land-use changes (Sly and Busch 1992). For example, walleye in southern Green Bay have experienced stresses on stock abundance because of spawning habitat degradation by sedimentation and restructuring of nearshore reefs (Schneider and Leach 1977).

A loss of offshore habitat has occurred through a combination of biotic influences, including a loss of genetic strains, fish-stocking practices, and behavior (Fitzsimons 1996). Historically, populations of lake trout spawned on a wide variety of substrate types, e.g. cobble, rubble, clay, and honeycombed bedrock, and at a wide range of depths (Fitzsimons 1996). However, spawning by contemporary lake trout stocks is restricted to cobble substrate in shallow depths (<16m) (Jude et. al. 1981 and Holey et al. 1995). With the reduction of the deep-water spawning stocks, there is an indirect loss in overall spawning habitat, because the deep offshore reefs are not being used by contemporary stocks that appear to prefer shallow spawning areas (Chotkowski and Marsden 1997).

Despite the strong evidence for nearshore reefs as the primary spawning ground for lake trout, the presence of predators and exotic species may prevent these reefs from supporting the natural reproduction of lake trout. Eggs spawned on shallow sites are susceptible to egg and fry predators such as carp and round gobies, which are not present on deep-water reefs (Krueger et al. 1995). In addition, zebra mussels are present on most shallow reefs in the lower Great Lakes and have a strong negative effect on lake trout spawning and egg survival (Marsden and Chotkowski 2001). The non-native zebra mussel colonizes rough textured structures and degrades substrate as well as interstitial water quality for egg development. Furthermore, the presence of zebra mussels may increase the local density of egg predators and damage to eggs (Marsden and Chotkowski 2001).

Artificial reefs have been constructed in Lake Michigan as an attempt to provide spawning habitat in areas of sparse natural spawning environment. Creque et al. (2006) found increased abundance of some species at an artificial reef compared to a control site, but not increased harvest. It has not been determined whether the additional spawning habitat provided by artificial reefs will increase sport fish production (Fitzsimons 1996). Continued evaluation of existing and future reef projects is needed to understand the effects of artificial reefs on the fish community in Lake Michigan.

The potential harm to natural reef habitat and function is significant through oil and gas development, windmill construction and artificial reef placements. The Great Lakes Fishery Commission recently supported development of policy and recommendations for evaluating energy-related and other lakebed alteration projects and protecting essential submerged bottomlands resources. Great Lakes jurisdictions, at a minimum, are encouraged to adopt and use the principles expressed in the position statement and guidelines in their own policies. These policies and guidelines are necessary to address energy-related proposals in order to prevent, minimize or mitigate harm to the public trust values of bottomlands habitat, assure long-term monitoring, and provide for coordinated decision-making among the Great Lakes states and the province of Ontario (Dempsey et al. 2006).

Significant Reef Habitats

Figure 4. Reef locations and lake trout refuge areas in Lake Michigan overlaid on a 2 arc second bathymetric grid.

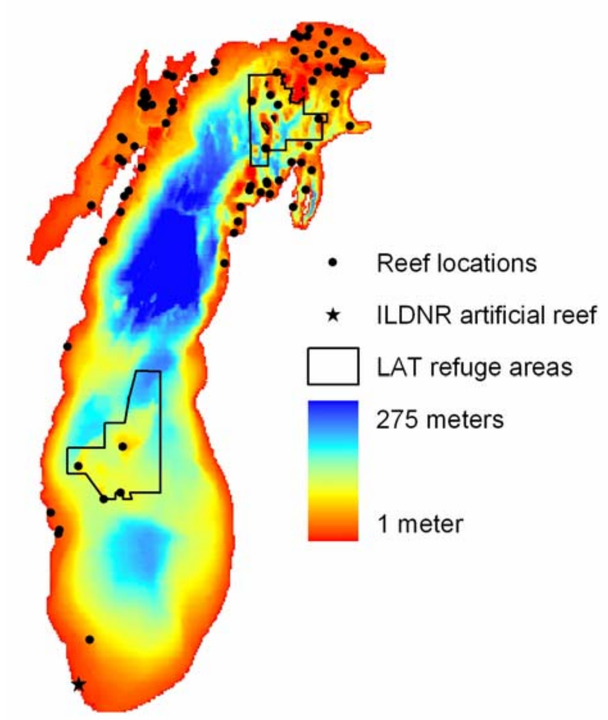
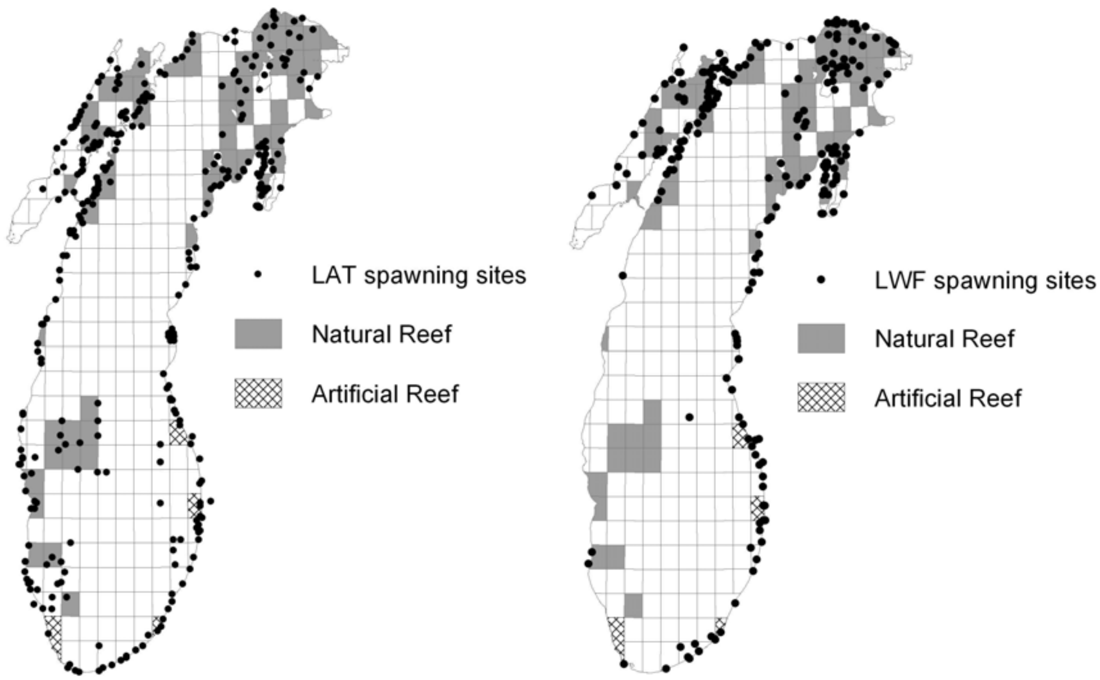


Figure 5. Locations of historic spawning sites from Goodyear et. al. (1982) for lake trout (LAT) and lake whitefish (LWF).



Summary of Data and Current Initiatives

Information about the historical distribution of reef spawners is limited in Lake Michigan. Peck (1979), and Coberly and Horrall (1980) identified reef spawning locations of lake trout in Michigan and Wisconsin waters from commercial fisheries catch data. Goodyear et al. (1982) compiled their work and others' into a spawning atlas for all of the Great Lakes. The atlas is a collection of available data for Lake Michigan species and subsequently gives a general distribution of spawning habitats (eg. Figure 5). A narrative version of the spawning atlas with locations for all 57 species in Lake Michigan is available for download at the USGS Great Lakes Science Center web site < http://www.glsc.usgs.gov> under products and publications. A digital version with spatially referenced locations is available in the Lake Michigan GIS. The spawning atlas is incomplete, however, since it does not quantify the historical abundance of spawners among sites. Dawson et al. (1997) used catch and effort records from Wisconsin and Michigan commercial fisherman to identify lake trout spawning sites. They found that two thirds of the historical catch of lake trout was located on or near offshore reefs but did not investigate catches from Illinois or Indiana waters.

Lidar and side-scan sonar are two of the more recent technologies that have been used to physically map substrate. USGS and the US Army Corps of Engineers Scanning Hydrographic Operational Airborne Lidar Survey (SHOALS) program collaborated to understand the relationship between habitat character and preferred sites for lake trout spawning in the Northeastern area of Lake Michigan, including Boulder Reef, Gull Island Reef, Little Traverse Bay, Trout and High Island Reef, Hog Island Reef, and Dahlia Shoals. The preliminary results of the Lidar survey show that the glacier forms at Boulder Reef, Gull Island Reef, and Dahlia Shoals are the most suitable reefs in terms of lake trout spawning habitat criteria (Barnes et. al. 2003). However, Lidar is unable to determine the presence of algae and zebra muscle growth that may impact these reefs (Barnes et. al. 2003). Direct underwater observations of bottom substrates have been made at some of the better known reef sites in Lake Michigan.

Direct evidence of spawning through egg and fry captures has been acquired at many nearshore and at a few select offshore reef sites (Jude et. al. 1981, Marsden and Janssen 1997, and Wagner 1981). Substantial numbers of lake trout eggs have been collected in southern and central Lake Michigan on man made structures along the shore (Fitzsimons 1996.) Of the observed offshore reefs, evidence of egg deposition has been seen on Julian's Reef, off the coast of Illinois (Marsden and Janssen 1997), and at the Mid-Lake Reef complex (Janssen et. al. Great Lakes Water Institute, unpublished data).

Artificial reefs have been used to supplement or increase fish production in marine and freshwater systems. The Great Lakes Fishery Commission has developed guidelines for evaluating requests for artificial reefs in the Great Lakes. The guidelines relate to artificial reef construction, placement and function, and their effect on natural reef habitats and fish populations. The guidelines define acceptable and unacceptable uses of artificial reefs, describe monitoring and evaluation programs, and recommend methods for evaluating artificial reef proposals (Gannon 1990). The Illinois Department of Natural Resources constructed an artificial reef of granite rubble 1.5 nautical miles offshore to attract smallmouth bass. Creque et al. (2006) compared fish density and presence at the reef site and a reference site before and after construction in 1998 through 2003. Their results show that relative density of centrarchids and overall species diversity was higher at the artificial reef site than at the reference site, although there was no difference in use among sites by pelagic species such as salmonids or alewife, or by round goby. The attraction of nearshore species such as smallmouth bass, rock bass, and largemouth bass to the artificial reef was likely due to availability of food and/or shelter and suitable summer temperatures. The artificial reef was placed too far offshore in unstable thermal habitat to provide suitable spawning habitat (Creque et al. 2006).

Impacted Species

Lake Michigan once supported the largest lake trout fishery in the world before lake trout were extirpated after the introduction of sea lamprey in the 1940s and 1950s, coupled with overfishing and habitat degradation (Eschmeyer 1957). In the mid-1980s, two lake trout refuge areas were established in Lake Michigan (See Figures 4, 5). Stocking efforts were concentrated in these areas and regulations prohibited fishing for lake trout within these refuges. Stocking programs have successfully built lake trout spawning stocks to historic levels at which natural reproduction occurred; however, current spawning success has been very limited (Holey et. el. 1995).

There are three main habitat criteria for successful lake trout spawning. First, coarse substrate with interstitial spaces is needed for egg incubation and to protect eggs from predation and strong water movements (Marsden et. al. 1995). Second, clean substrate without biologic growth and fine sediment is also important for egg incubation, as infilling of interstitial spaces can be lethal to eggs (Marsden et. al. 1995). Third, steep slopes adjacent to the spawning sites are significant for maintaining high water quality at the spawning site and providing access to deep water for juvenile lake trout (Marsden and

Krueger 1991). Other species that are also impacted by the degradation of nearshore reefs include lake whitefish, yellow perch, walleye, and smallmouth bass.

Information and Research Needs

- Continue mapping and identification of substrate types on a lakewide basis to identify all potential spawning locations.
- Understand why some reefs are not used by walleyes or lake trout.
- Quantify impacts of exotic species on survival of fish eggs.
- Identify unperturbed, high quality spawning habitat on spawning reefs.
- Quantitatively measure the extent and intensity of use of artificial reefs.
- Identify factors influencing survival of lake trout eggs on reefs.

Status of Environmental Objective #3-
Protect and restore reef spawning habitats

Species	Impediment to achievement for Nearshore Reefs	Impediment to achievement for Deepwater Reefs	Problems/issues to be addressed
Lake trout	Potentially	Unlikely	Degradation of interstitial spaces and water quality, predation by exotic species, loss of deep-spawning stocks
Walleye	Potentially	Unlikely	Walleyes are scarce on western reefs. Contribution of reef spawning walleye to total population abundance is not fully understood
Yellow perch	Yes	No	Alterations of essential habitat, predation by exotic species and competition for food resources
Smallmouth bass	Potentially	No	Scant evidence of nesting in the lake proper. Nest predators, degradation of nearshore reefs, potential of artificial reefs to increase production is unclear
Lake whitefish	Potentially	Unlikely	Loss of benthic forage abundance
Trout & Salmon	No	No	

Yes	Data exists documenting an impediment to achievement of the FCO
Potentially	Available data are inconclusive, but suggest a potential impediment
Inconclusive	Available data suggest neither an impediment or no impediment
Unlikely	Available data are inconclusive, but suggest that there is no impediment
No	Available data document no impediment

Environmental Objective # 4

Protect nearshore habitats, processes and water quality

Relevant Fish Community Objectives

Fish Community Objectives	Importance of Environmental Objective
• Salmonine Objective *Establish a diverse salmonine community capable of sustaining an annual harvest of 2.7 to 6.8 million kg (6 to 15 million lbs), of which 20-25% is lake trout.*	Nearshore zones are important to all salmonids that use these areas for spawning, nursery, feeding and as migratory pathways to tributary spawning reaches. Nearshore areas near tributary mouths are especially important for young salmonids leaving their natal streams.
• Planktivore Objective *Maintain a diversity of planktivore (prey) species at population levels matched to primary production and to predator demands. Expectations are for a lake wide planktivore biomass of 0.5 to 0.8 billion kg (1.2 to 1.7 billion lbs).*	Prey species utilize coastal areas for most life-history stages, and the density of prey is much greater in nearshore waters than in deeper offshore waters.
• Inshore Species Objective *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 (2 to 4 million lbs) for yellow perch and 0.1-0.2 million kg (0.2 to 0.4 million lbs) for walleye.*	Yellow perch, walleye, and smallmouth bass spend the majority of their life-cycle in the nearshore areas for spawning, nursery and feeding grounds. Rocky cobble shorelines along the southwest coast are preferred spawning areas for yellow perch.
• Other Species Objective *Protect and sustain a diverse community of native fishes, including other species not specifically mentioned earlier (for example, cyprinids, gars, bowfin, brook trout, and sculpins). These species contribute to the biological integrity of the fish community and should be recognized and protected for their ecological significance and cultural and economic values.*	The diversity of species is highest in the nearshore waters of Lake Michigan.
• Benthivore Objective *Maintain self-sustaining stocks of lake whitefish, round whitefish, sturgeon, suckers, and burbot. The expected annual yield of*	Lake whitefish use the nearshore zone for spawning and larval feeding areas. Sturgeon and suckers make use of the nearshore area for feeding.

lake whitefish should be 1.8-2.7 million kg (4 to 6 million lb).	
• Physical/Chemical Habitat Objective *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.* *Protect and enhance fish habitat and rehabilitate degraded habitats.*	Nearshore habitats are important to most species that live in the Great Lakes. Yet, the linkages between nearshore habitat alteration and fisheries production remain unclear. More attention should be given to the study, management, protection, and restoration of littoral areas.

Background

Nearshore waters are defined by the area from the shoreline out to the deepest depth contour where the thermocline intersects the lake bed in late summer or early fall (Edsall and Charlton 1997). By this definition, the nearshore area in Lake Michigan extends from shore out to the 30 meter contour (Schertzer et al. 1987). Although the nearshore zone in Lake Michigan comprises only 26 percent of the total surface area (Fig. 6) and 4.2 percent of the total lake volume, species diversity and biomass are higher in the nearshore zone than in the offshore area of the lake (Edsall and Charlton 1997).

Nearshore habitats consist of a range of substrates, water velocities, and aquatic vegetation types. These physical attributes help to provide essential conditions for specific activities of almost all species of the Great Lakes, including reproduction and areas of refuge for small fish (Steedman and Regier 1987). By providing access to coastal wetlands and tributaries, and linking offshore reefs and shoals to areas of larval productivity, it is also an area of transition.

Approximately 80 percent of fish species in the Great Lakes use nearshore areas in a variety of ways for at least part of the year (Lane et al. 1996). It is an area of permanent residence for some fishes such as Cyprinids, black bass, yellow perch and walleye. For salmonines such as Chinook salmon, coho salmon, and rainbow trout, nearshore waters serve as a migratory pathway to spawning habitats in connecting tributaries. The Pacific salmonids may use the nearshore zone as temporary feeding areas and lake trout and lake whitefish also may use the nearshore areas as nursery grounds.

The overall health of Lake Michigan's nearshore zone can be protected or hurt by the actions that humans take on the shoreline. As spawning, nursery, and feeding habitats are dependent upon a functioning coastal ecosystem, it is essential to continually study the impacts of development on coastal processes that shape nearshore fish habitats in order to manage, maintain and preserve the biodiversity in Lake Michigan nearshore ecosystem.

Issues

Littoral zones are sites of greatest human impact on the Great Lakes. A variety of human activities disrupt the form of nearshore habitats and impact the quality and function of the nearshore ecosystem. Habitat modification or loss as a result of dredging, diking, infilling, shoreline armoring, and breakwater construction may have negative impacts on fish populations (Goforth et al. 2005, Meadows et al. 2005). Pollution, including discharges, spills and agricultural runoff apply direct stresses to the organisms of the nearshore area. The presence of exotic species directly changes the fish community structure and often displaces native species of the nearshore zone Minns et al. 1994). Evident changes in littoral ecosystems have been linked with the stressors associated with anthropogenic changes. For example, there is a strong correlation between highly developed shorelines and the loss of nearshore habitats as well as deterioration of water quality (SOLEC 1996, Meadows et al. 2005).

The type of shoreline modification varies with the type of development. Large commercial and industrial developments such as marinas and docks have a serious localized impact on nearshore environments. Waukegan Harbor is located on the Illinois shoreline and is dredged every 1-5 years. The sand-mud mixture is dumped near the shoreline and these spoils, resulting from the dredging, could degrade spawning substrate or suffocate egg skeins in this area (Robillard and Marsden 2001). Large developments are often reserved for urban areas which make up only a small percentage of Lake Michigan's total shoreline. The connection between large-scale development in urban areas and pollution has attracted attention and subsequently, a body of research around these areas. Examples include the Environmental Protection Agency's listing of Areas of Environmental Concern (AOCs), and the federal requirement for Environmental Impact Statements for major development projects. The ownership of the majority of the shore of Lake Michigan, however, is in the hands of private citizens. Many shoreline residents harden their shoreline by building seawalls to control erosion in front of their property. The Lake Michigan shoreline is continually receiving pressure from second homeowners wanting to build a weekend getaway (U.S Department of the Interior 1994).

Coastal structures introduce wave diffraction, reflection, and forced breaking which upsets the equilibrium profiles of shorelines (Meadows et al. 2005). Effects of shoreline armoring have been more clearly demonstrated on the physical processes of the lake than on the biological processes. Given what is known about the inter-connectedness of ecosystems, however, the biological impacts from shoreline development can be theorized. Alterations in littoral drift can change the types of habitats for nearshore species, e.g. the surficial substrate, macrophytes, and water depth. Increased wave energy resulting from a seawall can change suspended sediment load and affect turbulence, which ultimately alters primary production as well as foraging success of fish larvae (McKenzie and Kiørboe 2000). Exaggerated sediment deposits can cut off corridors to wetlands or tributaries. The deposition of fine clast over coarse substrate such as cobble and gravels can degrade spawning and nursery habitat. Furthermore, effects of development can decrease habitat variability which can in turn decrease species diversity. Another problem associated with development is that shorelines are often straightened, removing irregularities along the shore, which changes the longshore currents and eventually reduces variation in lake beds (SOLEC 1996, Meadows et al.

2005).

Fluctuations in lake levels result from climate conditions, geologic activities and anthropogenic influences (Sellinger 1999). For the last 3,500 years, Lake Michigan's water level has ranged from 0.5 to 1.0 meters above and 0.5 meters below the historical average (Thompson and Baedke 1999). The nearshore areas that are exposed during low water level periods are more vulnerable to alterations. A climate model run by Kunkel et al. (2002) predicts a decline in lake levels during this century. Climate change has the potential to intensify changes in the nearshore zone, because warmer periods are associated with lower water levels due to a decrease in precipitation and an increase in evaporation (Larson 1999, Lofgren et al. 2002).

The majority of pollutants in Lake Michigan enter the lake through the nearshore zone. Discharges of municipal and industrial wastes from tributaries, shoreline discharges and surface runoff have degraded portions of Lake Michigan's littoral habitats (Edsall and Charlton 1997). In addition, agricultural runoff is a source of increased sediment inputs as well as annual loadings of herbicides and nutrients. Thermal-electric plants also are a threat to nearshore ecosystems, because they can increase water temperatures between 4°C and 20°C and can entrain and kill larvae, juveniles and small fish species (Edsall and Charlton 1997). One study in Lake Michigan showed that thermal-electric plants killed more than 75 billion fish eggs and larvae (Jensen et al. 1982).

The presence of exotic species impacts the ecology of the littoral zone and the waters around them. They are particularly a threat in these waters, because they are more abundant in nearshore waters than in offshore waters. Alewives use the nearshore area as spawning, nursery, and feeding areas and have caused major changes in the plankton community (Wells 1970). The increase in alewife populations may have negatively affected populations of other fishes using nearshore habitats such as lake whitefish, walleye, yellow perch, emerald shiner and rainbow smelt (Potter and Fleisher 1992). Ruffe also pose a threat to native nearshore species. Ruffe have similar diets and habitat requirements as yellow perch and their presence may result in interference competition (Savino and Kolar 1996; Fullerton et al. 1998). Exotic zooplankton species such as *Cercopagis pengoi*, and *Bythotrephes longimanus* may affect the survival and recruitment of larval yellow perch and alewife through effects on fish prey (Schulz and Yurista 1999; Creque and Dettmers 2003). Finally, the presence of zebra mussels may decrease the amount of food to planktivorous fish and cause substantial changes in the food web by removing phytoplankton and the smaller zooplankton from the water (Edsall and Charlton 1997).

Nearshore habitats play critical roles in the production of Lake Michigan's fishery. However, these areas have not been well studied and the impacts of human changes are not entirely understood. Until a more solid understanding is developed of the relationship between shoreline developments and nearshore habitats, alterations of littoral habitats will continue. The knowledge gap should be addressed so that natural littoral processes and habitats can be protected.

Significant nearshore habitats

Figure 6. Nearshore area

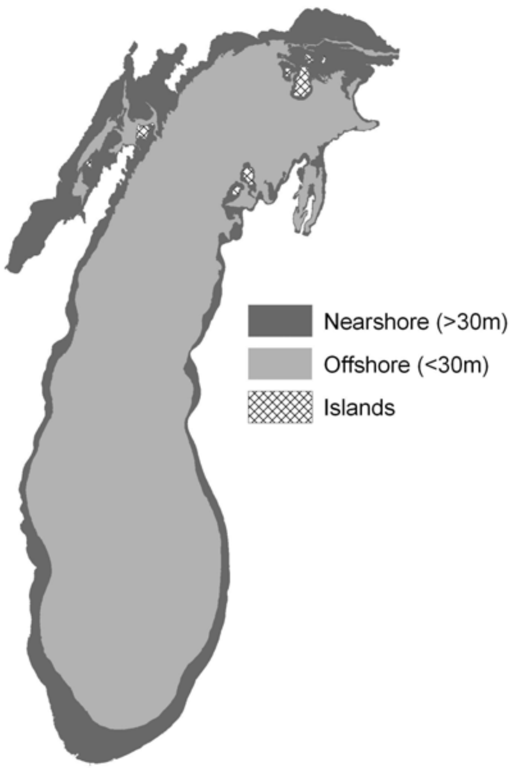


Figure 7. Degree of shoreline protection

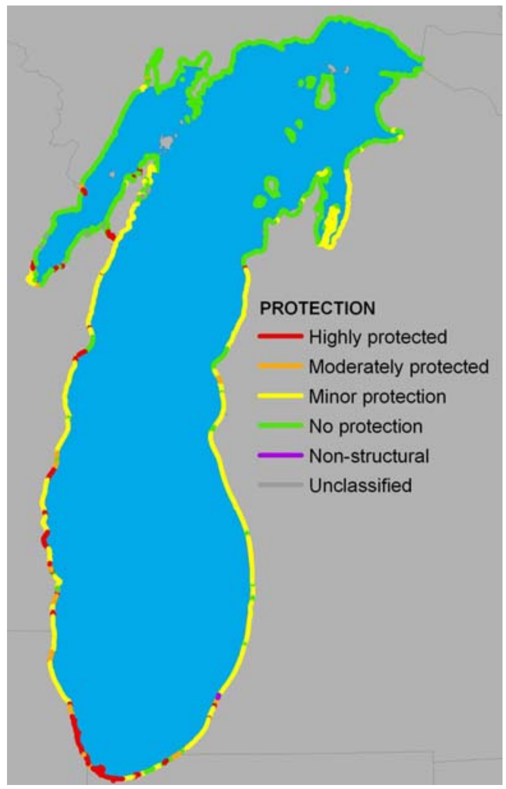
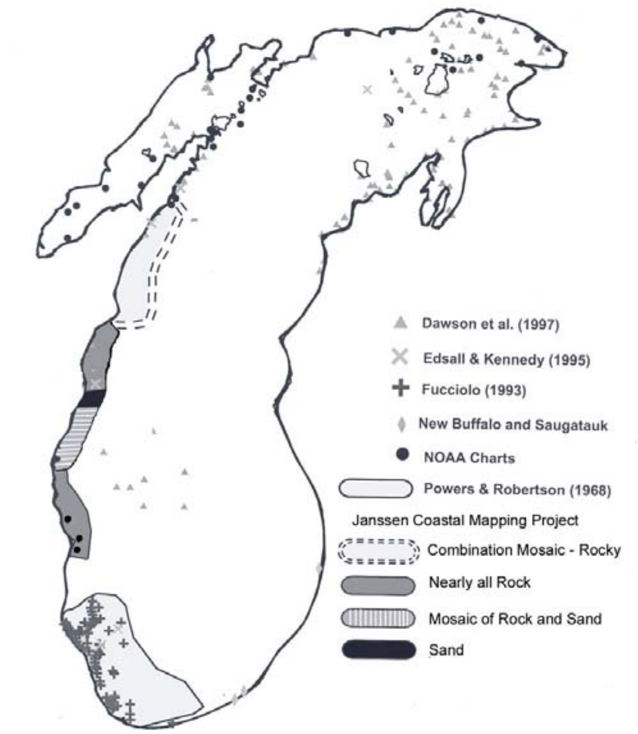


Figure 8. Rocky habitats in Lake Michigan (Janssen et al. 2004).



Summary of Data and Current Initiatives

Limited studies have been conducted that illustrate the linkages between anthropogenic environmental changes and fisheries production in the Great Lakes. Goforth and Carman (2005) related relative abundance (CPUE) of fish communities and their zooplankton and benthic prey to shoreline properties. Compared to sites with stable hard, bottom substrates or undeveloped sandy shoreline, fish CPUE was lower in nearshore areas adjacent to developed, mid-bluff shorelines and at sites with less stable substrates. Reduction in natural sediment transport and deposition processes caused by artificial structures were conducive to invasion by lithophilic species including non-native zebra mussels and round gobies (Goforth and Carman 2005, Meadows et al. 2005). In other Great Lakes, Minns et al. (1994) developed an index of biotic integrity for fish assemblages in the littoral zone of Areas of Concern, and demonstrated the index was sensitive to varying levels of ecosystem degradation.

The U.S. Army Corps of Engineers (ACOE) has funded extensive research projects describing the impacts of coastal development on erosion rates. The best available digital data on nearshore habitat types and distribution in the Great Lakes comes from the ACOE. Lake Michigan's nearshore zone is characterized by a variety of shore types ranging from high bluffs to low coastal wetlands (GLERL 1997). The predominant shore type along Lake Michigan is that of sandy beaches. Table 3 categorizes the major geomorphic shoreline classes and their relative abundance in Lake Michigan. The majority of the sandy beach shore along Lake Michigan has been formed by glacially deposited sands and gravels and then reformed by winds. The southern shore has a gently sloping nearshore zone and is dominated by lake plain, low bluffs, and sand dunes. The subaqueous zone is primarily sand and sand/gravel lag over clay (ACOE; Robillard and Marsden 2001). The northern shore has a more diverse geology with several types of exposed bedrock, coarse substrate beaches and sand dunes as well as extensive complexes of coastal wetlands (ACOE).

Table 3. Great Lakes shoreline geomorphic classes and calculated percent shore

Shore Type	% shore	Shore Type	% shore
Sandy Beach / Dunes	53	High (>15m) and Low (<15m) Bluff	5
High and Low Bluff with Beach	10.5	Wetlands	4
Baymouth-Barrier beaches	8	Bedrock (resistant)	3.5
Bedrock (non-resistant)	7	Coarse Beaches	1.5
Unclassified	6.5	Artificial	1

Although Lake Michigan has a low percentage of total artificial shoreline, the remaining natural shoreline has some degree of protection by small localized structures (Higgins 1998). For example, the sandy beaches along the eastern shore are classified as a natural geomorphic type, although they are often protected with erosion control structures such as groins and jetties. These types of stabilization structures redirect wave energy and interfere with the coastal erosion and nourishment processes associated with the natural state of the shore (Terich 1987, Meadows et al. 2005). The southern shore is the most heavily developed and protected in the basin where urbanization is concentrated, whereas the less developed northern shore is mostly natural, unprotected shoreline (Fig. 7, Table 4).

Table 4. Percent of unprotected shoreline in Lake Michigan's nearshore zone (from Higgins et al. 1998)

Zone name	Total length (km) of shoreline	Length (km) of unprotected shoreline	Percent unprotected
Northeast Island & Outflow region	1027.57	1006.78	98
Northern Basin	780.22	453.38	58
Green Bay	748.05	610.85	82
Traverse Bay	224.33	94.73	42
Southern Basin	614.73	34.06	6

Few studies have demonstrated linkages between natural and human-induced alterations to nearshore habitat and fisheries in the Great Lakes. More is known about how species use vegetated areas for spawning, nursery and feeding grounds than how they use open nearshore areas for the same functions (for more information on vegetated coastal areas see the coastal wetland section in this document). Creque and Dettmers (2003) related variation in abiotic and biotic variables to variability in year-class strength of nearshore fishes in the Illinois waters of Lake Michigan. Their study showed that the mechanisms influencing fish assemblages and recruitment may vary temporally and operate at localized scales (<100m). Water temperature and zooplankton abundance and composition may be factors affecting growth and abundance of larval fish in nearshore waters.

Efforts are underway to map and classify nearshore habitats. Waples et al. (2005) used multi-beam and single-beam sonar in conjunction with SCUBA to map nearshore habitats in western Lake Michigan. Mackey and Liebenthal (2005) developed a method to classify and map nearshore substrate distribution by using side-scan sonar, GPS and GIS technologies. They studied five Great Lake sites between 1999-2000, including sites in Lake Michigan, and showed substrate changes ranging anywhere from 9 to 31 percent per year at the sites. This evidence suggests that nearshore habitats are continually being created and destroyed and could have significant biological repercussions (Mackey and Liebenthal 2005). Albert et al. (2005) developed a hierarchical classification scheme for nearshore wetlands of the Great lakes including Lake Michigan. The wetlands were classified into three hydrogeomorphic classes including riverine, lacustrine and barrier-protected, then further divided by physical features and geologic processes. The wetland classes have associated animal and plant communities and specific physical attributes related to flow, sediment type, wave energy, water quality and hydrology (Albert et al. 2005). Researchers at the USGS Great Lake Science Center are using gap analysis to develop a coastal habitat classification system (Morrison et al. 2003).

Impacted Species

Lake Michigan's nearshore waters support almost all Great Lakes fishes at least some time during their life cycle (Edsall and Charlton 1997). These areas are the sites of important spawning, nursery and forage habitats for Lake Michigan's fisheries. Yellow perch and smallmouth bass are two of the important sport fishes that reside primarily in nearshore waters. Prey species including alewife and Cyprinids are concentrated in the nearshore area (Janssen and Luebke 2004). Nearshore areas, especially near mouths of natal tributaries are important for Chinook salmon, coho salmon, rainbow trout, and walleye. Studies have shown that nearshore waters in east central Lake Michigan appear to be important habitat for young Chinook salmon during their first summer after outward migration (Elliott 1994).

Yellow perch comprise 85 percent of all recreational sport fish caught in nearshore waters in Lake Michigan (Great Lakes Fishery Commission 1995). The rocky substrate on the west side of the lake (Fig. 8) provides the best spawning habitat for adult yellow perch (Robillard and Marsden 2001, Janssen et al 2005), and important foraging habitat for both juvenile yellow perch and adult alewives (Janssen and Luebke 2004). These rocky nearshore areas of the lake have been shown to be heavily populated in spring by yellow perch (Robillard and Marsden 2001). Over a recent 10-year period (1988-1997), yellow perch and alewife larvae comprised 90% of all larval fish collected in the nearshore waters of southwestern Lake Michigan (Creque and Dettmers 2003). Not only is yellow perch the most important nearshore sport fish in Lake Michigan, but it also serves as a significant ecological link between the nearshore and pelagic food webs.

Despite its former abundance, yellow perch have experienced dramatic declines in the past decade (Francis et al. 1996).

Information and Research Needs

Information and research needs as they relate to the environmental objective to protect nearshore habitats.

- Evaluate ecological functions and dynamics of nearshore ecosystems.
- Determine function and map the distribution of critical nearshore habitats.
- Determine appropriate scales for assessing, managing, protecting, restoring, and collecting data in nearshore ecosystems.
- Understand the links between geomorphic and biological processes.
- Determine the influence of water level fluctuations and climate change on nearshore habitats.
- Examine the effects of shoreline hardening on sediment transportation and consequential changes in fish habitats.
- Quantify spatial and temporal variation in the availability, stability, and resilience of critical nearshore fisheries habitats.

Status of Environmental Objective # 4-
Protect nearshore habitats, processes and water quality

Species	Impediment to achievement	Problems/issues to be addressed
Walleye Yellow perch Smallmouth bass Forage fish Benthos Phytoplankton	Yes	Loss and degradation of habitat through: Dredging Diking and infilling Shoreline armoring, second home development Urban and agricultural runoff Lake levels Exotic species
Lake trout Lake whitefish	Potentially	Degradation of nearshore spawning reefs
Trout and Salmon	Inconclusive	

Yes	Data exists documenting an impediment to achievement of the FCO
Potentially	Available data are inconclusive, but suggest a potential impediment
Inconclusive	Available data suggest neither an impediment or no impediment
Unlikely	Available data are inconclusive, but suggest that there is no impediment
No	Available data document no impediment

Environmental Objective # 5

Protect and restore fish community structure by promoting native species abundance and diversity and avoid further exotic species introductions

Relevant Fish Community Objectives

Fish Community Objectives	Importance of Environmental Objective
• Salmonine Objective *Establish a diverse salmonine community capable of sustaining an annual harvest of 2.7 to 6.8 million kg (6 to 15 million lbs), of which 20-25% is lake trout.*	Maintenance of a diverse salmonine predator community will control non-native planktivores such as rainbow smelt and alewife, which should enhance survival and diversity of native planktivores and lake trout.
• Planktivore Objective *Maintain a diversity of planktivore (prey) species at population levels matched to primary production and to predator demands. Expectations are for a lake wide planktivore biomass of 0.5 to 0.8 billion kg (1.2 to 1.7 billion lbs).*	Planktivore species depend upon adequate production of large-bodied zooplanktors for growth and survival of young and adult stages. Non-native species such as zebra mussel, alewife and Asian carp may alter biomass, species or size composition of zooplankton which may affect diversity or production of planktivores. Introduction of new non-native predators may disrupt productivity or diversity of planktivores.
• Inshore Species Objective *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 (2 to 4 million lbs) for yellow perch and 0.1-0.2 million kg (0.2 to 0.4 million lbs) for walleye.*	Food web disruption from non-native invertebrate species, and competition or predation from round goby and ruffe may permanently suppress or displace inshore populations of yellow perch, walleye and smallmouth bass through egg or larval predation, and competition for food.
• Other Species Objective *Protect and sustain a diverse community of native fishes, including other species not specifically mentioned earlier (for example, cyprinids, gars, bowfin, brook trout, and sculpins). These species contribute to the biological integrity of the fish community and should be recognized and protected for their ecological significance and cultural and economic values.*	Diverse fish assemblages can strengthen food web stability, and provide early warning signs of impacts on fisheries. Many native species are important to lake fisheries through their role as predators of, or prey for harvested gamefishes. Exotic species disrupt trophic relationships supporting fisheries by competing for food or space, and altering habitat, growth or survival of non-game fishes or harvested fishes.
• Benthivore Objective	Growth and yield of lake whitefish and other

Maintain self-sustaining stocks of lake whitefish, round whitefish, sturgeon, suckers, and burbot. The expected annual yield of lake whitefish should be 1.8-2.7 million kg (4 to 6 million lb).	benthivores are dependent upon stable populations of benthic invertebrates such as mayflies or Diporeia, which are sentinels of ecosystem health. Non-native species have depressed key benthic invertebrates, thereby altering energy flows for benthic species, reducing growth rates of native benthivores, forcing them to switch to less available pelagic resources.
• Physical/Chemical Habitat Objective *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.* *Protect and enhance fish habitat and rehabilitate degraded habitats.*	High quality physical/chemical environments are required to support the food webs that support lake fisheries. Temperature and dissolved oxygen conditions in many tributaries are heavily influenced by land use practices which modify nutrient and sediment loads, and affect temperature and dissolved oxygen.

Background

Biotic integrity of the Lake Michigan fish community has long been recognized by fisheries managers as being important for achievement of fish community objectives. The concept of biotic integrity, as conceived by Karr et al. (1986) for riverine fish communities, was well known to Great Lakes fisheries biologists. Bailey and Smith (1981) provided descriptions of the pre-settlement fish community, and Milner (1874) described pre-1900 fisheries. The history of changes forced by overfishing, environmental degradation and pollution, and non-native species introductions that resulted in loss of stability and productivity of lake fish populations are described by Smith (1968, 1972), Wells and McLain (1973), and Eck and Wells (1987).

Historically, the open waters of Lake Michigan supported a relatively stable and simple fish community. The dominant offshore predator species were the two large piscivores, lake trout and burbot. Offshore planktivore and macrobenthivore species included the coregonid species complex (ciscoes), and deepwater and slimy sculpins. Lake whitefish, in particular were common in Lake Michigan, and were important in the early 1900s commercial fishery. A more diverse fish fauna existed in nearshore waters with walleye, northern pike, and smallmouth bass representing the major predators; lake sturgeon, suckers and channel catfish representing the benthivores; and lake herring, yellow perch, and cyprinids the planktivorous prey species (Table 5) (Wells and McClain 1974).

Introduction of non-native species (Table 5), along with other factors such as over-exploitation and eutrophication, have disrupted the Lake Michigan fish community, and resulted in a reduction in diversity, productivity and biomass of the deepwater fish community (Smith 1972). Lake Michigan has suffered repeated invasions of exotic species since Europeans settled in the area. Sea lamprey, alewives, and rainbow smelt have had the greatest initial impacts on native fish populations in Lake Michigan. Sea lamprey were first recorded in Lake Michigan in 1936 and their establishment was primarily responsible for the near-elimination of lake trout by the 1960's (Coble et al. 1990). The commercial catch of lake trout declined by 95 percent between 1944 and 1949 (Coble et al.1990). Contemporaneous with the erosion of the lake trout populations, alewife and rainbow smelt populations increased. Alewives were first reported in Lake Michigan in 1949 (Miller 1957), and rainbow smelt in 1923 (Van Oosten 1936). As sea lamprey suppressed abundances of the deepwater piscivores (lake trout, burbot) and the large deepwater ciscoes, alewives and rainbow smelt increased. Alewives competed for food resources and consumed young-of-the-year of native fish species. They contributed to the decline of emerald shiners, deepwater sculpin, yellow perch, and bloater (Wells and McLain 1973). Today, alewife and rainbow smelt make up the majority of the diets of lake trout, Chinook salmon and walleye. The dependence on alewife as prey may have compromised the reproductive ability of these important piscivore species. For example, lake trout egg survival likely has decreased as a result of Early Mortality Syndrome (EMS) which results from a thiamine deficiency caused by high consumption of alewives (Fitzsimons et al. 1999). Alewives also suppress natural reproduction of native species including walleye (Day 1991), yellow perch (Mason and Brandt 1996), and lake trout (Krueger et al. 1999) by preying upon their fry.

Efforts to control sea lamprey, alewife and rainbow smelt populations have been implemented with moderate success in the Great Lakes. Lampricide (3-triflurormethyl-4-nitrophenol, or TFM) treatments began in the 1950s and reduced the abundance of adult sea lamprey in Lake Michigan by 80-90% by 1966 (Lavis et al. 2002). Stream lampricide treatments continue to be the primary strategy for controlling sea lamprey populations today, and average lamprey-induced annual mortality of lake trout has remained relatively low in the past 25 years (Lavis et al. 2002). The Great Lakes Fishery Commission implements an integrated pest management plan for sea lamprey through stocking of sterile males, trapping, barriers, and chemical treatments. Massive stocking of salmonines began in 1965 to control the abundance of alewives and provide a sport fishery (Madenjian et al. 2002). The stocking program has been effective in regulating alewife populations as their abundance decreased in the 1970s, and have not increased greatly since (Madenjian et al. 2002). Management agencies annually spend millions of dollars to support the programs that manage these exotic species.

Table 5. Representative fish and macroinvertebrate species in the Lake Michigan food web

Common name	Scientific name	Entry mechanism
Piscivores		
Lake trout	*Salvelinus namaycush*	Native
Burbot	*Lota lota*	Native
Chinook salmon	*Oncorhynchus tshawytscha*	Deliberate release
Coho salmon	*Oncorhynchus kisutch*	Deliberate release
Steelhead trout	*Oncorhynchus mykiss*	Deliberate release
Brown trout	*Salmo trutta*	Deliberate release
Northern pike	*Esox lucius*	Native
Walleye	*Sander vitreus*	Native
Benthivores		
Lake whitefish	*Coregonus clupeaformis*	Native
Deepwater sculpin	*Myoxocephalus thompsonii*	Native
Slimy sculpin	*Cottus cognatus*	Native
Yellow perch	*Perca flavescens*	Native
Bloater	*Coregonus hoi*	Native
Lake Sturgeon	*Acipenser fulvescens*	Native
Suckers	*Catostomidae*	Native
Planktivores		
Yellow perch	Perca flavescens	Native
Lake herring	Coregonus artedii	Native
Shiners	Cyprinidae	Native
Macroinvertebrates		
Amphipods	*Diporeia*	Native
Opossum shrimp	*Mysis relicta*	Native
Exotics		
Sea lamprey	*Petromyzon marinus*	Unintentional canal entry
Alewife	*Alosa pseudoharengus*	Unintentional canal entry
Rainbow smelt	*Osmerus mordax*	Deliberate release
Ruffe	*Gymnocephalus cernuus*	Ballast water introduction
Round goby	*Neogobius melanostomus*	Ballast water introduction
Spiny water flea	*Bythotrephes longimanus*	Ballast water introduction
Fishhook water flea	*Cercopagis pengoi*	Ballast water introduction
Zebra mussel	*Dreissena polymorpha*	Ballast water introduction
Quagga mussel	*Dreissena bugensis*	Ballast water introduction

Issues

Other new species have continued to invade Great Lakes ecosystems and compete for food and habitat with native species. The zebra mussel, a small bivalve native to the Black, Caspian, and Azov seas (Griffiths et al. 1991) was first recorded in Lake Michigan in 1989 near Chicago, and has since spread throughout the nearshore areas of Lake Michigan (Marsden et al. 1993). The related dreissenid Quagga mussel (Dreissena bugensis) occurs in deeper waters and has displaced zebra mussels where they overlap. Zebra mussels have made a significant impact on the benthic macroinvertebrate populations of Lake Michigan, and have altered the species composition of phytoplankton available to zooplankton. Zebra mussels selectively feed on diatoms and filamentous green algae, rejecting blue-green species which tend to bloom later in summer (Vanderploeg et al. 2001). Where they occur, zebra mussels have increased water clarity which stimulates growth of benthic algae and macrophytes. Although there is no direct linkage between occurrence of zebra mussels and loss of Diporeia, Diporeia have declined drastically in Lake Michigan, particularly in the southern basin (Nalepa et al. 1998). Diporeia are the favored prey of lake whitefish, sculpin species, and other benthivores. Disappearance of Diporeia has forced a shift in diets of lake whitefish to zebra mussels and other benthic invertebrates, with a loss in whitefish condition and growth (Pothoven et al. 2001).

The invasion of zebra mussels has facilitated invasion of other Ponto-Caspian invaders in what Ricciardi (2001) has described as an invasional meltdown. The availability of zebra mussel provided habitat for the non-native amphipod *Echinogammarus ischnus*, which competes directly with native Gammarus species. Zebra mussels also serve as prey for the round goby (*Neogobius melanostomus*), which were first reported in 1994 in Chicago (Janssen and Jude 2001). Round gobies are known to impact native sculpin and darter species through egg predation and competition for space (Jude 1997). They also prey on lake sturgeon and lake trout eggs, but are prey for adult lake sturgeon, smallmouth bass, yellow perch and walleye (http://www.dnr.state.oh.us/wildlife/PDF/estatus2003.pdf). Both round goby and Echinogammaus have expanded where zebra mussels occur. In contrast, tubenose gobies *Proterorhinus marmoratus* do not utilize zebra mussel as forage, and have been confined to Lake St. Clair and Lake Erie.

Eurasian ruffe were found in Lake Michigan in Bay de Noc during 2002. Ruffe could displace native species such as yellow perch, spottail shiner, and trout-perch because of its ability to tolerate a wide range of environmental conditions, its high reproductive rate and characteristics such as spiny rays that may discourage predators such as walleye and pike (Ogle 1998).

Zooplankton invaders also have affected the food web. The spiny water flea (*Bythotrephes longimanus*) and fishhook water flea (*Cercopagis pengoi*) are predaceous zooplanktors that prey on *Cladocera* favored by larval stages of fishes including cyprinids, yellow perch, and walleye (Lehman 1991, Vanderploeg et al. 2002). Juvenile salmonids, yellow perch and walleye have been shown to consume *Bythotrephes spp* (Elliott 1994*)*, but the nutritional value and the suitability of *Bythotrephes* spp as a food source for these species is not clear.

Ballast water and canals have been the primary vectors by which aquatic invasive species have entered the Great Lakes. Although there have been attempts by state and federal lawmakers to prevent further introductions into the Great Lakes, ballast water discharge is the greatest contributor of new aquatic nuisance species into the Great Lakes (Grigorovich et al. 2001). Recent research has focused on tradeoffs of using biocides to treat ballasted and un-ballasted ships with the potential harm caused by the chemicals on the environment (http://www.glerl.noaa.gov/res/Task_rpts/2003/nsland10-2.html). A bill passed by the State of Michigan in May 2005 requires ocean ships to kill ballast water invasive species (HB 4603 and SB 332).

Threats of new exotic species introductions to Lake Michigan are difficult to predict. Asian carp species, which include the bighead carp and silver carp, were accidentally released into the Mississippi River and could enter Lake Michigan via the Chicago Sanitary and Ship Canal. Currently, the Asian carp are only 28 miles downstream of an electric barrier that has been installed to prevent lake-ward migration <http://www.epa.gov/glnpo/invasive/asiancarp/index.html>. Asian carp are well-suited to cold water climates, and pose a significant threat to Lake Michigan fisheries because their large size, high fecundities and high weight-specific consumption rates would pose serious competition for limited food resources with sport and commercial fishes and their prey.

Summary of current and historic data

Status of food webs supporting Lake Michigan fisheries is monitored by multiple federal and state agencies. Fish community information is monitored by fisheries resource agencies in the states surrounding Lake Michigan (Michigan, Indiana, Illinois, Wisconsin), the United States Geologic Survey Great Lakes Science Center (USGS-GLSC) and US Fish and Wildlife Service (USFWS). Sportfish harvest data are monitored by all state resource agencies. Commercial harvest data are monitored by the state resource agencies, and the Inter-tribal Fisheries and Assessment Program of the Chippewa/Ottawa Resource Authority (CORA). Annual assessments of the offshore fish community at specific locations are reported by Michigan Department of Natural Resources and USFWS. Prey fish abundance is monitored though hydroacoustic and trawl surveys by USGS-GLSC, and by trawl or electrofishing surveys conducted by state resource agencies. Benthic invertebrate prey abundance for fishes is monitored by NOAA Great Lakes Environmental Research Laboratory (NOAA GLERL). Zooplankton prey densities and species composition are monitored by US EPA in offshore waters, and in southern Lake Michigan by NOAA GLERL. Phytoplankton species composition and biomass are monitored by US EPA. Efforts are underway to expand monitoring of forage fishes to the entire lake. With better lake coverage, efforts to develop lake wide estimates of sport fish prey items and their prey (eg. Figure 9) will improve.

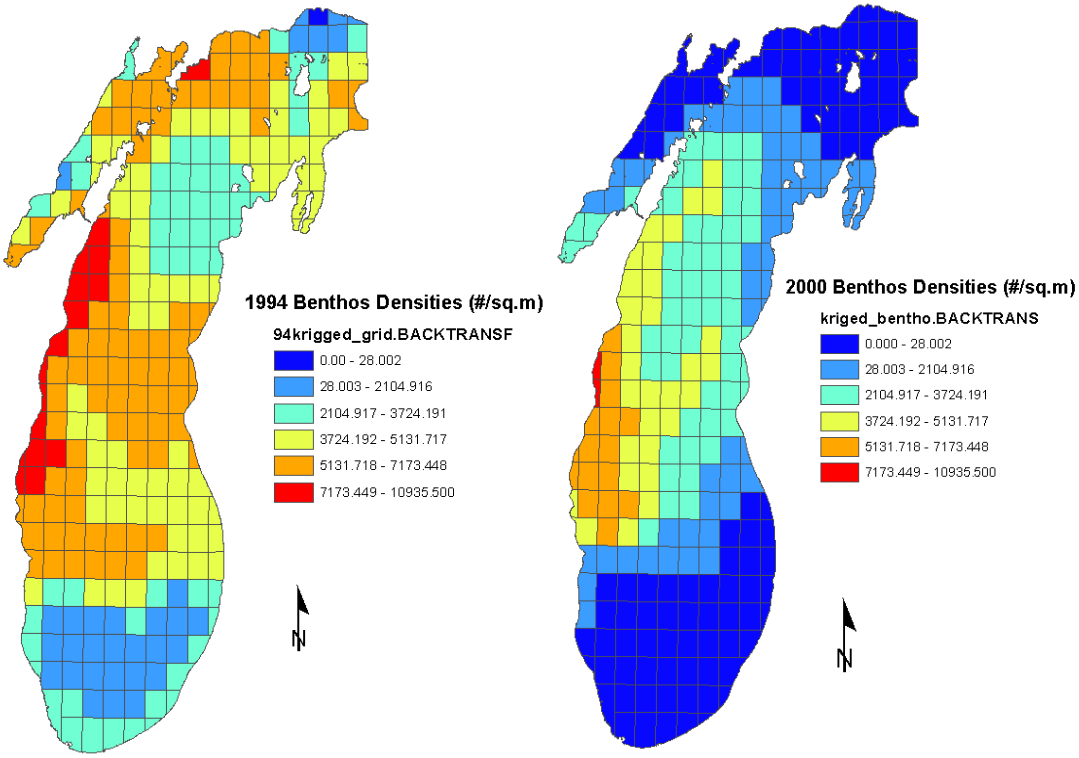
Approaches to monitoring exotic species are not consistent within Lake Michigan or across the Great Lakes. The sea lamprey monitoring and control program is centralized at the Great Lakes Fishery Commission (GLFC) which coordinates and funds these efforts. The USFWS conducts the sea lamprey control program for the GLFC through chemical treatment, tributary barriers, lamprey traps, and sterile-male release. Nearshore monitoring of exotics is not centralized, but is conducted by state or university personnel with annual surveys or through extended research projects. David Jude of The

University of Michigan and John Janssen of The University of Wisconsin, Milwaukee have studied invasion progress of round and tubenose gobies. Invasion progress of benthic invertebrates has been monitored by NOAA GLERL. Fish surveys conducted by Ball State University in Indiana waters and the Illinois Natural History Survey in Illinois waters have tracked abundance of exotic species in southern Lake Michigan.

An historic assessment of habitat and food webs supporting Lake Michigan fisheries was compiled through the US EPA mass balance study (LMMB: <http://www.epa.gov/glnpo/>), which sought to track the sources, sinks and pathways of contaminants through the food web. An imbalance between trophic demand by Lake Michigan salmonines and their planktivore prey base was hypothesized to have led to the Bacterial Kidney Disease (BKD) outbreak and subsequent decline in survival and harvest of Lake Michigan Chinook salmon (Stewart et al. 1981, Stewart and Ibarra 1991, Madenjian et al. 2002, Benjamin and Bence 2003). As a consequence, resource management agencies reduced stocking of Chinook salmon by 27% starting in 1999 to lower probability of a reoccurrence of the BKD outbreak.

A host of scientists are investigating food web disruption supporting Great Lakes fisheries. Shuter and Mason (2001) summarized existing mechanism of food web disruption and suggested fruitful avenues for research. Henry Vanderploeg, Thomas Nalepa and Steven Pothoven (NOAA GLERL), John Lehman (UM) and Gary Lamberti and David Lodge (Univ. Notre Dame) are monitoring spread and food web disruption by exotic invertebrate invaders in Lake Michigan. John Janssen (Univ. Wisconsin Milwaukee), and David Jude (UM), are monitoring status and trends in exotic fish species distributions. Related research on exotic species impacts is being conducted on other Great Lakes (A. Sarnelli, Michigan State University; Edward Mills, Cornell University.; Kim Schulz, Syracuse University; Timothy Johnson, OMNR; Hugh MacIsaac and Lynda Corkum, University of Windsor).

Figure 9. Interpolated densities (No./m^2) of Diporeia spp. in Lake Michigan 1994 and 2000. Data provided by Thomas Nalepa (NOAA GLERL).



Information and Research Needs

Information and research needs as they relate to the environmental objective to protect and restore fish community structure.

- Identify positive and negative effects of exotic species introductions on the Lake Michigan ecosystem.
- Determine effects of zooplankton density, size structure, and/or taxonomic composition on recruitment of yellow perch.
- Determine how inter- and intra-species dynamics of exotic species influence the dynamics and species composition of the Lake Michigan ecosystem.
- Determine stock structure, population dynamics and forage demand by the fish species comprising the inshore fish community.

- Determine how changes in species and biomass composition within inshore and/or open-water zooplankton populations influence prey fish biomass and energy flow between trophic levels.

Status of Environmental Objective # 5-
Protect and restore fish community structure by promoting native species abundance and diversity and avoid further exotic species introductions.

Species	Impediment to achievement	Problems/issues to be addressed
Lake trout Lake whitefish	Yes	Egg predation by alewives and round gobies Changes in diet because of declines in Diporeia and their effects on body condition
Sculpin	Yes	Egg predation and competition for habitat by round gobies.
Walleye Yellow perch	Yes	Competition for food resources and native species; fry predation by alewives; Competition for food and habitat by Eurasian ruffe
Zooplankton	Yes	*Bythotrephes longimanus* and *Cercopagis pengoi* prey on native *Cladocera*
Diporeia	Potentially	A link between increases in Zebra mussels and declines of Diporeia?

Yes	Data exists documenting an impediment to achievement of the FCO
Potentially	Available data are inconclusive, but suggest a potential impediment
Inconclusive	Available data suggest neither an impediment or no impediment
Unlikely	Available data are inconclusive, but suggest that there is no impediment
No	Available data document no impediment

Environmental Objective # 6-
Protect and restore water quality

Relevant Fish Community Objectives

Fish Community Objectives	Importance of Environmental Objective
• Salmonine Objective *Establish a diverse salmonine community capable of sustaining an annual harvest of 2.7 to 6.8 million kg (6 to 15 million lbs), of which 20-25% is lake trout.*	Lake trout and other salmonid species have consumption advisories of various levels due to bioaccumulation of contaminants. Contaminants are also suspected in having contributed to lake trout recruitment failures.
• Planktivore Objective *Maintain a diversity of planktivore (prey) species at population levels matched to primary production and to predator demands. Expectations are for a lake wide planktivore biomass of 0.5 to 0.8 billion kg (1.2 to 1.7 billion lbs).*	Nutrification can result in oxygen depletion of bottom waters, nuisance algal blooms or accumulations, and decreased water clarity thus degrading the habitat of prey species.
• Inshore Species Objective *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 (2 to 4 million lbs) for yellow perch and 0.1-0.2 million kg (0.2 to 0.4 million lbs) for walleye.*	Yellow perch, walleye, smallmouth bass, northern pike, catfish and panfish all have consumption advisories resulting from nearshore contamination of water and sediments. Nearshore habitats are degraded from nutrient enrichment and sedimentation from watershed runoff and erosion.
• Benthivore Objective *Maintain self-sustaining stocks of lake whitefish, round whitefish, sturgeon, suckers, and burbot. The expected annual yield of lake whitefish should be 1.8-2.7 million kg (4 to 6 million lb).*	Lake whitefish have varying levels of consumption advisories resulting from contaminant levels of PCBs and Dioxins in parts of Lake Michigan.
• Physical/Chemical Habitat Objective *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 overall water quality of Lake Michigan has shown signs of improvement in the past two decades. However, localized nearshore and tributary habitats in the Areas of Concern are still severely degraded. Land use changes continue to alter natural shorelines, wetlands and tributaries and increase threats to water quality.

Protect and enhance fish habitat and rehabilitate degraded habitats.	

Background

The water quality of Lake Michigan is influenced by activities in its drainage basin, its connecting tributaries and the open water, as well as the residency time of the lake's water. The Lake Michigan drainage basin comprises 45,600 square miles of land from the states of Michigan, Wisconsin, Indiana and Illinois and has the second longest retention time of the Great Lakes, up to 99 years (EPA 1995). Lake Michigan only has one natural outlet; the long water retention time is due to water having to both enter and exit via the Straits of Mackinac. The Chicago River formerly flowed into Lake Michigan, but in 1900 the river course was reversed, and today the Illinois Waterway serves to link Lake Michigan with the Mississippi River.

Lake Michigan's water quality varies regionally owing to differences in geology, latitude, hydrology, and land use. The environmental quality has been shown to deteriorate from the northern to the southern end of the lake. The northern part of the lake has more forested land and less development, agriculture and population density than the rest of the basin. It also has colder water temperatures as a function of higher latitudes. Green Bay is the western arm of Lake Michigan and its largest bay. Green Bay is separated from the lake by the Door and Garden peninsulas and is approximately 100 miles long. Green Bay has a highly productive fishery but also receives inputs from a number of pulp and paper mills. The southern basin is one of the most urbanized and populated areas in the Great Lakes, with industrialized cites of Gary, Chicago, and Milwaukee along the southern shore.

Degradation of the lake's water quality began with settlement and land use change. Agricultural development, forestry, urbanization, domestic and industrial waste discharges, and oil and chemical spills began to degrade the physical condition of the ecosystem as well as threaten the health of the human population in the Lake Michigan basin. In the late 1960's, eutrophication due to excessive inputs of nutrients was identified as a problem (IJC 1969). Phosphorus inputs were increasing from municipal and industrial wastes and urban and agricultural runoff (Neilson 1995). In response to the high nutrient loadings, The Great Lakes Water Quality Agreement Act (GLWQA) was enacted in 1972 as a bi-national commitment to restore and maintain the chemical, physical and biological integrity of the Great Lakes basin ecosystem. The act was revised in 1978 and 1987 and mandated that best management practices be developed to control all sources of pollutants. In the past twenty years, levels of toxic pollutants have decreased, but pollutants still have negative impacts on the physical and biological processes of Lake Michigan (EPA 1995). Some of these impairments include declines in abundance of fish, benthos and phytoplankton populations, loss of fish habitat, fish tumors, and restrictions on fish consumption (Koonce 1995).

Issues

Degradation of water quality affects the biological productivity of Lake Michigan's ecosystem. Nutrification, sedimentation and contamination are functions of natural as well as human activities and contribute to changes in the food web. Land use changes, point and non-point discharges, and air emission deposition jeopardize the water quality of the lake.

The availability of nutrients in the water column plays an important role in the lower trophic level of the food web. Nutrients are necessary for regulating the planktonic communities and maintaining the lake's production. Increased nutrient levels can result in eutrophication leading to an unbalanced ecosystem. Increases in nutrients lead to an increase in aquatic plant and algae production, a depletion of the water's dissolved oxygen content resulting from plant decay and oxygen uptake during algal blooms. In addition, increased turbidity from algae reduces the amount of light penetrating the water and decreases the growth of submergent vegetation which can result in a loss of habitat for fish and other aquatic organisms.

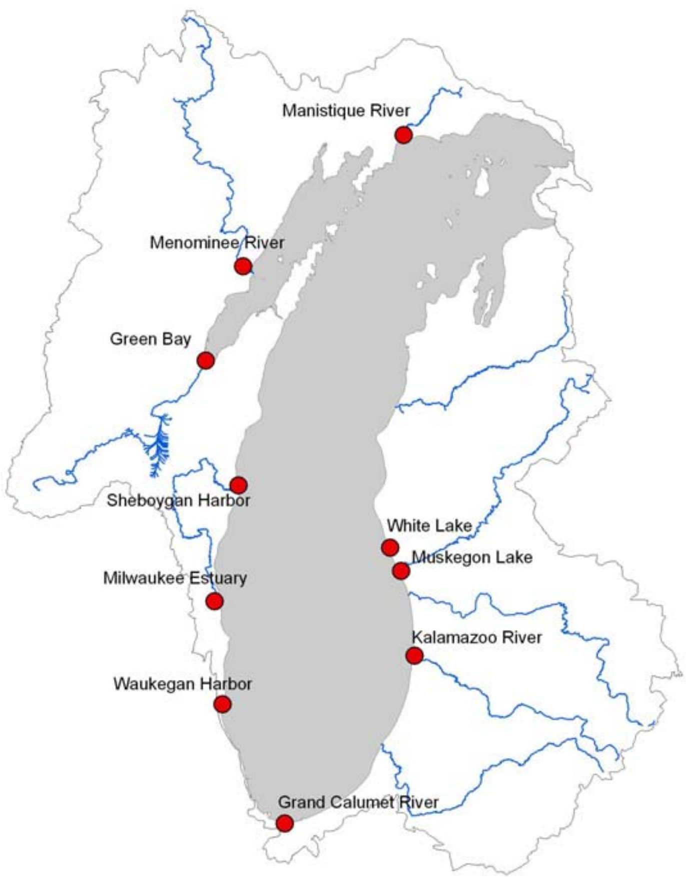
Phosphorus has the greatest potential to affect the lake's ecosystem by acting as a catalyst for eutrophication. Regulation of phosphorus through decreasing point sources from major water treatment plants, and bans on phosphorus in detergents have been a successful management strategy to control eutrophication (Johengen et al. 1994; Barbiero et al. 2002). Since 1981, phosphorus loadings in Lake Michigan have been below target loads set by the GLWQA of 5600 metric t/y (Neilson 1995), while increased chloride, nitrogen and silica concentrations have resulted from both increased loadings and biological cycling (Warren and Kreis 2005). In nearshore waters, zebra mussels (and more recently quagga mussels) are thought to have changed the dynamics of phosphorus cycling and increased water clarity, which along with increased tributary loadings of phosphorus from agriculture and urban areas is stimulating blooms of Cladophora, a benthic algae (Hecky et al. 2004). The consequences of algal blooms for fisheries are potential degradation of nearshore spawning and nursery habitat, and harm to social concerns including tourism, and angling nearshore.

Sedimentation of nearshore habitats is a water quality issue attributed to natural forces, but exacerbated by human activities. The expansion of urban development around the lake increases surface runoff and magnifies erosion in concentrated patterns. Agricultural practices such as tilling and overgrazing expose large areas of soil to wind and water erosion. Sedimentation can cloud water clarity, which reduces the growth of submerged aquatic vegetation, degrades fish spawning areas and food sources, and acts as a medium to transport and retain pollutants (Edsall and Charlton 1997).

Contaminants in the lake basin pose serious threats to the health of the Lake Michigan ecosystem. The various activities occurring in the Lake Michigan basin such as urban, industrial and agricultural land uses have left a legacy of contaminants in the lake. The most severely degraded areas in the lake are identified as Areas of Concern (AOCs). The GLWQA defines AOCs as areas that fail to meet the objectives of the agreement and impair beneficial use of the area's ability to support aquatic life. Lake Michigan has ten AOCs (Figure 10). The Grand Calumet River/Indiana Harbor Ship Canal, Milwaukee, and Green Bay AOCs are the most degraded in the basin (SOLEC 1994). Contamination of past steel-making practices through air emissions, sediment, and ground water has resulted in a loss of fish habitat in the Grand Calumet River AOC.

The area is classified as eutrophic, and the fish community is dominated by extremely pollution-tolerant species, carp and goldfish (Hartig 1993). Spawning areas in the Milwaukee River estuary are polluted, and modifications to channels by dams have degraded habitat and restricted natural reproduction of salmon, walleye, bass, pike and trout (Hartig 1993). Green Bay has a legacy of contaminants from pulp and paper mill releases into the Lower Fox River. Stocking efforts re-introduced muskellunge in Green Bay, and supported existing fish species such as walleye that are now reproducing naturally (Hartig 1993).

Figure 10. Lake Michigan Areas of Concern



The EPA's Lake Michigan Management Plan (LaMP) ranks pollutants based on the degree of association with impairments and the frequency of their occurrence (see Table 6). Critical pollutants are classified as especially persistent chemicals that biologically accumulate in the food web and pose greater threats to top predator fish such as lake trout and salmonids. Reproductive failure, increased mortality, malignancies, disruption of the immune and nervous systems, and carcinogenic effects can result from contaminants in the water (Beeton et al. 1999). Levels of heavy metals, certain pesticides and industrial chemicals such as polychlorinated biphenyl (PCB), dichlorodiphenyltrichloroethane (DDT), dieldrin, and polychlorinated dioxins have been identified in fish and exceed the accepted concentration for human consumption (Devault

1985). This has led to fish consumption advisories, which set guidelines in an attempt to limit the negative affects on human health. From 1970 to the mid-1980s, concentrations of PCBs, DDT, and dieldrin in lake trout declined steadily but have since leveled off (DeVault and Hesselberg 1996). Contaminant levels were still higher in lake trout from Lake Michigan than lake trout from any other of the Great Lakes (DeVault and Hesselberg 1996).

Although regulations have decreased the amount of contaminants entering the lake today, a legacy of pollution remains in the sediment, and wave action have the potential to increase levels of contaminants in the water column. Lake Michigan is estimated to have a total of 75,000 kg of PCBs and 35,000 kg of DDT, of which the majority is considered permanently buried in lake sediment (Golden et al 1993). Hornbuckle et al. (2004) showed that large-scale storms in unstratified waters can resuspend contaminated sediments and reintroduce these contaminants into the water column.

Table 6. Level 1 pollutants listed in the Lake Michigan LaMP 2004 (http://www.epa.gov/glnpo/lakemich/2004update/), and monitored through the Great Lakes Binational Toxic Strategy[1]. The GLBTS states "these substances occur in the water, sediment, or aquatic biota of the Great Lakes ecosystem and exert, singly or in a synergistic or additive combination, a toxic effect on aquatic, animal, or human life. They represent the immediate priority for virtual elimination through pollution prevention and other actions that will phase out their use, generation or release in a cost-effective manner".

Critical Pollutants	Pollutants of Concern	Pollutant Watch List
Total PCBs	Cadmium	Atrazine
Chlordane	Copper	PCB substitute compounds
Dioxins	Arsenic	Selenium
Mercury	PAHs[2]	
DDT/DDD/DDE	Zinc	
	Cyanide	
	Endrin	
	Cyanide	
	Heptachlor epoxide	
	Lindane	
	Chromium	
	Nickel	
	Alkyl-lead	
	Nutrients	
	Pathogens	
	Sediments	

[1]GLBTS Level 1 substances also include benzo (a) pyrene (B(a)P), octachlorostyrene (OCS), dieldrin/aldrin, and mirex. These substances are located primarily in tributaries and therefore do not qualify as LaMP critical pollutants.

Summary of Data and Current Initiatives

Understanding the processes controlling the cycling of nutrients, sediment, and contaminants has been the focus of several studies in Lake Michigan. The Lake Michigan Mass Balance (LMMB) study was begun in 1993 by EPA Great Lakes National Program Office (GLNPO) to measure and model contaminant cycling and availability within the Lake Michigan ecosystem. During 1994 and 1995, the study measured concentrations of PCBs, trans-nonachlor, atrazine and mercury in various components of the lake's ecosystem, i.e. atmosphere, tributaries, open water, sediments, and food webs. These data have been used to understand how toxic contaminants move into and around the Lake Michigan ecosystem. For example, results from the LMMB study show that the greatest external inputs of PCBs are from atmospheric vapor, followed by tributary inputs and the greatest losses are from volatilization and deep burial in lake sediments (McCarty et al. 2004). The Fox, Grand Calumet, and Kalamazoo Rivers had the largest tributary loads of PCBs to Lake Michigan (McCarty et al. 2004).

The Episodic Events Great Lakes Experiment (EEGLE) led by the National Oceanic and Atmospheric Administration's (NOAA) Great Lakes Environmental Research Laboratory (GLERL) was initiated in 1996 to study a turbidity plume that extended 200 miles along the southern coast of Lake Michigan. This project created integrated observational and modeling programs for monitoring resuspension events and assessing their impact on the lake's ecology. The plume is hypothesized to influence suspended sediments and internal recycling of nutrients and contaminants, thus impacting the overall ecology of Lake Michigan. Using a 3-D coupled physical and biological model, Chen et al. (2004) showed that phytoplankton dynamics were closely related to the physical mixing.

A new center of Excellence for Great Lakes and Human Health was established in 2004 by NOAA GLERL with a mission to understand the inter-relationships between the Great Lake ecosystem, water quality and human health. The center will focus on using ecosystem forecasting to define the relationships between land-use, hydrodynamics, water quality, beach closings, and algal blooms (Rochelle Sturtevant, NOAA GLERL personal communication).

Information and Research Needs

Information and research needs as they relate to the environmental objective to protect and restore water quality.

- Support cooperative lake-wide monitoring of water quality.
- Forecast ecosystem response to biological, chemical, physical and human-induced changes.
- Understand the impact of changing land use patterns on the ecology of Lake Michigan.

- Evaluate existing programs for their effectiveness at reducing critical pollutants.
- Monitor response of fish communities to remedial actions.
- Examine connections between water quality and fisheries productivity.

Status of Environmental Objective # 6- *Protect and restore water quality*

Species	Impediment to achievement	Problems/issues to be addressed
Lake trout Trout and Salmon Walleye Yellow perch Smallmouth bass Lake whitefish	Yes	Restrictions of fish consumption Reproductive failure Increased mortality Malignancies
Forage fish Benthos Phytoplankton	Yes	Nutrification

Yes	Data exists documenting an impediment to achievement of the FCO
Potentially	Available data are inconclusive, but suggest a potential impediment
Inconclusive	Available data suggest neither an impediment or no impediment
Unlikely	Available data are inconclusive, but suggest that there is no impediment
No	Available data document no impediment

Water quality section addendum:

Effects of water quality parameters and contaminants on Great Lakes fish behavior, energetics and ecology are well known for only a few variables, and are not appropriately discussed in great detail in the EO document. Useful summary publications on water quality criteria are available online including:

- A data compilation by Tewinkel and Dawson (2001) on habitat requirements and characteristics of life stages of 18 selected Great Lakes fishes.

- A summary edited by Wisner and Christie (1987) provides useful and accessible data on thermal requirements for 116 Great Lakes fishes. The data are organized by temperature effects on fish survival, preferences, growth, reproduction and early survival development.

Emerging Issues

Climate Change and Water Levels

The climate of the Great Lakes region is expected to become both warmer and drier during the twenty first century. These changes in climate potentially could have serious impacts on the Lake Michigan ecosystem. By the end of this century, climate models predict that temperatures in the Great Lakes region will warm by 3 to 7°C in winter and by 3 to 11°C in summer (Wuebbles and Hayhoe 2003). Climate change will alter the physical forces i.e. precipitation, wind speeds, evaporation that impact lake levels and other factors which maintain the Lake Michigan ecosystem.

Great Lakes water levels are projected to decrease as a result from climate change. Shifts in the climate are estimated to result in a decrease in the Lake Michigan - Huron lake levels by 0.72 meters by 2030 and 1.38 meters in 2090 (Lofgren et al. 2002). The Canadian Coupled Climate Model (CGCM1) and the Hadley Coupled Climate Model (HadCM2) both show future increases in temperature, precipitation, evaporation, surface runoff, soil moisture and surface wind speeds (Sousounis and Grover 2002; Wuebbles and Hayhoe 2003). Although overall precipitation is projected to increase, the patterns of precipitation will become much more variable. Winters will receive more precipitation while summers may possibly see a decrease in rainfall. Even if the annual precipitation over the Great Lakes region does not change significantly, evaporation during winter months will contribute to lower lake levels. Warmer temperatures decrease the extent and length of ice cover over Lake Michigan, resulting in a greater amount of open area where water can evaporate.

Water levels in coastal wetland areas also would decrease as a consequence of climate change and lower lake levels on Lake Michigan (Mortsch and Quinn 1996). The decrease in wetland area will reduce the capacity for moving and filtering nutrients, pollutants, and sediments from land into the lake. Lower lake levels will also lead to conflicts with the shipping, water diversion and possibly hydropower industries (Cohen and Miller 2001).

Climate has strong and complex effects on aquatic ecosystems, fish populations and fisheries (eg. Cushing 1983). In marine ecosystems, for example, Pacific salmon stocks (Beamish and Noakes 2002) are strongly influenced by fluctuations in decadal scale climate patterns (Pacific Decadal Oscillation) that affect stocks differently in different regions of western North America, and require spatially complex management schemes. McFarlane et al. (2002) attributed the fall and rise of Pacific sardine populations to overfishing, decadal fluctuations in climate and conservative management plans. Drinkwater (2002) attributed the failure of Atlantic cod to rebound from overfishing in the northwest Atlantic Ocean to unfavorable regime shifts in the North Atlantic Oscillation. In the Great Lakes region, evidence for climate impacts on fisheries is pervasive. Thermal habitat volume in lakes is strongly correlated with fisheries yield (Christie and Regier 1982) because it structures lake ecosystems and drives biological processes, and temperature gradients produce ecotones of enhanced lake productivity, consumption and growth of lake organisms (Magnuson et al. 1979, Brandt et al. 1980). Temperature or temperature variability has been correlated with survival of sensitive early life stages and recruitment of species including lake whitefish (Taylor et al. 1987), bloater (Rice et al. 1987), alewife (Huefeld et al. 1982, Casselman 2002, Madenjian et al. in press), steelhead (Seelbach 1993, Rutherford unpublished data), and smallmouth bass (Shuter et al. 2002). Recently, positive correlations between tributary discharge and fish recruitment suggest tight linkages exist between watersheds and Great Lakes fisheries (Zafft 1992, Ludsin and Stein 2001, Rutherford , unpub. data).

Recent predictions of climate change impacts on Great Lakes fishes and fisheries have varied with species' thermal preferences and habitats. Stefan et al. (2001) predicted global warming would expand habitat for warmwater fishes, and reduce or eliminate summer habitats of coolwater and coldwater fishes in small North American lakes. Brandt et al. (2002) concluded that global warming would extend duration and depth of the thermocline, and duration of the growing season for coldwater and coolwater fishes in Lake Michigan, thereby improving their bioenergetic growth potential. Casselman (2002) analyzed data on temperature and fish yields in Lake Ontario to develop predictions of fish recruitments under warming scenarios during different seasons. Walleye and northern pike recruitments appeared to increase under increased summer temperatures, while recruitment of coldwater lake trout would decrease. Shuter et al. (2002) used a spatially-extensive database of fishery yields and fish growth characteristics to predict impact of climate change on walleye and smallmouth bass abundances. Climate change scenarios were hypothesized to have greatest and most immediate impact on species like smallmouth bass whose recruitments are positively correlated with summer temperatures and negatively correlated with cold winter temperatures. As water levels drop and coastal wetland areas decrease, competition for habitats will increase for fish species that utilize coastal wetland habitats for spawning, nursery, feeding and shelter areas,

Increased variability in recruitment of key forage fish species and their predators resulting from climate variability may complicate management objectives for sustainable Great Lakes fisheries and fish communities. For example, most Great Lakes predator populations are artificially controlled by hatchery production rather than by density-dependent feedback mechanisms. In such a system, hatchery production is maximized in response to public demand at the risk of exceeding the ecosystem's capacity to support stocking rates. Recently, management practices have qualitatively considered the status of prey fish populations when making stocking decisions. However, variable natural reproduction of predators and their prey generated by climate change may complicate stocking decisions based solely on prey fish supply, and potentially disrupt the balance between predator demand and prey supply.

In the Great Lakes, the ability to identify linkages between climate, aquatic ecosystems, fish population dynamics and fisheries has improved tremendously through collaborative relationships and expertise between state and federal research and management agencies, and universities. The availability of extensive time series of data on fish community abundances and harvests (Madenjian et al. 2002, Casselman 2002) now permits characterization of natural variability and prediction of future climate impacts. Hydrodynamic circulation models now available for Lake Michigan permit understanding of how lake circulation patterns may retain or advect fish larvae away from favorable nursery areas, with implications for fish recruitment (Beletsky et al. 2004) and movement. Studies of land-use patterns, watershed dynamics and fisheries habitat allow prediction of direct and indirect effects of climate change on tributary habitats and their adfluvial fish populations.

Information and Research Needs:

- Understand and predict climate change impacts on fish habitats, fish vital rates, and fisheries harvest over multiple spatial scales, ranging from tributaries to open-lake habitats, and incorporate that knowledge into fisheries management policies.
- Quantify historic natural population variability of young-of-year or yearling fish abundances on annual and decadal time scales, and relate the variability to historic climate patterns.
- Use regression and simulation models to predict climate change impacts on key lake fishes across multiple spatial scales.

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